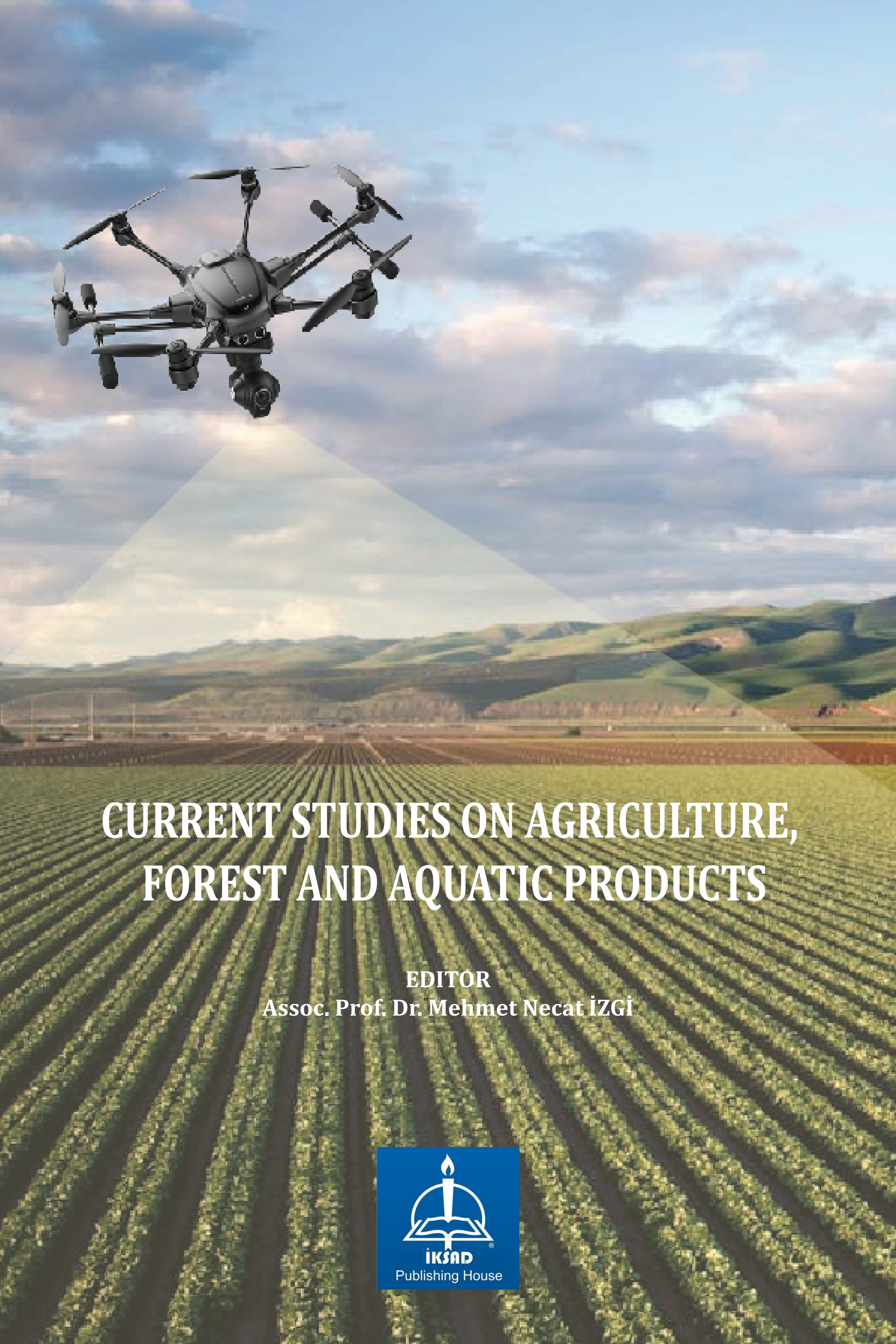


CURRENT STUDIES ON AGRICULTURE, FOREST AND AQUATIC PRODUCTS

EDITOR
Assoc. Prof. Dr. Mehmet Necat İZGİ

İKSAD
Publishing House

CURRENT STUDIES ON AGRICULTURE, FOREST AND AQUATIC PRODUCTS

EDITOR
Assoc. Prof. Dr. Mehmet Necat İZGİ

AUTHORS
Prof. Dr. Funda TURAN
Prof. Dr. Hüseyin PEKER
Prof. Dr. Tamer ERYİGİT
Prof. Dr. Tolga DEPCİ
Assoc. Prof. Dr. Arzu MUTLU
Assoc. Prof. Dr. Emine KAYA ALTOP
Assoc. Prof. Dr. Murat DIKILITAŞ
Assoc. Prof. Dr. Orkun BABACAN
Assoc. Prof. Dr. Sema KARAKAŞ DİKİLİTAŞ
Assoc. Prof. Dr. Şule CEYLAN
Assoc. Prof. Dr. Timuçin TAŞ
Assist. Prof. Dr. Fevzi ALTUNER
Dr. Ayşegül ERGENLER
Dr. Ferhat UĞURLAR
Res. Assist. Ramazan AYAŞ
Ahmet ŞEKEROĞLU
Ceren Ayşe BAYRAM
Emir Kulal ALTUNER
Hasret GÜNEŞ
Melis ÇELİK GÜNEY
Mustafa GÜNEŞDOĞDU
Mohammed Oday AL HAMDANI
Mert EYİLİ
Nazan KOLUMAN (DARCAN)
Süreyya Betül RUFAİOĞLU
Yavuzkan PAKSOY

İKSAD Publishing House

Institution of Economic Development and Social
Researches Publications®
(The Licence Number of Publicator: 2014/31220)
TÜRKİYE TR: +90 342 606 06 75
USA: +1 631 685 0 853
E mail: iksadyayinevi@gmail.com
www.iksadyayinevi.com

It is responsibility of the author to abide by the publishing ethics rules.
Iksad Publications – 2024©

ISBN: 978-625-367-898-2
Cover Design: İbrahim KAYA
November / 2024
Ankara / Türkiye
Size = 16 x 24 cm

DOI: https://dx.doi.org/10.5281/zenodo.14042631

CONTENTS

PREFACE

Agriculture today faces an array of challenges that stem from environmental shifts, population growth, and the demand for sustainable food production. Addressing these challenges requires a proactive approach rooted in research, innovation, and collaboration. Each chapter in this volume offers insights that contribute to a broader understanding of the dynamics shaping agricultural practices. Rather than focusing solely on regional specifics, this book encourages readers to consider the global context, recognizing that agriculture plays a pivotal role in both ecological balance and economic stability. The authors have meticulously explored ways to bridge the gap between traditional methods and modern demands, suggesting paths to enhance productivity while safeguarding resources. By examining the agricultural landscape through a scientific lens, this book underscores the importance of adaptive strategies to secure a sustainable future. It is our hope that these collected efforts will serve as a valuable resource for all who seek to advance agriculture toward a more resilient and responsible framework. As such, the work presented here aims to inspire ongoing efforts to bring agricultural practices closer to their ideal state—one that harmonizes human needs with the health of our planet.

Assoc. Prof. Dr. Mehmet Necat İZGİ[1]

[1] Mardin Artuklu University, Kızıltepe Vocational School, Crop and Animal Production Department, 47100, Artuklu-Mardin, Turkey; necatizgi@artuklu.edu.tr; https://orcid.org/:0000-0003-1657-1169

CHAPTER 1

HONEY BEE (*Apis mellifera* L.) NUTRIENTS AND NUTRITIONAL PHYSIOLOGY; A REVIEW

Mustafa GÜNEŞDOĞDU[1]*, Ahmet ŞEKEROĞLU[2]

[1] Department of Animal Production and Technologies, Faculty of Applied Sciences, Muş Alparslan University, 49250, Muş, Türkiye. 1; m.gunesdogdu@alparslan.edu.tr
[2] Department of Animal Production and Technologies, Faculty of Agricultural Sciences and Technologies, Niğde Ömer Halisdemir University, 51240, Niğde, Türkiye. 2; ahmet.sekeroglu@nigde.edu.tr
*Correspondence: m.gunesdogdu@alparslan.edu.tr

Introduction

Honey bees (*Apis mellifera* L.) are the most important species for the sustainability of flowering plants. They are also one of the most important bee species with worldwide ecological and economic value (Güneşdoğdu et al., 2023). Nutrition is the intake of nutrients required by the body from the outside via the mouth. Honey bees also need food to survive (Haydak, 1970). The nutrition of honey bees can be analyzed on three levels (nutrition of the bee colony, nutrition of the adult bees, nutrition of the larvae) (Ulutaş and Özkırım, 2018). The nutrition of bees depends to a large extent on the environment, in particular on the composition of the flora in the landscape (Donkersley et al., 2014). The composition of the flora varies both in the landscape and over time (Rivera et al., 2015).

This study focuses on the question "What role does nutrition play in the development, health and physiology of honey bees?". That is, the nutritional requirements of bees and their relationship to vitellogenin (Vg), adipose tissue, gut flora, hypopharyngeal and mandibular glands and disease will be investigated.

1. Food Collection by Honey Bees

A honey bee colony consists of a queen, drones, and worker bees. The queen and the drones do not visit flowers to find food during their entire life. Only the worker bees (sterile female bees) are responsible for foraging. The worker bees have various roles in the colony, from emergence to death. Genotype and environment have a major influence on these behaviors (Robinson, 2002) Worker bees collect nectar (including honeydew honey), pollen, water and propolis from nature. Depending on the needs of the colony, different amounts of these nutrients are collected at different times of the year. The collection and storage of pollen and nectar is influenced by the genetic make-up of the worker bees (Robinson and Page, 1989). Worker bees collect pollen from flowering plants in pollen baskets (corbiculae) on their hind legs and carry it to the colony (Free, 1963). The bees are usually specialized in collecting pollen from a particular type of flower. Therefore, the pollen they carry to the colony each time belongs to a single flower species (Gruter and Ratnieks, 2011). A bee carries about 15 mg of pollen to the colony each time (Seeley, 1986). Bees can recognize differences in nectar concentration and prefer highly concentrated nectar (Afik et al., 2006). The bees carry the nectar in their honey stomach to the bee colony. A worker bee carries about 30 mg of nectar to the colony each time (Seeley, 1995). The meteorological conditions and the distance from the food source have a direct influence on the collection of food by forager bees (Sponsler et al., 2017; Malagnini et al., 2022).

2. Honey Bee Foods

Like other living creatures, honeybees need vital components to survive and reproduce. The information on bee nutrition comes from studies carried out since the 1950s. In recent years, the number of nutritional studies has decreased significantly. Honey bees need carbohydrates (nectar and honey), amino acids (pollen), lipids (fatty acids and sterols), vitamins, minerals (salt) and water. In order for bees to survive and reproduce, these nutrients must be present in the colony in direct proportion to each other (Huang, 2010). The physiological differences between worker bees, queen bees and drones also lead to differences in their nutrient requirements (Hrassnigg and Crailsheim, 2005).

2.1. Carbohydrates

Honey bees, like other living organisms, need carbohydrates as a source of energy. All carbohydrates are converted into ATP (adenosine triphosphate) in the Krebs cycle and thus into fuel for the cells. This produces carbon dioxide and glucose as by-products. Glucose is used as an energy source, the surplus is stored in the body as fat. In contrast to the larvae, adult bees only have small glycogen stores (0.05-0.47 mg/bee) (Hrassnigg and Crailsheim, 2005). A worker bee needs 11 mg of sugar per day (Huang et al., 1989). A colony of about 50,000 adult bees needs 1.1 liters of sugar syrup (1:0.5) per day (Huang, 2010). Nectar, honey, and honeydew honey are the main sources of carbohydrates in the bees' natural diet (Nicolson and Human, 2008). The sugar concentration in nectar is between 5 % and 75 %. The most concentrated sugars in nectar are sucrose, glucose and fructose. The ratio between these three sugars depends on the nectar source (Nicolson and Thornburg, 2007). Adult bees can utilize glucose, fructose, sucrose, trehalose, maltose and melezitose. However, they cannot digest raminose, xylose, arabinose, galactose, mannose, lactose, raffinose and melibiose (Huang, 2010). These sugars are contained in around 40% of soybean meal and are toxic for use as a pollen substitute (Barker, 1977).

The phytochemicals in nectar are largely considered useful to bees. Phenolic acids, flavonoids, alkaloids and terpenoids are the most abundant phytochemicals in nectar (Liao et al., 2017; Palmer-Young et al., 2017). Their composition and concentrations vary depending on the flower taxon (Palmer-Young et al., 2019). Among the phenolic acids and flavonoids, p-coumaric acid and quercetin are important for bee health. Increased consumption of phytochemicals increases longevity, reduces *Nosema* spp. Infestation, and minimizes exposure to pesticides (Liao et al., 2017; Bernkalu et al., 2019). Storage of nectar in the bee colony, the nectar carried by the forager bees to the bee colony is transported by the bees by trophallaxis (mouth-to-mouth relationship) for storage in the comb cells (Camazine et al., 1991). The water contained in the nectar is evaporated by the bees (Park, 1925). The evaporation of the water and the displacement between the comb cells accelerate the process of ripening the nectar into honey (Eyer et al., 2016). Honey with sufficient evaporated water (<20%) has a high concentration of sugars (>80%). The most abundant sugars in honey are glucose and fructose. Various enzymes (invertase, diastase, glucose oxidase) are added to the honey during the conversion of nectar into honey (Doner, 1977). In times of scarcity, when nectar is not flowing, bee colonies are generally fed with carbohydrates. Sucrose syrup, invert sugar, high fructose corn syrup and various fruit juices are used as carbohydrate sources (Neupane and Thaba, 2005). Grape syrup is not recommended as it causes dysentery in bees (Barker and Lehner, 1978). When feeding bees, the ratio of fructose:sucrose is 18% in the first three days of larval development, and 45% in the last two days. During the larval stage, about 59.4 mg of carbohydrates are consumed (Rostais et al., 2005).

2.2 Proteins

The units formed in the male reproductive organs of flowering plants are called "pollen" (Krell, 1996). Pollen is found as 2.5-250 µm grains in the anthers of seed plants (Couto and Couto, 2006). Pollen is the source of proteins, minerals, lipids and vitamins for the bees (Herbert and Shimanuki, 1982). The type and nutritional composition of pollen varies depending on the season, climate, plant species and age of the plant. All animals require essential amino acids such as arginine, histidine, isoleucine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan and valine, which must be supplied externally and cannot be synthesized by the body (De Groot, 1953). The source of these amino acids for bees is pollen. The protein content of bee pollen is given as over 40 %, but is generally between 7.5 % and 35 %. The carbohydrate content is between 15 and 50 %, and in some wind-pollinated plants the starch content is up to 18% (Krell, 1996). Its color characteristics are highly variable and can appear in many different colors such as yellow, red, black and purple. Pollen contains 1-20 % fatty acids and sterols, vitamins (except A, K, B12) and various minerals (Bogdanov, 2011). Among the lipids, the essential fatty acids (EFA) are the most important, which are contained in the pollen to around 5.1%. Acids such as linoleic acid, γ-linolenic acid and archaic acids are represented with 0.4 %. Phospholipids reach 1.5 %, while phytosterols, especially P-sitosterol, make up 1.1% (Szczesna, 2006). Macronutrients (calcium, phosphorus, magnesium, sodium and potassium) and micronutrients (iron, copper, zinc, manganese, silicon and selenium) account for around 1.6% (Campos et al., 2010). The average biological value of pollen is 72 (van Tets and Hulbert, 1999), and it also has antifungal, antimicrobial and antiviral effects and promotes the healing of burns (Kroyer and Hegedus, 2001; Almaraz-Abarca et al., 2004; Basim et al., 2006). A standard colony (10 frames) collects about 10-26 kg (Wille et al.,1885) of pollen per year and consumes 13.4-17.8 kg of pollen (Crailsheim et al., 1992). The protein content of pollen varies between 2.5% and 61% (Roulston et al., 2000). The forager bees prefer pollens with a high protein content (Ghosh et al., 2020). About 15 to 30 % of the adult worker bees in the colony are pollen collectors (Ellis et al., 2020). The pollen carried to the colony is stored by the worker bees in the comb cells as "bee bread". A newborn adult worker bee consumes around 65 mg of pollen in ten days (Crailsheim et al., 1992). A larva consumes 25.0-37.5 mg of protein. This corresponds to 125 - 187.5 mg of pollen (Hrassnigg and Crailsheim, 2005). An adult bee consumes an average of 3.4 - 4.3 mg/day of pollen (Crailsheim et al., 1992). Bee colonies that are fed a low nutritional value or too little pollen produce less brood. Vitollegenin is the main source of protein storage in the hemolymph. This protein can reach up to 80 µg/µL in winter bees. This lipoprotein has a direct effect on the onset of foraging behavior and life expectancy (Amdam et al., 2003). It also shortens the lifespan of adult worker bees (Knox et al., 1971). In colonies fed with pollen or substitute products in spring, the negative effects on honey yield (Mattila and Otis, 2006a), Varroa mite (Janmaat and Winston, 2000), and Nosema infection (Mattila and Otis, 2006b) are lower. Pollen-collecting worker bees store the pollen in the comb cells when they return to the colony. The worker bees in the bee colony press the pollen and add honey (Anderson et al., 2014). This stored pollen is called bee bread (perga). The protein content of bee bread is in a narrower range (10-30%) than that of pollen. The fat content (3-8%) is lower than that of pollen (Bonvehi and Jorda, 1997; Herbert and Shimanuki, 1978c). Brood production and the nutrition of bee brood are dependent on proteins. If the stored pollen (bee bread) is not sufficient, the behavior of brood eating (cannibalism) is observed by the workers (Schmickl and Crailsheim, 2002). A higher protein content in the bee diet has a negative effect on life expectancy and population growth (Zheng et al., 2014).

The nurse bees in the bee colony feed all members of the colony. Honey and bee bread or royal jelly and young bee milk secreted by the nurse bees are used directly for feeding (Hrassnigg and Crailsheim, 1998). The size of the mandibular and hypopharyngeal glands of the young nurse bees reaches a maximum at the age of 6 to 10 days with the intake of pollen (Pernal and Currie, 2000). The nurse bees are the most important pollen consumers in a bee colony. They ingest much more pollen than the forager bees and have a digestive enzyme (protease) in their midgut. The size of the hypopharyngeal glands correlates with protease activity (Moritz and Crailsheim, 1987). The exine layer, known as the pollen wall, is the physical barrier to digestion. It serves to protect the pollen and consists of a very rare structure called sporopollenin (O'Rourke and Buchmann, 1991). The transit time of pollen through the gut varies between 2 and 24 hours (Crailsheim, 1990), and about 75% is digested (Schmidt and Buchmann, 1985). The rate of pollen digestion is determined by the proportion of empty pollen grains that are ingested with the feces and remain undigested (Crailsheim et al., 1992; Human et al., 2007). Another method is to determine the protein content in feed and feces (DeGrandi-Hoffman et al., 2016; Schmidt and Buchmann, 1985). If the bees are fed with pollen substitutes (e.g. soy meal), they can digest about 25 % of the protein (DeGrandi-Hoffman et al., 2016). In the early larval stage, however, the pollen cannot be digested. The main reason for this is the lack of bacterial flora in the digestive tract. In the later larval stages, the bacterial flora develops with the consumption of the pollen (Powell et al., 2014).

2.3 Lipids

Lipids are an important source of energy and are mainly metabolized during the honey bee's breeding season. Pollen contains between 1 % and 20 % lipids (Roulston et al., 2000). Essential fatty acids are an important component of this. Fatty acids such as linoleic and g-linolenic acid make up 0.4 % of the total lipid concentration, phospholipids 1.5% (Szczesna, 2006). An oleic acid concentration of more than 2 % shortens the lifespan of adult bees (Manning et al., 2007). Sterols are a form of lipids that play an important physiological role in insects. Depending on the sterol preference of the bees, the choice of host plant varies when foraging (Vanderplanck et al., 2020). They prefer different plants that have the required sterol composition (Chakrabarti et al., 2019a). The sterols in pollen are vital for honey bees, as are the phytosterols that are digested by worker bees: 24-methylenecholesterol (the most important sterol), sitosterol and isofucosterol (Svoboda et al., 1982). The most abundant sterol in pollen is 24-methylenecholesterol. This sterol makes up 41.2 % of the total sterols (Xu and Gao, 2013). Bees cannot convert phytosterols into cholesterol. Since almost all insects cannot synthesize sterols, they must ingest them with their diet. Sterols prolong the lifespan of bees, increase the protein content in their head and the fat content in their abdomen (Chakrabarti et al., 2020; Chakrabarti et al., 2019b). It is also the most important sterol in the pupa. Bees cannot convert C28 and C29 phytosterols into each other, and nurse bees absorb them from their tissues and pass them on to their offspring (Svoboda et al., 1986). Monofloral pollen contains very little of these sterols (Vanderplanck et al., 2014). Foods with a low fat content are not attractive to bees. Pollen substitutes should contain 3 to 8 % fat (Huang, 2010). The ratio of proteins and fats in diet is important for bees. The ratio of proteins:fats in pollen collected at different times is 10:1 (Avni et al., 2009). A low ratio of omega-6 to omega-3 fatty acids improves the learning performance of honey bees (Arien et al., 2015).

2.4. Vitamins

Bees cover their vitamin requirements from pollen. They need vitamins especially during brood rearing. In contrast to the fat-soluble vitamins, the water-soluble vitamins are particularly abundant in pollen (Roulston and Cane, 2000). Bees need thiamine, riboflavin, nicotinamide, pyridoxine, pantothenic acid, folic acid, ascorbic acid and biotin (Huang, 2010). Adding the fat-soluble vitamins A, D, E, and K to bee feed increases brood production (Herbert and Shimanuki, 1978a).

2.5. Minerals

The mineral requirements of honey bees are not yet fully understood. However, it is estimated that they require large amounts of potassium, phosphate and magnesium. Excess sodium, sodium chloride and calcium are toxic to honey bees. An ash content in the pollen of more than 2 % prevents brood formation (Huang, 2010). Bee feed containing 1000 ppm potassium, 500 ppm calcium, 300 ppm magnesium and 50 ppm sodium, zinc, manganese, iron and copper has a positive effect on brood rearing (Herbert and Shimanuki, 1978b).

2.6. Water

Water is vital for bees (Nicolson, 2009). If honey bees are dehydrated, they can die within a few days. Honey bees need water for two purposes (Yeninar et al., 2015). Firstly, to dilute the honey and facilitate the addition of honey to the brood food. Secondly, they use it to cool the hive when the ambient temperature rises above 35 °C (Genç and Dodoloğlu, 2002). The bees' water requirements depend on the temperature inside and outside the hive and on the activities inside the hive (e.g. brood rearing, water requirements of the individuals). The bees need a source of clean water near the hive. Adding a small amount of salt to the water makes it more attractive (Huang, 2010). Physiologically, bees need water for the digestion of ingested nutrients, excretion of waste and transportation to target organs (Yeninar et al., 2015). When water is scarce, nutrition, physiology, brood production and behavior are impaired (Yeninar et al., 2015). The optimum relative humidity for normal brood activity in the bee colony should be 90-95%. If the relative humidity drops, the eggs and larvae dry out and die (Doull, 1980). As brood activity increase, so does the need for water. Approximately 66 % of the brood food consists of water. Bees prefer water with a temperature of 18-32°C (Genç and Dodoloğlu, 2002).

2.7. Supplementary Feeding in Hobeybees

The health of honey bees and the development of the bee colony depend on the nutrients in the hive. Honey bees obtain their carbohydrate requirements from nectar and all other nutrients, especially proteins, from pollen (Brodschneider and Crailsheim, 2010). Understanding the nutritional requirements of honey bees (*Apis mellifera*) and developing strategies for managing bee colonies according to the correct feeding models, creating more disease-resistant populations in bee colonies, high yields and avoiding bee losses make an important contribution (Sabir et al., 2000). In recent years, the decline in plant biodiversity due to climate change and the prolonged dry season have led to a decline in bee colonies, insufficient fat tissue in winter bees due to protein deficiency and a shortened lifespan. Bees need large and suitable pasture areas. Shrinking pasture areas due to drought lead to a decline in bee foraging, population growth and natural food resources (Varol and Yücel, 2019). In beekeeping practice, sucrose is used instead of honey when there is insufficient flora, while a complete substitute feed for pollen has not yet been developed. Therefore, pollen becomes a limiting factor in maintaining the health of the colony (Shumkova et al., 2017). Autumn care and feeding is particularly important in beekeeping. The rearing of young brood with additional feeding in the fall reduces possible winter losses (Akyol et al., 2006). However, due to climate change, drought in spring and summer and persistent rainfall increase the bees' pollen requirements. The most natural protein feed for bees is a mixture of honey and pollen (Dodoloğlu and Emsen, 2007). However, the inadequate production, cost and contamination of pollen with various diseases limit its use in beekeeping. Studies show that various flours, meals and yeasts can be used as a substitute for pollen. There are studies that show that the use of these products at any time of the year is important for the bees. Pollen substitutes are becoming increasingly important to create strong and healthy bee colonies. For bees, the substitute feed must have a high nutritional value and be tasty. A well-prepared pollen substitute feed can reduce the stress caused to bee colonies by a lack of food (Köseoğlu et al., 2019). In Turkey, there is still no pollen substitute feed with sufficient effectiveness. Colonies should have sufficient honey stores to raise brood, carry out daily tasks and survive dry periods. In the event of a honey shortage, sugar syrup should be added (Hays, 1984). Within the hive, the nurse bees are responsible for feeding the queen, the drones and the young and old young bees of the colony. The nurse bees play a fundamental role in the population dynamics of the colony by providing the nutrients necessary for the development of the young and adult individuals of different physiological ages, classes and sexes that develop in the colony, either directly or through metabolism (royal jelly) (Crailsheim et al., 2013). The protein required for the production of royal jelly is obtained from fresh pollen introduced into the bee colony or from bee bread, a fermented product. The pollen is a source of protein, carbohydrates, vitamins, minerals and fats for bees (Roulston and Buchmann, 2000; Stanley and Linskens, 1974). Pollen substitutes, which are added to bee cakes, cover the pollen requirement relatively well. Diets prepared with substances such as skimmed milk powder, soy flour, and meal and brewer's yeast have a great effect on bee colonies (Stace, 2000). Adult honey bees are generally fed a carbohydrate:protein (C:P) diet. The protein ratio determines the food intake. Carbohydrate-rich feeds are consumed more (Stabler et al., 2015).

2.8. Substitute Feeds

Beekeepers have two ways of promoting brood rearing in their honey bee colonies. The first is to move the colonies to areas with a variety of flowers, and the second is to feed them. Both options have a major impact on beekeepers' economic decisions. The term pollen supplement feeding means that there is some pollen and/or nectar in the field where the colonies are located and the colonies are fed with supplements to which a small amount of pollen is added. The term pollen substitute means that the nectar and pollen source in the area where the colonies are located is completely absent and the beekeeper feeds liquid substitutes with a high sugar content and solid substitutes with added protein as a pollen substitute (Somerville, 2000).

2.9. Biological Value of Foods

Biological value - the ratio between the amount of dietary protein remaining in the body for the synthesis of new tissue and the amount absorbed in the intestine. In other words, it is the amount of nitrogen (N) that is digested and absorbed from the digestive system and remains in the body for bodily functions. This value is calculated with the equation ((consumed N - (fecal N + urinary N) / (consumed N - fecal N)) x 100 (Kutlu, 2008). The pollen grains are filtered in the honey stomach of the bees and passed on to the stomach proper. Nitrogenous liquid waste produced during digestion is absorbed from the blood via the Malpigi tubes and passed into the small intestine (Winston, 1987). The biological value of the egg is assumed to be 100, and the biological value of the other nutrients is used as the basis for calculation. The average biological value of pollen is 72 (van Tets and Hulbert, 1999). The biological value of milk, red meat, soy and casein is 88, 80, 75 and 80 respectively (Çelebi and Karaca, 2006).

2.10. The Digestive System of Honeybees

The morphology, behavior, biology and physiology of honey bees vary depending on the environment to which they are adapted. This leads to a great diversity among bee species (Ruttner, 1992; Güler and Toy, 2008). This diversity leads to differences in the structure of the digestive system of individual species and ecotypes (Lebrun, 1985; Santos and Serrao, 2006). The digestive system of insects consists of three main parts: the foregut, the midgut and the hindgut. These three parts of the gut harbor a community of beneficial or commensal (neither harmful nor beneficial) bacteria (Mattila et al., 2012). In honey bees, the foregut consists of the oral cavity, the esophagus and the honey stomach, the midgut consists of the stomach proper and the hindgut consists of the ileum and the rectum. There is a proventricular valve between the honey stomach and the stomach proper, which prevents the passage of transported nutrients. The stomach proper is primarily responsible for the digestion and absorption of pollen, while the ileum and rectum are responsible for osmotic control and the absorption of water and ions (Gajger vd., 2011). The honey stomach is responsible for the transportation of nutrients (Silici and Özkök, 2009). The honey stomach is found in the queen, the drone and the worker bee. However, it is most developed in the worker bee. The malpigi tubes are located at the junction of the midgut and hindgut. These tubes fulfill similar functions to the kidneys in mammals (Özbakır and Alişiroğlu, 2019). The rectum expands in winter and in bad weather so that digestive waste can be retained for longer (Winston, 1987). Digestive enzymes throughout the digestive tract include diastase, invertase, glucose oxidase, catalase, lipase and proteases. Diastase is an amylase from the hypopharyngeal gland (HPG) that acts as an enzyme that breaks down starch into dextrins and sugars. Invertase converts sucrose into glucose and fructose. Glucose oxidase converts glucose into D-glucono-1,5-lactone and hydrogen peroxide. The glycosidase formed in the HPG catalyzes the hydrolysis of glycosides to produce glucose (Pontoh and Low, 2002). Trypsin, chymotrypsin and elastase are the most important proteases secreted by the epithelial cells of the midgut and serve to break down proteins in the midgut (Giebel et al., 1971; Sagili et al., 2005). The digestive tract contains a community of many microorganisms called microflora. There are nine different bacterial communities in the digestive tract of bees, the proportions of which change with age (Hroncova et al., 2015). These are *Lactobacillus, Bifidobacterium, Gilliamella, Bortonella, Klebsiella, Snodgrasselia, Bombella, Hafnia-obesumbacterium,* and *Commensalibacter*. The highest amounts are *Lactobacillus* Firm-4 and *Lactobacillus* Firm-5 (Cuesta-Mate et al., 2021). These bacteria are involved in growth, development, disease control, and strengthening the immune system (Raymann and Moran, 2018). The bacterial flora of the hindgut is richer than that of the foregut and midgut (Corby-Harris et al., 2014). The digestive fluid of bees contains the enzymes sucrose and α-glucosidase, which cause the conversion of sucrose. Proteinases are involved in the production of amino acids. Lipase is abundant in the midgut (Standifer, 1967). The epithelial tissues of the digestive tract, which in bees extends from the mouth to the anus, are like a wall that protects the bees from internal and external factors ((Terra, 1990; Vilmos and Kurucz, 1998; Yücel et al., 2022b). The flora in this system regulates immune functions by detoxifying harmful and toxic substances ingested with food (Gaifullina et al., 2017). These bacteria lower the pH and O_2 levels in the gut (Jeyaprakash et al., 2003; Mohr and Tebbe, 2006; Zheng et al., 2017). The disruption of the balance of this microflora through the unconscious use of antibiotics is considered to be the main cause of bee losses (Yücel et al., 2022b).

3. Physiologic Effects of Foods

3.1. Nutrition-Vitellogenin Relationship

Honey bees (*Apis mellifera*) are the most widespread social insect community. In order to save a bee colony from complete extinction, it is necessary to know the needs of the individual bees (Weinstock et al., 2006). Several proteins are synthesized in the honey bee's body that are important for the structure and hierarchical order of the colony (Wolschin and Amdam, 2007).

One of these proteins is vitellogenin (Vg), which has a glycolipoprotein structure (Yücel et al., 2022a). The ratio of proteins, lipids and carbohydrates in its structure is 91 %, 7 % and 2 % respectively. Phospholipid and diacylglycerol are the main lipid components. It is rich in mannose as a carbohydrate (Wheeler and Kawooya, 1990). Vitellogenin (Vg), which is found in vertebrates and invertebrates (Byrne et al., 1989), was first identified by Pan et al. (1969). Vg is a female-specific protein that is mainly synthesized from fat body (Belle's, 2003; Wyatt and Davey, 1996). It is synthesized during vitellogenesis (egg maturation) as part of the synthesis of vitellin, the so-called egg yolk protein (Pan vd., 1969). The juvenile hormone secreted by the gland of the *corpus allatum* in the posterior part of the bee brain triggers the secretion of this protein (Salmela et al., 2015). Vitellogenin was detected in the middle of the pupal stage in queen bees, at the end of the pupal stage in worker bees and after emerged in drone bees (Piulachs et al., 2003). In a more recent study, worker bees were reported to synthesize vitellogenin 2-3 days after emerged as adults (Amdam et al., 2010). Within three days of queen emerged, approximately 70% of the hemolymph protein is consist of Vg. This percentage (40%) is lower in adult worker bees (Barchuk et al., 2002). The Vg gene of the honey bee consists of a polypeptide with a length of 5,440 bp and 1,770 amino acids (Piulachs et al., 2003). In the first 7 days of the adult stage of worker bees, this protein increases, while in the following days the juvenile hormone increases (Robinson, 2002). This organic compound increases the lifespan of bees and the egg production of queens (Tanaka and Hartfelder, 2004; Corona et al., 2007) and is involved in body fat metabolism (Alaux et al., 2010). Once released in the body fat cells, it enters the hemolymph and is directed to the hypopharyngeal glands (HPG) to produce royal jelly (Amdam and Amholt, 2002; Holldobler and Wilson, 2009). By comparing HPG size and Vg in the fat body, the division of labor of worker bees within the colony can be determined. For example, the Vg content in the fat body of nurse bees is high (Amdam and Omholt, 2003; Tsuruda and Page, 2009), while it is low in forager bees (Crailsheim, 1992). The content of this protein in the hemolymph and adipose tissue is highest in winter bees (60-90 μg/μl) and lowest in forager bees (0-5 μg/μl; Seehuus et al., 2006). In adult developing worker bees, foraging activity is triggered by a decrease in Vg synthesis from two weeks of age (Amdam et al., 2010). The rate of Vg synthesis varies depending on the density of pollen sources in nature and pollen quality (Amdam et al., 2010). There is also an increasing tendency to forage for pollen rather than nectar (Nelson et al., 2007). In the digestive system of bees, the Vg content changes with the change in flora (Miller et al., 2019). Vg has antibacterial, antiviral and antifungal effects on various pests (Wang et al., 2011; Zhang et al., 2011). It has a positive effect on the oxidative stress tolerance of bees (Seehuus et al., 2006). It supports the viability of immune cells (Amdam et al., 2004) and suppresses foraging behavior under unfavorable conditions for bees (Amdam et al., 2005). Functions such as the transport of carbohydrates, lipids, phosphates, vitamins, metals and hormones (Chen et al., 1997; Sappington and Raikhel, 1998). Excessive accumulation of Vg in the hemolymph of worker bees can extend the lifespan from 4-8 weeks to 8 months. This has been observed in long-lived winter bees (Diutinus) (Smedal et al., 2009). In addition, worker bees in breeding colonies can have more Vg in summer than winter bees (Amdam and Omholt, 2002). In honey bees, Vg is a monomeric protein of 180 kDa (Havukainen et al., 2011; Havukainen et al., 2012). Plant protection products (neonicotinoids, pyrethroids, organophosphates) influence Vg synthesis (Christen et al., 2019). Infection with Nosema ceranea in young nurse bees reduces vitellogenin synthesis (Antúnez et al., 2009), while infection with bee larvae increases Vg synthesis in young adult bees (BenVau and Nieh, 2017). Immune cells are transferred to the hypopharyngeal glands via Vg, demonstrating that immunity can be transferred intergenerationally (Harwood et al., 2018). Bacteria and pathogens carried into the colony by forager bees are passed on to the queen via food. These pests are broken down in the queen's body, bind to vitellogenin and are transferred to the eggs produced. The eggs are naturally immunised against pathogens in the queen's body (Salmela et al., 2015). There is little research on Vg in honey bees. This research is mainly in the fields of biochemistry, agriculture, environment, health and pharmacology (Yücel et al., 2022a).

3.2. Nutrition - Fat Body Relationship

The fat body is a dynamic tissue involved in lipid-carbohydrate metabolism, protein synthesis, amino acid and nitrogen metabolism, the endoxin system and the detoxification of nitrogen metabolism. Adipose tissue plays an important role in energy storage and utilization in bees (Arrese and

Soulages, 2010). Fat bodies are single-layered fat cells under the cuticle of honey bees. They are located in the dorsal and ventral parts of the abdomen. The fat bodies are functionally comparable to the liver and adipose tissue of vertebrates and play a central role in vertebrate fat, protein and carbohydrate metabolism (Alaux et al., 2010). The brain and adipose tissue actively communicate via the nervous system, hormones, small neurotransmitters and peptides (Leopold and Perrimon, 2007). Guard bees have more abdominal fat than forager bees. This tissue increases with the protein diet after growing up (Winston, 1987). A worker bee that transitions from keeping to foraging loses about 50% of its abdominal fat (Toth and Robinson, 2005). Young bees begin to lose abdominal fat before they become foragers (Toth and Robinson, 2005) and have a greater ability to fly (Harrison, 1986). The reduction of the insulin receptor substrate gene in the fat body results in forager bees collecting more pollen and less nectar (Wang et al., 2010). A shortening of the day length during the period of weight gain causes an increase in this tissue (Fluri and Bogdanov, 1987). Triglycerols make up about 80 % of the fat, the second most common compound being phospholipids at 20% (Tzompa-Sosa et al., 2014; Ekpo et al., 2009). C18 fatty acids, in particular oleic acid, linoleic acid and linolenic acid, are contained in large quantities in the oil (Tzompa-Sosa et al., 2014). Palmitic acid is also relatively high. The fatty acid profile is influenced by the bees' diet (Bukkens, 2005). Although the fat content of the abdomen can be calculated using different methods, a simple method is to calculate the dry weight of the abdomen (El Ghabawy et al., 2022). In this method, the abdomens of adult bees are collected on the 5th, 7th and 10th day of life and their weight (mg) after three days of drying at 45 °C (IKAA) is used as the first abdominal dry weight. In this method, ethyl ether is added to the abdomens in a tube and shaken in a shaker for 24 hours. They are then dried again at 45 °C for three days and the second abdominal dry weight (IKSAA) is calculated (El Ghabawy et al., 2022; Mashal et al., 2023). The fat body was calculated using the formula described below by El Ghabawy et al.:

$$ALA\ (mg/g) = 1000 \times \left(\frac{FDAW}{AWASD}\right)$$

Where;

ALA: Abdominal Lipid Amount.

FDAW: First Drying Abdomen Weight.

AWASD: Abdomen Weight After Second Drying.

3.3. Nutrition – Hypopharyngeal Glands (HPG) Relationship

The pollen is the source of proteins, lipids, sterols, vitamins, minerals and some carbohydrates for honey bees (Todd and Betherick, 1942). The nutrients resulting from the digestion of pollen are converted into jelly-like royal jelly and brood food in the glands on the head (hypopharyngeal glands) of the worker bee and offered to the colony for consumption (Harrassnigg and Crailsheim, 1998). The food produced in the glands is distributed to the individuals by trophallaxis behavior (mouth-to-mouth) (Crailsheim, 1991). Although the hypopharyngeal gland is present in all individuals of the colony, it is most developed in the worker bees (Britto et al., 2004). In worker bees, these glands are located on both sides of the head, in front of the brain and between the compound eyes (Cruz-Landim and Costa, 1998; Hrassnigg and Crailsheim, 1998). These secretory cells have a diameter of 30-50 µm (Richter et al., 2016). These glands consist of structures called acini. HPG develops rapidly in worker bees in the first 24 hours after the adult bees emerge in the colony. However, this changes in colonies with cages, without brood and with brood (Crailsheim and Stolberg, 1989). Recent studies have shown that the glands develop from the first day of the pupal stage (Klose et al., 2017; Ahmad et al., 2021). Gland development is directly influenced by the availability of food in the colony (Schmidt et al., 1995; Nicolson, 2011). Acini length measurement is a common method to measure the size of the glands. In some studies, it was reported that there was no difference in acini gland size between the pollen, protein supplement and control (high fructose corn syrup) groups, and in another study, there was no difference in acini gland size between bees fed pollen and protein supplement. A worker bee has the largest acini size in the first four days after hatching as an adult and a smaller acini size in the following days (DeGrandi-Hoffman et al., 2010). Glands can store nutrients. Pollen- and protein-rich forage fed in the fall allows for good glandular development and nutrient storage in bees, and after winter these stored nutrients are used when brood activity begins (DeGrandi_Hoffman et al., 2010). In colonies fed diets containing 25.0, 29.5, 34.0 and 38.5 % crude protein, the highest acini size was found in the 34 % crude protein diet. In addition, the egg size of worker bees was largest at 12 days of age (Zheng et al., 2014). When comparing the egg size of bees fed pure bee pollen and protein supplements, the supplements were more effective (DeGrandi-Hoffman et al., 2010; Zheng et al., 2014). HPG size varies among bees fed monofloral pollen. For example, colonies fed Castanea sp. and Asparagus sp. pollen have larger glands than those fed Helianthus sp. and Sinapis sp. pollen (Omar et al., 2017). In addition, supplementing the diet with vitamin C increases gland size (Zahra and Talal, 2008). However, pesticides in the diet cause a reduction in HPG size (Heylen et al., 2011; Hatjina et al., 2013; Zaluski et al., 2017). In bees, HPG development is determined using two different methods. The first, a simple method, determines the dry weight of the head of adult nurse bees. The second method is based on bees collected on the 3rd, 6th, 9th, 12th, 15th and 18th day after the worker bees hatch. The glands separated from the heads of the collected bees are mounted on a slide with saline solution (0.9 % NaCl). The length and width of the acini forming the glands are then measured (Omar et al., 2017; Mashal et al., 2023). The hypopharyngeal glands development was calculated as follow (Omar et al., 2017):

$$ASA(mm^2) = \frac{4}{3}\pi\left(\frac{a+b}{4}\right)^3$$

Where:

ASA: Acini surface area.

a: Maximum length of acini.

b: Maximum width of acini.

$\pi = 3.14$.

3.4.Nutrition - Mandibular Glands (MB) Relationship

Honey bees are dependent on nature for the physiological needs of the members of their colony. Nectar is a source of energy and pollen is a source of lipids, proteins, vitamins and minerals (Potts et al., 2016). These proteins are involved in the development of mandibular glands in worker bees (DeGrandi-Hoffman et al., 2010). These glands are important exocrine glands responsible for the biosynthesis of royal jelly acids. However, very little is known about the effects of MB on bee nutrition (Zhang et al., 2022). In queen bees in colonies, the mandibular glands are composed of two x-1 hydroxydecenoic acids and are involved in the release of pheromones (Le Conte and Hefetz, 2008). In worker bees, the MB produce royal jelly acids containing 10-hydroxy-2-desenoic acid

(10-HDA) and its precursor 10-hydroxy-2-desenoic acid (10-HDAA), which regulate larval growth (Kinoshita and Shuel, 1975). The amount of 10-HDAA in MBs gradually increases during the first 20 days after worker bees hatch, reaching a peak on day 25 (Yang et al., 2017). They also excrete small amounts of 9-oxo-2-desenoic acid (9-ODA) and its precursor 9-hydroxy-2-desenoic acid (9-HDA) (Brown et al., 1961; Wang et al., 2016). The C16 and C18 fatty acids ingested with the pollen are reduced to C10 fatty acids by the mandibular glands (Wringht et al., 2018). The ingested proteins are broken down into amino acids in the intestine by the enzyme protease and used for the biosynthesis of royal jelly (de Jong et al., 2019). In the absence of natural pollen sources, the maintenance of brood activity depends on royal jelly production. Therefore, bee colonies should be supplied with protein substitutes in times of pollen scarcity (Carrillo et al., 2015). MB development is influenced by the quality and quantity of the protein source (Schmidt et al., 1987). Feeds containing 20% soybean meal and brewer's yeast as a protein supplement stimulate these glands and promote the production of royal jelly (Mattila and Otis, 2007). The largest gland size in worker bees in colonies fed diets containing 0 %, 23 %, 25 % and 27 % crude protein was found in diets containing 23 % protein. Protein feeds lead to an increase in the area and height of these glands (Camilli vd., 2021). The larger the area and height of these glands, the greater their ability to secrete nutrients (Renzi et al., 2016; Smodis Skerl and Gregorc, 2010). It has been found that various substitute feeds other than pollen (Peters et al. 2010) have no effect on the physiology of MBs (Zhang et al., 2022).

3.5. Nutrition – Intestinal Microbiota Relationship

The gut microbiota of honey bees consists of anaerobic and microaerophilic bacterial species (Engel et al., 2013; Moran, 2015). Some of the species found in the bee gut are *Gilliamella apicola, Snodgrassella alvi, Parasaccharibacter apium, Lactobacillus* spp. and *Bifidobacterium* spp. (Corby-Harris, 2016; Kwong et al., 2017) as well as *Frischella perrara* and *Bartonella apis*, which are unique to the genus *Apis* (Martinson et al., 2012; Powell et al., 2014). The microbiota provides the gut with a low pH value and short-chain fatty acids (Zheng et al., 2017). The gut microbiota of bees is subject to seasonal changes depending on the diet (Almeida et al., 2023). Bees fed sucrose syrup had fewer *Rhizobiales* and *Bifidobacteria* bacterial species than those fed honey and wheat starch (D'Alvise et al., 2018). B. apis increases in the digestive tract of bees fed with Eucalyptus grandis pollen (Schmidt and Engel, 2016; Castelli et al., 2020). It has been reported that the density of *Bactobacillus* spp. does not change when food contaminated with some pesticides, antibiotics and herbicides is consumed (Raymann et al., 2016; Motta et al., 2018; Alberoni et al., 2021; Motta and Moran, 2020). The addition of *Lactobacillus* spp. and *Bifidobacterium* spp. to bee feed can increase resistance to disease by increasing the gut microbiota (Maggi et al., 2013; Arredondo et al., 2017). Four bacterial species (*Apilactobacillus, Fructobacillus fructosus, Acinetobacter boissieri, Neokomagataea*) increase in the gut microbiota with the increase in nectar collection (Neveling et al., 2012). The addition of various pesticides to honey bee feed in non-lethal doses leads to a decrease in *Bombilactobacillus* species and an increase in *Lactobacillus* and fungi in the gut (Favaro et al., 2023).

3.6. Nutrition – Diseases Relationship

The resistance of bees to disease decreases due to the effects of malnutrition, pathogens and environmental factors. Numerous studies have been carried out to investigate the relationship between nutrition and resistance to bee diseases. The proportion of fatty tissue is particularly high in bees that are fed high-quality protein sources. The parasite Varroa destructor uses the bees' fatty tissue as its main food source (Ramsey et al., 2019). Both field and cage studies show that bees fed inadequate and poor quality pollen are susceptible to Nosema spp. and the Varroa parasite and their lifespan is shortened (Huang, 2010; Eischen and Graham, 2008; Rinderer and Kathleen, 1977). In bees fed with pollen, Nosema disease develops faster, in contrast to the gut of bees fed with bee bread and sugar syrup (Porrini et al., 2011). N. ceranae spores are reduced in bees fed with sunflower pollen (Helianthus annuus) (Giacomini et al., 2018). Bees fed with good and high-quality pollen are resistant to viral diseases (DeGrandi-Hoffman et al., 2010). When bees infected with the Varroa parasite were fed pollen and sugar, the pollen-fed bees lived longer (Alaux et al., 2011). This leads to the conclusion that there is no difference between polyfloral and monofloral pollen in the physiology and survival time of honey bees. However, colonies fed with polyfloral pollen are more resistant to parasitic diseases and live longer when infected (Di Pasquale et al., 2013). When comparing colonies fed with fresh pollen and protein replacement feed, the pollen-fed colonies showed a lower pathogen load and better overwintering ability (DeGrandi-Hoffman et al., 2016). Pollen protects bees from bacterial and fungal diseases through the antimicrobial effects of capric, lauric, myristic, linoleic and linolenic acids. Linoleic acid, for example, has an inhibitory effect on the development of Paenibacillus larvae bacteria (Manning, 2001; Cushnie and Lamb, 2005). Feeding high quality pollen has been reported to reduce the harmful effects of Varroa mite and deformed wing virus (Frizzera et al., 2022), although some researchers have found no change (DeGrandi-Hoffmann et al., 2020). Feeding bees with pollen and protein substitutes in times of pollen scarcity prevents the increase in Varroa parasite density (Giacobino et al., 2022). In colonies fed with a mixture of amino acids and vitamins, disease and parasite rates decrease with increasing hygienic behavior (Stanimirovic et al., 2022). Saturated and unsaturated fatty acids in pollen have an antibacterial effect. Lauric, palmitoleic, linoleic, linolenic, undecanoic and myristic acids in particular have this effect on *Paenibacillus larvae* (Hornitzky, 2003).

4. Conclusion

The honey bee colony, with its highly specialized social structure and architecture, acts as a unit to achieve specific biological goals. Favorable environmental conditions and nutrition are two crucial components for the successful adaptation and productivity of bees. Ongoing research on the nutritional needs and foraging behavior of honey bees will help improve honey bee nutritional supplements, habitat recommendations, and colony management. This review summarizes the hypotheses of numerous researchers on the nutritional and physiological changes of worker bees from egg to death. We hope that the scientists who benefit from this review will contribute further thoughts and questions in the field of nutritional and physiological studies.

References

Afik, O., Dag, A., Kerem, Z., Shafir, S., 2006. Analyses of avocado (Persea americana) nectar properties and their perception by honeybees (*Apis mellifera*). Journal of Chemical Ecology. 32: 1949–1963. https://doi.org/10.1007/s10886-006-9124-8

Ahmad, S., Khan, S. A., Khan, K. A., Li, J., 2021. Novel insight into the development and function of hypopharyngeal glands in honey bees. Frontiers in Physiology. 11: 615830. https://doi.org/10.3389/fphys.2020.615830

Akyol, E., Yeninar, H., Sahinler, N., Güler, A., 2006. The effects of additive feeding and feed additives before wintering on honey bee colony performances, wintering abilities and survival rates at the East Mediterranean region. Pakistan Journal of Biological Sciences. 9(4): 589-592. https://doi.org/10.3923/pjbs.2006.589.592

Alaux, C., Ducloz, F., Crauser, D., Conte, Y. L., 2010. Diet effects on honeybee immunocompetence. Biology Letters. 6(4): 562–565. https://doi.org/10.1098/rsbl.2009.0986

Alaux, C., Dantec, C., Parrinello, H., Le Conte, Y., 2011. Nutrigenomics in honey bees: Digital gene expression analysis of pollen's nutritive effects on healthy and varroa-parasitized bees. BMC Genomics. 12: 496. https://doi.org/10.1186/1471-2164-12-496

Alberoni, D., Favaro, R., Baffoni, L., Angeli, S., Di Gioia, D., 2021. Neonicotinoids in the agroecosystem: In-field long-term assessment on honeybee colony strength and microbiome. Science of The Total Environment. 144116. https://doi.org/10.1016/j.scitotenv.2021.144116

Almaraz-Abarca, N., Campos, M. D. G., Avila-Reyes, J. A., Naranjo-Jimenez, N., Herrera-Corral, J., González-Valdez, L. S., 2004. Variability of antioxidant activity among honeybee-collected pollen of different botanical origin. Interciencia. 29(10): 574–578.

Almeida, E. A., Ribière, C., Frei, W., Kenny, D., Coffey, M. F., O'Toole, P. W., 2023. Geographical and seasonal analysis of the honeybee microbiome. Microbial Ecology. 85: 765-778. https://doi.org/10.1007/s00248-022-02860-2

Amdam, G. V., Omholt, S. W., 2002. The regulatory anatomy of honeybee lifespan. Journal of Theoretical Biology. 216(2): 209-228. https://doi.org/10.1006/jtbi.2002.2545

Amdam, G. V., Omholt, S. W., 2003. The hive bee to forager transition in honeybee colonies: the double repressor hypothesis. Journal of Theoretical Biology. 223(4): 451-464.

Amdam, G. V., Aase, A. L., Seehuus, S. C., Kim Fondrk, M., Norberg, K., Hartfelder, K., 2005. Social reversal of immunosenescence in honey bee workers. Experimental Gerontology. 40: 939-947.

Amdam, G. V., Simo˜es, Z. L., Hagen, A., Norberg, K., Schrøder, K., Mikkelsen, Ø., Kirkwood, T. B., Omholt, S. W., 2004. Hormonal control of the yolk precursor vitellogenin regulates immune function and longevity in honeybees. Experimental Gerontology. 39: 767–773.

Amdam, G., Ihle, K., Page, R., 2010. Regulation of honeybee worker (*Apis mellifera*) life histories by vitellogenin. In: Hormones, Brain and Behavior Online. Elsevier Inc.

Amdam, G. V., Norberg, K., Hagen, A., Omholt, S. W., 2003. Social exploitation of vitellogenin. Proceedings of the National Academy of Sciences. 100: 1799–1802.

Anderson, K. E., Carroll, M. J., Seehan, T., Mott, B. M., Maes, P., Corby-Harris, V., 2014. Hive-stored pollen of honey bees: Many lines of evidence are consistent with pollen preservation, not nutrient conversion. Molecular Ecology. 23: 5904–5917.

Antúnez, K., Martín-Hernández, R., Prieto, L., Meana, A., Zunino, P., Higes, M., 2009. Immune suppression in the honey bee (*Apis mellifera*) following infection by *Nosema ceranae* (Microsporidia). Environmental Microbiology. 11: 2284–2290.

Arien, Y., Dag, A., Zarchin, S., et al., 2015. Omega-3 deficiency impairs honey bee learning. Proceedings of the National Academy of Sciences USA. 112(51): 15761–15766.

Arredondo, D., Castelli, L., Porrini, M., Garrido, M., Eguaras, M., Zunino, P., Antúnez, K., 2017. *Lactobacillus kunkeei* strains decreased the infection by honey bee pathogens *Paenibacillus larvae* and *Nosema ceranae*. Beneficial Microbes. 9: 1–12. https://doi.org/10.3920/BM2017.0075

Arrese, E. L., Soulages, J. L., 2010. Insect fat body: Energy, metabolism, and regulation. Annual Review of Entomology. 55: 207–225.

Avni, D., Dag, A., Shafir, S., 2009. The effect of surface area of pollen patties fed to honey bee (*Apis mellifera*) colonies on their consumption, brood production and honey yields. Journal of Apicultural Research. 48(1): 23-28.

Barchuk, A. R., Bitondi, M. M. G., Simo˜es, Z. L. P., 2002. Effects of juvenile hormone and ecdysone on the timing of vitellogenin appearance in hemolymph of queen and worker pupae of *Apis mellifera*. Journal of Insect Science. 2(1): 9.

Barker, R. J., 1977. Some carbohydrates found in pollen and pollen substitutes are toxic to honey bees. Journal of Nutrition. 107: 1859–1862.

Barker, R. J., Lehner, Y., 1978. Laboratory comparison of high fructose corn syrup, grape syrup, honey, and sucrose syrup as maintenance food for caged honey bees. Apidologie. 9: 111–116.

Basim, E., Basim, H., Özcan, M., 2006. Antibacterial activities of Turkish pollen and propolis extracts against plant bacterial pathogens. Journal of Food Engineering. 77: 992–996.

Belle´s, X., 2003. Vitellogenesis directed by juvenile hormone. In: Raikhel, A. (Ed.), Reproductive Biology of Invertebrates, vol. 9. Recent progress in Vitellogenesis. Wiley, New York.

BenVau, L. R., Nieh, J. C., 2017. Larval honey bees infected with *Nosema ceranae* have increased vitellogenin titers as young adults. Scientific Reports. 7: 14144.

Bernkalu, E., Bjostad, L., Hogeboom, A., et al., 2019. Dietary phytochemicals, honey bee longevity and pathogen tolerance. Insects. 10(1): 14.

Bogdanov, S., 2011. Pollen: Nutrition, functional properties, health: A review. Bee Product Science. 1–34.

Bonvehi, J. S., Jorda, R. E., 1997. Nutrient composition and microbiological quality of honeybee-collected pollen in Spain. Journal of Agricultural and Food Chemistry. 45: 725–732.

Bukkens, S. G. F., 2005. Insects in the human diet: Nutritional aspects. In: Paoletti, M. G. (Ed.), Ecological Implications of Minilivestock; Role of Rodents, Frogs, Snails, and Insects for Sustainable Development. Science Publishers, New Hampshire, pp. 545–577.

Britto, F. B., Caetano, F. H., de Moraes, R. L., 2004. Comparative analysis of morphological, structural and morphometric patterns of *Polistes versicolor* (Olivier) (Hymenoptera: Vespidae) hypopharyngeal glands. Neotropical Entomology. 33: 321–326.

Brodschneider, R., Crailsheim, K., 2010. Nutrition and health in honey bees. Apidologie. 41: 278–294.

Brown, W. H., Felauer, E. E., Freure, R. J., 1961. Some new components of royal jelly. Canadian Journal of Chemistry. 39: 1086–1089. https://doi.org/10.1139/v61-134.

Byrne, B. M., Gruber, M. A. B. G., Ab, G., 1989. The evolution of egg yolk proteins. Progress in Biophysics and Molecular Biology. 53(1): 33–69. https://doi.org/10.1016/0079-6107(89)90005-9.

Camazine, S., 1991. Self-organizing pattern-formation on the combs of honey bee colonies. Behavioral Ecology and Sociobiology. 28: 61–76.

Campos, M., Firgerio, C., Lopes, J., Bogdanov, S., 2010. What is the future of bee-pollen? Journal of Analytical Atomic Spectrometry. 2: 131–144.

Camilli, M. P., de Barros, D. C., Justulin, L. A., Tse, M. L. P., de Oliveira Orsi, R., 2021. Protein feed stimulates the development of mandibular glands of honey bees (*Apis mellifera*). Journal of Apicultural Research. 60(1): 165-171.

Carrillo, M. P., Kadri, S. M., Veiga, N., Orsi, R. D. O., 2015. Energetic feedings influence beeswax production by *Apis mellifera* L. honeybees. Acta Scientiarum. Animal Sciences. 37(1): 73–76. https://doi.org/10.4025/actascianimsci.v37i1.24191.

Castelli, L., Branchiccela, B., Garrido, M., Invernizzi, C., Porrini, M., Romero, H., Santos, E., Zunino, P., Antúnez, K., 2020. Impact of nutritional stress on honeybee gut microbiota, immunity, and *Nosema ceranae* infection. Microbial Ecology. 1–12.

Chakrabarti, P., Lucas, H. M., Sagili, R. R., 2019a. Evaluating effects of a critical micronutrient (24-methylenecholesterol) on honey bee physiology. Annals of the Entomological Society of America. 113(3): 176–182.

Chakrabarti, P., Lucas, H. M., Sagili, R. R., 2020. Novel insights into dietary phytosterol utilization and its fate in honey bees (*Apis mellifera* L.). Molecules. 25: 571.

Chakrabarti, P., Morre, J. T., Lucas, H. M., et al., 2019b. The omics approach to bee nutritional landscape. Metabolomics. 15: 127.

Chen, J.S., Sappington, T.W., Raikhel, A.S., 1997. Extensive sequence conservation among insect, nematode, and vertebrate vitellogenins reveals common ancestry. Journal of Molecular Evolution, 44, 440–451.

Christen, V., Vogel, M.S., Hettich, T., Fent, K. (2019). A Vitellogenin Antibody in Honey Bees (Apis mellifera): Characterization and Application as Potential Biomarker for Insecticide Exposure. Environmental Toxicology and Chemistry, 38(5), 1074–1083.

Corby-Harris, V. (2016). Parasaccharibacter apium, gen. nov., sp. nov., improves honey bee (Hymenoptera: Apidae) resistance to Nosema. Journal of Economic Entomology, 109(2), 537–543.

Corby-Harris, V., Maes, P., Anderson, K.E. (2014). The bacterial communities associated with honey bee (Apis mellifera) foragers. PLoS ONE, 9(4), e95056. https://doi.org/10.1371/journal.pone.0095056

Corona, M., Velarde, R.A., Remolina, S., Moran-Lauter, A., Wang, Y., Hughes, K.A., Robinson, G.E. (2007). Vitellogenin, juvenile hormone, insulin signaling, and queen honey bee longevity. Proceedings of the National Academy of Sciences of the United States of America, 104(17), 7128–7133. https://doi.org/10.1073/pnas.0701909104

Couto, R.H.N., Couto, L.A. (2006). Apicultura: Manejo e Produtos. Funep, Jaboticabal, Brazil, 3rd edition.

Crailsheim, K. (1990). The protein balance of the honey bee worker. Apidologie, 21, 417–429.

Crailsheim, K., Schneider, L.H.W., Hrassnigg, N., Bühlmann, G., Brosch, U., Gmeinbauer, R., Schöffmann, B. (1992). Pollen consumption and utilization in worker honeybees (Apis mellifera carnica): Dependence on individual age and function. Journal of Insect Physiology, 38, 409–419.

Crailsheim, K. (1991). Interadult feeding of jelly in honeybee (Apis mellifera L.) colonies. Journal of Comparative Physiology B, 161, 55–60.

Crailsheim, K., Stolberg, E. (1989). Influence of diet, age and colony condition upon intestinal activity and size of the hypopharyngeal glands in the honeybee (Apis mellifera L.). Journal of Insect Physiology, 35, 595–602.

Crailsheim, K., Brodschneider, R., Aupinel, P., Behrens, D., Genersch, E., Vollmann, J., Riessberger-Gallé, U. (2013). Standard methods for artificial rearing of Apis mellifera larvae. Journal of Apicultural Research, 52(1), 1–16.

Cuesta-Maté, A., Renelies-Hamilton, J., Kryger, P., Jensen, A.B., Sinotte, V.M., Poulsen, M. (2021). Resistance and vulnerability of honeybee (Apis mellifera) gut bacteria to commonly used pesticides. Frontiers in Microbiology, 12, 717990. https://doi.org/10.3389/fmicb.2021.717990

Cruz-Landim, C.D., Costa, R. (1998). Structure and function of the hypopharyngeal glands of Hymenoptera: A comparative approach. Journal of Comparative Biology, 3, 151–163.

Cushnie, T.P.T., Lamb, A.J. (2005). Antimicrobial activity of flavonoids. International Journal of Antimicrobial Agents, 26, 343–356.

Çelebi, Ş., Karaca, H., "Yumurtanın besin değeri, kolesterol içeriği ve yumurtayı n-3 yağ asitleri bakımından zenginleştirmeye yönelik çalışmalar", Atatürk Üniversitesi Ziraat Fakültesi Dergisi, 37(2), 257:265, 2006.

D'Alvise, P., Böhme, F., Codrea, M.C., Seitz, A., Nahnsen, S., Binzer, M., Rosenkranz, P., Hasselmann, M. (2018). The impact of winter feed type on intestinal microbiota and parasites in honey bees. Apidologie, 49(3), 252:264.

DeGrandi-Hoffman, G., Chen, Y., Rivera, R., Carroll, M., Chambers, M., Hidalgo, G., De Jong, E.W. (2016). Honey bee colonies provided with natural forage have lower pathogen loads and higher overwinter survival than those fed protein supplements. Apidologie, 47(2), 186:196.

DeGrandi-Hoffman, G., Corby-Harris, V., Chen, Y., Graham, H., Chambers, M., de Jong, E.W., Ziolkowiski, N., Kang, Y., Gage, S., Deeter, M., Simone-Finstrom, M., de Guzman, L. (2020). Can supplementary pollen feeding reduce *Varroa* mite and virus levels and improve honey bee colony survival? Experimental and Applied Acarology, 82(4), 455:473.

DeGrandi-Hoffman, G., Chen, Y., Huang, E., Huang, M.H. (2010). The effect of diet on protein concentration, hypopharyngeal gland development and virus load in worker honey bees (*Apis mellifera* L.). Journal of Insect Physiology, 56(9), 1184:1191.

De Groot, A.P. (1953). Protein and amino acid requirements of the honeybee (*Apis mellifera* L.). Physiologia Comparata et Oecologia, 3(1), 1:83.

De Jong, E.W., DeGrandi-Hoffman, G., Chen, Y., Graham, H., Ziolkowski, N. (2019). Effects of diets containing different concentrations of pollen and pollen substitutes on physiology, *Nosema* burden, and virus titers in the honey bee (*Apis mellifera* L.). Apidologie, 50(6), 845:858. https://doi.org/10.1007/s13592-019-00695-8Di

Pasquale, G., Salignon, M., Le Conte, Y., Belzunces, L.P., Decourtye, A., Kretzschmar, A., Suchail, S., Brunet, J., Alaux, C., 2013. Influence of pollen nutrition on honey bee health: do pollen quality and diversity matter? PLoS One 8, e72016.

Dodologlu, A., Emsen, B., 2007. Effect of supplementary feeding on honey bee colony. Journal of Applied Animal Research. 32: 199–200.

Doner, L.W., 1977. The sugars of honey - a review. Journal of the Science of Food and Agriculture. 28: 443–456.

Donkersley, P., Rhodes, G., Pickup, R.W., et al., 2014. Honeybee nutrition is linked to landscape composition. Ecology and Evolution. 4: 4195–4206.

Doull, K.M., 1980. Relationships between consumption of a pollen supplement, honey production and brood rearing in colonies of honeybees *Apis mellifera* L. Apidologie. 11: 367–374.

Ekpo, K.E., Onigbinde, A.O., Asia, I.O., 2009. Pharmaceutical potentials of the oils of some popular insects consumed in southern Nigeria. African Journal of Pharmacy and Pharmacology. 3: 51–57.

Engel, P., James, R.R., Koga, R., Kwong, W.K., Quinn, S., et al., 2013. Standard methods for research on *Apis mellifera* gut symbionts. Journal of Apicultural Research. 52(4): 1–24.

El Ghabawy, I.A., Omar, R.E., Khattab, M.M., Nowar, E.E., 2022. The novelty of *Azolla pinnata* as a promising alternative feed for honeybee, *Apis mellifera* (L.). Egyptian Academic Journal of Biological Sciences. A, Entomology. 15(2): 35–49.

Eischen, F.A., Graham, R.H., 2008. Feeding overwintering honey bee colonies infected with *Nosema ceranae*. Proceedings of the American Bee Research Conference. American Bee Journal. 148: 555.

Ellis, A., Ellis, J.D., O'Malley, M.K., et al., 2020. The benefits of pollen to honey bees. ENY152 Entomology and Nematology Department. Gainesville (FL): UF/IFAS Extension.

Eyer, M., Neumann, P., Dietemann, V., 2016. A look into the cell: honey storage in honey bees, *Apis mellifera*. PLOS ONE. 11(8): e0161059.

Favaro, R., Garrido, P.M., Bruno, D., Braglia, C., Alberoni, D., Baffoni, L., Tettamanti, G., Porrini, M.P., Gioia, D.D., Angeli, S., 2023. Combined effect of a neonicotinoid insecticide and a fungicide on honeybee gut epithelium and microbiota, adult survival, colony strength and foraging preferences. Science of the Total Environment. 905: 167277. https://doi.org/10.1016/j.scitotenv.2023.167277

Fluri, P., Bogdanov, S., 1987. Effects of artificial shortening of the photoperiod on honeybee (*Apis mellifera*) polyethism. Journal of Apicultural Research. 26(2): 83–89.

Free, J.B., 1963. The floral constancy of honeybees. Journal of Animal Ecology. 32: 119–132.

Frizzera, D., Ray, A.M., Seffin, E., Zanni, V., Annoscia, D., Grozinger, C.M., Nazzi, F., 2022. The beneficial effect of pollen on *Varroa*-infested bees depends on its influence on behavioral maturation genes. Frontiers in Insect Science. 2: 864238. https://doi.org/10.3389/finsc.2022.864238Gaifullina LR, Saltykova ES, Nikolenko AG. 2017. Honey as a synbıotıc food product. Biomics. 9(1): 12-23.

Gajger, I., Kozaric, Z., Berta, D., Nejedli, S. and Petrinec, Z., "Effect of the herbal preparation Nozevict on the mid-gut structure of honeybees (*Apis mellifera*) infected with Nosema sp. Spores", ***Veterinarni Medicina***, 56 (1), 344-351, 2011.

Genç F, Dodoloğlu A, 2002. Arıcılığın Temel Esasları. Atatürk Üniversitesi Ziraat Fakültesi Ders Yayınları no: 166. Atatürk Üniversitesi Ziraat Fakültesi Ofset Tesisi. Erzurum.

Ghosh, S.; Jeon, H.; Jung, C. Foraging behavior and preference of pollen sources by honey bee (*Apis mellifera*) relative to protein contents. *J. Ecol. Environ*. **2020**, *44*, 4.

Giacobino, A., Pacini, A., Moliner, A., Bulacio-Cagnolo, N., Merke, J., Orellano, E., Gaggiotti, M. and Signorini, M., ‘’ Impact of nutritional and sanitary management on Apis mellifera colony dynamics and pathogen loads’’, Spanish J. Agric. Res., 20(4), e0305, 2022. https://doi.org/10.5424/sjar/2022204-19634

Giacomini, J. J., J. Leslie, D. R. Tarpy, E. C. Palmer-Young, R. E. Irwin, and L. S. Adler. 2018. Medicinal value of sunflower pollen against bee pathogens. Scientific reports 8 (1): 14394.

Giebel W, Zwilling R, Pfleiderer G (1971) The evolution of endopeptidases - XII. The proteolytic enzymes of the honeybee (Apis mellifica L). Comp Biochem Physiol 38B, 197-210

Gruter C, Ratnieks FLW. 2011. Flower constancy in insect pollinators—adaptive foraging behavior or cognitive limitation? *Commun. Integr. Biol.* 4:633–36

Güneşdoğdu M, Bayram A, Işıkber AA, Şekeroğlu A, Bozkurt H. (2023). Insecticidal Effect of a Natural Turkish Diatomaceous Earth Formulation on Greater Wax Moth. Turkish Journal of Agriculture - Food Science and Technology, 11(12): 2372-2376, DOI: https://doi.org/10.24925/turjaf.v11i12.2372-2376.6436

Güler, A., Toy, H., “Morphological characteristics of the honey bee (*Apis mellifera* L.) of the Sinop Türkeli region”, ***Journal of Agricultural Faculty of Ondokuz Mayıs University,*** 23(3), 190-197, 2008.

Harrison, J.M., 1986. Caste-specific changes in honey bee flight capacity. Physiol. Zool. 59, 175–187.

Harwood, G., Amdam, G., Freitak, D., The role of Vitellogenin in the transfer of immüne elicitors from gut to hypopharyngeal glands in honey bees (*Apis mellifera*), *Journal of Insect Physiology* (2018), doi: https://doi.org/10.1016/j.jinsphys.2018.12.006

Hatjina, F., Papaefthimiou, C., Charistos, L., Dogaroglu, T., Bouga, M., Emmanouil, C., et al. (2013). Sublethal doses of imidacloprid decreased size of hypopharyngeal glands and respiratory rhythm of honeybeesin vivo. Apidologie 44, 467–480. doi: 10.1007/s13592-013-0199-4

Havukainen, H., Halskau, Ø., Skjaerven, L., Smedal, B., and Amdam, G. V. (2011) Deconstructing honeybee vitellogenin. Novel 40 kDa fragment assigned to its N terminus. *J. Exp. Biol.* 214, 582–592

Havukainen, H., Underhaug, J., Wolschin, F., Amdam, G., and Halskau, Ø. (2012) A vitellogenin polyserine cleavage site. Highly disordered conformation protected from proteolysis by phosphorylation. *J. Exp. Biol.* 215, 1837–1846

Haydak M. (1970). Honey bee nutrition, Annu.Rev. Entomol.,15:43-456.

Hays, G.W.J., "Supplemental feding of honeybees", ***Am. Bee J.*** 124(35-37), 108- 109, 1984.

Herbert EW, Shimanuki H. 1978c. Chemical composition and nutritive value of bee-collected and beestored pollen. *Apidologie* 9:33–40

Herbert, E.W. and Shimanuki, H., "Effect of fat soluble vitamins on the brood rearing capabilities of honey bees fed a synthetic diet", ***Ann. Entomol. Soc. Am***., 71, 689–691, 1978a.

Herbert, E.W. and Shimanuki, H., "Mineral requirements for brood-rearing by honey bees fed a synthetic diet", ***J. Apic. Res***., 17, 118–122, 1978b.

Herbert, W.E.J. and Shimanuki, H., "Effect of population density and available diet on the rate of brood rearing by honey bees off ered a pollen substitute", ***Apidologie*** 13, 21 – 28, 1982.

Heylen, K., Gobin, B., Arckens, L., Huybrechts, R., and Billen, J. (2011). The effects of four crop protection products on the morphology and ultrastructure of the hypopharyngeal gland of the European honeybee, Apis mellifera. Apidologie 42, 103–116. doi: 10.1051/apido/2010043

Holldobler, B. and Wilson, E. O. (2009). The superorganism: the beauty, elegance, and strangeness of insect societies. WW Norton & Company.

Hornitzky, M. A. Z. 2003. Fatty acids - An alternative control strategy for honey bee diseases, 23 pp. Barton, ACT: Rural Industries Research and Development Corporation, Australia.

Hrassnigg N, Crailsheim K. 1998. Adaptation of hypopharyngeal gland development to the brood status of honeybee (*Apis mellifera* L.) colonies. *J. Insect Physiol.* 44:929–39

Hrassnigg N., Crailsheim K. (2005) Differences in drone and worker physiology in honeybees (*Apis mellifera* L.), Apidologie 36, 255–277.

Hroncova, Z., Havlik, J., Killer, J., Doskocil, I., Tyl, J., Kamler, M., Titera, D., Hakl, J., Bunesova, V., ve Rada, V. (2015). Variation in Honey Bee Gut Microbial Diversity Affected by Ontogenetic Stage, Age and Geographic

Location. PLoS ONE, 10, e0118707. DOI: 10.1371/journal.pone.0118707.

Huang Z, 2010. Pollen nutrition affects honey bee stress resistance. Terrestrial Arthropod Reviews, 5(2), 175-189.

Huang, Z.Y., Otis, G.W. and Teal, P.E.A. "Nature of brood signal activating the protein synthesis of hypopharyngeal gland in honey bees, *Apis mellifera* (Apidae: Hymenoptera)", ***Apidologie,*** 20, 455 – 464, 1989.

Human H, Nicolson SW, Strauss K, Pirk CWW, Dietemann V. 2007. Influence of pollen quality on ovarian development in honeybees (*Apis mellifera scutellata*). *J. Insect Physiol.* 53:649–55

Janmaat, A.F. and Winston, M.L. "Removal of Varroa jacobsoni infested brood in honey bee colonies with diff erent pollen stores", ***Apidologie*** 31, 377 – 385, 2000.

Jeyaprakash, A., Hoy, M. A. & Allsopp, M. H. Bacterial diversity in worker adults of Apis mellifera capensis and Apis mellifera scutellata (Insecta: Hymenoptera) assessed using 16S rRNA sequences. J. Invertebr. Pathol. 84, 96–103 (2003).

Knox, D.A., Shimanuki, H. and Herbert, E.W. "Diet and the longevity of adult honey bee", ***Journal of Ecomonic Entomology***, 64, 1415-1416, 1971.

Köseoğlu, M., Topal, E., Tunca, R.I., Yücel, B. ve Yıldızdal, I., "Bal arılarında kışlama öncesi farklı beslemenin koloni gelişimine etkileri" ***Anadolu***, 29(2), 85-92, 2019.

Kinoshita, G., & Shuel, R. W. (1975). Mode of action of royal jelly in honeybee development. X. Some aspects of lipid nutrition. Canadian Journal of Zoology, 53(3), 311–319. https://doi.org/10.1139/z75-040

Klose, S. P., Rolke, D., and Baumann, O. (2017). Morphogenesis of honeybee hypopharyngeal gland during pupal development. Front. Zool. 14:22. doi: 10.1186/s12983-017-0207-z

Krell, R., "Value-added products from beekeeping", ***FAO Agricultural Services Bulletin No. 124 Food and Agriculture Organization of the United Nations Rome***, 1996.

Kroyer, G. and Hegedus, N., "Evaluation of bioactive properties of pollen extracts as functional dietary food supplement," ***Innovative Food Science & Emerging Technologies***, 2(3), 171–174, 2001.

Kutlu, H.R., "Yem değerlendirme ve analiz yöntemleri", ***Çukurova Üniversitesi, Zootekni Bölümü Ders Notları,*** http://www.zootekni.org.tr/upload/File/sunular/tm.pdf, (27/09/2023), s. 68, 2008.

Kwong, W. K., Medina, L. A., Koch, H., Sing, K., Jia, E., Soh, Y., Ascher, J. S., Jaffé, R., Moran, N. A. (2017) Dynamic microbiome evolution in social bees. Sci. Adv. 3 (e1600513), 1–17.

Le Conte, Y., & Hefetz, A. (2008). Primer pheromones in social hymenoptera. Annual Review of Entomology, 53, 523–542. https://doi.org/10.1146/annurev.ento.52. 110405.091434

Lebrun, D., "Structures digestives et régimes alimentaires des termites", ***Actes Collection Insectes Sociaux***, 19 (2), 43-44 (in French), 1985.

Leopold, P., Perrimon, N., 2007. Drosophila and the genetics of the internal milieu. Nature 450: 186-188

Liao, L.H., Wu, W.Y. and Berenbaum, M.R., "Behavioral responses of honey bees (*Apis mellifera*) to natural and synthetic xenobiotics in food", ***Sci. Rep.,*** 7(1), 15924, 2017.

Maggi M, Negri P, Plischuk S, Szawarski N, DePiano F, De Feudis L, Eguaras M, Audisio C (2013) Effects of the organic acids produced by a lactic acid bacterium in Apis mellifera colony development, Nosema ceranae control and fumagillin efficiency. Vet Microbiol https://doi.org/10.1016/j.vetmic.2013.07.030

Martinson, V., Moy, J., Moran, N. A. (2012) Establishment of characteristic gut bacteria during development of the honeybee worker. Appl. Environ. Microbiol. 78 (8), 2830–40.

Malagnini, V., Cappellari, A., Marini, L., Zanotelli, L., Zorer, R., Angeli, G., Ioriatti, C., Fontana, P., 2022. Seasonality and landscape composition drive the diversity of pollen collected by managed honey bees. Front. Sustain. Food Syst. 6, 865368 https://doi.org/10.3389/fsufs.2022.865368

Manning, R (2001) Fatty acids in pollen: a review of their importance for honey bees. Bee World, 82(2):60-75.

Manning, R., Rutkay, A., Eaton, L. and Dell, B., "Lipid-enhanced pollen and lipid-reduced flour diyet and their effect on the longevity of honey bees (*Apis mellifera* L.)", ***Aust. J. Entomol***., 46, 251–257, 2007.

Mashal TF, Omar RE, Khattab MM, Nowar EN (2023). Physiological Impacts of Some Food Additives on Honeybee Workers (*Apis mellifera* L.). Egypt. Acad. J. Biolog. Sci., 16(3):63-79.

Mattila, H.R. and Otis, G.W. (2006a). Influence of pollen diet in spring on development of honey bee (Hymenoptera: Apidae) colonies, ***Journal of Economic Entomology,*** 99, 604–613.

Mattila, H.R. and Otis, G.W., "Effects of pollen availability and nosema infection during the spring on division of labor and survival of worker honey bees (Hymenoptera: Apidae)", ***Environmental Entomology***, 35, 708–717, 2006b.

Mattila, H. R., & Otis, G. W. (2007). Dwindling pollen resources trigger the transition to broodless populations of longlived honeybees each autumn. Ecological Entomology, 32(5), 496–505. https://doi.org/10.1111/j.1365-2311.2007.00904.x

Mattila, H.R., Rios, D., Walker-Sperling, V.E., Roeselers, G. and Newton, I.L., "Characterization of the active microbiotas associated with honey bees reveals healthier and broader communities when colonies are genetically diverse", 2012.

Miller DL, Parish AJ, Newton IL. 2019. Transitions and transmission: Behavior and physiology as drivers of honey bee-associated microbial communities. Current opinion in microbiology, 50: 1-7. doi:https://doi.org/10.1016/ j.mib.2019.08.001

Mohr, K. I. & Tebbe, C. C. Diversity and phylotype consistency of bacteria in the guts of three bee species (Apoidea) at an oilseed rape feld. Environ. Microbiol. 8, 258–272 (2006).

Moran, N. A. (2015) Genomics of the honey bee microbiome. Curr. Opin. Insect Sci. 10: 22–28.

Motta, E.V.; Moran, N.A. Impact of glyphosate on the honey bee gut microbiota: Effects of intensity, duration, and timing of exposure. Msystems 2020, 5.

Motta, E.V.; Raymann, K.; Moran, N.A. Glyphosate perturbs the gut microbiota of honey bees. Proc. Natl. Acad. Sci. USA 2018, 115, 10305–10310.

Moritz B, Crailsheim K. 1987. Physiology of protein digestion in the midgut of the honeybee (*Apis mellifera* L.). *J. Insect Physiol.* 33:923–931.

Nelson CM, Ihle K, Amdam GV, Fondrk MK, Page RE (2007) The gene *vitellogenin* has multiple coordinating effects on social organization. PLoS Biol 5:673–677.

Neupane K.R., Thapa R.B. (2005) Alternative to offseason sugar supplement feeding of honeybees, J. Inst. Agric. Anim. Sci. 26, 77–81.

Neveling DP, Endo A, Dicks LMT (2012) Fructophilic Lactobacillus kunkeei and Lactobacillus brevis isolated from fresh fowers, bees and bee-hives. Curr Microbiol 65:507–515. https://doi. org/10.1007/s00284-012-0186-4

Nicolson SW, Thornburg RW. 2007. Nectar chemistry. In *Nectar and Nectaries*, ed. SW Nicolson, M Nepi, E Pacini. Dordrecht, Neth.: Springer.

Nicolson, S.W. and Human, H., "Bees get a head start on honey production", ***Biol. Lett.,*** 4, 299-301, 2008.

Nicolson, S.W., "Water homeostasis in bees, with the emphasis on sociality", ***J. Exp. Biol***., 212, 429-434, 2009.

O'Rourke MK, Buchmann SL. 1991. Standardized analytical techniques for bee-collected pollen. *Environ. Entomol.* 20:507–513.

Omar, E., Abd-Ella, A. A., Khodairy, M. M., Moosbeckhofer, R., Crailsheim, K., and Brodschneider, R. (2017). Influence of different pollen diets on the development of hypopharyngeal glands and size of acid gland sacs in caged honey bees (Apis mellifera). Apidologie 48, 425–436. doi: 10.1007/s13592-016-0487-x

Özbakır G.Ö., Alişiroğlu D.G. (2019) Nutritional Physiology and Metabolism of Honey Bees, J. Anim. Prod., 2019, 60 (1): 67-74, DOI: 10.29185/ hayuretim.523081

Palmer-Young, E.C., Farrell, I.W. and Adler, L.S. et al., "Chemistry of floral rewards: intraand interspecific variability of nectar and pollen secondary metabolites across taxa", ***Ecol. Monogr.,*** 89(1), e01335, 2019.

Palmer-Young, E.C., Tozkar, O.C. and Schwarz, R.S. et al., "Nectar and pollen phytochemicals stimulate honey bee (Hymenoptera: Apidae) ımmunity to viral ınfection", ***J. Econ. Entomol.***, 110(5),1959–72, 2017.

Pan ML, Bell WJ, Telfer WH. 1969. Vitellogenic blood protein synthesis by insect fat body. Science, 165(3891), 393-394. doi: https://doi.org/10.1126/science.165.3891.393

Park W. 1925. The storing and ripening of honey by honeybees. *J. Econ. Entomol.* 18:405–10

Pernal SF, Currie RW. 2000. Pollen quality of fresh and 1-year-old single pollen diets for worker honey bees (*Apis mellifera* L.). *Apidologie* 31:387–409.

Peters, L., Zhu-Salzman, K., & Pankiw, T. (2010). Effect of primer pheromones and pollen diet on the food producing glands of worker honey bees (Apis mellifera L.). Journal of Insect Physiology, 56(2), 132–137. https://doi.org/10.1016/j.jinsphys.2009.09.014

Piulachs MD, Guidugli KR, Barchuk AR, Cruz J, Simões ZLP et al (2003) The vitellogenin of the honey bee, *Apis mellifera* : structural analysis of the cDNA and expression studies. Insect Biochem Mol Biol 33:459–465

Pontoh J, Low NH. 2002. Purification and characterization of β-glucosidase from honey bees (*Apis mellifera*). Insect Biochemistry and Molecular Biology, 32(6): 679-690.

Porrini, M. P., E. G. Sarlo, S. K. Medici, P. M. Garrido, D. P. Porrini, N. Damiani, and M. J. Eguaras. 2011. Nosema ceranae development in Apis mellifera: influence of diet and infective inoculum. Journal of Apicultural Research 50 (1): 35-41.

Potts, S. G., Imperatriz-Fonseca, V., Ngo, H. T., Aizen, M. A., Biesmeijer, J. C., Breeze, T. D., Dicks, L. V., Garibaldi, L. A., Hill, R., Settele, J., & Vanbergen, A. J. (2016). Safeguarding pollinators and their values to human well-being. Nature, 540(7632), 220–229. https://doi.org/10.1038/nature20588

Powell JE, Martinson VG, Urban-Mead K, Moran NA. 2014. Routes of acquisition of the gut microbiota of the honey bee Apis mellifera. Applied and environmental microbiology, 80(23): 7378-7387. doi:https://doi.org/10.1128/AEM.01861-14

Ramsey, S. D., R. Ochoa, G. Bauchan, C. Gulbronson, J. D. Mowery, A. Cohen, and D. Hawthorne. 2019. *Varroa destructor* feeds primarily on honey bee fat body tissue and not hemolymph. Proceedings of the National Academy of Sciences 116 (5): 1792-1801.

Raymann, K.; Shaffer, Z.; Moran, N.A. Antibiotic exposure perturbs the gut microbiota and elevates mortality in honeybees. PLoS Biol. 2017, 15, e2001861.

Raymann, K. and Moran, N.A., “The role of the gut microbiome in health and disease of adult honey bee workers”, ***Current Opinion in Insect Science*** 26, 97–104, 2018.

Renzi, M. T., Rodriguez-Gasol, N., Medrzycki, P., Porrini, C., Martini, A., Burgio, G., Maini, S., & Sgolastra, F. (2016). Combined effect of pollen quality and thiamethoxam on hypopharyngeal gland development and protein content in Apis mellifera. Apidologie, 47(6), 779–788. https://doi.org/10. 1007/s13592-016-0435-9

Richter, K. N., Rolke, D., Blenau, W., and Baumann, O. (2016). Secretory cells in honeybee hypopharyngeal gland: polarized organization and agedependent dynamics of plasma membrane. Cell Tissue Res. 366, 163–174. doi: 10.1007/s00441-016-2423-9

Rinderer, E.T., Kathleen, E.D., 1977. Worker honey bee response to infection with Nosema apis: influence of diet. J. Econ. Entomol. 70, 431–433.

Rivera MD, Donaldson-Matasci M, Dornhaus A. (2015). Quitting time: When do honey bee foragers decide to stop foraging on natural resources? Front Ecol Evol., 3:50.

Robinson GE, Page RE. 1989. Genetic determination of nectar foraging, pollen foraging, and nest-site scouting in honey bee colonies. *Behav. Ecol. Sociobiol.* 24:317–23

Robinson GE. 2002. Genomics and integrative analyses of division of labor in honeybee colonies. *Am. Nat.* 160: 160–172.

Rortais A., Arnold G., Halm M.-P., Touffet-Briens F. (2005) Modes of honeybees exposure to systemic insecticides: estimated amounts of contaminated pollen and nectar consumed by different categories of bees, Apidologie 36, 71–83.

Roulston T.H., Cane J.H. (2000) Pollen nutritional content and digestibility for animals, Plant Syst. Evol. 222, 187–209.

Roulston, T.H. and Buchmann, S.L., “A phylogenetic reconsideration of the pollen starch-pollination correlation”, ***Evol. Ecol. Res***., 2, 627-643, 2000.

Roulston, T.H., Cane, J.H. and Buchmann, S.L., “What governs protein content of pollen: pollinator preferences, pollen–pistil interactions, or phylogeny?”, ***Ecol. Monogr.***, 70, 617–43, 2000.

Ruttner, F., “Naturgeschichte der Honigbienen”, ***München, Germany: Ehrenwirth***, 1992 (in German).

Sabir, A.M., Suhail, A., Akram, W., Sarwar, G. and Saleem, M., “Effect of some pollen substitute diet on the development of *Apis mellifera* L. colonies’’, ***Pakistan Journal of Biological Sciences***, 3(5), 890-891, 2000.

Sagili, R.R., Pankiw, T. and Zhu-Salzman, K., “Effects of soybean trypsin inhibitor on hypopharyngeal gland protein content, total midgut protease activity and survival of the honey bee (*Apis mellifera* L.)’’, ***J. Insect Physiol***. 51, 953–957, 2005.

Salmela H; Amdam G.V; Freıtak D (2015) Transfer of Immunity from Mother to Offspring Is Mediated via Egg-Yolk Protein Vitellogenin. PLoS Pathog, 11(7):e1005015. Doi:10.1371/jornal.ppat. 1005015.

Santos, C.G. and Serrão, J.E., “Histology of the ileum in bees (Hymenoptera, Apoidea)”, ***Brazilian Journal of Morphological Sciences***, (23), 405-413, 2006.

Sappington, T.W., Raikhel, A.S., 1998. Molecular characteristics of insect vitellogenins and vitellogenin receptors. Insect Biochemistry and Molecular Biology 28, 277–300.

Schmickl T, Crailsheim K. 2002. How honeybees (*Apis mellifera* L.) change their broodcare behavior in response to non-foraging conditions and poor pollen conditions. Behavioral Ecology and Sociobiology 51: 415–425.

Schmidt, K.; Engel, P. Probiotic Treatment with a Gut Symbiont Leads to Parasite Susceptibility in Honey Bees. Trends Parasitol. 2016, 32, 914–916.

Schmidt JO, Buchmann SL. 1985. Pollen digestion and nitrogen utilization by *Apis mellifera* L. (Hymenoptera: Apidae). *Comp. Biochem. Physiol. A Physiol.* 82:499–503.

Schmidt, J. O., Thoenes, S. C., & Levin, M. D. (1987). Survival of honey bees, Apis mellifera (Hymenoptera: Apidae), fed various pollen sources. Annals of the Entomological Society of America, 80(2), 176–183. https://doi.org/10.1093/aesa/80.2. 176

Schmidt, L. S., Schmidt, J. O., Rao, H., Wang, W., and Xu, L. (1995). Feeding preference and survival of young worker honey bees (Hymenoptera: Apidae) fed rape, sesame, and sunflower pollen. J. Econ. Entomol. 88, 1591–1595. doi: 10.1093/jee/88.6.1591

Seehuus, S. C., Norberg, K., Gimsa, U., Krekling, T., and Amdam, G. V. (2006) Reproductive protein protects functionally sterile honey bee workers from oxidative stress. *Proc. Natl. Acad. Sci. U.S.A.* 103, 962–967

Seeley TD. 1986. Social foraging by honeybees: how colonies allocate foragers among patches of flowers. *Behav. Ecol. Sociobiol.* 19:343–54

Seeley TD. 1995. The Wisdom of the Hive: The Social Physiology of Honey Bee Colonies. Cambridge, MA: Harvard Univ. Press.

Shumkova, R., Zhelyazkova, I., Lazarov, S. and Balkanska, R., "Effect on the chemical composition of the body of worker bees (*Apis mellifera* L.) fed with stimulating products", ***Macedonian Journal of Animal Science***, 7 (1- 2), 129-135, 2017.

Silici, S. ve Özkök, D., "Bal arısı biyolojisi ve yetiştiriciliği", ***Eflatun Yayınevi, 1. Basım***, Ankara, s.: 236, 2009.

Smedal, B., Brynem, M., Kreibich, C. D., and Amdam, G. V. (2009) Brood pheromone suppresses physiology of extreme longevity in honeybees (*Apis mellifera*). *J. Exp. Biol.* 212, 3795–3801

Smodis Skerl, M. I., & Gregorc, A. (2010). Heat shock protein and cell death in situ localization in hypopharingeal glands of honeybee (Apis mellifera carnica) workers after imidacloprid or coumaphos treatment. Apidologie, 41(1), 73–86. https://doi.org/10.1051/apido/2009051

Somerville, D., "Honey bee nutrition and supplementary feding", ***Agnote DAI/178, NSW Agriculture, Orange, NSW***, Australia, 2000.

Sponsler, D.B., Matcham, E.G., Lin, C.-H., Lanterman, J.L., Johnson, R.M., 2017. Spatial and taxonomic patterns of honey bee foraging: A choice test between urban and agricultural landscapes. J. Urban Ecol. 3, juw008. https://doi.org/10.1093/jue/ juw008

Stabler D, Paoli PP, Nicolson SW,Wright GA. 2015. Nutrient balancing of the adult worker bumblebee (*Bombus terrestris*) depends on the dietary source of essential amino acids. *J. Exp. Biol.* 218:793–802

Stace, P., "Protein bee feeds and their economic use", ***Beekeeping in Australis***, http:// www. Honeybee.com.au/library/beefeeds.html, 2000.

Stanimirovic, Z., Glavinic, U., Ristanic, M., Jelisic, S., Vejnovic, B., Niketic, M. and Stevanovic., "Dıet Supplementatıon Helps Honey Bee Colonıes in Combat Infectıons By Enhancıng Theır Hygıenıc Behavıour'', Acta Veterinaria-Beograd, 72 (2), 145-166, 2022.

Stanley, R.G. and Linskens, H.F "Pollen: Biology, biochemistry, management", ***Heidelberg, Germany: Springer Verlag***., 1974.

Standifer, L. N. (1967). A comparison of the protein quality of pollens for growth-stimulation of the hypopharyngeal glands and longevity of honey bees, Apis mellifera L.(Hymenoptera: Apidae). *Insectes Sociaux*, *14*(4), 415-425.

Svoboda, J.A., Herbert, E.W. and Thompson, M.J. et al., "Selective sterol transfer in the honey bee: Its significance and relationship to other hymenoptera", ***Lipids***, 21,97–101, 1986.

Svoboda, J.A., Thompson, M.J., Herbert, E.W., Shortino, T.J. and Szczepanik-Vanleeuwen, P.A., "Utilization and metabolism of dietary sterols in the honey bee and the yellow fever mosquito", ***Lipids,*** 17, 220–225, 1982.

Szczesna, T., "Long chain fatty acids composition of honeybee-collected pollen", ***J. Apic. Sci***., 50(2), 65–79, 2006.

Tanaka ED, Hartfelder K. 2004. The initial stages of oogenesis and their relation to differential fertility in the honey bee (Apis mellifera) castes. Arthropod Struct Dev, 33(4):431-442. doi:https://doi.org/10.1016/j.asd.2004.06.006

Terra WR, 1990. Evolution of digestive systems of insects. Annu. Rev. Ent. 35: 181–200. doi:https://doi.org/10.1016/S0065-2806(08)60164-2

Todd, F.E., Betherick, O. (1942). 'The composition of pollens', Journal of Economic Entomology 35, pp. 312–317.

Toth, A.L., Robinson, G.E., 2005. Worker nutrition and division of labour in honey bees. Anim. Behav. 69, 427–435.

Tsuruda, J. M. and Page, R. E. (2009). The e_ects of young brood on the foraging behavior of two strains of honey bees (apis mellifera). Behavioral ecology and sociobiology, 64(2):161-167.

Tzompa-Sosa, D.A. Yi, L.Y. van Valenberg, H.J.F. van Boekel, M.A.J.S. Lakemond, C.M.M. (2014). Insect lipid profile: aqueous versus organic solvent-based extraction methods, Food Res. Int. 62: 1087–1094.

Ulutaş, K, Özkırım A. (2018). Importance of nutrition for honey bee health. Mellifera, 18(1): 30-35.

Van Tets, I.G. and Hulbert, A.J., "A comparison of the nitrogen requirements of the eastern pygmy possum, cercartetus nanus, on a pollen and on a mealworm diet", ***Physiological and Biochemical Zoology,*** 72(2), 127-137, 1999.

Vanderplanck, M., Zerck, P.L. and Lognay, G. et al., "Generalized host-plant feeding can hide sterol-specialized foraging behaviors in bee-plant interactions", ***Ecol Evol***, 10(1),150–62, 2020.

VanderplanckM,MoermanR,Rasmont P, Lognay G, Wathelet B, et al. 2014.Howdoes pollen chemistry impact development and feeding behaviour of polylectic bees? *PLOS ONE* 9:e86209

Varol, E. and Yücel, B., "The effects of environmental problems on honey bees in view of sustainable life", ***Mellifera***, 19(2), 23-32, 2019.

Vilmos P, Kurucz E. 1998. Insect immunity: evolutionary roots of the mammalian innate immune system. Immunology letters, 62(2): 59-66 doi:https://doi.org/10.1016/S0165-2478(98)00023-6

Wang, Y., Ma, L., Zhang, W., Cui, X., Wang, H., Xu, B., 2016. Comparison of the nutrient composition of royal jelly and worker jelly of honey bees (Apis mellifera). Apidologie 47, 48–56. https://doi.org/10.1007/s13592-015-0374-x.

Wang Y, Mutti NS, Ihle KE, Siegel A, Dolezal AG, et al. (2010) Downregulation of honey bee IRS gene biases behavior toward food rich in protein. PLoS Genet 6: e1000896. doi:10.1371/journal.pgen.1000896

Wang, S., Wang, Y., Ma, J., Ding, Y., and Zhang, S. (2011) Phosvitin plays a critical role in the immunity of zebrafish embryos via acting as a pattern recognition receptor and an antimicrobial effector. *J. Biol. Chem.* 286, 22653–22664

Weinstock GM, Robinson GE, Gibbs RA, Worley KC, Evans JD, Maleszka R, Robertson HM, Weaver DB, Beye M, Bork P, Elsik CG, Hartfelder K, Hunt GJ, Zdobnov ME, Amdam GV, Bitondi MMG, Collins AM, Cristino AS, Lattorf HMG, Lobo HC. 2006. Insights into social insects from the genome of the honeybee Apis mellifera. Nature, 443(7114): 931-949. doi:https://doi.org/ 10.1038/nature05260

Wheeler D.E. and Kawooya J.K. (1990). Purification and characterization of honey bee vitellogenin. Archives of Insect Biochemistry and Physiology, 14: 253-267.

Wille, H., Wille, M., Kilchenmann, V., Imdorf, A. and Bühlmann, G., "Pollenernte und Massenwechsel von drei *Apis mellifera*-Völkern auf demselben Bienenstand in zwei aufeinanderfolgenden Jahren", ***Rev. Suisse Zool***., 92, 897–914, 1985.

Wringht, G.A., Nicolson, S.W., Shafir, S., 2018. Nutritional physiology and ecology of honey bees. Annu. Rev. Entomol. 63, 327–344. https://doi.org/10.1146/annurevento-020117-043423.

Winston ML. 1987. The biology of the honey bee. Harvard University Press, Cambridge, MA, USA. p. 281

Wolschin F, Amdam GV. 2007. Comparative proteomics reveal characteristics of life-history transitions in a social insect. Proteome Science, 5(1): 1-11. doi: https://doi.org/10.1186/1477-5956-5-10

Wyatt, G.R., Davey, K.G., 1996. Cellular and molecular actions of juvenile hormone. II. Roles of juvenile hormone in adult insects. Adv. Insect Physiol. 26, 1–155.

Xu, X., Gao, Y., 2013. Isolation and characterization of proteins and lipids from honeybee (Apis mellifera L.) queen larvae and royal jelly. Food Res. Int. 54, 330–337. https:// doi.org/10.1016/j.foodres.2013.07.030.

Yang, X. H., Yang, S. F., & Wang, R. M. (2017). Comparative proteomic analysis provides insight into 10-hydroxy-2- decenoic acid biosynthesis in honey bee workers. Amino Acids, 49(7), 1177–1192. https://doi.org/10.1007/s00726- 017-2418-1

Yeninar, H., Akyol, E., Yörük, A. (2015). Effects of Additive Feeding with Pollen and Water on Some Characteristics of Honeybee Colonies and Pine Honey Production. Turkish Journal of Agriculture -Food Science and Technology, 3(12):948-951.

Yücel H., Ekinci K., Karaman A., Yeninar H., Koca Karaman H. (2022a). Factors affecting colony losses in honey bees (Apis mellifera). Turkish Journal of Agriculture - Food Science and Technology, 10(9): 1662-1670, 2022. doi: https://doi.org/10.24925/turjaf.v10i9.1662-1670.5221

Yücel, H., Ekinci, K., Karaman, A., Kar, B. ve Yazdıç, F., "Bal arılarının sindirim kanalında bulunan probiyotik kökenli bifidobacterium sp.'nin glikozit hidrolaz enzimatik ve bibliyometrik analizi", ***Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi,*** 12(2), 622-632, 2022b.

Zahra, A., and Talal, M. (2008). Impact of pollen supplements and vitamins on the development of hypopharyngeal glands and brood area in honey bees. J. Apic. Res. 52, 5–12.

Zaluski, R., Justulin, L. A., and de Oliveira Orsi, R. (2017). Field-relevant doses of the systemic insecticide fipronil and fungicide pyraclostrobin impair mandibular and hypopharyngeal glands in nurse honeybees (Apis mellifera). Sci. Rep. 7:15217. doi: 10.1038/s41598-017-15581-5

Zhang G, Chen Y, Yuqi Wu, Wang S, Zheng H & Hu F. (2022): The effect of nutritional status on the synthesis ability, protein content and gene expression of mandibular glands in honey bee (Apis mellifera) workers, Journal of Apicultural Research, DOI: 10.1080/00218839.2022.2080951

Zhang, S., Wang, S., Li, H., and Li, L. (2011) Vitellogenin, a multivalent sensor and an antimicrobial effector. *Int. J. Biochem. Cell Biol.* 43, 303–305.

Zheng B., Wu Z., Xu, B. (2014). The Effects of Dietary Protein Levels on the Population Growth, Performance, and Physiology of Honey Bee Workers During Early Spring. J. Insect Sci. 14(191), DOI: 10.1093/jisesa/ieu053

Zheng H, Powell JE, Steele MI, Dietrich C, Moran NA. 2017. Honeybee gut microbiota promotes host weight gain via bacterial metabolism and hormonal signaling. Proceedings National Academy of Sciences of the USA 114:4775-4780.

CHAPTER 2

YIELD ESTIMATION MODELS IN PRECISION AGRICULTURE

Mohammed Oday AL HAMDANI[1]
Süreyya Betül RUFAİOĞLU[2]

[1] Harran University, Faculty of Agriculture, Soil Science and Plan Nutrition, Sanliurfa, Turkiye ORCID NO: https://orcid.org/0000-0001-9170-6639 Email: Hamudibang95@gmail.com[1]

[2] Harran University, Faculty of Agriculture, Soil Science and Plan Nutrition, Sanliurfa, Turkiye , ORCID NO: https://orcid.org/ 0000000152858568
Email: sureyyarufaioglu@harran.edu.tr

INTRODUCTION

These observations correspond with earlier research conducted in industrial and urban locales, revealing analogous trends in heavy metal pollution (Alloway, 2013); (Akbar, 2009). Nonetheless, discrepancies may arise across distinct geographical contexts. It is imperative to discern the specific local factors and origins of heavy metal pollution within the examined area to formulate focused remediation strategies. Yield estimation constitutes a pivotal element of precision agriculture, establishing the foundation for optimal resource distribution, informed decision-making, and enhanced sustainability within agricultural frameworks (Coble, 2018). Conventional yield estimation techniques, which depend on field sampling, historical datasets, and expert evaluations, provide limited precision owing to their failure to accommodate spatial and temporal variability (Basso, 2013). To mitigate these shortcomings, contemporary yield estimation frameworks integrate geostatistical methodologies, machine learning algorithms, and remote sensing innovations to facilitate more accurate and scalable yield forecasts (Feng, 2020).

Geostatistical approaches, encompassing Ordinary Kriging and Inverse Distance Weighting (IDW), leverage spatial interrelations among data points to refine yield predictions, thus rendering insights into soil variability and crop heterogeneity across extensive fields (Goovaerts, 1997); (Hengl, 2009). Predictive accuracy is augmented by machine learning frameworks, including Random Forests, Support Vector Machines, and Artificial Neural Networks, which analyze intricate, non-linear connections among environmental elements and agricultural output (Kim, 2021). For example, deep learning architectures have proven effective in analyzing high-dimensional datasets, including meteorological, edaphic, and field sensor data, consequently surpassing conventional regression techniques in yield prediction endeavors (amilaris, 2018).

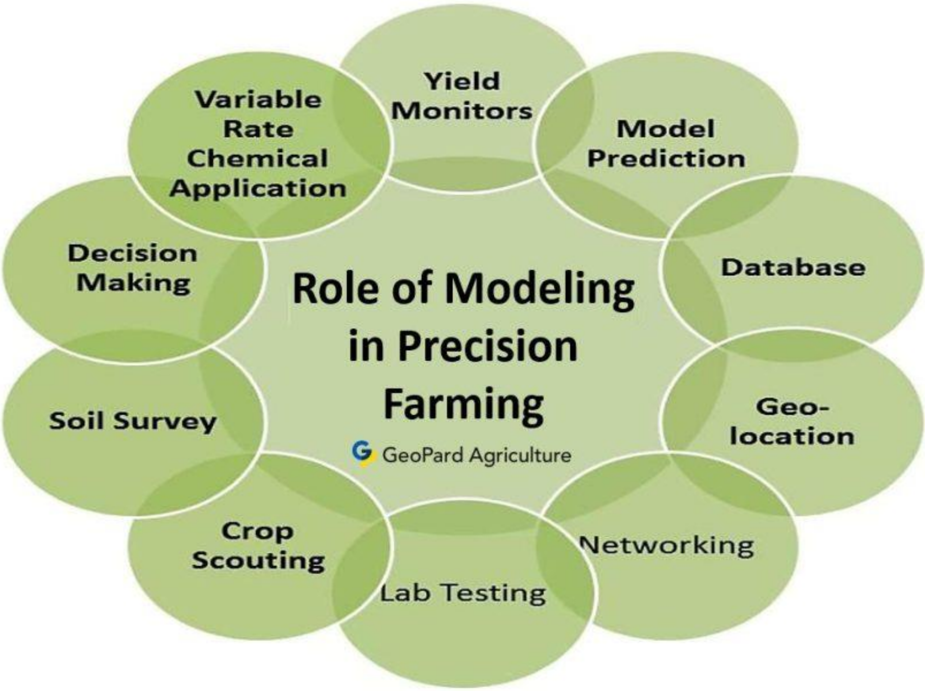


Figure.1. Role of modelling in Precision (URL.1.)

Multispectral and hyperspectral imaging from satellite and UAV platforms, as remote sensing tools, deliver crucial insights into crop health, development stages, and stress signals, with metrics such as the Normalized Difference Vegetation Index (NDVI) indicating strong correlations with yield (Xie, 2018). The integration of such remote sensing data with Geographic Information Systems (GIS) facilitates meticulous mapping and examination of yield-related parameters at a detailed level, promoting site-specific management strategies (Mulla, 2013).

Empirical investigations across diverse crop systems exemplify the practical utilization of these models. For instance, in the context of corn yield estimation, the amalgamation of Random Forest algorithms with NDVI data sourced from satellite imagery has revealed significant enhancements in accuracy, augmenting predictive capabilities by as much as 20% in comparison to linear models (Liakos, 2018). Similarly, the yield estimation for wheat and rice has seen advancements through the alliance of machine learning approaches and geostatistical models with UAV-generated images, allowing for detailed yield mapping in varied terrains (Roth, 2021).

Regardless of these strides, difficulties continue to exist, particularly related to data integration and scalability. The establishment of robust yield models necessitates addressing data quality concerns, challenges related to model interpretability, and the elevated costs associated with sophisticated sensing technologies (Wolfert, 2017). Prospective avenues in yield estimation entail the incorporation of Internet of Things (IoT) devices and real-time data analysis via artificial intelligence, thereby enhancing the agility and applicability of precision agriculture models (Tsouros, 2019). By scrutinizing these methodologies, this chapter highlights the transformative potential of data-driven yield estimation models in promoting sustainable agricultural practices.

Precision agriculture has surfaced as a revolutionary methodology in agronomy, distinguished by its dependence on data-centric strategies aimed at enhancing crop management and optimizing yield results. This fundamental transformation is predominantly driven by technological advancements, including remote sensing, geospatial analysis, and machine learning, which empower agricultural practitioners to make more informed and location-specific decisions (Liakos et al., 2018). A pivotal element of precision agriculture is yield forecasting—the act of estimating crop yield prior to harvest—which is instrumental in directing resource distribution, organizing harvest schedules, and assessing economic repercussions (Basso, 2013).

Historically, yield forecasting techniques have depended on historical datasets and expert-driven methodologies, frequently augmented by field sampling. However, these approaches exhibit constraints in adequately capturing the spatial and temporal variability of crop and soil conditions across extensive agricultural areas (Coble, 2018). For example, yield predictions grounded in historical averages tend to neglect site-specific elements, leading to subpar projections and less effective resource management (Feng, 2020). Consequently, these conventional methods are progressively being enhanced or supplanted by sophisticated yield forecasting models, which amalgamate spatial data from remote sensing, in-situ sensors, and advanced analytical tools.

In contemporary times, machine learning methodologies, exemplified by Random Forests, Support Vector Machines, and Artificial Neural Networks, have captured interest for their proficiency in examining intricate, non-linear relationships involving crop yields and environmental elements, like climatic factors, soil attributes, and management practices (Liakos, 2018). Machine learning facilitates the processing of extensive datasets, uncovering complex patterns that traditional regression techniques may overlook. As an illustration, deep learning models have revealed notable effectiveness in processing high-dimensional data collections, including multispectral images acquired via UAVs, ultimately facilitating precise yield estimations (Kim, 2021).

A vital part of modern yield analysis relates to geostatistics, involving practices such as Ordinary Kriging and Inverse Distance Weighting (IDW). These techniques enable spatial interpolation, enhancing predictions by utilizing the spatial autocorrelation present among data points throughout the agricultural field (Goovaerts, 1997); (Hengl, 2009). Notably, Kriging has proven to be effective in areas with heterogeneous soil attributes, offering a mechanism to consider spatial discrepancies in soil properties, which often serve as critical determinants of crop yield (Mulla, 2013).

Innovative approaches to remote sensing, involving satellite and UAV-utilized multispectral and hyperspectral imaging, have altered the landscape of yield forecasting by supplying timely details on crop condition, developmental phases, and potential stressors (Xie, 2018). Through indices such as the Normalized Difference Vegetation Index (NDVI), these technologies provide insights into vegetative vigor, which is a robust indicator of yield potential. By integrating remote sensing with Geographic Information Systems (GIS), precision agriculture can create detailed spatial maps that inform site-specific management practices, ultimately fostering greater efficiency and sustainability within agricultural systems (Mulla, 2013).

The capability of yield estimation models to improve productivity and sustainability is manifest; nonetheless, numerous challenges persist. Factors such as the quality of data, the integration of various platforms, and the intricacy of environmental variables continue to hinder the accuracy and applicability of models across a range of agricultural scenarios (Wolfert, 2017). In light of these hurdles, innovative technologies, including Internet of Things (IoT) gadgets and real-time data evaluation, possess the capacity to refine these models, promoting more adaptable and responsive yield predictions ahead (Tsouros, 2019).

This chapter investigates the diverse yield estimation methodologies presently employed in precision agriculture, encompassing traditional techniques as well as advanced machine learning and remote sensing methodologies. Through a comprehensive analysis of contemporary case studies and practical applications, the chapter underscores the transformative significance of these models in improving yield predictability and fostering sustainable agricultural practices.

FACTORS AFFECTING CROP YIELD

crop yield is the outcome of these productivity-determining interactions as affected by biotic and abiotic factors which may either enhance or suppress their influence depending on environmental conditions, plant variety involved in gene regulation at any specific stage resulting variation from species to genotype through agronomic practices. Understanding these components, in order to build accurate yield prediction models helps improve the efficiency of inputs for farming.

Soil Characteristics

Numerous factors, such as textural properties of the soil structure and nutrient content can determine how good a plant is. If the soil is fertile, crops can thrive; however; if it does not have enough nutrients, they may never produce as much yield. It is well established that the soil properties like pH, organic matter content and Cation Exchange Capacity (CEC) have a direct influence on nutrient availability to plants (Schmidt, 2014). In addition, physical attributes of soil such as texture and compaction affect root growth. aeration, water infiltration, and other factors that are essential to crop health (Brady, 2010). Soil mapping and sampling are frequently used in precision agriculture to evaluate these factors and manage soil variability through site-specific nutrient management (Mulla, 2013).

Availability of Water and Irrigation

A vital resource for crop production, water has an impact on physiological functions like photosynthesis and nutrient absorption. Water stress caused by inadequate rainfall or inadequate irrigation management can drastically lower crop yields (Tardieu, 2010). On the other hand, too much water can cause nutrient leaching and root diseases. Water-use efficiency can be improved with advanced irrigation techniques like drip and subsurface irrigation, especially in arid and semi-arid areas (Fereres, 2007).

Climate and Weather Conditions

Depending on the crop variety, management techniques, and environmental circumstances, biotic and abiotic variables interact in a complicated way to affect crop production, each of which contributes differently to productivity results. Optimizing agricultural inputs and creating precise yield estimate models require an understanding of these elements. Properties of Soils The texture, structure, and nutritional makeup of the soil are the main factors that determine crop output. Healthy crop development is encouraged by nutrient-rich soils, but the potential yield might be severely limited by poor soils. According to (Schmidt, 2014), the pH, organic matter content, and cation exchange capacity of the soil all have a direct effect on the nutrients that plants can access. Furthermore, physical attributes of the soil, such bulk density and texture, affect aeration, water infiltration, and root penetration—all of which are vital for crop health (Brady, 2010). Soil is commonly used in precision agriculture.

Crop Variety and Genetics

The potential yield of crops is largely determined by their genetic composition. According to (Fischer, 2014), improved crop varieties created through breeding programs have greater potential yields, are more resilient to stress, and are resistant to pests and diseases. Genetically modified (GM) crops, for instance, have been developed for characteristics like insect and drought resistance, which have led to notable increases in production, especially in difficult-to-reach areas (Qaim, 2009). (Tadesse, 2019) assert that local adaptation is crucial to agricultural performance, making the selection of the appropriate crop variety for a particular climate or location crucial to optimizing production.

Pest and Disease Pressure

According to some estimates, pests and diseases can cause up to 20–40% of crop losses worldwide, which is a significant amount of crop loss (Savary, 2019). Pests, such as weeds, insects, and diseases, can affect crop health by decreasing nutrient absorption and photosynthetic efficiency (Oerke, 2006).

Precision agriculture uses remote sensing for early identification and monitoring of pest and disease outbreaks, while integrated pest management (IPM) and contemporary chemical treatments assist lessen these consequences (Mahlein, 2016).

Fertilization and Nutrient Management

Since plants need enough nitrogen, phosphorous, potassium, and other micronutrients for healthy development, nutrient availability is a critical component of agricultural output. Though excessive or insufficient fertilizer applications can result in lower yields and environmental issues such nutrient runoff, fertilizer applications are necessary to augment soil nutrients (Tilman, 2002). More economical and ecologically friendly fertilizing techniques are now possible because to precision nutrient management, which is based on soil and crop sensing technology (Fageria, 2005).

Management Practices

Crop yield is greatly impacted by management techniques including tillage, crop rotation, planting density, and weed control. As to (Larkin, 2010), tillage techniques have an impact on soil structure and root growth, whereas crop rotation and cover cropping can enhance soil fertility and lessen pest burden. According to research, no-till farming can increase soil moisture retention and decrease erosion, both of which can increase production in some situations (Derpsch, 2010).

Machine Learning Models in Yield Estimation

Education has always been one of the mainstays of our society, providing both knowledge for individual minds and a prop to personal growth. It gives people the tools, information, skills that they require to thrive and live full work lives in society. Besides book knowledge, education helps people develop complex ways of thinking that can solve problems and create things; that make up what we call creativity. Educational facilities provide people of all ages with information and skills to enable them to cope with future challenges. In this way education supports the idea of lifelong learning, while immersing our people in the habits necessary to attain success at work and personal life. Because when we invest in education, we are laying a cornerstone for both personal and professional success in the future. And by investing in the future of society, we grant talented people an opportunity to realize their full potential.

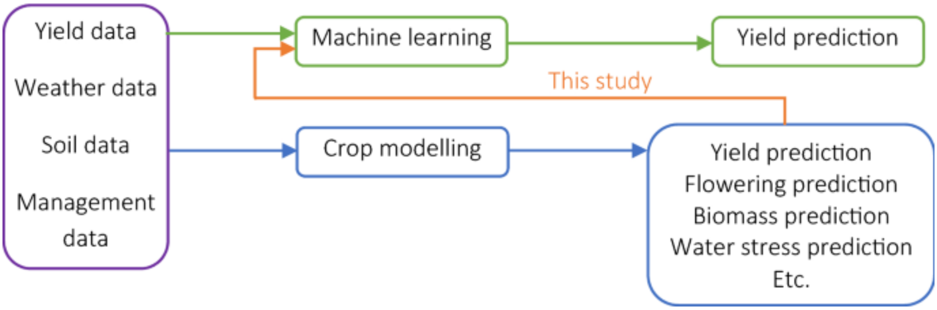


Figure.2. Example of yield modeling flowchart (Shahhosseini et al.,2021)

1-Random Forest (RF)

Education has consistently served as a fundamental pillar within our society, imparting knowledge to individual intellects and fostering personal development. It equips individuals with the essential tools, information, and competencies necessary for thriving and leading fulfilling professional lives within the community. In addition to academic knowledge, education cultivates intricate cognitive processes that enable problem-solving and innovation, which constitute the essence of what we recognize as creativity. Educational institutions offer individuals of diverse age groups the requisite information and skills to prepare them for the challenges that lie ahead. In this manner, education endorses the concept of lifelong learning while ingraining within individuals the habits vital for achieving success in both professional and personal domains. For when we allocate resources toward education, we are establishing a foundational element for future personal and professional accomplishments. As well, by focusing on the future of society through investment, we are reinforcing how vital education is as a mechanism for growth and development. RF models are less prone to overfitting compared to individual decision trees, making them suitable for yield prediction across diverse environments.

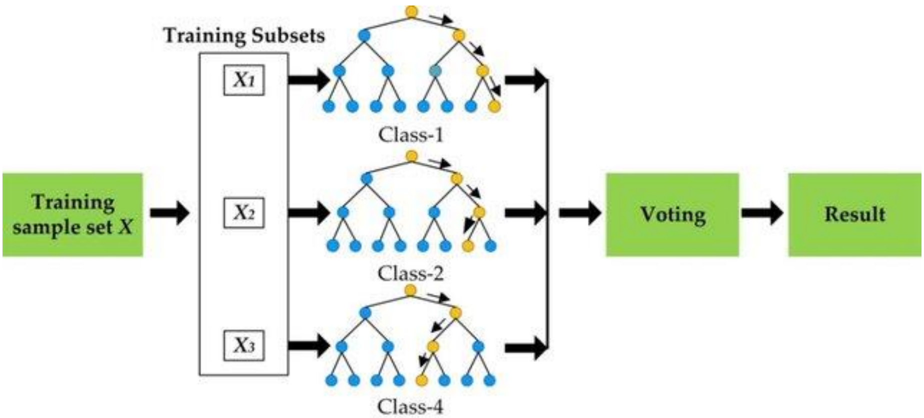


Figure 3. The process of producing Random Forest (RF) results (Wu and Jiao.,2019).

Applications:

Random Forest is a popular tool in precision agriculture that uses meteorological information, soil characteristics, remote sensing indices, and management techniques to forecast crop yields. For instance, by combining a big dataset of past yields and climate variables, (Jeong, 2016)showed that RF could accurately forecast both global and regional maize yields. In other research, RF has been used to accurately estimate the yields of soybeans, rice, and wheat (Goovaerts, 1997).

2-Support Vector Machines (SVM)

In supervised learning, algorithms called Support Vector Machines, abbreviated SVMs, are employed for tasks that involve classification and regression. In the context of yield estimation, SVM models operate by identifying the hyperplane that optimally segregates data points within a high-dimensional space, thereby maximizing the separation between distinct classes or regression results (Mountrakis, 2011). In situations where the correlation between input variables and yield is not linear, SVMs provide distinct benefits as they can use kernel functions to map data into dimensions that are higher.

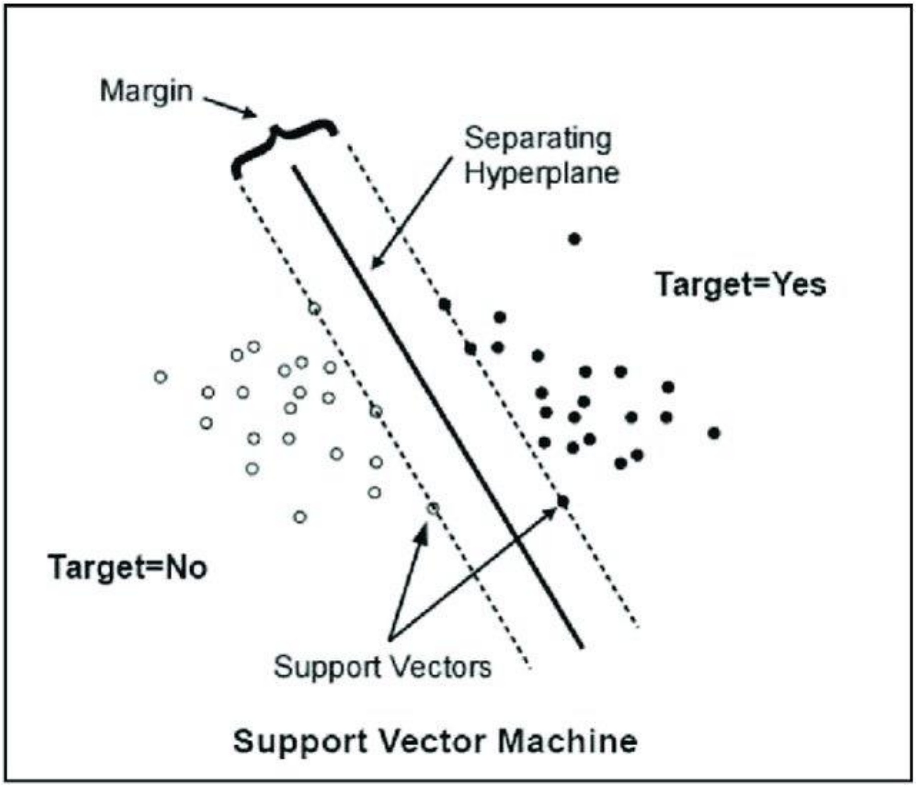


Figure.4. Support Vector Machine (SVM) (Rady and Anwar.,2019).

Applications: SVMs have found utility in a multitude of agricultural contexts, notably in yield forecasting. (Gao, 2020) made use of SVMs to project rice yield by leveraging remote sensing data, thereby reaching notable levels of predictive accuracy. The capacity of SVMs to process high-dimensional datasets renders them adept at amalgamating disparate information sources, including satellite imagery, soil characteristics, and climatic factors, into yield estimation frameworks.

3-Artificial Neural Networks (ANNs)

Artificial Neural Networks (ANNs), taking cues from the layout of the human brain, are made up of layers of linked nodes (neurons) that manage input data through weighted connections. ANNs exhibit significant flexibility and can effectively model complex, nonlinear relationships, rendering them particularly suitable for yield estimation endeavors (Crane-Droesch, 2018). Deep learning, a specialized domain of ANNs, employs multiple hidden layers to discern intricate patterns within extensive datasets, thereby enhancing prediction accuracy. ANNs demonstrate superior performance in scenarios where the relationship between input and output variables is markedly nonlinear and challenging for simpler models to encapsulate.

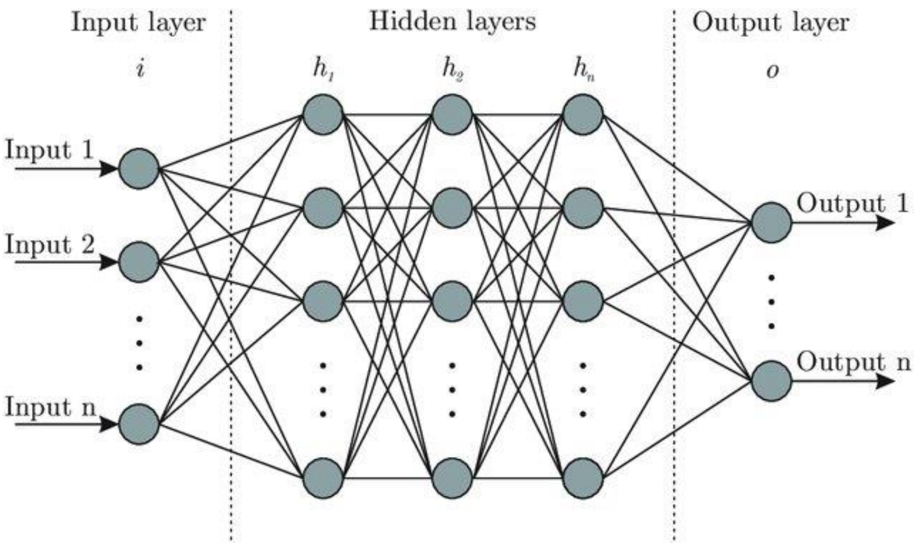


Figure.5. Artificial neural network architecture (Bre et al.,2018).

Applications:

ANNs have been effectively utilized in estimating crop yields, particularly when synthesizing multi-source data such as meteorological, soil, and remote sensing information. For instance, (Crane-Droesch, 2018) applied ANNs to forecast maize yield across the U.S. Corn Belt, revealing a performance advantage over conventional linear models by elucidating complex interactions among climatic variables. Similarly, (Chen, 2016) illustrated the effectiveness of ANNs in enhancing soybean yield predictions by integrating remote sensing and meteorological data.

4-Gradient Boosting Machines (GBMs)

Gradient Boosting Machines (GBMs) represent another ensemble learning methodology; however, in contrast to Random Forest, GBM models construct trees in a sequential manner, with each subsequent tree targeting the errors of its predecessors. This iterative approach facilitates GBMs in achieving high accuracy in yield prediction tasks, particularly when the relationships between inputs and outputs are complex and nonlinear (Chen, 2016). A widely recognized variant of GBM is XGBoost, celebrated for its efficiency and scalability.

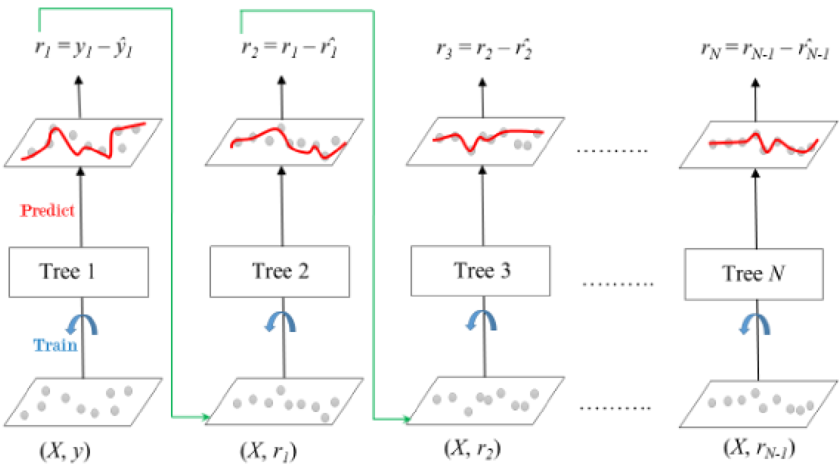


Figure.6. Gradient Boosting Machines (GBM) (URL.2)

Applications:

GBMs have been employed in yield estimation scenarios, demonstrating considerable advancements over traditional regression methodologies. For instance (Pantazi, 2016) implemented GBMs to forecast wheat yield utilizing remote sensing data and soil attributes, achieving high predictive accuracy. GBMs are especially effective in incorporating high-dimensional data from diverse sources, encompassing climate, soil, and crop characteristics.

5- Convolutional Neural Networks (CNNs)

A family of deep learning models called convolutional neural networks is typically employed for image processing applications. CNNs are being utilized more and more in agriculture to analyze drone and satellite pictures in order to estimate crop yields. These models are capable of automatically identifying patterns in spatial data that are associated with yield, such as crop canopy features or vegetation indices (Rouse, 1973).

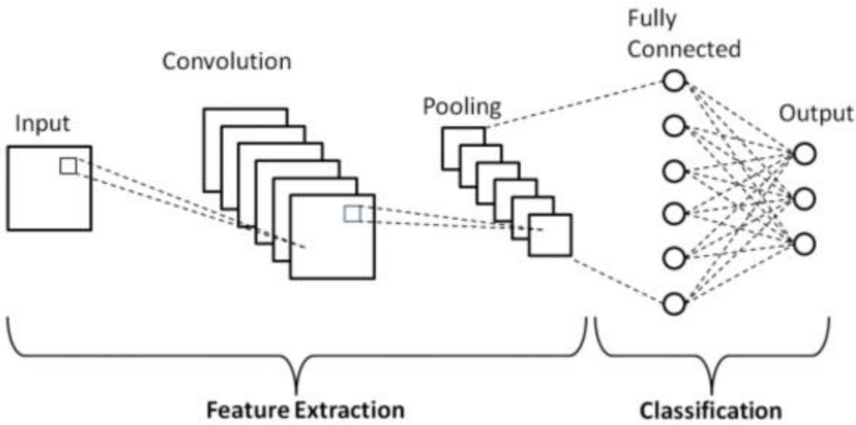


Figure.7.CNN representation (URL.3).

Applications:

Gain estimate from remote sensing data, especially high-resolution satellite pictures, has been accomplished through the use of CNNs. (Rouse, 1973), for instance, showed how CNNs may enhance yield prediction by using spatial patterns in agricultural areas by using them to forecast crop yields based on multispectral images. Precision agriculture, where high spatial resolution is essential for site-specific management choices, benefits greatly from these models.

6- K-Nearest Neighbors (KNN)

K-Nearest Neighbors is a straightforward yet powerful machine learning model for classification and regression applications. KNN predicts the result of yield estimate by identifying the data points that are closest to a particular input (neighbors) and average their yields. As a non-parametric approach, KNN is appropriate for yield estimate in a variety of agricultural scenarios as it does not assume anything about the distribution of the underlying data (Masoud, 2013).

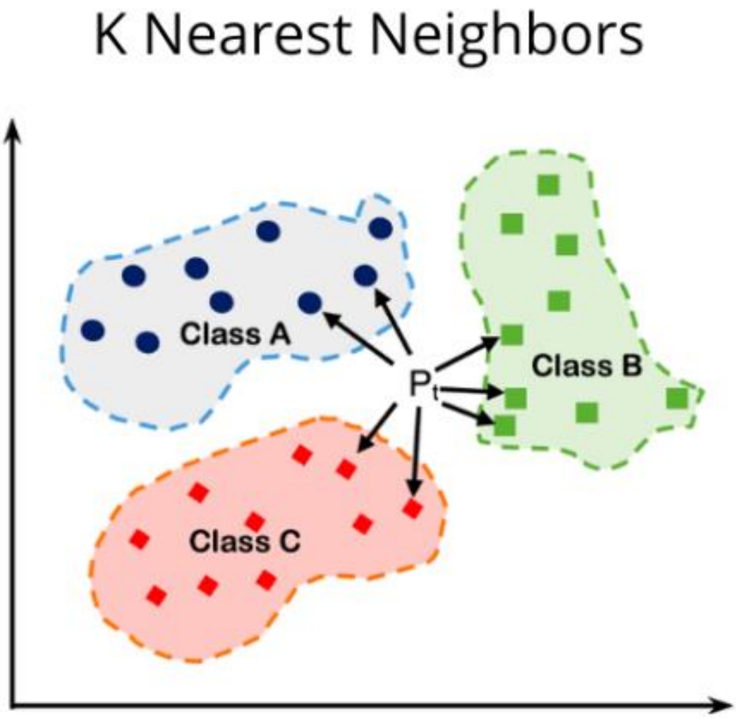


Figure.8. K Nearest Neighbors (URL.4).

Applications:

In small-scale studies with restricted data availability, KNN has been used to estimate yield for a variety of crops. By examining soil characteristics, meteorological data, and management techniques, (Masoud, 2013), for example, employed KNN to forecast crop yields in smallholder farming systems. KNN might not be as advanced as other models, but

7- Deep Learning Approaches

In addition to conventional Artificial Neural Networks (ANNs) and Convolutional Neural Networks (CNNs), advanced deep learning architectures such as Recurrent Neural Networks (RNNs) and Long Short-Term Memory (LSTM) networks are increasingly employed to elucidate temporal dependencies inherent in the dynamics of crop growth and yield. These architectures demonstrate particular efficacy in the context of time-series datasets, such as historical yield statistics or meteorological patterns observed throughout growing seasons (Goodfellow, 2016). By assimilating temporal patterns, these models have the potential to enhance the precision of yield forecasts, especially in contexts characterized by variable climatic conditions.

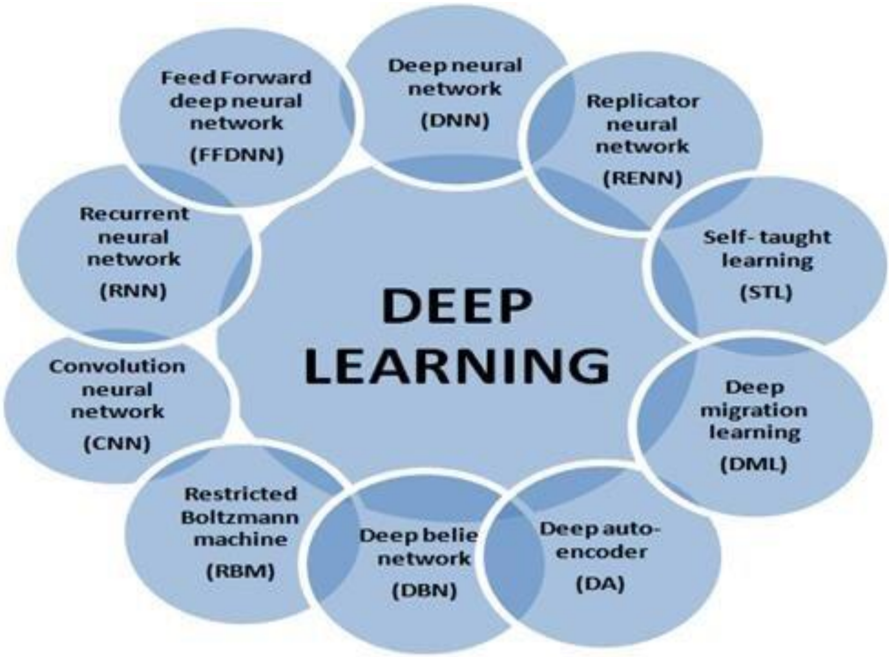


Figure.9. Deep learning approaches (Narsimha et al.,2022).

Applications:

Deep learning frameworks have been deployed across diverse scenarios for the estimation of crop yields. As an example, (Goodfellow, 2016) depicted the prowess of deep learning algorithms in forecasting maize yield through the use of satellite imagery, securing superior accuracy when compared to typical methodologies. Likewise, RNNs and LSTMs have been harnessed to project crop yields by scrutinizing historical weather information, thereby establishing their significance as instrumental resources in mitigating the impacts of climate variability.

Remote Sensing and GIS in Yield Estimation

In precision agriculture, geographic information systems (GIS) and remote sensing have become essential tools, especially for estimating crop production. Large agricultural regions may now be continuously monitored thanks to these technologies, which also provide information on environmental elements, soil conditions, and the health of crops. While GIS makes it possible to spatially analyse and integrate this data with other geographic datasets, remote sensing uses drones, satellites, and other aerial platforms to gather data about crops and their surroundings. With an emphasis on the application of particular vegetation indices like the Normalized Difference Vegetation Index (NDVI), this section addresses the use of remote sensing technologies and GIS in yield estimation.

Figure. Satellite image (URL.5).

An effective way to gather geographical and temporal data on crop growth, soil moisture, and climatic variables is through the use of remote sensing devices. Numerous vegetation indices may be derived by processing multispectral and hyperspectral data from satellite imaging, aerial photography, and drone-based sensors. In order to evaluate crop health, stress levels, and development stages—all of which are directly tied to yield—these indicators are essential.

Multispectral and hyperspectral imaging: Multiple spectral bands, usually in the visible and near-infrared (NIR) ranges, are used by multispectral sensors to gather information on the health and vigor of plants. Contrarily, hyperspectral sensors record information over hundreds of small spectral bands, giving more precise details on the metabolic makeup of crops (Thenkabail, 2014). Both types of sensors are essential for monitoring crop conditions and estimating yields.

Applications in Yield Estimation:

Crop development may be tracked using remote sensing data, which offers information on plant production and health throughout the growing season. (Zhang, 2019), for instance, estimated maize yield by examining changes in plant canopy structure and vigor over time using multispectral data from drones. The efficiency of remote sensing in forecasting agricultural productivity was demonstrated by the correlation between these data and yield measurements taken on the ground.

2- Geographic Information Systems (GIS) in Yield Estimation

GIS plays a critical role in integrating spatial data from various sources, including remote sensing, soil surveys, and climatic records, to produce detailed maps of crop yield potential. GIS allows for the spatial analysis of yield-related factors, such as soil properties, topography, and weather patterns, facilitating site-specific management practices.

Spatial Data Integration:

With Geographic Information Systems (GIS), it is possible to unify data gathered through remote sensing technologies, terrestrial observations, and extra geospatial datasets, which supports the formulation of predictive frameworks for farming yield. To illustrate, soil features, including the constitution of organic matter and pH measurements, can be diligently mapped out and associated with Normalized Difference Vegetation Index (NDVI) data to elevate the precision of yield forecasts (Mulla, 2013). By merging spatial data layers, GIS contributes to producing more precise, site-specific yield forecasts while advancing precision agriculture practices dedicated to optimizing the use of essential resources such as water and fertilizers.

Applications within Precision Agriculture:

The implementation of GIS within precision agriculture has proven instrumental in the creation of yield maps that delineate spatial variability across agricultural fields. Such maps empower farmers to adopt variable rate application (VRA) techniques for fertilizers and irrigation, thereby augmenting operational efficiency and mitigating environmental consequences (Gheysari, 2020). Furthermore, GIS-facilitated yield models provide farmers the means to assess crop productivity across diverse management zones and modify their agricultural practices accordingly.

3-Vegetation Indices in Yield Estimation: Focus on NDVI

The Normalized Difference Vegetation Index (NDVI) stands as one of the most extensively utilized remote sensing methodologies for yield estimation. NDVI is computed utilizing reflectance data from red and near-infrared wavelengths, serving as a dependable metric for evaluating plant vitality and biomass (Rouse, 1973). Elevated NDVI readings generally indicate healthier, more robust crops, which frequently correlate with enhanced yield potential.

NDVI Formula:

$$NDVI = \frac{(NIR - Red)}{(NIR + Red)}$$

Where:

- NIR is the near-infrared reflectance (which healthy vegetation reflects strongly).
- Red is the red reflectance (which healthy vegetation absorbs for photosynthesis).

Benefits of NDVI in Yield Estimation:

Timely assessment: NDVI can be continually computed throughout the growing season, furnishing timely insights into crop vitality and anticipated yield (Becker-Reshef, 2010). Non-invasive: As NDVI is derived from remote sensing information, it facilitates non-invasive monitoring of crop conditions across extensive areas. Yield correlations: A plethora of research has established robust correlations between NDVI figures and crop yield, affirming its status as a trustworthy instrument for yield forecasting. To illustrate, (Reynolds, 2000) revealed that NDVI-based maps for wheat growth are capable of accurately predicting the final yields.

Utilization of NDVI in Yield Estimation:

NDVI has been employed across numerous crops to forecast yields. For example, (Lobell, 2015) utilized NDVI derived from satellite data to project wheat yields in varied regions, demonstrating that NDVI effectively captures spatial yield variability linked to environmental factors and management strategies. In a similar vein, (Becker-Reshef, 2010) leveraged NDVI for global wheat production monitoring, exemplifying the index's potential to aid extensive yield estimation initiatives.

Alternative Vegetation Indices:

While NDVI is the predominant index employed, other vegetation indices, such as the Enhanced Vegetation Index (EVI) and the Soil-Adjusted Vegetation Index (SAVI), have also found application in yield estimation. EVI enhances the NDVI methodology by mitigating the effects of atmospheric conditions and canopy background signals, rendering it more applicable in regions characterized by dense vegetation (Huete, 2002). Conversely, SAVI incorporates adjustments for soil brightness in areas with limited vegetation, thereby enhancing accuracy in arid or semi-arid environments (Huete A. R., 1988).

4. Integrating Remote Sensing and GIS for Precision Yield Estimation

The amalgamation of remote sensing and Geographic Information System (GIS) technologies establishes a robust framework for yield estimation within the domain of precision agriculture. Remote sensing facilitates the acquisition of timely, spatially intricate data regarding crop conditions, whereas GIS empowers the synthesis and analysis of this data alongside other geospatial determinants that impact yield. Together, these methodologies promote the creation of more exact, site-oriented yield predictions and refine decision-making procedures in the field of agricultural administration.

Precision Yield Mapping: Yield mapping entails the integration of remote sensing data with yield monitor data procured from harvesting machinery to formulate comprehensive maps illustrating spatial yield variability within agricultural fields. Such maps are indispensable for discerning zones of high and low productivity, thereby enabling targeted management interventions (Schimmelpfennig, 2016). For instance, (Mulla, 2013) underscored the application of yield maps derived from remote sensing data and GIS to inform the variable rate application of fertilizers, resulting in enhanced efficiency and diminished input expenditures.

Applications in Climate Resilience:

Remote sensing and GIS also play a critical role in improving climate resilience in agriculture. By monitoring crop performance in real-time and predicting yields based on current conditions, these tools help farmers adapt to climate variability and mitigate the risks of crop failure (Lobell, 2015).

Case Studies in Yield Estimation using Remote Sensing, GIS, and Machine Learning

The efficiency of combining machine learning models, Geographic Information Systems (GIS), and remote sensing technologies has been shown in a number of case studies focused on yield estimate. These studies demonstrate how these methods may be used to improve agricultural production and decision-making by offering useful insights into how they can be utilized across various crops, geographical locations, and climatic characteristics. The implementation of these cutting-edge technologies for precise yield estimate is demonstrated in this part through a number different case studies from various geographical locations and agricultural systems.

Maize Yield Estimation in the U.S. Corn Belt

Objective:

This case study conducted by (Crane-Droesch, 2018)elucidates the application of machine learning techniques, specifically Artificial Neural Networks (ANNs), for the prognostication of maize yield within the confines of the U.S. Corn Belt. The research integrates an array of data sources, inclusive of extensive climatic records, soil properties, and agronomic practices, to construct a comprehensive yield prediction framework.

Methodology:

Data Inputs: The model incorporated historical climatic variables, encompassing precipitation and temperature, in conjunction with soil texture, organic matter concentrations, and nitrogen fertilization rates.

Machine Learning Model: An ANN was meticulously developed and trained utilizing the dataset to elucidate the nonlinear interactions among these variables and maize yield. We applied NDVI data derived from satellites to examine plant health over the growth period, yielding vital information about crop advancement.

Results:

The ANN model markedly surpassed traditional linear regression models by effectively capturing the nonlinear ramifications of climatic variability on maize yield. Utilizing NDVI readings, the model effectively gauged crop health on-the-fly, which further refined the forecasting precision for yields.

Conclusion:

This case study underscores the efficacy of amalgamating climatic data, soil attributes, and remote sensing indices with machine learning methodologies for the prediction of maize yield, thereby furnishing significant insights for strategic decision-making in expansive commercial agriculture.

2. Wheat Yield Estimation in the Punjab Region of Pakistan

Objective: This investigation by (Lobell, 2015) explores the utilization of remote sensing technologies, specifically the Normalized Difference Vegetation Index (NDVI) and Enhanced Vegetation Index (EVI), for forecasting wheat yields in the Punjab region of Pakistan. This region is marked by heterogeneous cropping systems, rendering it a notably challenging milieu for precise yield estimation.

Methodology:

Remote Sensing Data: The researchers employed satellite imagery to extract NDVI and EVI, concentrating on critical growth phases of wheat, such as heading and grain filling.

GIS Integration: Geographic Information Systems (GIS) were utilized to amalgamate spatial layers of soil characteristics, irrigation infrastructure, and historical yield data.

Yield Prediction Model: A regression model was formulated, utilizing NDVI and EVI as pivotal predictors, alongside climatic and management data.

Results:

The NDVI and EVI metrics recorded during the heading phase of wheat were identified as strong prognostic indicators of final yield. The study exhibited that the integration of remote sensing data with GIS substantially enhanced yield predictions, achieving an accuracy rate exceeding 80% in comparison to conventional ground-based estimations.

In conclusion:

This investigation demonstrates the ability of remote sensing and GIS technologies to generate consistent, large-volume predictions for wheat yields, especially in territories known for their intricate agricultural setups. This methodology aids in the optimization of irrigation schedules and resource distribution within the agricultural framework of Punjab.

1. Rice Yield Estimation in Taiwan Using Support Vector Machines (SVMs)

Objective: (Tseng, 2020) undertook an empirical investigation to estimate rice yield in Taiwan utilizing Support Vector Machines (SVMs) predicated on remote sensing data in conjunction with ground observations. The principal aim of the investigation was to clarify how SVM models could proficiently predict yields by identifying the nonlinear relationships between environmental factors and agricultural output.

Methodology:

Data Inputs: The SVM model incorporated multispectral remote sensing data, which encompassed NDVI and Leaf Area Index (LAI), alongside terrestrial measurements of soil moisture and temperature.

Remote Sensing: Multispectral satellite imagery was systematically acquired throughout the cultivation season, emphasizing critical growth phases such as tillering and grain ripening.

Modeling Approach: SVMs were harnessed to forecast rice yields predicated on the integration of remote sensing and ground-truth data. The model was calibrated utilizing historical datasets from prior growing seasons.

Results:

The SVM model exhibited a substantial degree of accuracy, evidenced by an R^2 value of 0.87 for its rice yield predictions. The employment of NDVI and LAI as key predictors enabled the model to effectively address the spatial heterogeneity in crop health across various fields.

Conclusion:

This case study substantiates the efficacy of SVMs in elucidating intricate, nonlinear relationships between environmental variables and rice yields. The amalgamation of remote sensing data with machine learning models facilitated robust predictions, thereby enhancing resource management and strategic decision-making in rice cultivation.

2. Yield Mapping and Variable Rate Application in Wheat Farming in Australia

Objective: (Mulla, 2013) executed a case study in Australia to illustrate the application of Geographic Information Systems (GIS) and remote sensing technologies for precision yield mapping within the domain of wheat agriculture. The primary objective of this investigation was to elucidate the advantages associated with the implementation of variable rate application (VRA) of fertilizers, contingent upon yield forecasts derived from remote sensing data.

Methodology:

Remote Sensing: Satellite imagery was employed to compute the Normalized Difference Vegetation Index (NDVI) and other relevant vegetation indices throughout the entirety of the wheat cultivation period.

GIS Integration: Geographic Information Systems were utilized to delineate spatial disparities in wheat yields, amalgamating NDVI data with soil characteristics, topographical features, and historical yield datasets. Yield maps were developed through the integration of remote sensing data along with yield monitoring information acquired from harvesting equipment.

Variable Rate Application: The resultant yield maps served as a framework to facilitate the VRA of fertilizers, thereby enabling site-specific management of nutrient applications.

The Support Vector Machine (SVM) model showcased a significant level of accuracy, reaching an R^2 coefficient of 0.87 in the projections concerning rice yield. The incorporation of the Normalized Difference Vegetation Index (NDVI) and Leaf Area Index (LAI) as principal predictors facilitated the model's ability to capture the spatial heterogeneity in crop health across various agricultural fields.

Conclusion: This case study illustrates the effectiveness of Support Vector Machines (SVMs) in elucidating intricate, nonlinear interactions between environmental factors and rice yields. The integration of remote sensing data with machine learning methodologies yielded dependable predictions, thereby enhancing resource management and informed decision-making within the realm of rice cultivation.

3. Yield Mapping and Variable Rate Application in Wheat Farming in Australia

(Mulla, 2013) conducted an empirical investigation in Australia to elucidate the applications of Geographic Information Systems (GIS) and remote sensing technologies for the precise mapping of yield in wheat cultivation. The objective of the study was to underscore the advantages of variable rate application (VRA) of fertilizers predicated on yield forecasts derived from remote sensing data.

Methodology:

Remote Sensing: The analysis employed satellite imagery to compute the Normalized Difference Vegetation Index (NDVI) and other pertinent vegetation indices throughout the duration of the wheat growing season.

GIS Integration: Geographic Information Systems were utilized to delineate spatial discrepancies in wheat yields, amalgamating NDVI data with soil characteristics, topographical features, and historical yield datasets.

Yield Mapping: Yield maps were constructed employing remote sensing data alongside yield monitor data obtained from harvesting equipment.

Variable Rate Application: The resultant yield maps informed the VRA of fertilizers, facilitating site-specific management of nutrient inputs.

Results:

The implementation of GIS-based yield maps empowered agronomists to administer fertilizers at varying rates informed by the productivity levels of distinct field zones. Consequently, this methodology culminated in an 18% enhancement in fertilizer use efficiency and a 12% augmentation in overall wheat yields, alongside marked reductions in input expenditures.

Conclusion:

This investigation demonstrates the remarkable opportunities that lie in the collaboration of remote sensing with GIS in precision farming. The methodologies of yield mapping and VRA not only contributed to the enhancement of wheat yields but also facilitated reductions in input costs, thereby establishing a sustainable framework for extensive agricultural operations.

5. Soybean Yield Estimation in the Brazilian Cerredo Using Gradient Boosting Machines (GBM)

(Pantazi, 2016) analyzed the effectiveness of Gradient Boosting Machines (GBMs) in estimating soybean yields in the Brazilian Cerredo, a region identified for its stringent agricultural operations. The investigation aimed to clarify the extent to which Gradient Boosting Machines (GBMs), in conjunction with remote sensing data, are capable of forecasting yields across vast and diverse agricultural terrains.

Methodology:

Data Inputs: The GBM model integrated remote sensing data, encompassing NDVI, Enhanced Vegetation Index (EVI), and soil moisture indices, in conjunction with ground-based assessments of soil properties and climatic data.

Modeling Approach: The GBM methodology was selected owing to its proficiency in managing intricate, high-dimensional datasets. The model underwent training utilizing an extensive dataset that encompassed multiple growing seasons.

Remote Sensing Integration: Satellite data procured from the MODIS sensor were employed to monitor vegetation dynamics throughout the growing season.

Results:

The GBM model realized an accurate rate of 85% in the prediction of soybean yields, significantly surpassing conventional regression models. The use of remote sensing data facilitated the model's ability to comprehensively address the spatial inconsistencies found in crop growth, influenced by fluctuations in soil moisture levels and agricultural management methods.

Conclusion:

This case study accentuates the merits of employing GBMs in conjunction with remote sensing data for the estimation of yields within large-scale, heterogeneous agricultural systems. The model's aptitude for addressing complex interactions among variables rendered it particularly adept at predicting yields in the Brazilian Cerrado.

Studies Conclusion:

These case studies illuminate the pragmatic applications of remote sensing, GIS, and machine learning models in the estimation of yields across diverse crops and geographical regions. These sophisticated technologies demonstrate their capability to boost the precision of predicting crop yields, maximize resource efficiency, and enhance decision-making strategies in agricultural management. The synergistic integration of remote sensing data, geospatial analysis, and sophisticated modeling techniques is imperative for the advancement of precision agriculture and for tackling the contemporary challenges faced in farming.

Challenges and Future Directions Ahead

Yield estimation within the domain of precision agriculture, notwithstanding its advancements, encounters numerous substantial obstacles. The precision of remote sensing data can be compromised by factors such as cloud obstruction, atmospheric disturbances, and sensor inadequacies, which subsequently impede data integrity and yield forecasting. Furthermore, the amalgamation of heterogeneous data sources, including edaphic characteristics, climatological information, and remote sensing visuals, necessitates intricate processing and storage methodologies. Although machine learning algorithms possess considerable potential, they frequently demand extensive datasets for training, which may not be readily accessible across all geographical areas. Also, numerous agricultural specialists are without the vital technical knowledge and equipment essential for the complete execution of these tech upgrades.

Future Directions

Future investigations into yield estimation ought to prioritize the enhancement of data fusion methodologies, thereby facilitating the cohesive amalgamation of heterogeneous datasets. Breakthroughs in sensor technology, encompassing hyperspectral imaging and sharp satellite imagery, hold promise for markedly improving monitoring accuracy. Furthermore, the creation of machine learning models that are more accessible, characterized by diminished data requisites and intuitive user interfaces, may serve to democratize the application of technology. There exists an increasing enthusiasm for real-time yield estimation utilizing Internet of Things (IoT) devices and automated analytical processes, which could foster anticipatory decision-making within the agricultural sector. The proliferation of these technologies into developing regions will be crucial for the assurance of global food security and the promotion of sustainable agricultural practices.

References

Akbar, K. (2009). Heavy Metals in the Environment: Sources and Impact on Health, Environmental Science and Technology series. *This source discusses the distribution and impact of heavy metal pollutants, focusing on urban and industrial areas.*

Alloway, B. (2013). Heavy Metals in Soils: Trace Metals and Metalloids in Soils and their Bioavailability. *3rd Edition, Springer*.

amilaris, A. &.-B. (2018). Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture*, 70-90.

Basso, B. C. (2013). Review of crop yield forecasting methods and early warning systems. *IFAD & FAO, Rome*.

Becker-Reshef, I. J. (2010). Monitoring global croplands with coarse resolution Earth observations: The Global Agriculture Monitoring (GLAM) project. *Remote Sensing*, 1589-1609.

Bre, F., Gimenez, J. M., & Fachinotti, V. D. (2018). Prediction of wind pressure coefficients on building surfaces using artificial neural networks. *Energy and Buildings*, *158*, 1429-1441.

Brady, N. C. (2010). Elements of the nature and properties of soils. *Pearson Education.*

Chen, T. &. (2016). XGBoost: A scalable tree boosting system. *Proceedings of the 22nd ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, 785-794.

Coble, K. H. (2018). Big data in agriculture: A challenge for the future. *Applied Economic Perspectives and Policy*, 79-96.

Crane-Droesch, A. (2018). Machine learning methods for crop yield prediction and climate change impact assessment in agriculture. *Environmental Research Letters*, 114003.

Derpsch, R. F. (2010). Current status of adoption of no-till farming in the world and some of its main benefits. *International Journal of Agricultural and Biological Engineering*, 1-25.

Fageria, N. K. (2005). Enhancing nitrogen use efficiency in crop plants. *Advances in Agronomy*, 97-185.

Feng, Q. L. (2020). UAV remote sensing for urban vegetation mapping: A review. *Remote Sensing, 12(9)*, 1446.

Fereres, E. &. (2007). Deficit irrigation for reducing agricultural water use. *Journal of Experimental Botany*, 147-159.

Fischer, R. A. (2014). Crop yields and global food security: Will yield increase continue to feed the world? *ACIAR Monograph No. 158.*

Gao, J. L. (2020). Crop yield prediction based on machine learning models: An extensive review. . *Computers and Electronics in Agriculture*, 105469.

Gheysari, M. R. (2020). A GIS-based model for spatial optimization of irrigation water use efficiency in wheat production. *Agricultural Water Management*, 105910.

Goodfellow, I. B. (2016). Deep Learning. MIT Press.

Goovaerts, P. (1997). Geostatistics for natural resources evaluation. . *Oxford University Press.*

Hengl, T. H. (2009). A generic framework for spatial prediction of soil properties by regression kriging. *Geoderma*, 75-93.

Huete, A. D. (2002). Overview of the radiometric and biophysical performance of the MODIS vegetation indices. *Remote Sensing of Environment*, 195-213.

Huete, A. R. (1988). A soil-adjusted vegetation index (SAVI). *Remote Sensing of Environment*, 295-309.

Jeong, J. R. (2016). Random forests for global and regional crop yield predictions. *PLOS ONE*.

Kim, Y. C. (2021). Machine learning approaches to data fusion and crop yield estimation: A case study in South Korea. . *Agricultural and Forest Meteorology, 307,* , 108473.

Larkin, R. P. (2010). Rotation and cover crop effects on soilborne potato diseases, tuber yield, and soil microbial communities. *Plant Disease*, 1491-1502.

Liakos, K. G. (2018). Machine learning in agriculture: A review. *Sensors, 18(8)*, 2674.

Lobell, D. B. (2015). A scalable satellite-based crop yield mapper. *Remote Sensing of Environment*, 324-333.

Mahlein, A. K. (2016). Plant disease detection by imaging sensors–parallels and specific demands for precision agriculture and plant phenotyping. *Plant Disease*, 241-251.

Masoud, N. M. (2013). Application of K-nearest neighbor method in agricultural management. *International Journal of Agronomy and Agricultural Research*, 37-42.

Mountrakis, G. I. (2011). Support vector machines in remote sensing: A review. *ISPRS Journal of Photogrammetry and Remote Sensing*, 247-259.

Mulla, D. J. (2013). Twenty-five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering*, 358-371.

Narsimha, B., Raghavendran, C. V., Rajyalakshmi, P., Reddy, G. K., Bhargavi, M., & Naresh, P. (2022). Cyber defense in the age of artificial intelligence and machine learning for financial fraud detection application. *IJEER*, *10*(2), 87-92.

Oerke, E. C. (2006). Crop losses to pests. *The Journal of Agricultural Science*, 31-43.

Pantazi, X. E. (2016). Wheat yield prediction using machine learning and advanced.

Qaim, M. (2009). The economics of genetically modified crops. *Annual Review of Resource Economics*, 665-693.

Rady, E. H. A., & Anwar, A. S. (2019). Prediction of kidney disease stages using data mining algorithms. *Informatics in medicine unlocked*, *15*, 100178.

Reynolds, M. P. (2000). Using physiology and breeding to enhance adaptation of wheat to rainfed environments. *Euphytica*, 175-183.

Roth, A. W. (2021). UAV-based multi-spectral remote sensing for yield prediction of winter wheat. *Remote Sensing*, 1869.

Rouse, J. W. (1973). Monitoring vegetation systems in the Great Plains with ERTS. *Proceedings of the Third Earth Resources Technology Satellite (ERTS) Symposium*, 309-317.

Savary, S. W. (2019). The global burden of pathogens and pests on major food crops. *Nature Ecology & Evolution*, 430-439.

Shahhosseini, M., Hu, G., Huber, I., & Archontoulis, S. V. (2021). Coupling machine learning and crop modeling improves crop yield prediction in the US Corn Belt. *Scientific reports*, *11*(1), 1606.

Schimmelpfennig, D. (2016). Farm profits and adoption of precision agriculture. *Economic Research Report No. 217. United States Department of Agriculture, Economic Research Service.*

Schmidt, J. P. (2014). Spatial analysis of soil fertility for site-specific crop management. *Advances in Agronomy*, 1-39.

Tadesse, W. B. (2019). Wheat production and breeding in Sub-Saharan Africa: Challenges and opportunities in the face of climate change. *International Journal of Climate Change Strategies and Management,*, 488-507.

Tardieu, F. &. (2010). Dissection and modelling of abiotic stress tolerance in plants. *Current Opinion in Plant Biology*, 206-212.

Thenkabail, P. S. (2014). Hyperspectral remote sensing of vegetation. *CRC Press*.

Tilman, D. C. (2002). Agricultural sustainability and intensive production practices. *Agricultural sustainability and intensive production practices*, 671-677.

Tseng, Y.-H. C.-L.-W. (2020). Estimating rice yield using support vector machines with multispectral imagery and environmental data. *Computers and Electronics in Agriculture*, 105095.

Tsouros, D. C. (2019). A review on UAV-based applications for precision agriculture. *Information*, 349.

Wolfert, S. G. (2017). Big data in smart farming–A review. *Agricultural Systems*, 69-80.

Wu, X., Gao, Y., & Jiao, D. (2019). Multi-label classification based on random forest algorithm for non-intrusive load monitoring system. *Processes*, *7*(6), 337.

Xie, C. S. (2018). Remote sensing applications in precision agriculture: A case study in northeastern China. *Agricultural Water Management*, 201-210.

Zhang, X. L. (2019). Estimating maize yield at field scale using UAV-based RGB and hyperspectral data fusion. *Remote Sensing*, 1851.

URL.1. How Modeling For Precision Agriculture Can Optimize Practices? - GeoPard Agriculture

URL.2. Gradient Boosting Machines (GBM) with Python Example | by İlyurek Kılıç | Medium

URL.3. Overview of Convolutional Neural Networks

URL.4. K Nearest Neighbours — Introduction to Machine Learning Algorithms | by Sachinsoni | Medium

URL.5. Crop Yield Estimation using Remote Sensing and GIS ArcGIS | Udemy

CHAPTER 3

AGROINTELLIGENCE: HARNESSING MACHINE LEARNING FOR DIGITAL FARMING

Süreyya Betül RUFAİOĞLU[1]
Mohammed Oday AL HAMDANI[2]

[1] Harran University, Faculty of Agriculture, Soil Science and Plan Nutrition, Sanliurfa, Türkiye ORCID NO: https://orcid.org/0000000152858568 Email: sureyyarufaioglu@harran.edu.tr
[2] Harran University, Faculty of Agriculture, Soil Science and Plan Nutrition, Sanliurfa, Türkiye ORCID NO: https://orcid.org/0000-0001-9170-6639 Email: Hamudibang95@gmail.com

INTRODUCTION

AgroIntelligence refers to the use of machine learning and artificial intelligence in agriculture—a revolutionary change in farming practices toward efficiency, productivity, and sustainability for what is being called "digital farming" (Wolfert, 2017). The most pressing challenges in agriculture, such as increasing food production, making agriculture resilient to climate change, and optimizing resources, are addressed. In digital farming, data-driven decision-making gives the farmer the possibility of supervising, anticipating, and handling all aspects related to crop production in a much more precise way. This would be real-time monitoring of field conditions, crop health, and resource use, brought about by integrating IoT devices and remote sensing with advanced data analytics into AgroIntelligence.

At the heart of AgroIntelligence lies machine learning, which churns through reams of agricultural data to provide actionable insights. Similarly, by using predictive models, farmers can make better decisions regarding crop selection, irrigation, pest control, and fertilizer application for better yields and reduced environmental impacts (Liakos, 2018). For example, real-time weather data and soil moisture levels can be analyzed to optimize irrigation scheduling, significantly reducing water waste and hence supporting sustainable resource management (Kamilaris, 2018). Similarly, crop yield prediction models use historical and environmental data to accurately forecast crop production, hence aiding in planning and resource allocation (Shamshirband, 2021).

Figure 1. Robots in agriculture (URL1).

Adoption of geospatial technology in AgroIntelligence, through remote sensing and geographic information systems (GIS), gives better mapping of fields and monitoring of crop growth patterns, soil variability, and pest infestations. It will also be expected to enable more resource-efficient practices, such as reducing unnecessary applications of chemicals and water, and lowering the costs associated with traditional farming practices (Mulla, 2013). With the rising demand all over the world for sustainable agriculture, AgroIntelligence helps in offering an invaluable opportunity for transforming agricultural practices around the globe. Applications of this transformative potential remain critical because of challenges in data management, privacy concerns, and limitations in the technical infrastructure with respect to rural areas. It will be very important to address these challenges for the wide diffusion of AgroIntelligence and for supporting farmers both in developed and developing regions to meet their food security and sustainability goals.

MACHINE LEARNING TECHNIQUES IN AGRICULTURE

Machine learning has grown to be a very important tool in agriculture. It helps in tackling the most complex challenges through allowing predictive modeling, classification, and optimization of agriculture-related processes.

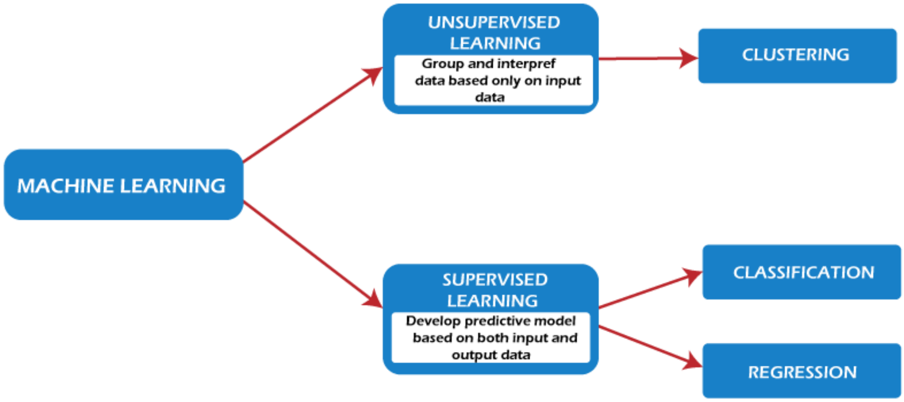


Figure.2. Machine Learning (URL2).

Generally, ML techniques in agriculture come in the form of supervised and unsupervised techniques of learning and reinforcement learning. The application of these techniques has spanned different agricultural applications, ranging from yield prediction and disease detection to resource management and climate adaptation (Liakos, 2018).

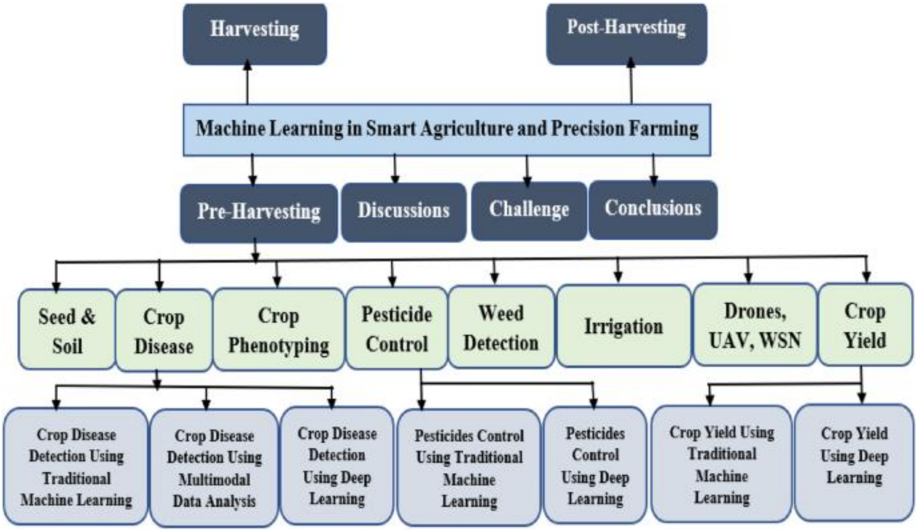


Figure.2. Machine learning in agriculture (Shaikh et al.,2022).

Supervised Learning

It requires training the models with labeled data to make it effective in many such applications that call for data classification and prediction. Its applications in agriculture are for plant disease classification, crop yield prediction, and soil health assessment, using the SVM, Decision Trees, Random Forests, and Linear Regression algorithms. For example, SVM has been applied successfully to identify crop diseases based on their visible patterns from images. For this purpose, Random Forests have been used in crop yield prediction, analyzing historical weather data, soil conditions, and stages of crop growth to assist farmers in the planning of their activities to reach optimum yield with resource allocation. This is according to (Chlingaryan, Machine learning approaches for crop yield prediction and nitrogen status estimation in precision agriculture: A review., 2018).

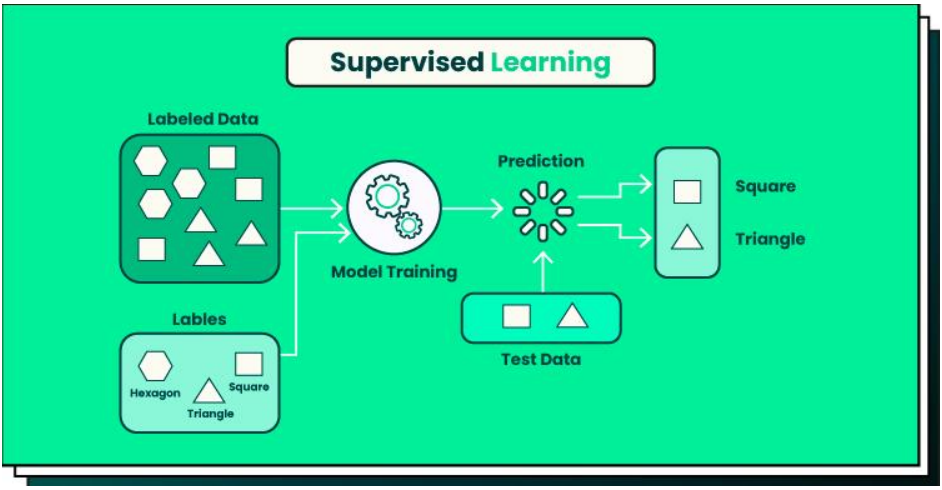


Figure.3. Supervised Learning (URL3).

Unsupervised Learning

Unsupervised learning need not take in labeled data and, as such, turns out to be pretty useful when analyzing high-dimensional, unlabeled datasets that are quite prevalent across the agricultural domain. It also encompasses such techniques as clustering and principal component analysis for the analysis of soil properties and segmentation of agricultural fields to identify patterns in crop health. For instance, clustering techniques can classify areas based on soil types or nutrient levels, hence helping farmers manage the soil resources with efficiency. PCA, on the other hand, comes in handy to assist in dimensionality reduction, hence making it easy to process big datasets from sensors and remote sensing as stated by (Lobell D. B., 2017).

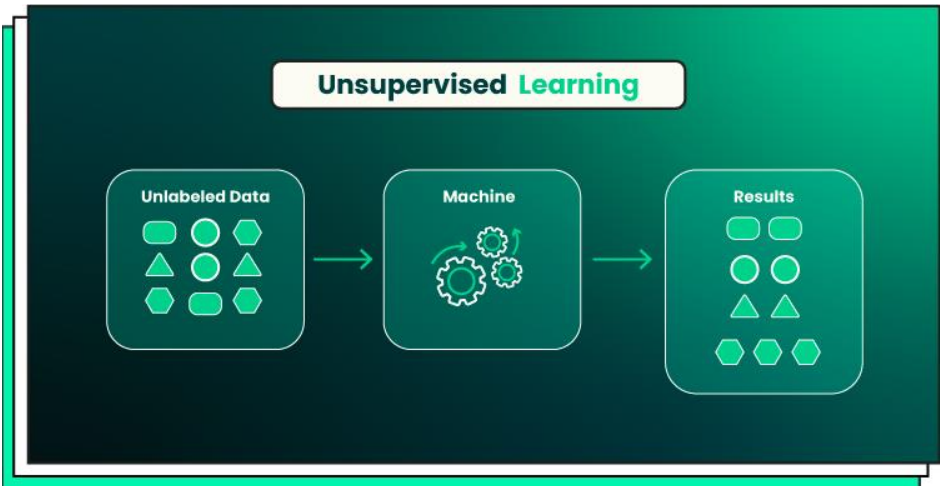


Figure.3. Unsupervised Learning (URL3).

Deep Learning

Deep learning, a subclass of ML, uses neural networks to identify complex patterns and relationships in large volumes of data. In agriculture, CNNs are also being more commonly adopted in image processing for crop classification, weed detection, and disease identification, while RNNs apply to time-series data. Image analysis through CNN enables farmers to monitor the health of crops precisely. It can therefore be useful in the analysis of time-series data, such as weather patterns or soil moisture levels, to provide insight into adaptive irrigation management. (Kamilaris, 2018)

Reinforcement Learning

Reinforcement learning is a relatively new technique in agriculture that uses training of models for making a sequence of decisions to maximize a cumulative reward. It finds applications in precision agriculture, ranging from robotic weeding and autonomous navigation in the field to dynamic decision-making concerning resource management. An example of RL specifically involves the optimization of irrigation system scheduling to balance water conservation with crop yield demands.

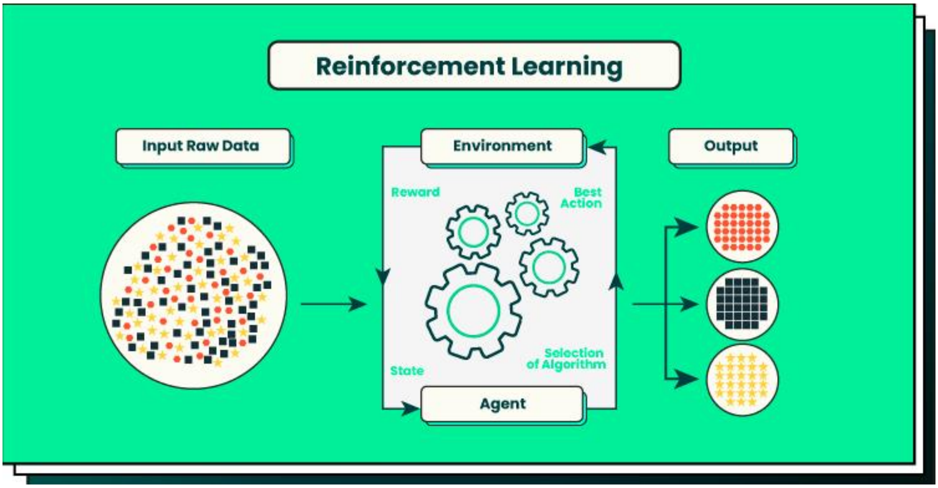


Figure.4. Reinforcement Learning (URL3).

These ML techniques work together to achieve many agricultural problems in precision farming, like optimized resource utilization, waste reduction, and productivity enhancement. Even though ML shows great promise, there are some challenges in applying ML to agriculture due to heterogeneity of data, needs for technical infrastructure, and domain-specific training data. Further improvement is needed through long-term research and development of robust datasets to enhance the role that ML can play for innovation in agriculture: improving crop management, disease control, and sustainable practices.

GEOSPATIAL DATA IN DIGITAL FARMING

It includes satellite imagery, remote sensing, and GIS; being a highly integral part of digital farming due to very precise, spatially resolved information on agricultural fields. The technology helps farmers monitor conditions of their fields in real time, make assessments of their crop health, and inform decisions concerning resource allocation accordingly. Geospatial data also enabled precision agriculture to be more effective and accessible. This is especially true as the ability to acquire data from sources such as satellite systems and drones becomes more available (Lobell D. B., 2017).

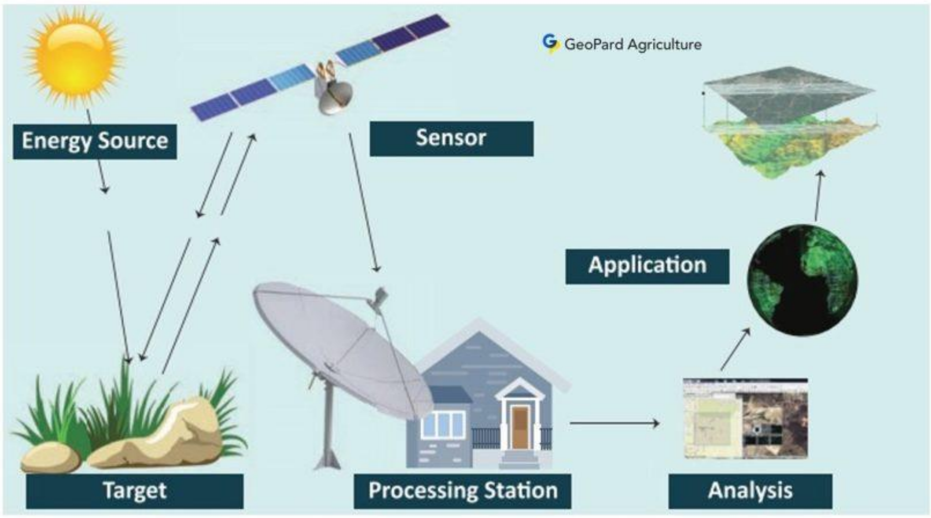


Figure.5. Flowchart of Remote sensing data process (URL.4).

Role of Remote Sensing in Agriculture

Remote sensing, through data acquired from satellite platforms such as Landsat and Sentinel, provides multispectral images that can be used to understand crop health, soil moisture, and water stress. This information allows the calculation of NDVI and other spectral indices, which are related to crop health and nutritional status.

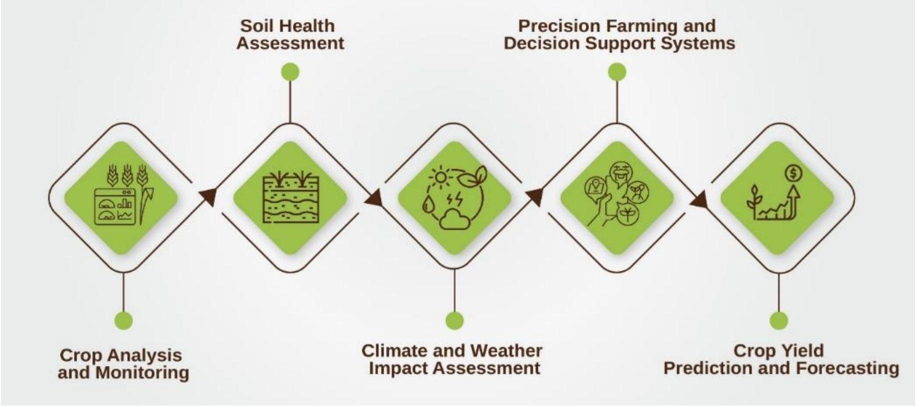


Figure.6. Application of remote sensing in agriculture (URL.5).

Farmers use such indices for identifying potential pest-infested areas, as well as nutrient and water stress sites, therefore developing site-specific interventions. According to (Kussul, 2017), this helps them in detecting sections with probable pest attacks, lack of fertilizer, or water stress; this therefore enables them to take appropriate measures. Combining all information together, including ground sensors, will help the farmer with fertilization, irrigation, and application of control measures against diseases and pests.

Drones and UAVs in Precision Agriculture

UAV or drones have high-resolution imagery with which much more localized monitoring of crop and soil conditions can be performed. A drone can take clear pictures at particular growth phases of crops by using cameras or sensors that are mounted on them. These pictures offer near monitoring of the plant health conditions, weed distribution, and canopy cover.

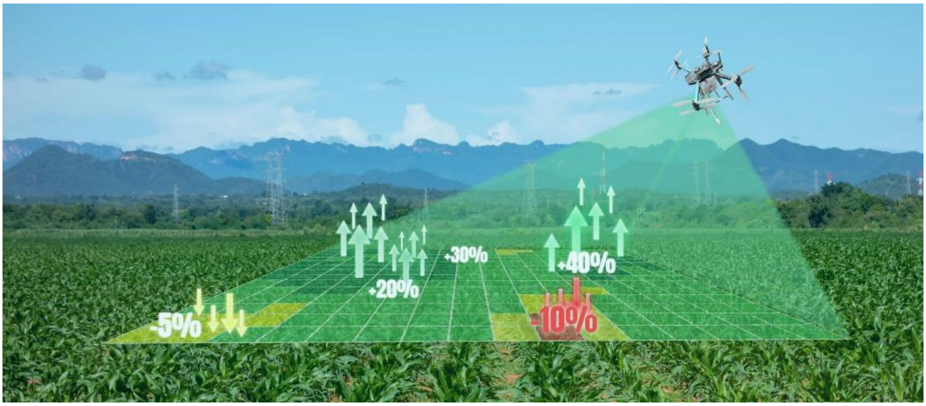


Figure.7. Drones and UAVs in Precision Agriculture (URL.6).

This technology will be highly useful in the case of large farms where on-ground monitoring could be extremely time-consuming and laborious. Considering the perspectives of (Zhang C. &., The application of small unmanned aerial systems for precision agriculture: A review., 2012), an integrated approach using drone data with machine learning algorithms can easily detect subtle changes in crop color, texture, and structure, usually indicative of an early stage of disease or nutrient deficiency.

Geographic Information Systems

GIS is indispensable in mapping the spatial variation of the field conditions and enables farmers to visualize the pattern of crop growth, soil composition, and moisture distribution. Accordingly, GIS-based systems make it possible for VRA of inputs like fertilizers, pesticides, and irrigation by developing maps that delineate zones where different levels of inputs must be applied. This in turn helps avoid applications that are not necessary, hence reducing costs and impacts on the environment (Mulla, 2013). Further, integration of GIS data together with historic data, current conditions, and predictive analytics therefore provides the ability to perform long-term planning and risk management within farming.

Applications of Geospatial Data in Digital Farming

Other applications include crop yield prediction, soil analysis, and climate adaptation strategies. For instance, crop yield prediction models make use of multi-temporal satellite data, weather patterns, and soil characteristics to come up with a forecast of yield. This model will help farmers in resource allocation by minimizing uncertainty and making optimal use of inputs as per recommendations. Geospatial data also enables adaptation to climate through the identification of climate-resilient crop zones, hence helping farmers in the choice of crop and management practices that are appropriate for the changing environmental conditions.

Future Directions and Challenges

Even though the benefits are great, there are overriding concerns about high cost, data processing complexity, and limited access to enabling technologies in rural areas. These most definitely are hurdles to cross. On the other hand, advances in machine learning and cloud computing will make data analysis more efficient and accessible. In the near future, the increased affordability of satellites and drones will help raise the integration into digital farming practices and, correspondingly, heighten precision agriculture's role in the sustainable production of food.

Predictive Analytics for Crop Management

By leveraging machine intelligence and extensive data analysis approaches, predictive analytics is fundamental in transforming agricultural management by improving the ability to foresee critical factors including production levels, illness spread, and effective resource allocation. By harnessing both historical and contemporaneous data pertaining to meteorological conditions, soil characteristics, crop health metrics, and pest dynamics, predictive models empower agricultural practitioners to undertake proactive, data-informed decision-making, thereby enhancing both crop productivity and sustainability. These analytical frameworks transmute agricultural data into pragmatic insights that underpin diverse facets of crop management, encompassing activities ranging from planting and fertilization to pest mitigation and harvest scheduling.

Yield Prediction

Yield forecasting represents one of the most extensively utilized applications of predictive analytics within the agricultural sector. Frameworks that incorporate climatic details, soil properties, and phenological information about crops can successfully estimate crop production. Machine learning strategies including Random Forests, Support Vector Machines (SVM), and Gradient Boosting are regularly applied in yield forecasting owing to their skill in addressing complicated and nonlinear interactions that exist in agricultural data (Khaki & Wang, 2019). Accurate yield forecasts aid agricultural producers in resource planning, labor allocation, and financial management, which are imperative for both smallholder and large-scale farming enterprises.

Pest and Disease Forecasting

The significance of predictive analytics extends to the early detection of pests and diseases, enabling farmers to enact control strategies prior to the escalation of infestations. Through the examination of environmental parameters, historical pest incidence, and indicators of crop vitality, predictive models can delineate conditions favorable for pest proliferation. For instance, the application of time-series analysis in conjunction with climatic data has facilitated the prediction of pest outbreaks such as that of the fall armyworm, thereby assisting farmers in mitigating crop losses and curtailing pesticide applications (Barbedo, 2019). Such forecasting models not only enhance crop health but also contribute to environmental sustainability by diminishing the reliance on chemical interventions.

Resource Optimization

Predictive analytics further contributes to the optimization of resource application, including water, fertilizers, and pesticides, thereby minimizing waste and reducing operational expenditures. To give an example, models for irrigation scheduling harness data from soil moisture monitors, weather forecasts, and crop hydration specifications to establish specific irrigation volumes, consequently reducing water usage and safeguarding crop health. Similarly, fertilizer optimization models are adept at forecasting nutrient needs predicated on soil test results and patterns of crop nutrient uptake, thereby enhancing both soil health and agricultural productivity (Liakos et al., 2018). Through the integration of these models into agricultural management practices, farmers can effectively align crop requirements with sustainable resource utilization.

Climate Adaptation Strategies

The variability of climate presents a formidable challenge to agricultural production, and predictive analytics serves a crucial function in assisting farmers to adapt. By scrutinizing historical climate datasets in conjunction with records of crop performance, predictive models can proffer recommendations regarding crop selection, planting schedules, and management practices that are congruent with anticipated climatic conditions. Furthermore, predictive models facilitate the identification of resilient crop varieties and stress-resistant methodologies, thereby equipping farmers to navigate shifting climate patterns and safeguard against weather-induced crop losses (Shamshirband et al., 2021).

Harvest Optimization

Harvest optimization frameworks predict the most advantageous time for harvesting based on crop maturity, weather forecasts, and prevailing market conditions. These models consider variables such as yield potential and crop quality to advise on the optimal harvest timing, thereby assisting farmers in achieving maximum profitability. Additionally, predictive models that analyze market prices and supply chain dynamics can further inform farmers' post-harvest strategies, reducing storage losses and maximizing revenue streams (Zhao et al., 2020).

IMPACT AND IMPLICATIONS OF AGROINTELLIGENCE ON GLOBAL FOOD SYSTEMS

This brings in the integration of AgroIntelligence, using machine learning, AI, IoT, and data analytics in agriculture, to transform the global food system and its deeper implications for food security, economic stability, sustainability, and governance. AgroIntelligence holds tremendous promise for addressing some of the world's greatest outstanding issues facing agricultural systems, ranging from climate-related risks to inefficiencies in resource use and socioeconomic inequalities. Here follows a more detailed analysis of how AgroIntelligence is influencing the leading components of the global food system.

1.Improving Food Security through Predictive Capabilities

AgroIntelligence helps food security by giving farmers and policymakers predictive analytics on which to make proactive decisions. Machine learning models can now accurately forecast crop yields, analyze climate-related risks, and assess soil health for improved and more resilient agricultural planning to minimize the risks of food scarcity.

For example, predictive models based on historical data and weather forecasts have been shown to improve the accuracy of yield prediction and optimize planting schedules. It has been found that the use of AI-driven predictive tools could reduce variability in yields by up to 30%, hence stabilizing food production and supporting food availability in regions where climatic fluctuations are more frequent (Kamilaris, 2018); (Jin, 2016).

2. Economic Benefits and Market Stability for Farmers:

Among the many benefits of digital farming technologies, those that add to economic resilience include input use optimization, enhanced crop quality, and matching production to market demand. Through increased resource efficiency (for example, through precision irrigation and nutrient application), farmers can significantly reduce their costs and waste. Moreover, with AgroIntelligence tools, farmers get real-time market analysis to make informed decisions about when and where to sell their produce for maximum returns. For example, precision agriculture has been proved to increase crop yields by 5-20%, resulting in high income gains for farmers (Fountas, 2020); (Zhang C.

&.). Such tools for smallholders, faced with market uncertainties and resource constraints, contribute much to closing the economic gap between small and large agricultural enterprises (Dumler et al., 2021).

3. Environmental Sustainability and Resource Conservation:

AgroIntelligence will guide sustainable practices in agriculture and reduce the environmental impact of farming activities. Technologies in precision farming allow for optimum application of inputs like water, fertilizers, and pesticides; this not only reduces costs but also cuts down on pollution and soil degradation.

According to (Gebbers, 2010), precision agriculture can save up to 40% of fertilizers without losing yield, reducing nutrient runoff and water contamination substantially. Further, data-driven irrigation management saves water—most important in regions where this resource becomes scarce. These practices add up to maintaining long-term sustainability because soil health is preserved, greenhouse gas emissions are lowered, and biodiversity is promoted.

4. Building Resilience to Climate Change

One of the greatest challenges to the global food system is perhaps that of adapting to climate change. The phenomenon seeks to threaten agricultural productivity through increasingly common cases of drought, flooding, and extreme temperatures. AgroIntelligence allows farmers to adjust their practices to the changing climate through climate-smart agriculture, guided by real-time data and advanced analytics. Climate models, when integrated with geospatial data, can drive anticipatory actions, such as shifting planting dates, adopting drought-resistant crop varieties, and adjusting resource allocations based on projected weather patterns. In other words, the research states that climate-responsive farming, powered by AgroIntelligence, could improve yields and reduce climate-induced losses by as much as 15% (Basso, 2020).

5. Advancing Data-Driven Policy and Governance:

AgroIntelligence also changes the governance of agriculture, making available to policymakers accurate and updated data on agricultural productivity, the use of resources, and environmental impact. The data can inform policy decisions on subsidies, resource allocations, and sustainability initiatives toward better practices in agriculture. The governments of regions such as Europe and North America have already begun to include digital agriculture data in the policy frameworks toward achieving sustainable food production and resilience to climate shocks (Commission, 2020). Moreover, transparency in data supports accountability because stakeholders at any point of the supply chain can use real-time data to verify sustainability and fair-trade claims.

6. Ethical Considerations and Equity in AgroIntelligence Adoption

While AgroIntelligence is beneficial, there are ethical considerations pertaining to data ownership, privacy, and equitable access. The smallholder farmers, mostly in developing countries, may not have the resources or even the digital literacy to put in place and therefore use advanced technologies to their advantage, hence potentially widening the gaps already present in the agricultural sector.

It is in this line that initiatives such as open-source platforms and government subsidies on digital tools democratize access to the AgroIntelligence technologies (Bronson, 2019; Daum & Birner, 2020). Otherwise, there is the risk that the benefits of AgroIntelligence will go to large-scale farmers only, hence wider socio-economic gaps.

7. Implications for Global Food Trade and Supply Chains:

AgroIntelligence transforms the world's food supply chains by introducing more transparency, efficiency, and traceability. Technologies like blockchain, combined with AI, provide end-to-end visibility of the supply chain, thereby allowing stakeholders to monitor quality, track origins, and reduce losses. This is of great importance in enhancing consumer trust, mostly in regions with strict food safety standards. Moreover, through logistics optimization and reduction of spoilage, AgroIntelligence helps to make the food supply chain more resilient to dynamic response to disruptions, as proven during the COVID-19 pandemic (Feng, 2020); (Kamilaris, 2018).

ETHICAL, SOCIAL, AND REGULATORY CONSIDERATIONS IN AGROINTELLIGENCE

The use of AgroIntelligence in digital farming gives rise to complex ethical, social, and regulatory concerns, especially as AI, machine learning, and big data increasingly reconfigure cultivation practices in agriculture. These considerations center around equitable access, data ownership and privacy, labor dynamics, environmental justice, and regulatory frameworks that ensure responsible implementation. Addressing these is critical for AgroIntelligence to be integrated sustainably into agricultural systems in a manner in which farmers of various socioeconomic backgrounds can benefit without any unintended bad outcomes.

1. Data Ownership and Privacy

One of the most important ethical issues in AgroIntelligence involves data ownership and privacy. Indeed, large volumes of data generated through sensors, drones, and other digital farming tools are the bedrock on which AgroIntelligence is based. But it raises questions of who owns and controls the data, especially when the data is collected on small farms by companies or external organizations. Farmers may not fully understand the implications of data-sharing agreements or have limited control over how their data is used. Transparent and fair data agreements are crucial in building trust between farmers and technology providers (Wolfert, 2017); (Carolan, 2017). As the European Parliament points out, farmers are to be owners and have a say over data collected on their farms, with the support of data sovereignty and privacy rights (Parliament, esolution on the digital transformation in agriculture and rural areas, 2019).

2. Equitable Access to Digital Farming Technologies

The rapid modernization of digital agriculture runs the risk of increasing the gap between large-scale commercial farms and smallholders, especially in low-income countries. Upscale of this advanced digital technology, such as predictive analytics and precision equipment, normally brings high up-front costs and technical know-how, which may be an impediment to smallholder farmers who lack these resources. In fact, (Bronson, 2019) points out that without intervention through democratization—like government subsidies or open-source platforms—AgroIntelligence could instead further increase the inequalities, limiting the benefits of this technology to those that can afford it. To address this, CGIAR's Platform for Big Data in Agriculture focuses on inclusive access to digital agriculture, providing data and tools that support smallholders (CGIAR, 2019).

3. Dynamics of Labor and Employment Issues

AgroIntelligence is an automation of agricultural tasks that greatly impacts labor dynamics, especially in rural communities where agriculture provides the main source of employment. Automated machinery, robot harvesters, and AI-driven monitoring systems can save labor, hence possibly bringing about job displacements where labor is an intense input especially in producing regions (Lioutas, 2019). Automation, though increasing productivity and cutting costs, may have a negative effect on small-scale farmers and farmworkers whose livelihoods depend on traditional labor-intensive farming practices. Policymakers need to balance the benefits of automation with strategies that support displaced workers, such as retraining programs or initiatives that foster high-skill employment in digital agriculture sectors.

4. Environmental Justice and Sustainable Practice

While AgroIntelligence may potentially contribute to more sustainable resource use, increasing concerns arise about its overall environmental impact—in particular, regarding data infrastructure and energy use. Moreover, the processing of data for AI models and huge data storage necessitates massive energy input, which contributes directly to carbon emissions and strains resources. There is also a risk of environmental injustice when rich areas will be able to use digital agriculture, while resource-scarce areas remain without access and further deteriorate their environment (Jakku, 2019). Implementing environmental justice principles, which prioritize equitable access to sustainable agricultural technology, is critical for promoting inclusive and responsible AgroIntelligence practices (Barrett, 2020).

5. Algorithmic Bias and Fairness

Algorithmic bias in AgroIntelligence systems poses ethical risks by potentially skewing predictions and recommendations in favor of certain demographics or regions. For example, if the predictive models are trained on data from large-scale, monoculture farms, they might not work well for diverse cropping systems used by smallholders, making less optimal recommendations than needed—a bias that could impact yields and sustainability. This may perpetuate systemic inequalities, where by default, farmers operating outside of the predominant data sources are at a disadvantage.Ensuring algorithms are fair requires the data sets to be diverse, covering a large extent of agricultural practices and environmental conditions (Coble, 2018).

6. Regulation and Governance Frameworks

This has created a gap in governance, as the rapid adoption of digital technologies in agriculture has outpaced regulatory frameworks, leaving gaps in data security, labor protections, and environmental standards.Effective regulation is essential to establish standards in relation to data use, privacy, and fair competition in digital agriculture. The European Union's General Data Protection Regulation may be a good starting point toward ensuring the privacy of agricultural data and farmers against unauthorized use of their data by guaranteeing accountability among data processors (Wolfert, 2017).

In addition, global frameworks, such as the one of the Food and Agriculture Organization's—Code of Conduct for the Responsible Use of Data, provide guidelines for ethical use of data, transparency, and engagement with stakeholders in digital agriculture (FAO, 2020).

7. Social Perceptions and Acceptance of AgroIntelligence

Social acceptance is one of the important factors affecting the adoption and success of AgroIntelligence.Perceptions of digital tools among farmers depend on trust in technology providers, perceived benefits, and ease of use. Studies have shown that if farmers see direct value in their operations for using AgroIntelligence tools, they are more inclined to adopt them; in addition, reassurance regarding data security is important for farmers in (Eastwood, Managing socio-ethical challenges in the development of smart farming: From a fragmented to a comprehensive approach for responsible research and innovation., 2019).

Likewise, there should be transparent communication with farmers on benefits, risks, and ethical considerations of AgroIntelligence, and engaging farmers in development and decision-making processes of such technologies. 8. Policy Recommendations for Ethical and Equitable AgroIntelligence The ethical, social, and regulatory challenges in AgroIntelligence can be put forward with comprehensive policies that induce responsible development and equitable access. Efforts by the government, academic institutions, and private companies are needed to undertake frameworks that ensure fair data usage, support marginal farmers, and address labor concerns. Some recommended policy actions include: Data Rights and Ownership: Develop guidelines that will ensure farmers retain data rights, keeping control over farm-generated data. Subsidized Access for Smallholders: The provision of financial support or subsidies to small-scale farmers in accessing digital tools and related training. Transparency in algorithm development: Encourage companies to use diverse data and open their algorithm design to avoid biases. Sustainability Standards for AI: Implementing metrics for sustainability that help in evaluating the environmental impact of digital farming technologies.

CHALLENGES AND FUTURE DIRECTIONS IN AGROINTELLIGENCE

AgroIntelligence is transformative, though it still faces quite a number of technical, socioeconomic, and infrastructural challenges to overcome in order to achieve wider adoption and effectiveness in digital farming. They range from problems of data access and model accuracy to deeper concerns relating to environmental impact and scalability. They indicate, therefore, areas of future research and development. Advancements in computing, data access, and collaborative development promise to overcome these barriers and seize the full potential of AgroIntelligence (Wolfert, 2017).

Data Quality and Accessibility

The first and foremost challenge in AgroIntelligence entails the generally limited availability and quality of agricultural data, with an emphasis on developing regions. Most ML and AI algorithms require large quantities of high-quality data to work with a great level of accuracy. However, data on crop health, soil composition, and pest behavior are usually incomplete, inconsistent, or even unavailable due to the lack of technical infrastructure and the lack of standardized data-collection practices (Liakos, 2018). Moreover, even though remote sensing and IoT devices produce so much valuable data, most small-scale farmers lack the equipment needed to harvest such data for their use in practicing precision agriculture.

Technical Complexity and Model Interpretability In general, machine learning models, especially deep learning algorithms, are complex and not easy to understand for non-experts. This kind of complexity might become an impediment to decision-making at the farm level if farmers do not understand or trust model predictions (Kamilaris, 2018). Providing more interpretable models and user-friendly interfaces is important to improve widespread adoption of AgroIntelligence.

Recent advances in XAI have provided promising tools to bridge this gap, allowing model outputs to be more transparently interpretable to end-users.

Infrastructure and Digital Divide

Infrastructure limitations, such as poor internet connectivity, insufficient computing resources, and low power availability, continue to be major challenges, especially in rural areas. These limitations further hinder farmers' access to cloud-based implements, predictive models, and real-time data processing, finally leading to the non-scalability of the digital farming technologies. These challenges can be overcome only through both governmental and private investment in rural digital infrastructure and, in parallel, with initiatives to make digital tools and resources accessible at subsidized costs for small-scale farmers (Wolfert, 2017). Privacy and Data Security

Increased use of data-intensive technologies in agriculture raises concerns about data privacy and security. The policies regarding data ownership and sharing are mostly unclear, especially for the data generated from IoT devices and shared across platforms. Unless assurance on data protection, transparency in how their data will be used, and with whom it will be shared, farmers can be quite reluctant to use digital tools. Developing the security and transparency of data governance frameworks will help to address these concerns and build trust among users in (Jakku, 2019).

Environmental and Ethical Concerns

Whereas AgroIntelligence can optimize input use and reduce waste, questions arise concerning the overall environmental impact of practices encouraged by intensive farming. Increased reliance on precision farming technologies could lead to more inputs like fertilizers and pesticides being overused if not properly managed. Another issue surrounds the displacement of labor due to automation and robotics in performing certain agricultural tasks.

These problems can be put right only with a proper balancing of productivity with sustainability (Carbonell, 2016).

Future Directions

Advancements in Sensor Technology and IoT Integration: New developments in sensor technology, especially low-cost IoT devices, will make it easier to gather accurate real-time data on soil health, crop growth, and environmental conditions, particularly for resource-limited settings.

The role of collaboration and open data initiatives: Collaborative data-sharing platforms and open data initiatives can be very important in improving data availability and quality. Projects that will encourage data sharing between research institutions, governments, and the private sector will give greater robustness to predictive models.

Cloud and Edge Computing

Edge computing solutions will be crucial for real-time data processing in remote areas, reducing the need for internet connectivity by processing data directly at the collection site (Shi, 2016). This innovation will expand AgroIntelligence capabilities to regions with limited infrastructure. Sustainability-Centered AI: Research in AI applications that focus on sustainability measures, such as reduced chemical usage or optimal water use, will help mitigate environmental issues and induce ethics in farming. Education and Capacity Building: The training of farmers on digital literacy and AgroIntelligence tools is critical to ensure access and adoption are fair. Knowledge sharing activities, particularly in underserved communities and rural areas, can possibly empower farmers to use AgroIntelligence in an effective and responsible manner. These future directions signal an increasing focus on accessibility, interpretability, and sustainability within AgroIntelligence, to make digital farming technologies effective and equitable. The challenges ahead will involve multi-stakeholder approaches, engaging both policy initiatives coupled with technological innovation, to ensure the benefits of AgroIntelligence extend to all farmers around the world.

CASE STUDIES IN DIGITAL FARMING APPLICATIONS

Case studies of digital farming give varying applications of AgroIntelligence, from precision irrigation to disease prediction and real-time monitoring systems. These cases bring out how the digital farming tools are adapted in varied agricultural systems and show their effectiveness, scalability, and challenges in real-world contexts.

Case Study 1: Precision Irrigation in Viticulture (California, USA):

The California wine industry has integrated precision irrigation technologies to optimize water use amid recurring droughts. By using IoT sensors and remote sensing, vineyards can monitor soil moisture and water stress in vines, enabling data-driven irrigation management. For instance, the VineView system utilizes satellite imagery and thermal sensors to assess vine health, allowing growers to apply water precisely where it's needed.

This targeted irrigation approach has decreased water use by up to 25% while maintaining the quality of the grapes (King, 2018). This success demonstrates how effective digital solutions can be in areas experiencing water shortage and points toward the potential of digital farming in resource management.

Case Study 2: Crop Disease Prediction in Rice Cultivation (India)

Rice farmers in India have disease-predicting models to help them deal with bacterial leaf blight, a common disease found in paddy fields. IIT developed a predictive tool using machine learning models based on climatic conditions, soil properties, and crop history that alert farmers on periods of high risk for disease outbreak. Such an early warning system has helped farmers take timely measures to protect their crops, thus reducing yield losses and decreasing the use of pesticides by about 20% (Panchal, 2020). This example underlines how predictive analytics can be used to reduce the risk of crop diseases and enhance resilience in smallholder farming systems.

Case Study 3: Smart Greenhouses in Horticulture (Netherlands)

The Netherlands has become one of the global leaders in smart greenhouse technology, linking climate, lighting, and nutrient management systems. Companies like Priva and Philips have developed greenhouses that could automatically adjust light intensity, temperature, and humidity—all depending on crop needs and external weather conditions.

The very same study on tomato production under smart greenhouses shows that this technique achieved a 30% increase in yield per square meter and 20% reduction in energy use compared with conventional greenhouses (Bakker, 2020). The cited case, therefore, points out that digital farming enables controlled environmental agriculture to contribute toward sustainability and efficiency when facing challenges of land and resource limitations.

Case Study 4: Variable Rate Fertilization in Maize Production (Brazil)

Brazilian maize producers have adopted variable rate fertilization technology that uses satellite and drone data to generate fertility maps, showing nutrient variability across fields. This allows farmers to apply fertilizers only in areas where the land needs more nutrients, thereby reducing overall fertilizer application by 15-20% and diminishing nutrient runoff. This approach, espoused and guided by corporations like Embrapa (the Brazilian Agricultural Research Corporation), has reduced the costs of production and the environmental impacts associated with them while keeping yields high (Martins, 2019). Variable rate fertilization in Brazil shows just how economically and environmentally sound technologies of precision agriculture can be for large-scale row cropping.

Case Study 5: Real-Time Pest Monitoring in Soybean Production (China)

A real-time pest monitoring system was placed in soybean fields to combat the soybean aphid, a destructive pest in China. Thus, the developed monitoring system, by means of IoT sensors integrated with computer vision, detects pests and sends an alert to the farmers through a mobile app. The system reduced the need for pesticide application by targeting only the affected areas and contributed to a 30% reduction in aphid infestation during the growing season, as pointed out by (Zhao, 2021). The case study thus explains the role of real-time monitoring in integrated pest management for sustainable pest control and maintenance of crop productivity. Future Directions for Case-Based Digital

Farming Applications These case studies show that digital farming technologies can respond to unique challenges in diverse agricultural settings. As digital farming will surely advance, future applications can also be directed to integrate blockchain for traceability, open-source platforms that are more accessible by farmers, and sharing data to advance predictive models for scaled-up operations. More research is needed in this regard for the localized application and culturally appropriate technologies that will make AgroIntelligence more inclusive for the diverse landscape of agricultural systems.

CONCLUSION

The incorporation of AgroIntelligence into the realm of digital agriculture signifies a pivotal transformation within agricultural frameworks, wherein data analytics, artificial intelligence, and machine learning coalesce to confront some of the most urgent issues related to food production, ecological sustainability, and global food security. This shift exceeds the boundaries of just technological growth; it embodies a deep re-evaluation of agricultural techniques that can potentially boost the efficiency, strength, and adaptability of food systems in confronting the obstacles brought on by climate change, demographic expansion, and scarce resources.

The engagement of anticipatory data analysis, locational intelligence, and automated learning frameworks in farming presents an opportunity for substantial improvements in efficiency and sustainability. Through the provision of insights regarding crop vitality, soil integrity, and resource demands, AgroIntelligence equips farmers to engage in informed, data-driven decision-making that optimizes crop yields while mitigating environmental repercussions (Kamilaris, 2018); (Basso, 2020). These functionalities are essential for advancing sustainable intensification—achieving augmented yields on established agricultural terrains without encroaching upon ecologically sensitive regions (Godfray, 2010).

As this sector develops, the related ethical, societal, and regulatory concerns similarly escalate. Issues surrounding equitable access to digital instruments and technologies, the ramifications for labor dynamics, data privacy concerns, and algorithmic equity necessitate meticulous scrutiny. Although there is potential for AgroIntelligence to aid farmers and reinforce economic resilience, it raises significant concern about the possibility of worsening the inequalities that exist between well-capitalized large farms and smallholder producers, particularly in areas facing economic hardships. The establishment of regulatory frameworks and inclusive policies is imperative to reconcile these disparities and ensure equitable access to AgroIntelligence for farmers across various scales (Bronson, 2019).

Furthermore, the environmental sustainability aspects of AgroIntelligence demand rigorous evaluation. While digital agriculture has demonstrated appreciable capacity in reducing input consumption and enhancing operational efficiency, the energy-intensive characteristics associated with data processing and storage introduce novel environmental challenges that warrant attention. The implementation of sustainable practices in the development of AgroIntelligence, including energy-efficient data centers and ecologically sound computing methodologies, will be vital in curtailing the ecological footprint of digital agricultural technologies (Jakku, 2019); (Barrett, 2020).

In summary, AgroIntelligence possesses extraordinary potential to transform agriculture by augmenting productivity, sustainability, and resilience. However, the actualization of this potential necessitates a comprehensive approach that considers the ethical, social, and regulatory dimensions inherent in digital agriculture. By promoting responsible innovation—where equitable access, environmental justice, and inclusive governance are foregrounded—AgroIntelligence can make a substantial contribution to global food security and sustainable agricultural methodologies. As scholars, practitioners, and policymakers engage with this dynamic field, the insights and frameworks cultivated will play a pivotal role in shaping a future where digital and data-driven agriculture adeptly addresses the diverse requirements of an expanding global populace (FAO, 2020).

REFERENCES

Bakker, M. W. (2020). Sustainable intensification of greenhouse vegetable production with a focus on crop yield and energy efficiency. *Agricultural Systems*, 102889.

Barrett, H. &. (2020). Perceptions of the fourth agricultural revolution: What's new and what's enduring about agriculture 4.0? *Topics in Life Sciences*, 759–769.

Basso, B. &. (2020). Digital agriculture to design sustainable agricultural systems. *Nature Sustainability*, 254–256.

Bronson, K. (2019). Looking through a responsible innovation lens at uneven engagements with digital farming. *NJAS-Wageningen Journal of Life Sciences*, 100294.

Carbonell, I. (2016). The ethics of big data in agriculture. *Internet Policy Review*, 1–13.

Carolan, M. (2017). Publicising food: Big Data, precision agriculture, and co-experimental techniques of addition. *Sociologia Ruralis*, 135–154.

CGIAR. (2019). CGIAR Platform for Big Data in Agriculture. *Retrieved from https://bigdata.cgiar.org/*.

Chlingaryan, A. S. (2018). Machine learning approaches for crop yield prediction and nitrogen status. *Computers and Electronics in Agriculture*, 61–69.

Chlingaryan, A. S. (2018). Machine learning approaches for crop yield prediction and nitrogen status estimation in precision agriculture: A review. *Computers and Electronics in Agriculture*, 61–69.

Coble, K. H. (2018). Big Data in Agriculture: A Challenge for the Future. *Applied Economic Perspectives and Policy*, 79–96.

Commission, E. (2020). Farm to Fork Strategy: For a Fair, Healthy and Environmentally-Friendly Food System. *European Union*.

Eastwood, C. K. (2019). Managing socio-ethical challenges in the development of smart farming: From a fragmented to a comprehensive approach for responsible research and innovation. *Journal of Agricultural and Environmental Ethics*, 9704-5.

Eastwood, C. K. (2019). Managing socio-ethical challenges. *Journal of Agricultural and Environmental Ethics*, 741–768.

FAO. (2020). Code of Conduct for the Responsible Use of Data. *Food and Agriculture Organization of the United Nations.*

Feng, S. Z. (2020). Applying Blockchain Technology to Improve Agri-Food Traceability: A Review of Development Methods,. *Journal of Cleaner Production*, 121031.

Fountas, S. M. (2020). Farm management information systems: The case of precision agriculture. *Computers and Electronics in Agriculture*, 170.

Gebbers, R. &. (2010). Precision agriculture and food security. *Science, 327*, 828-831.

Godfray, H. C. (2010). Food security: The challenge of feeding 9 billion people. *Science, 327*, 812–818.

Jakku, E. T. (2019). If data is the lifeblood, why don't farmers want to share it? Journal of Rural Studies. 58–69.

Jin, X. &. (2016). Machine learning for crop yield prediction and climate resilience: A review. *Computers and Electronics in Agriculture, 145,*, 297–308.

Kamilaris, A. &.-B. (2018). Deep learning in agriculture: A survey. *Computers and Electronics in Agriculture*, 70–90.

King, S. E. (2018). Precision viticulture: Remote and proximal sensing applications in vineyard management. *Australian Journal of Grape and Wine Research*, 2–6.

Kussul, N. L. (2017). Deep learning classification of land cover and crop types using remote sensing data. *IEEE Geoscience and Remote Sensing Letters*, 778–782.

Liakos, K. G. (2018). Machine learning in agriculture: A review. *Sensors*, 2674.

Lioutas, E. D. (2019). Key questions on the use of big data in farming: An activity theory approach. *NJAS-Wageningen Journal of Life Sciences*, 100297.

Lobell, D. B. (2017). Satellite remote sensing for real-time management of crops. *Phil. Trans. R. Soc. B,*.

Lobell, D. B. (2017). Satellite remote sensing for real-time management of crops. *Philosophical Transactions of the Royal Society B*.

Martins, L. D. (2019). Variable rate fertilization for precision agriculture in maize production: Economic and environmental benefits. *Agricultural Engineering International*, 100–107.

Mulla, D. J. (2013). Twenty-five years of remote sensing in precision agriculture: Key advances and remaining knowledge gaps. *Biosystems Engineering*, 358–371.

Panchal, P. S. (2020). Crop disease detection using machine learning: A review. *International Journal of Advanced Research in Science and Engineering*, 54–63.

Parliament, E. (2019). esolution on the digital transformation in agriculture and rural areas. *Retrieved from https://www.europarl.europa.eu*.

Parliament, E. (2019). Resolution on the digital transformation in agriculture and rural areas. *Retrieved from https://www.europarl.europa.eu*.

Shaikh, T. A., Mir, W. A., Rasool, T., & Sofi, S. (2022). Machine learning for smart agriculture and precision farming: towards making the fields talk. *Archives of Computational Methods in Engineering*, *29*(7), 4557-4597.

Shamshirband, S. F. (2021). A review on deep learning applications in digital agriculture. *Artificial Intelligence in Agriculture*, 187–203.

Shi, W. C. (2016). Edge computing: Vision and challenges. *IEEE Internet of Things Journal*, 637–646.

Wolfert, S. G. (2017). Big Data in Smart Farming – A review. *Agricultural Systems*, 69–80.

Zhang, C. &. (2012). The application of small unmanned aerial systems for precision agriculture: A review. *Precision Agriculture*, 693-712.

Zhang, C. &. (2012). The application of small unmanned aerial systems for precision agriculture: A review. *Precision Agriculture*, 693–712.

Zhang, C. &. (n.d.). The application of small unmanned aerial systems for precision agriculture. *Precision Agriculture*, 693-712.

Zhao, J. L. (2021). Application of IoT-based pest monitoring system for soybean aphid management in China. *Computers and Electronics in Agriculture*, 186.

URL.1. Gallery – Agrointelli

URL.2. Machine Learning Techniques - Javatpoint

URL.3. Top 6 Machine Learning Techniques for Predictive Modeling

URL.4. Applications of (GIS) Geoinformatics in Agriculture - GeoPard Agriculture

URL.5. Applications of Remote Sensing in Agriculture - Kheti Buddy

URL.6. https://mapware.com/blog/precision-agriculture-drones-modern-farm-management/

CHAPTER 4

DEGRADATION OF PESTICIDES VIA STRESS-TOLERANT MICROORGANISMS

Assoc. Prof. Dr. Murat DIKILITAŞ[1]
Assoc. Prof. Dr. Sema KARAKAŞ DİKİLİTAŞ[2]
Dr. Ferhat UĞURLAR[3]

[1] Harran University, Faculty of Agriculture, Department of Plant Protection, Sanliurfa, Türkiye. m.dikilitas@gmail.com, ORCID: 0000-0002-7399-4750
[2] Harran University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Sanliurfa, Türkiye. skarakas@harran.edu.tr, ORCID: 0000-0003-1617-9407
[3]Harran University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Sanliurfa, Türkiye. ferhatugurlar@gmail.com, ORCID: 0000-0002-3663-3497

INTRODUCTION

Pesticides are highly toxic chemicals used to control pests and diseases and improve crop production in agriculture. They might be produced in standard formulations to control pests and pathogens or in specific formulations to control specific organisms, or they might be designed to eradicate pests and weeds. Whatever the reasons they have been designed for, pesticide toxicity should not be justified due to the inefficiency of other alternate approaches to control pests and pathogens. Even the safest methods developed in pesticide technology would not make pesticides safer. Instead, they are all toxic, poisonous chemical substances that will stay toxic forever. Pesticides can carry significant risks for the environment and human beings. They can easily disrupt cell metabolism by damaging DNA structures, reducing fertility and other metabolic dysfunctions, and interfering with the human immune system (Dikilitas et al., 2020). Pesticide use is increasing as crop yield and quality increase, although farmers, pesticide producers, and consumers are generally aware of these harmful sites. Many pesticide companies have now been trying to produce chemicals with either low toxicity or short half-life to reduce the impact of toxicity. Generally, pesticides, including plant growth regulators, leaf defoliants, insecticides, fungicides, herbicides, etc., are toxic chemicals used at high or low concentrations. Even if these chemicals are applied at very low doses to control the target organisms, they still leave residues behind them. Nevertheless, improper use and repetitive application of pesticides result in further toxicity and increased residue contamination. The issue of residue has become a significant environmental threat, posing serious risks to our future due to its harmful effects, including carcinogenicity and mutagenicity. Although pesticides have been produced as less toxic with shorter half-lives than before, farmers or pesticide users then make more frequent applications since they are not aware of the instructions about the proper use (Addy-Orduna et al., 2019; Dikilitas et al., 2020; Wend et al., 2024).

This century began with a better understanding of the toxicity and side effects of pesticides. More effective restrictions on pesticide use are now aimed at reducing remaining environmental problems. The new healthcare system in many countries, particularly in European and American systems, has zero tolerance for any residues on crop plants and non-target organisms. This concept suggests that pesticide residues should not contact humans and crop products. Organic pesticides, in this respect, might be a good approach due to lower toxicity when compared to those of conventional pesticides. However, this will not solve the residual problems either.

Pesticides are classified according to their hazard level based on their LD_{50} values (Torrens and Castellano, 2014; WHO, 2020). They disrupt the function of cellular metabolism and lead to changes in defense mechanisms through the production of stress metabolites such as malondialdehyde (MDA); reactive oxygen species (ROS), including H_2O_2, O^-, O_2^- and OH^-; and reactive nitrogen species (RNS) (Qian et al., 2018; Shakir et al., 2018; Annabi et al., 2019; Jena et al., 2023; Alfei et al., 2024). An imbalance in oxidative processes has the potential to damage diverse cellular components. The whole organism is then easily affected by the adverse effects of pesticides. Under oxidative stress, lipids, protein, and DNA structures could undergo adverse changes and disrupt cellular signaling (Dikilitas et al., 2012; Chan et al., 2019; Kesawat et al., 2023; Olufunmilayo et al., 2023). Most pesticides inhibit acetylcholinesterase enzymes and the nervous system in target and non-target organisms (Adenubi et al., 2018). For example, neurotoxic pesticides such as organophosphates, carbamates, organochlorines, and pyrethroids have been reported to exacerbate Parkinson's disease by impairing the nervous system and disrupting the nigrostriatal dopamine pathway (Costa et al., 2008; Jokanovic, 2018, Afsheen et al., 2024; Polaka et al., 2024). Herbicides, conversely, inhibit photosynthesis and act as a plant hormone; however, they also result in significant disturbances in non-target organisms.

Although pesticides have become safer than before, the so-called safer pesticides also have similar effects and pose the same threat to target and non-target organisms, only the effect may appear at later stages than the conventional pesticides do. We must remember that pesticide-treated organisms may gain tolerance and tolerate much higher doses at the expense of lower growth rates. This finally results in more pesticide applications and more residue problems in the soil or crops or crop products. This is an ongoing problem since the pesticide-resistant pests could multiply, develop, and even become more resistant in the next generation or generations.

Pesticides are generally very resistant to degradation. Therefore, higher organisms are constantly exposed to the toxicity of these chemicals either directly or through the food chain. Therefore, it could quickly accumulate in critical human organs and the environment. For example, most people who live near pesticide-applied areas or visit pesticide-contaminated areas have now been linked to many diseases such as cancer, Alzheimer's, Parkinson's diseases, respiratory diseases, etc. (Yan et al., 2016; Dereumeaux et al., 2020; Meftaul et al., 2021). The first signs of pesticide toxicity in humans might appear externally, such as eczema-like symptoms, dermatitis, allergic respiratory symptoms, and hypersensitive reactions. In prolonged cases, the residues might accumulate in adipose tissues, disrupt the blood cells and cause diseases in lymphoid organs. In severe cases, most of the pesticides might lead to mutations in chromosomes and result in carcinoma of the liver, lungs and many other vital organs.

After the pesticide application to target organisms or the soil, pesticides can move from fields to water reservoirs via surface run-off or drainage canals and contaminate water and water resources. For example, pesticides terbuthylazine (TBA) and desethylterbuthylazine (DET) have been found in maize-growing soils for five months after application. After the harvest, 4% of the total TBA remained predominantly within the uppermost 20 cm layer of soil (Stipicevic et al., 2017). Likewise, Sun et al. (2018) indicated that about 80 to 90% of the herbicides used remain in the environment as toxic residues and represent a potential danger to the ecosystem and crops in subsequent years. Pesticide accumulation also leads to reduced respiration in the soil and its microbial population (Lallaouna et al., 2023; Sharma et al., 2023). For example, it was reported that fungal biomass decreased by 47% due to exposure to endosulfan, while bacterial biomass decreased by 76% (Xie et al., 2011; Gill and Garg, 2014).

The residuals of pesticides cause harmful effects in non-target organisms and soil microbiota and deteriorate soil quality. Soil enzymatic activities are accepted as one of the most critical soil quality criteria, and they play significant roles in nutrient cycles and fertilization. Decreased enzyme levels in soils are one of the early signs of soil deterioration, in contrast to chemical or physical measurements. Pesticide residues are severely impacting soil enzymes, which catalyse the biochemical reactions in the soil. They predominantly exert detrimental effects on enzymatic reactions in the soil. They may cause everlasting modifications in the soil microflora, and they can inhibit the population of nitrogen-fixing bacteria such as *Azotobacter*, *Rhizobium*, and

Azospirillum spp. and cellulose and phosphate solubilizing fungi (Prashar and Shah, 2016; Doolotkeldieva et al., 2018). Jastrzebska and Kucharski (2007) pointed out that fungicides such as cyprodinil and dimoxystrobin significantly suppressed the activities of dehydrogenase, phosphatase, and urease in soil. Similarly, Nare et al. (2014) found that deltamethrin, endosulfan, and profenos pesticides significantly reduced soil dehydrogenase enzyme activities. Dehydrogenase enzyme activity is a valuable indicator due to its presence in viable cells. Therefore, increased microbial activity or treatments increasing microbial activity would increase enzyme activity. Additionally, Kaurin et al. (2020) stated that soil dehydrogenase and urease activities were significantly reduced over many weeks compared to untreated control soils. Pesticides can have detrimental impacts on soil microorganisms that can persist for years. Therefore, less harmful pesticides should be selected or produced. Also, the cultivation of pesticide-polluted soils with pesticide-tolerant plants might increase the health conditions of soils. For example, pesticide-contaminated soil was cultivated with alfalfa, achieving much higher enzyme activity levels (Tu et al., 2011).

Ecological problems have been greatly influenced by pesticide pollution, in addition to increased environmental pollution caused by factors such as salinity, drought, water stress, heavy metal stress, oil spills, etc. For instance, by spraying pesticides such as the herbicide oxyfluorfen and the insecticide chlorpyrifos in different dosages The microbial population that Biodiversity and enzymatic activity in the soil decreased dramatically (Franco-Andreu et al., 2016). Pesticide use resulted in greater inhibition of soil enzyme activity and microbial populations in non-irrigated soils. The authors propose that the slower degradation of pesticides, compared to irrigated soils, is influenced by the reduced activity of the microbial population. The inhibition of microbial communities involved in the nitrogen, phosphorus, and sulfur cycles may also have had a significant impact (Tejada et al., 2015). Therefore, the prolonged drought can negatively affect enzymatic activities. Most microbial populations are diminished due to the toxic effects of pesticides, while a few remaining groups manage to survive and flourish despite the presence of these toxic substances. These adapted microorganisms develop tolerance to pesticides and can degrade even more toxic pesticides with greater efficiency. Therefore, stress-tolerant microorganisms may metabolize pesticide residues and use them as energy due to the involvement of carbon molecules, which help the growth and development of microorganisms. These residual parts could then be transformed into degradable organic compounds, which may be less toxic.

Although advised doses negatively affect non-target or target organisms, even lower doses can have adverse effects on non-target organisms, potentially over time. Therefore, applying low doses to the pests may not control the population of the pests while disrupting human metabolism (Dikilitas et al., 2017). In theory, pesticides should be utterly degraded to the non-toxic level quickly. New generations of pesticides, e.g., synthetic pyrethroids, were produced to be less toxic and readily biodegradable than organochlorine pesticides (Rehman et al., 2014). For instance, natural pyrethroids have a constant effect that quickly penetrates the nervous system of insects. Although detoxification occurs more quickly in soil than in other habitats, they are toxic to non-target organisms even in low concentrations. For example, very low doses of pesticides can severely affect the health status of children and newborns due to a weakness in their immune systems (Alleva et al., 2018; Qi et al., 2022; Sarailoo et al., 2022). Their DNA could also be easily damaged when compared to adults.

Pesticides in agriculture

Aiming for increases in food production has been the prime important subject for all countries due to increased population and reduced cultivated areas. By the middle of this century, the world population is estimated to reach at least just over 10 billion. The FAO has indicated that global food production must expand by 70% to keep pace with the increasing population demand (Gill and Garg, 2014; Hunter et al., 2017). World population growth and environmental pollution have placed immense strain on agricultural systems. Producers have been using far more chemicals, herbicides, fungicides, insecticides, and fertilizers than they did in the past to boost crop yields. A significant part of the budget in agricultural expenditure has been made on pesticides. Scientists have been designing new formulations of pesticides to increase crop production with safer pesticides possessing shorter half-lives. The importance of pesticides in protecting agricultural products is undeniable in both developed and developing countries, and they have significantly contributed to enhancing crop yield and quality in modern agriculture.

However, their residual effects and their toxicity towards non-target organisms have long been recognized. However, repeated applications over the years have posed significant threats to food safety and environmental health. Pesticide use is projected to rise due to global population growth and growing food needs. For example, the use of insecticides has significantly increased agricultural production in China (Delang, 2017). It was reported that the application of pesticides avoided the loss of nearly 90 million tons of grains, 1.65 million tons of cotton, and 78 million tons of vegetables (Zhang et al., 2011; Delang, 2017). As is well known, pesticides should ideally be toxic to the target organisms; However, their bioaccumulation in the environment and entry into the food chain can result in significant risks to non-target organisms. Their concentrations beyond a specific limit can be highly toxic and no longer sustain and help to increase agricultural production. The solution or help for the increases in crop production becomes a problem for the environment and humans. Therefore, biodegradation speed and eco-friendly sites should be credited. However, most of the pesticides produced so far have been non-specific and may target beneficial organisms and humans.

Pesticide and soil pollution

At the turn of the century, with the Industrial Revolution, the production of goods and industrial products began rapidly, which led to environmental pollution. However, we have now realized that pollution threatens our present and future lives. In this sense, developing countries are particularly vulnerable to environmental pollution.

Generally, we can describe pollution as substances or energies in excess amounts that are not tolerable. Pollutants can occur due to natural or anthropogenic activities in nature. As they build up over the years or generations, they can reduce the quality of life and result in severe health damage. However, if they break down very quickly via living organisms, they could be no more threats. Our agricultural soils are contaminated with pesticides and residues and contain heavy metals, plastics, glass, paper, etc. Pesticides represent a significant category of pollutants in agricultural soils. Suppose we could reduce the application of pesticides or residue levels in the soil in an environmentally friendly way. In that case, this approach might also be tested for other pollutants in the soil.

While pesticides are employed to enhance agricultural output, their accumulation in the soil and foods can harm our health. Pesticides are generally sprayed on plants as fungicides, herbicides, and insecticides. However, they are also sprayed directly or indirectly into the soil. They may persist in the environment for extended periods or be transported over considerable distances. Therefore, they could pose a significant threat if they are not degraded efficiently to the non-toxic level. Although people know the potential and chronic danger of pesticides, and producers are trying to produce much safer pesticides with low toxicity and short half-lives, we still need to be careful about their toxicity.

Before discussing the harmful effects and long-lasting presence of pesticides, it is essential to categorize these substances based on their operational mechanism. Pesticides are generally grouped into non-systemic and systemic types. Non-systemic pesticides remain outside the plant's vascular system and do not enter plant tissue. However, systemic pesticides can infiltrate plant tissues and be move through the vascular system (Özkara et al., 2016; Lozowicka, 2020). We can also classify pesticides according to their chemical properties. They can be classified into various groups including organochlorine, organophosphorus, carbamates, pyrethroids, amides, etc. Due to their complex chemical structures, organochlorine pesticides tend to accumulate in nature and persist in the environment compared to others. Due to their neurotoxicity, they can lead to severe disorders in mammals and fish, birds and other non-target organisms. Their low concentrations also cause severe health damage. Therefore, most of them have been banned over the years (Willet et al., 1998; Gardes et al., 2021). Conversely, organophosphates are highly toxic pesticides that affect the nervous system of both target and non-target organisms. Compared to these organochlorine compounds, they are more easily degradable. However, their severe toxicities and side effects increase the effects of this group of pesticides. Their low residues also pose significant health risks. Pyrethroids, amides, and anilines are relatively less toxic pesticides. Pyrethroids are synthetic compounds modeled on pyrethrins that are naturally obtained from the flowers of *Chrysanthemum cinerariaefolium* (Gajendiran and Abraham, 2018). Another group of pesticides is aniline, which includes trifluralin herbicides. Imidazole and triazole herbicides have also been newly developed pesticides with various toxic effects on mammals and humans

(Jablonska-Trypuc et al., 2017). Another group of pesticides is the nicotinoid family, which includes acetamiprid, imidacloprid, thiacloprid and thiamethoxam (Simon-Delso et al., 2015). Imidacloprid is the most widely used insecticide worldwide compared to other pesticides such as organophosphate, organochloride, and carbamate insecticides. Neonicotinoids are less toxic to non-target organisms. However, due to their persistent toxic effects, some European countries and the USA have banned some of the pesticides in this group (Millot et al., 2017; Bivehed et al., 2020).

Pests, including microorganisms, insects, rodents, birds, weeds, etc., have caused significant crop losses, and almost one-third of the crops have been lost due to these organisms. Considering the increase of the world population by one-third by the middle of this century, along with the crop loss caused by biotic agents, the use of pesticides will have a significant impact in the coming decades. Unfortunately, non-pesticidal agriculture would not be possible for quite a long time. If non-pesticidal agriculture is achieved, this would be made with plant-derived pesticides. However, the residue problem and pollution would still be the subject of concern when dealing with the reduction of the toxicity of pesticides.

Many pesticide formulations have been used to reach target organisms. However, only 1% of the pesticides used reach the target organisms; The remainder was reported to remain in the environment (Delang, 2017). Due to the frequent use of pesticides, even low concentrations have increased concern about human and environmental health. Many pesticides with long half-lives have still been in the environment. For example, organochlorine pesticides were detected almost 30 years after use in surface waters (Larson et al., 1997). Due to their persistence in nature, they could meet with humans and other non-target organisms, and they could cause severe health disorders. For example, it has been anticipated that it will take over 30 years for dichlorodiphenyltrichloroethane (DDT) to degrade (Afful et al., 2010). Because these substances do not easily decompose in nature, it has been proposed that they be broken down through chemical, microbial, physical, and biological processes. Since most pesticides are liposoluble, they quickly accumulate in fatty parts of non-target organisms such as breast milk, blood and fatty tissues (William et al., 2008; Yadav et al., 2015). The chronic and acute effects of pesticides cannot be overestimated due to enormous life loss and toxicity. For example, each year, roughly 300,000 people die, and around 3 million people are hospitalized due to severe acute and 25 million less severe poisonings globally (Jeyaratnam, 1990; Gunnell et al., 2007; Jors et al., 2018). For example, Bawa et al. (2018) reported that breast milk can contain detectable levels of polychlorinated biphenyls and organochlorine pesticides. They reported that DDT levels decreased from 18,211 to 490 ng g-1 lipid weight over 15 years with a half-life of 3.5 years. Similar findings have also been observed with organochlorine pesticides. Since these chemicals are highly resistant to degradation, toxic, and bioaccumulative due to their lipophilic and hydrophobic properties, once they enter the food chain, they rapidly accumulate in lipid-rich human tissues (Müller et al., 2017; Bawa et al., 2018).

Most countries are becoming populated, and their fertile lands and water resources are being reduced, along with the increase in pollution. In some countries, pollution is so high that farming cannot be performed on most of their valuable lands (Delang, 2017). The main reasons for pollution originate from excessive pesticides and anthropogenic activities. Pesticides can easily reach surface water via runoff and can travel long distances.

In short, we summarized the effects of pesticides on the soil environment where pesticides accumulate or possibly degrade. Most pesticides applied to the soil tend to accumulate there and stay in the long run. The repeated application of pesticides, even at low doses, results in further soil accumulations. Pesticides, however, could undergo various degradation depending on the chemical structure, soil properties, soil flora, light, temperature, etc. The degraded pesticides or pesticides in the degradation process could change the microbial diversity and biochemical reactions (Munoz-Leoz et al., 2011; Gill and Garg, 2014). As a result of biochemical reactions, soil fertility is reduced, and the soil ecosystem is disturbed. For example, many herbicides applied to the soil were declared to decrease the growth of fluorescent bacteria and suppress soil respiration (Gill and Garg, 2014; Rose et al., 2016). Pesticide applications may also act differently on different microorganisms. For example, they increase the bacterial biomass while decreasing those of fungi (Xie et al., 2011). Some microorganisms may utilize applied pesticides as a source of energy. For example, wastewater from agricultural soil containing chlorpyrifos increased the growth and development of some bacterial microorganisms which use carbon complexes of pesticides as energy sources

(Bhagobaty and Malik, 2010; Parte et al., 2017). The pesticide cycle in nature and its possible degradation routes, including its residues, are illustrated in Fig 1.

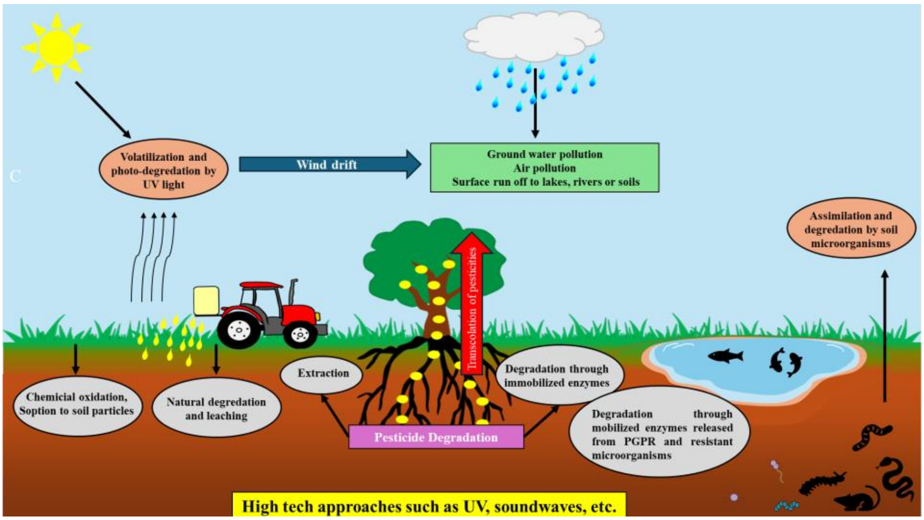


Figure 1. A schematic illustration of the pesticide cycle and its possible degradation routes in an ecosystem. Pesticides might hang in the air and wreak havoc on non-target flying animals or reach lands or lakes far from the point of application via wind drift or rain. They could also leach below the root zone of plants via rain or heavy irrigation. Degradation of pesticides has many routes; one of the most essential pathways is biodegradation, which involves plants, animals and microorganisms. After physical and chemical degradation of pesticides, tiny particles are adsorbed into soil particles or organic matter and then enter cells of microorganisms; their enzymatic reactions turn those toxic chemical substances into less or non-toxic forms by adding OH^- or other groups. In some cases, extracellular enzymes through plant roots or microorganisms are involved. Possible combinations of microorganisms with high-tech approaches could be made to increase the degradation capacity of microorganisms.

Use of plants or animals for pesticide removal

Some pesticides stay for several weeks, while some stay for several years, contingent upon their composition and soil conditions. In recent years, living organisms have been used to remediate contaminated environments. It is economically viable and ecologically sustainable, offering numerous advantages compared to alternative physicochemical approaches for the treatment of polluted soils. The main biological agents that clean up the contaminated soil are bacteria, fungi, yeast, plants, and earthworms.

Long before the employment of bacterial strains, many plant species, including halophytes, were used to remove pesticide residues from the soils or environments contaminated with pesticides. Cleaning with plants or phytoremediation is a technology that cleans up contaminated sites effectively via inexpensive approaches. For example, Mitton et al. (2016a) identified sunflowers as the best candidates for the removal of the organochlorine pesticide endosulfan from soils. The main problem is that the selected plant species should grow well in soil contaminated with pesticides (Perez et al., 2008). Low toxicity to pesticides should also be recognized. Mitton et al. (2016a) emphasized that the uptake and translocation of compounds were crucial factors in selecting sunflowers for effectively removing residual compounds, due to their high biomass production. Mitton et al., (2016b) stated that the protein content, antioxidant capacity, enzyme activity and SH group could complement chemical analysis in selecting candidates for phytoremediation purposes. The concept of phytoremediation or plant-assisted bioremediation has been used for many years, and it has recently emerged as a promising strategy for removing pesticides from contaminated soils. A microenvironment rich in enzymes and organic matter around the roots of plants facilitates pesticide degradation. In this microenvironment, rhizospheric and endophytic bacteria play significant roles and speed up the degradation process. For example, ndophytic bacteria are typically non-pathogenic and produce various natural compounds that promote plant growth while aiding in the biodegradation of soil pollutants. As a common mechanism, pesticides adsorbed onto root surfaces are mixed with soil following decomposition of roots and then the microbial population around the organic matter degrades the pesticides. Many plant species, from herbs to trees, remove pesticide residues from the soil (Akbar and Sultan, 2016; Han et al., 2017; Hwang et al., 2017; Tarla et al., 2020; Takkar et al., 2022; Martínez-Burgos et al., 204). Upon genetic modification of rhizospheric or endophytic bacteria through gene transfer, the degradation capacity of microorganisms could be increased to detoxify pollutants in the soil or wastes, and the efficacy of these microorganisms could be further increased when combined with those of resistant plants.

Plants used for phytoremediation could be classified based on their specific mechanisms of action. In phytoextraction, plants could extract contaminants from soil or water through their root system, accumulate them there, or transport them to the stems or leaves. Finally, these plants are harvested leaving a small portion of contaminants in the soil. Perennial plants or trees in this concept would perform better. For example, Mukherjee and Kumar (2012) reported that maize (*Zea maize*) and mustard (*Brassica campestris*) plants removed organochlorine pesticide endosulfan via the phytoextraction method with 47.2% and 34.5% ratios, respectively. Another approach to phytoremediation is rhizofiltration, in which the pollutants are either adsorbed on the root surface or absorbed by the plant roots (Tiwari et al., 2019; Dubchak and Bondar, 2019). An extensive rooting system developed hydroponically in clean water is gradually acclimatized to the pesticide-polluted water. The plants are grown in the polluted area to eliminate pesticide residues. Once the roots are saturated, they are harvested and disposed of safely. Another possibility of phytoremediation is phytostabilization, in which the contaminated soils are stabilized by vegetation and the toxic pollutants are immobilized. The rooted vegetation prevents the dissemination of contaminants via wind or windblown dust. Grass or bushy types of plants become more suitable due to their fibrous root systems (Lyu et al., 2018; Liu et al., 2019). One of the most efficient phytoremediation approaches depends on phytodegradation or phytotransformation capacity (Parween et al., 2018; Abdullah et al., 2020). In this concept, exudates or enzymes released from plant roots can degrade the pesticide residues into smaller units (Buyanovsky, 1995; Singh and Singh, 2017; Riskuwa-shehu and Ijah, 2018). However, this degradation is not a complete breakdown. Transformation of chemicals into non-toxic or less toxic forms is expected. Following the absorption of pesticides, plant enzymes like nitroreductases enhance the polarity of the pollutants by introducing functional groups, such as hydroxyl groups (-OH). Subsequently, biomolecules, including glucose and amino acids, are appended to the polarized sites to further augment polarity (Jape et al., 2019). Root exudates such as glucose, alcohol, organic acids, or enzymes in soil microflora could enhance microbial growth and development and their enzymatic activities by supplying them with nutrients. In this way, the efficacy of microorganisms increases due to synergistic effects, and more toxic pesticides can be degraded efficiently by supply. The plant roots may also loosen the soil and facilitate the dissemination of air and water, which helps microorganisms secrete more metabolites. Many extracellular enzymes play significant roles in degrading organic pollutants (Burns et al., 2013). Laccases, lignin peroxidases, Mn-dependent peroxidases, proteases, cellulases, chitinases, etc. are becoming increasingly important to reduce the impact of environmental pollutants. Increasing the concentration of these enzymes could contribute to soil fertility and health. Sanchez-Hernandez et al. (2015), for example, stated that earthworm-induced carboxylesterase activity was an efficient bioscavenger for pesticide-contaminated areas. Sanchez-Hernandez et al., (2015) also suggested that combining this enzyme with other enzymes, such as dehydrogenase, could be a suitable biomarker of pesticide exposure. Sanchez-Hernandez et al., (2014) reported that soil incubated for 10 weeks with *Lumbricus terrestris*, a large, reddish worm species widely distributed worldwide, ensured high levels of carboxylesterase activity and efficiently degraded pesticides in the soil.

It is essential to consider the plant species while aiming to remove pesticide residues from the soil. For example, consuming vegetables grown in highly contaminated pesticide soil could cause a health risk in human metabolism. Wu et al., (2019) stated that DDT, not easily degraded in soils, was investigated in terms of removal via vegetables. The authors noted that consuming Chinese mustard, napa cabbage, and Bok choy grown in pesticide-contaminated areas showed a high cancer health risk. The authors suggested that planting these vegetables might increase the degradation of DDT while increasing the health risk to humans. Therefore, plantations used for the removal of pesticides could be carefully designed.

Use of Stress-adaptive Bacteria and Recent Trends and Approaches for Pesticide Degradation

Pesticides are prone to degrade after their application to the soil or plants. Its persistence is measured by its half-life, in which the pesticide concentration is naturally broken down into half by the indicated time. Therefore, the simple structure of a pesticide makes the time for degradation quicker. Pesticide degradation can be divided into three categories: Non-persistent, moderate-persistent and persistent, in which the half-lives are less than 30 days, 30 to 100 days and more than 100 days, respectively (Gavrilescu, 2005). Pesticides in soil primarily break down through microbial and chemical reactions. How long the pesticide stays in the soil is determined not only by the chemical structure but also by soil components, and the microbial quality of the soil has, on the other hand, great values (Lv et al., 2010). Degradation capacity also depends on temperature, soil moisture, soil pH, and soil aeration, which quickly absorb sunlight. The intensity of sunlight and the duration of exposure play a crucial role in the breakdown of the pesticide structure. However, soil treatment with pesticides can reduce populations of beneficial microorganisms (Meena et al., 2020). For example, microorganisms that convert atmospheric nitrogen into nitrates can be destroyed with the herbicide triclopyr (Pell et al., 1998). Numerous examples show that pesticides can disrupt the biological mechanisms of beneficial fungi and bacteria in soil (Aktar et al., 2009).

The degradation of pesticides via immobilized extracellular enzymes by plant roots or mobilized enzymes by microorganisms is often used (Romero et al., 2010; Alvarez et al., 2017). Soil microorganisms can degrade pesticides and turn them into less or non-toxic compounds. Most pesticides in the soil are biodegradable, but a few are recalcitrant, showing complete resistance to biodegradation (Ha et al., 2016). One of the most important criteria is that the degradation process should not produce toxic by-products or inhibitory chemicals to plants or other beneficial bacteria or fungi in the soil. Considering these strategies at the first stage would be accepted as a successful step. As in the phytoremediation strategies, there are various techniques for microorganisms to be used, such as venting, a technique that involves injecting oxygen or nutrients into the soil to support the bioremediation process (Chawla et al., 2012). Fine-textured soils might have low permeability in this system, restricting oxygen dissemination. The moisture level could be problematic in this soil type due to increased water retention and smaller pores. This method works better in well-drained and coarse-textured soils. Bioasparging is another approach used in microbial systems. In this system, air injection under pressure below the water table increases the oxygen concentration in groundwater and accelerates the biodegradation of pesticides by soil bacteria (Parween et al., 2018). Another approach is bioaugmentation, also known as the breakdown of pollutants by microorganisms. In this system, a sufficient amount of water, nutrients and oxygen are introduced into contaminated areas to increase the activity of microorganisms (Parween et al., 2018). Finally, another promising approach is composting. Plants such as pesticides are degraded by microorganisms at high temperatures between 55° and 65°C; during the degradation process, increased temperature results in increased contaminant solubility, further increasing metabolic activity (Chen et al., 2015). Bacteria and fungi are the main extracellular enzyme-producing microorganisms that biodegrade pesticides. Microorganisms modify and transform pesticides by introducing minor molecule changes and rendering them non-toxic compounds (Kumar and Sharma, 2019).

Bioremediation studies will gain more popularity if large-scale cleaning up or degradation of pesticides is achieved. Sagarkar et al. (2014) conducted a comprehensive study of the large-scale degradation process of atrazine. They compared the degradation between natural attenuation and enhanced bioremediation by a bacterial consortium consisting of three novel bacterial strains such as Arthrobacter sp., Pseudomonas sp. and Bacillus sp., which have different genetic atrazine degradation potential. They stated that the effective bioremediation of atrazine could be successfully extended to field applications using a microbial consortium. They also reported that bioaugmentation had no effect on natural microflora after one month of the study. Interestingly, atrazine degradation began after 6 days in soils previously exposed to atrazine compared to soils where no atrazine was used in the past. When combating pesticide pollution, it is important to use screening tests to find the most effective isolation. The higher degradation capacity of an isolate would enable better and quickly results. Jadhav and David (2016) reported that *Chryseobacterium indologenes* strain SSJ1 removed 89.06% of pesticide flubendiamide (a new class of insecticide with a broad spectrum of activity against lepidopteran pests) at 35 °C within 5 days. Sometimes, the fusion of bacterial strains gives more reliable and optimistic results than those of each isolate in terms of the degradation of pesticides. For instance, Aggag et al. (2017) reported that fusions of *Bacillus megaterium*, *Pseudomonas fluorescens*, and *Rhizobium legumino-sarum* showed a highly increased Chlorpyrifos biodegradation when compared to that of each parental bacteria. Not only can the same species be combined among themselves to degrade the pesticides, but also other genetically distant species could be incorporated to degrade the stubborn pesticides. Tang et al. (2012) reported that tribenuronmethyl (TBM), a member of the sulfonylurea herbicide family, was caused by Bacillus sp. was dismantled. Strain BS2, Microbacterium sp. strain BS3 and Cellulosimicrobium sp. Strain BS11. Significant TMB removal was quite high when indigenous earthworms were incorporated with *Bacillus* sp. strain BS2. The authors stated that TBM was used as substrates, and indigenous earthworms stimulated the mineralization of pesticide ingredients and activated microbial fauna.

Naturally, pesticides have been degraded according to their half-life periods. Environmental conditions and the concentrations of pesticides have other factors that affect degradation capacity. As an illustration, Soliman et al., (2012) found that most of the insecticides were affected by UV rays, and their efficacy decreased when the pesticides were stored at 45 °C compared to 25 °C. New technologies to clean up pesticide-contaminated soils have recently been set up and studied. These technologies have promising potential and are environmentally friendly sites. For example, Duong et al., (2009) reported that ultrasonication during low short irradiation (6 h) could remove organic pollutants such as fluoranthene, phenanthrene, and hexachlorobenzene, although the removal efficiencies were low. However, intermittent ultrasonication over longer periods (46 h) had a better capacity to remove the organic pollutants. Although this technology is new and still developing, it might have great potential to diminish elevated levels of persistent organic chemicals in soils. The ultrasound technology might not be enough to remove pesticides from the soil with a single treatment. Duong et al. (2010) proposed the addition of a specific quantity of water to the soil to enhance the effectiveness of ultrasound treatment. One of the main disadvantages of this technique is that ultrasonic treatment cannot be carried out for a very long period of time due to the strong local heating in the soil.

To increase the efficacy of pesticide degradation, technologies used to remove pesticides have been combined. Wang et al. (2016) stated that the combination of ultrasonic irradiation technology with Fentons and Fenton-like reagents not only effectively degraded the diazinon insecticide but also rapidly reduced its toxicity. Again, the degradation of toxic pesticides (carbofuran and iprodine) or their toxic stubborn mixtures was eliminated by the UV/H_2O_2 system under optimal conditions (Lopez-Alvarez et al., 2016). In another study, 2-phenoxyethanol was removed from water at different concentrations using high-frequency ultrasound (600 kHz) in batch mode (Boutamine et al., 2018). Approximately, 100 min of treatment was required for the complete disappearance of the chemical at 10 mg L^{-1} concentration. The combination of ultrasound with UV irradiation (15 mW cm-2, 253.7 nm) increased the degradation of 2-phenoxyethanol. During the treatment, liquid temperature and pH had no influence on the removal rate of the contaminant. The authors stated that UV-assisted ultrasound technology increased the oxidation of organic matter. The effect was significant after 2 h of treatment. A similar approach was taken by Brillas (2014), who found that UV photoelectron Fenton and solar photoelectron Fenton had a synergistic effect on the degradation process of organic pollutants from acidic wastewater through the formation of OH ions and Fe(III) complexes produce carboxylic acids. The author stated that using sunlight can save the energy costs of UV lamps. The combination of H_2O_2 was also made with ultrasound technology for the decomposition of methidathion, and the process gave better decomposition than ultrasound alone (Farooq et al., 2008).

When bioremediation techniques were combined with effective clean-up techniques, much higher efficiency should be expected. A combination of bacteria (more accessible to culture and easy to modify with molecular biology techniques) with high technical approaches might improve the efficacy of pesticide removal capacity. Budarz et al., (2019) recently stated that pesticide chlorpyrifos was successfully degraded via photoreactive TiO_2 nanoparticles. They reported that 80 % of chlorpyrifos was degraded to chlorpyrifos oxon and 3,5,6-trichloro-2-pyridinol after 24 h, either in the presence or absence of bacteria. Although the addition of bacteria did not increase the degradation ratio, this approach is a good start for the future challenges of the degradation of pesticides. Similarly, Petsas and Vagi (2017) reported that photocatalytic degradation of organophosphorus pesticides such as azinphosethyl, azinphosmethyl, dimethoate, disulfoton, and fenthion was achieved using TiO_2 (photocatalyst) and UV irradiation. Furthermore, the addition of H_2O_2 (oxidizing agent) to the illuminated water suspensions resulted in higher synergistic effects in the degradation of the pesticides. The authors stated that the combination of these elements offers good potential for small-scale applications. The advantages of a photocatalytic system lie in its simple design and the availability of UV lamps and semiconductor powder (TiO_2) at low cost as a catalyst.

Recently, membrane filtration technology has been used, and promising results have been obtained (Khan et al., 2015). The pesticide chlorpyrifos showed low degradation at 5 ppm concentration via the treatment of ZnO nanoparticles. When the pesticide in a solvent underwent photocatalytic breakdown and was subsequently filtered via cellulose acetate mixed polymeric membrane discs at low pressure, it resulted in higher degradation capacity than photocatalytic degradation carried out using ZnO. Again, Yang and Zhang (2019) reported that the vacuum VUV/UV/chlorine method rapidly degraded the pesticides, namely atrazine, dimethoate, bromacil, prometon, propoxur, and propachlor in just 60 seconds in water. The authors stated that hydroxyl radicals were transformed into reactive chlorine species, the degradation of which was much higher. Pesticide degradation via microorganisms and high-tech approaches or their possible combinations are presented in Table 1.

Although bioremediation is convenient due to its cost-effective characteristics, its limitations and disadvantages should be well evaluated. For example, unknown toxic and potentially volatile substances could be produced as by-products. Sometimes, deleting the pesticides to non-toxic levels can take several months. When genetically improved microorganisms are developed and used for the efficient degradation of pesticides, this could seem to be a success at first sight. However, they could be a later-stage problem that might stay in nature and become difficult to remove. They may reduce the biodiversity of microorganisms. Also, some stubborn chemicals cannot be biodegraded via biological sources.

Table 1. Residual pesticide damage and remediation through microorganisms and high-tech approaches.

Pesticide	Implications	Effective microbial species	High-tech approaches	*Combinations of microbial and high-tech approaches	References
Chlorpyrifos	Chlorpyrifos (CPS) is an organophosphate pesticide.	*Pseudomonas nitroreducens* AR-3	-	-	Aswathi et al., (2019)
		Arthrobacter sp. HM01			Mali et al., (2022)
2,4-D	A systemic herbicide	*Pseudomonas nitroreducens*	-	-	Gongora-Echeverria et al., (2020)
		Arthrobacter sp. *Sphingomonas* sp. *Stenotrophomonas* sp.			Vanitha et al., (2023)
Carbofuran	An insecticide used in field crops such as potatoes, corn and soybeans.	*Burkholderia cepacia* PCL3	-	-	Pimmata et al., (2013)
		Enterobacter sp.			Mustapha et al. (2020)
		Acremonium sp.			Kaur and Balomajumder et al., (2020)
		Bacillus sp. strain DT1			Duc, (2022)
Carbofuran	An insecticide used in field crops such as potatoes, corn and soybeans		-	-	Wang et al., (2020)
Diazinon	A nonsystemic organophosphate insecticide.	*Pseudomonas nitroreducens*	-	-	Aswathi et al., (2019)
		Apergillus niger			Hamad, (2020)
		Diazinon-degrading *Bacillus altitudinis DB26–*			Nasrollahi et al., (2020)

		R and *B. subtilis subsp. inaquosorum B6–L*			
		Sphingobium sp.			Wang et al., (2022)
Atrazine	Herbicide	*Ochrobactrum* sp.	-	-	Gongora-Echeverria et al., (2020)
		Bacillus thuringiensis	-	-	Hsieh et al., (2020)
			Bioelectroventing	-	Dominguez-Garay et al., (2017)
		Denitratisoma, Thiobacillus Rhodocyclaceae_unclassified Azospirillum Anaerolinea	-		Bao et al., (2024)
Glyphosate	Herbicide	*Lysinibacillus sphaericus*	-	-	Rodriguez et al., (2019)
		Chryseobacterium *sp.*			Zhang et al., (2023)
Pyraclostrobin	A fungicide used to control significant plant pathogens	-	-	Microbial degradation coupled with the Fenton process	Zhao and Kong, (2018)
	Burkholderia sp.			-	Liu et al., (2024)
Azoxystrobin	A broad-spectrum systemic fungicide	-	UVC photolysis, VUV photolysis, UVC-assisted titanium dioxide photocatalysis	-	Choi et al., (2020)
			Ultrasound-assisted pesticide degradation		El Dine et al., (2023)
Metalaxyl	A fungicide with systemic function against *Pythium* and *Phytophthora*.	*Candida tropicalis*	-	-	Derbalah et al., (2020)

Lambda-Cyhalothrin and Deltamethrin	These pyrethroids are used as commercial and household insecticides.	*Raoultella ornithinolytica*-ZK4	-	-	Zhang et al., (2019)
		Brucella intermedia *Alcaligenes faecalis* *Aquamicrobium terrae*			Anwar et al., (2023)
Imidacloprid, Acetamiprid, Thiamethoxam, Chlorantraniliprole and Flubendiamide	Insecticides.	-	-	Solarisation with soil microbiota	Diaz-Lopez et al., (2020)
		Labrys portucalensis F11		-	Boufercha et al., (2022)
Endosulfan	Organochlorine insecticide and acaricide	*Klebsiella* sp., *Acinetobacter* sp., *Alcaligenes* sp., *Flavobacterium* sp., *and Bacillus* sp.	-	-	Kafilzadeh et al., (2015)
		Trametes hirsuta (Fungi)	-		Bisht et al., (2019)
		-	Ag/TiO2/Fe3O4 catalyst and UV-C light		Turkyılmaz and Kucukcongar, (2024)
Methyl Parathion	An organophosphate insecticide	*Cupriavidus oxalaticus*	-	-	Tiwari et al., (2020)
		-	Ag/TiO2/Fe3O4 nanocomposite and UV-C assisted		Nasiripur et al., (2021)
Malathion	An organophosphate insecticide	-	-	UV/H_2O_2 Pretreatment	Cedillo-Herrera et al., (2020)
			Dielectric barrier discharge	-	Cong et al., (2021)

CONCLUSIONS and PROSPECTS

Pesticides have been produced and used extensively to increase crop production and control pests. However, concerns over environmental and human health issues are rising globally, particularly in developing countries. The main issue is to reduce pesticide toxicity to non-target organisms and to increase the ecological removal rate. Many approaches have been employed, such as physical and chemical soil amendments, phytoremediation, microbial remediation, or high technological approaches such as electrochemical, ultrasound, UV light, etc. Studies regarding pesticide degradation capacity have been on an increasing trend. Improving the pesticide degradation potential of microorganisms depends on understanding their metabolic and molecular pathways. Using high-throughput technologies will bring our success to the next level if we combine biological and technological approaches. Finding or generating bacteria that could degrade the pesticide in the short term would decrease the toxicity of pesticides. One of the main issues to tackle with pesticide degradation is to apply biological materials to large-scale areas. So far, most studies have shown that pesticide degradation is laboratory-oriented and cannot be implemented directly in large-scale applications. However, this could be achieved by combining advanced technologies with biological systems which create the oxidation process. Based on this chapter, studies regarding pesticide degradation should be credited, and cost-effective studies in large industrial or agricultural-scale applications should be encouraged to get the desired results.

Acknowledgement

It should be remembered that all pesticides containing plant-, microbial-, organic- or inorganic-based formulations are poisonous and cause severe health damage. It is implausible that non-poisonous formulations will be developed in the future. However, it is essential to create easily degradable pesticides. Therefore, any approaches that rapidly degrade toxic chemicals should be credited if the next generations of living organisms are to be protected. The authors declare that there is no conflict of interest. This study does not criticize the use of pesticides. Instead, it emphasizes the use of pesticides in an environmentally friendly way.

We dedicate this chapter to my deceased friend Sabit Dogan who always looked at life from a bright angle through his closed eyes.

REFERENCES

Abdullah, S. R. S., Al-Baldawi, I. A., Almansoory, A. F., Purwanti, I. F., Al-Sbani, N. H., & Sharuddin, S. S. N. (2020). Plant-assisted remediation of hydrocarbons in water and soil: Application, mechanisms, challenges and opportunities. *Chemosphere*, *247*, 125932.

Addy-Orduna, L. M., Brodeur, J. C., & Mateo, R. (2018). Oral acute toxicity of imidacloprid, thiamethoxam and clothianidin in eared doves: A contribution for the risk assessment of neonicotinoids in birds. *The Science of the Total Environment*, *650*(Pt 1), 1216-1223.

Adenubi, O. T., Ahmed, A. S., Fasina, F. O., McGaw, L. J., Eloff, J. N., & Naidoo, V. (2018). *Pesticidal plants as a possible alternative to synthetic acaricides in tick control: A systematic review and meta-analysis.*

Afful, S., Anim, A. K., & Serfor-Armah, Y. (2010). Spectrum of organochlorine pesticide residues in fish samples from the Densu Basin. *Res J Environ Earth Sci*, *2*(3), 133-138.

Afsheen, S., Rehman, A. S., Jamal, A., Khan, N., & Parvez, S. (2024). Understanding Role of Pesticides in Development of Parkinson's Disease: Insights from Drosophila and Rodent Models. *Ageing Research Reviews*, 102340.

Aggag, S., Shoman, R., Moussa, M., & Yacout, M. (2017). Organophosphorus pesticides biodegradation by three bacterial genera and their protoplast fusants. *Journal of Applied Biological Sciences*, *11*(3), 29-32.

Akbar, S., & Sultan, S. (2016). Soil bacteria showing a potential of chlorpyrifos degradation and plant growth enhancement. *brazilian journal of microbiology*, *47*(3), 563-570.

Aktar, W., Sengupta, D., & Chowdhury, A. (2009). Impact of pesticides use in agriculture: Their benefits and hazards. *Interdisciplinary Toxicology*, *2*(1), 1-12.

Alfei, S., Schito, G. C., Schito, A. M., & Zuccari, G. (2024). Reactive Oxygen Species (ROS)-Mediated Antibacterial Oxidative Therapies: Available Methods to Generate ROS and a Novel Option Proposal. *International Journal of Molecular Sciences*, *25*(13), 7182.

Alleva, R., Manzella, N., Gaetani, S., Bacchetti, T., Bracci, M., Ciarapica, V., Monaco, F., Borghi, B., Amati, M., Ferretti, G., & Tomasetti, M. (2018). Mechanism underlying the effect of long-term exposure to low dose of pesticides on DNA integrity. *Environmental Toxicology*, *33*(4), 476-487.

Alvarez, A., Saez, J. M., Costa, J. S. D., Colin, V. L., Fuentes, M. S., Cuozzo, S. A., Benimeli, C. S., Polti, M. A., & Amoroso, M. J. (2017). Actinobacteria: Current research and perspectives for bioremediation of pesticides and heavy metals. *Chemosphere*, *166*, 41-62.

Annabi, E., Ben Salem, I., & Abid-Essefi, S. (2019). Acetamiprid, a neonicotinoid insecticide, induced cytotoxicity and genotoxicity in PC12 cells. *Toxicology Mechanisms and Methods*, *29*(8), 580-586.

Aswathi, A., Pandey, A., & Sukumaran, R. K. (2019). Rapid degradation of the organophosphate pesticide–Chlorpyrifos by a novel strain of Pseudomonas nitroreducens AR-3. *Bioresource technology*, *292*, 122025.

Anwar, S., Liaqat, A., Munir, A., Ashraf, M. F., & Iqbal, S. (2023). Bioaugmentation of a novel bacterial consortium in cotton-planted soil for degradation of lambda-cyhalothrin. *Pedosphere*.

Bao, Y., Zhao, S., Wu, N., Yuan, Y., Ruan, L., & He, J. (2024). Degradation of Atrazine by an Anaerobic Microbial Consortium Enriched from Soil of an Herbicide-Manufacturing Plant. *Current Microbiology*, *81*(5), 117.

Bawa, P., Bedi, J. S., Gill, J. P. S., Aulakh, R. S., Kumar, A., & Arora, K. (2018). Persistent organic pollutants residues in human breast milk from Bathinda and Ludhiana districts of Punjab, India. *Archives of environmental contamination and toxicology*, *75*, 512-520.

Bhagobaty, R. K., & Malik, A. (2010). Utilization of chlorpyrifos as a sole source of carbon by bacteria isolated from wastewater irrigated agricultural soils in an industrial ares of western Uttar Pradesh, India.

Bisht, J., Harsh, N. S. K., Palni, L. M. S., Agnihotri, V., & Kumar, A. (2019). Biodegradation of chlorinated organic pesticides endosulfan and chlorpyrifos in soil extract broth using fungi. *Remediation Journal*, *29*(3), 63-77.

Bivehed, E., Gustafsson, A., Berglund, A., & Hellman, B. (2020). Evaluation of Potential DNA-Damaging Effects of Nitenpyram and Imidacloprid in Human U937-Cells Using a New Statistical Approach to Analyse

Comet Data. *Exposure and Health*, *12*(3), 547-554.

Boufercha, O., Monforte, A. R., Boudemagh, A., Ferreira, A. C., Castro, P. M., & Moreira, I. S. (2022). Biodegradation and Metabolic Pathway of the Neonicotinoid Insecticide Thiamethoxam by Labrys portucalensis F11. *International Journal of Molecular Sciences*, *23*(22), 14326.

Boutamine, Z., Hamdaoui, O., & Merouani, S. (2018). Sonochemical and photosonochemical degradation of endocrine disruptor 2-phenoxyethanol in aqueous media. *Separation and Purification Technology*, *206*, 356-364.

Brillas, E. (2014). A review on the degradation of organic pollutants in waters by UV photoelectro-Fenton and solar photoelectro-Fenton. *Journal of the Brazilian Chemical Society*, *25*, 393-417.

Budarz, J. F., Cooper, E. M., Gardner, C., Hodzic, E., Ferguson, P. L., Gunsch, C. K., & Wiesner, M. R. (2019). Chlorpyrifos degradation via photoreactive TiO2 nanoparticles: Assessing the impact of a multi-component degradation scenario. *Journal of hazardous materials*, *372*, 61-68.

Burns, R. G., DeForest, J. L., Marxsen, J., Sinsabaugh, R. L., Stromberger, M. E., Wallenstein, M. D., Weintraub, M. N., & Zoppini, A. (2013). Soil enzymes in a changing environment: Current knowledge and future directions. *Soil Biology and Biochemistry*, *58*, 216-234.

Buyanovsky, G. A., Kremer, R. J., Gajda, A. M., & Kazemi, H. V. (1995). Effect of corn plants and rhizosphere populations on pesticide degradation. *Bulletin of environmental contamination and toxicology*, *55*(5), 689-696.

Cedillo-Herrera, C. I., Roé-Sosa, A., Pat-Espadas, A. M., Ramírez, K., Rochín-Medina, J., & Amabilis-Sosa, L. E. (2020). Efficient malathion removal in constructed wetlands coupled to UV/H2O2 pretreatment. *Applied Sciences*, *10*(15), 5306.

Chan, K. X., Phua, S. Y., & Van Breusegem, F. (2019). Secondary sulfur metabolism in cellular signalling and oxidative stress responses. *Journal of Experimental Botany*, *70*(16), 4237-4250.

Chawla, N., Suneja, S., Kukreja, K., & Kumar, R. (2012). Bioremediation of Pesticides: An Overview. *Pesticide Research Journal*, *24*(2), 113-131.

Chen, M., Xu, P., Zeng, G., Yang, C., Huang, D., & Zhang, J. (2015).

Bioremediation of soils contaminated with polycyclic aromatic hydrocarbons, petroleum, pesticides, chlorophenols and heavy metals by composting: Applications, microbes and future research needs. *Biotechnology advances*, *33*(6), 745-755.

Choi, S. W., Shahbaz, H. M., Kim, J. U., Kim, D. H., Yoon, S., Jeong, S. H., Park, J., & Lee, D. U. (2020). Photolysis and TiO2 photocatalytic treatment under UVC/VUV irradiation for simultaneous degradation of pesticides and microorganisms. *Applied Sciences*, *10*(13), 4493.

Cong, L., Huang, M., Zhang, J., & Yan, W. (2021). Effect of dielectric barrier discharge plasma on the degradation of malathion and chlorpyrifos on lettuce. *Journal of the Science of Food and Agriculture*, *101*(2), 424-432.

Costa, L. G., Giordano, G., Guizzetti, M., & Vitalone, A. (2008). Neurotoxicity of pesticides: A brief review. *Front Biosci*, *13*(4), 1240-1249.

Delang, C. O. (2017). Causes and distribution of soil pollution in China. *Environmental & Socio-Economic Studies*, *5*(4), 1-17.

Derbalah, A. S. H., El-Banna, A., & Saad Allah, M. (2020). Efficiency of Candida tropicalis for potential degradation of metalaxyl in the aqueous media. *Current Microbiology, 77*, 2991-2999.

Dereumeaux, C., Fillol, C., Quenel, P., & Denys, S. (2020). Pesticide exposures for residents living close to agricultural lands: A review. *Environment international*, *134*, 105210.

Díaz-López, M., García, C., Garrido, I., Navarro, S., Vela, N., Nicolás, E., Fenoll, J., & Bastida, F. (2019). Solarization-based pesticide degradation results in decreased activity and biomass of the soil microbial community. *Geoderma*, *354*, 113893.

Dikilitas, M., Kocyigit, A., Bilinc, H., & Taskin, A. (2012). Genotoxic effects of low doses of pesticides on mononuclear leukocyte isolated from higher cells. *Fresenius Environmental Bulletin*, *21*(9), 2833-2838.

Dikilitaş, M., Koçyiğit, A., Güler, E. M., & Karakaş Dikilitaş, S. (2017). *Low doses of pesticide exposure cause oxidative stress and DNA damage in fibroblast cells*. https://openaccess.bezmialem.edu.tr/entities/publication/61618df8-54de-4d40-b51e-0cd0ab00d94

Domínguez-Garay, A., Quejigo, J. R., Dörfler, U., Schroll, R., & Esteve-Núñez,

A. (2018). Bioelectroventing: An electrochemical-assisted bioremediation strategy for cleaning-up atrazine-polluted soils. *Microbial Biotechnology*, *11*(1), 50-62.

Doolotkeldieva, T., Konurbaeva, M., & Bobusheva, S. (2018). Microbial communities in pesticide-contaminated soils in Kyrgyzstan and bioremediation possibilities. *Environmental Science and Pollution Research*, *25*(32), 31848-31862.

Dubchak, S., & Bondar, O. (2019). Bioremediation and Phytoremediation: Best Approach for Rehabilitation of Soils for Future Use. Içinde D. K. Gupta & A. Voronina (Ed.), *Remediation Measures for Radioactively Contaminated Areas* (ss. 201-221). Springer International Publishing.

Duc, H. D. (2022). Enhancement of carbofuran degradation by immobilized Bacillus sp. strain DT1. *Environmental Engineering Research*, *27*(4).

Duong, P. T., Shrestha, R. A., Sillanpää, M., & Virkutytė, J. (2010). Ultrasound-assısted treatment of kaolın artıfıcıally contamınated wıth phenanhtrene, fluoranthene and hexachlorobenzene. *Journal of Envıronmental Engıneerıng and Landscape Management*, *18*(4), 251-258.

El Dine, L. J., Trivella, A. S., Budzinski, H., Al Iskandarani, M., Mazellier, P., & Brahim, M. (2023). Degradation of azoxystrobin, methoxyfenozide, and propyzamide by ultrasound treatment. *Environmental Science and Pollution Research*, *30*(53), 114239-114248.

Farooq, R., Shaukat, S. F., Khan, A. K., & Farooq, U. (2008). Ultrasonic induced decomposition of methidathion pesticide. *Journal of Applied Sciences*, *8*(1), 140-145.

Franco-Andreu, L., Gómez, I., Parrado, J., García, C., Hernández, T., & Tejada, M. (2016). Behavior of two pesticides in a soil subjected to severe drought. Effects on soil biology. *Applied Soil Ecology*, *105*, 17-24.

Gajendiran, A., & Abraham, J. (2018). An overview of pyrethroid insecticides. *Frontiers in Biology*, *13*, 79-90.

Gardes, T., Portet-Koltalo, F., Debret, M., & Copard, Y. (2021). Historical and post-ban releases of organochlorine pesticides recorded in sediment deposits in an agricultural watershed, France. *Environmental Pollution*, *288*, 117769.

Gavrilescu, M. (2005). Fate of Pesticides in the Environment and its

Bioremediation. *Engineering in Life Sciences*, *5*(6), 497-526.

Gill, H. K., & Garg, H. (2014). Pesticide: Environmental impacts and management strategies. *Pesticides-toxic aspects, 8*(187), 10-5772.

Góngora-Echeverría, V. R., García-Escalante, R., Rojas-Herrera, R., Giácoman-Vallejos, G., & Ponce-Caballero, C. (2020). Pesticide bioremediation in liquid media using a microbial consortium and bacteria-pure strains isolated from a biomixture used in agricultural areas. *Ecotoxicology and Environmental Safety, 200*, 110734.

Gunnell, D., Eddleston, M., Phillips, M. R., & Konradsen, F. (2007). The global distribution of fatal pesticide self-poisoning: Systematic review. *BMC Public Health*, *7*(1), 357.

Ha, H., Mahanty, B., Yoon, S., & Kim, C. G. (2016). Degradation of the long-resistant pharmaceutical compounds carbamazepine and diatrizoate using mixed microbial culture. *Journal of Environmental Science and Health, Part A*, *51*(6), 467-471.

Hamad, M. T. M. H. (2020). Biodegradation of diazinon by fungal strain Apergillus niger MK640786 using response surface methodology. *Environmental Technology & Innovation*, *18*, 100691.

Han, Y., Mo, R., Yuan, X., Zhong, D., Tang, F., Ye, C., & Liu, Y. (2017). Pesticide residues in nut-planted soils of China and their relationship between nut/soil. *Chemosphere*, *180*, 42-47.

Hsieh, H. Y., Lin, C. H., Hsu, S. Y., & Stewart, G. C. (2020). A *Bacillus* Spore-Based Display System for Bioremediation of Atrazine. *Applied and Environmental Microbiology*, *86*(18), e01230-20.

Hunter, M. C., Smith, R. G., Schipanski, M. E., Atwood, L. W., & Mortensen, D. A. (2017). Agriculture in 2050: Recalibrating targets for sustainable intensification. *Bioscience*, *67*(4), 386-391.

Hwang, J. I., Lee, S. E., & Kim, J. E. (2017). Comparison of theoretical and experimental values for plant uptake of pesticide from soil. *PloS one*, *12*(2), e0172254.

Jabłońska-Trypuć, A., Wołejko, E., Wydro, U., & Butarewicz, A. (2017). The impact of pesticides on oxidative stress level in human organism and their activity as an endocrine disruptor. *Journal of Environmental Science and Health, Part B*, *52*(7), 483-494.

Jadhav, S. S., & David, M. (2016). Biodegradation of flubendiamide by a newly isolated Chryseobacterium sp. Strain SSJ1. *3 Biotech*, *6*(1), 31.

Jape, P., Maheshwari, V., & Chaudhari, A. (2019). Microbial Degradation of Nitroaromatic Pesticide: Pendimethalin. Içinde D. P. Singh, V. K. Gupta, & R. Prabha (Ed.), *Microbial Interventions in Agriculture and Environment* (ss. 531-544). Springer Singapore.

Jastrzebska, E., & Kucharski, J. (2007). Dehydrogenases, urease and phosphatases activities of soil contaminated with fungicides. *Plant Soil and Environment*, *53*(2), 51.

Jena, A. B., Samal, R. R., Bhol, N. K., & Duttaroy, A. K. (2023). Cellular Red-Ox system in health and disease: The latest update. *Biomedicine & Pharmacotherapy*, *162*, 114606.

Jeyaratnam, J. (1990). Acute pesticide poisoning: A major global health problem. *World health statistics quarterly 1990; 43 (3): 139-144*.

Jokanović, M. (2018). Neurotoxic effects of organophosphorus pesticides and possible association with neurodegenerative diseases in man: A review. *Toxicology*, *410*, 125-131.

Jørs, E., Neupane, D., & London, L. (2018). Pesticide Poisonings in Low- and Middle-Income Countries. *Environmental Health Insights*, *12*, 1178630217750876. https://doi.org/10.1177/1178630217750876

Kafilzadeh, F., Ebrahimnezhad, M., & Tahery, Y. (2015). Isolation and identification of endosulfan-degrading bacteria and evaluation of their bioremediation in Kor River, Iran. *Osong public health and research perspectives*, *6*(1), 39-46.

Karakas, A. K., Guldur, M. E., & Ahmad, P. (2019). Chapter twenty-three effects of envıronmentally-frıendly pestıcıdes on humans and the envıronment MURAT DIKILITAS, ERAY SIMSEK, SEMA. *Trends in Landscape, Agriculture, Forest and Natural Science*, 320.

Kaur, P., & Balomajumder, C. (2020). Bioremediation process optimization and effective reclamation of mixed carbamate-contaminated soil by newly isolated Acremonium sp. *Chemosphere*, *249*, 125982.

Kaurin, A., Gluhar, S., Tilikj, N., & Lestan, D. (2020). Soil washing with biodegradable chelating agents and EDTA: Effect on soil properties and plant growth. *Chemosphere*, *260*, 127673.

Kesawat, M. S., Satheesh, N., Kherawat, B. S., Kumar, A., Kim, H. U., Chung, S. M., & Kumar, M. (2023). Regulation of reactive oxygen species during salt stress in plants and their crosstalk with other signaling molecules—Current perspectives and future directions. *Plants*, *12*(4), 864.

Khan, S. H., Suriyaprabha, R., Pathak, B., & Fulekar, M. H. (2015). Photocatalytic degradation of organophosphate pesticides (Chlorpyrifos) using synthesized zinc oxide nanoparticle by membrane filtration reactor under UV irradiation. *Front. Nanosci. Nanotechnol*, *1*, 23-27.

Kumar, A., & Sharma, S. (Ed.). (2019). *Microbes and Enzymes in Soil Health and Bioremediation* (C. 16). Springer Singapore.

Lallaouna, R., Ababsa, N., Della, Y., & Boudjabi, S. (2023). Soil respiration as an indicator of soil quality under agrochemical treatment in a semi-arid area of southern Mediterranean. *Arabian Journal of Geosciences*, *16*(9), 531.

Larson, S. J. (2019). *Pesticides in surface waters: Distribution, trends, and governing factors*. CRC Press.

Liu, H., Xiong, C., Wang, S., Yang, H., & Sun, Y. (2024). Biodegradation of the strobilurin fungicide pyraclostrobin by Burkholderia sp. Pyr-1: Characteristics, degradation pathway, water remediation, and toxicity assessment. *Environmental Pollution*, *348*, 123833.

Liu, T., Xu, S., Lu, S., Qin, P., Bi, B., Ding, H., Liu, Y., Guo, X., & Liu, X. (2019). A review on removal of organophosphorus pesticides in constructed wetland: Performance, mechanism and influencing factors. *Science of the Total Environment*, *651*, 2247-2268.

Lopez-Alvarez, B., Villegas-Guzman, P., Peñuela, G. A., & Torres-Palma, R. A. (2016). Degradation of a toxic mixture of the pesticides carbofuran and iprodione by UV/H 2 O 2: Evaluation of parameters and implications of the degradation pathways on the synergistic effects. *Water, Air, & Soil Pollution*, *227*, 1-13.

Łozowicka, B., Kaczyński, P., Mojsak, P., Rusiłowska, J., Beknazarova, Z., Ilyasova, G., & Absatarova, D. (2020). Systemic and non-systemic pesticides in apples from Kazakhstan and their impact on human health. *Journal of Food Composition and Analysis*, *90*, 103494.

Lv, J., Shi, R., Cai, Y., Liu, Y., Wang, Z., Feng, J., & Zhao, M. (2010). Assessment of 20 organochlorine pesticides (OCPs) pollution in suburban soil in Tianjin, China. *Bulletin of environmental contamination and toxicology*, *85*, 137-141.

Lyu, T., Zhang, L., Xu, X., Arias, C. A., Brix, H., & Carvalho, P. N. (2018). Removal of the pesticide tebuconazole in constructed wetlands: Design comparison, influencing factors and modelling. *Environmental Pollution*, *233*, 71-80.

Mali, H., Shah, C., Patel, D. H., Trivedi, U., & Subramanian, R. B. (2022). Degradation insight of organophosphate pesticide chlorpyrifos through novel intermediate 2, 6-dihydroxypyridine by *Arthrobacter sp.* HM01. *Bioresources and Bioprocessing*, *9*(1), 31.

Martínez-Burgos, W. J., de Souza Vandenberghe, L. P., de Mello, A. F. M., de Carvalho, J. C., Valladares-Diestra, K. K., Manzoki, M. C., Scapini, T., Pozzan, R., Liew, R. K., & Soccol, V. T. (2024). Bioremediation strategies against pesticides: An overview of current knowledge and innovations. *Chemosphere*, 142867.

Meena, R. S., Kumar, S., Datta, R., Lal, R., Vijayakumar, V., Brtnicky, M., Sharma, M. P., Yadav, G. S., Jhariya, M. K., & Jangir, C. K. (2020). Impact of agrochemicals on soil microbiota and management: A review. *Land*, *9*(2), 34.

Meftaul, I. M., Venkateswarlu, K., Dharmarajan, R., Annamalai, P., & Megharaj, M. (2020). Pesticides in the urban environment: A potential threat that knocks at the door. *Science of the Total Environment*, *711*, 134612.

Millot, F., Decors, A., Mastain, O., Quintaine, T., Berny, P., Vey, D., Lasseur, R., & Bro, E. (2017). Field evidence of bird poisonings by imidacloprid-treated seeds: A review of incidents reported by the French SAGIR network from 1995 to 2014. *Environmental Science and Pollution Research*, *24*(6), 5469-5485.

Mitton, F. M., Ferreira, J. L. R., Gonzalez, M., Miglioranza, K. S., & Monserrat, J. M. (2016). Antioxidant responses in soybean and alfalfa plants grown in DDTs contaminated soils: Useful variables for selecting plants for soil phytoremediation? *Pesticide Biochemistry and Physiology*, *130*, 17-21.

Mitton, F. M., Gonzalez, M., Monserrat, J. M., & Miglioranza, K. S. (2016). Potential use of edible crops in the phytoremediation of endosulfan residues in soil. *Chemosphere*, *148*, 300-306.

Mukherjee, I., & Kumar, A. (2012). Phytoextraction of endosulfan a remediation technique. *Bulletin of environmental contamination and toxicology*, *88*, 250-254.

Muñoz-Leoz, B., Ruiz-Romera, E., Antigüedad, I., & Garbisu, C. (2011). Tebuconazole application decreases soil microbial biomass and activity. *Soil Biology and Biochemistry*, *43*(10), 2176-2183.

Mustapha, M. U., Halimoon, N., & Johari, W. L. W. (2020). Optimization of carbofuran insecticide degradation by Enterobacter sp. Using response surface methodology (RSM). *Journal of King Saud University-Science*, *32*(3), 2254-2262.

Müller, M. H. B., Polder, A., Brynildsrud, O. B., Karimi, M., Lie, E., Manyilizu, W. B., Mdegela, R. H., Mokiti, F., Murtadha, M., & Nonga, H. E. (2017). Organochlorine pesticides (OCPs) and polychlorinated biphenyls (PCBs) in human breast milk and associated health risks to nursing infants in Northern Tanzania. *Environmental research*, *154*, 425-434.

Naré, R. W. A., Savadogo, P. W., Gnankambary, Z., Nacro, H. B., & Sedogo, P. M. (2014). Effect of three pesticides on soil dehydrogenase and fluorescein diacetate activities in vegetable garden in Burkina Faso. *Current Research Journal of Biological Sciences*, *6*(2), 102-106.

Nasiripur, P., Zangiabadi, M., & Baghersad, M. H. (2021). Visible light photocatalytic degradation of methyl parathion as chemical warfare agents simulant via GO-Fe3O4/Bi2MoO6 nanocomposite. *Journal of Molecular Structure*, *1243*, 130875.

Nasrollahi, M., Pourbabaei, A. A., Etesami, H., & Talebi, K. (2020). Diazinon degradation by bacterial endophytes in rice plant (Oryzia sativa L.): A possible reason for reducing the efficiency of diazinon in the control of the rice stem–borer. *Chemosphere*, *246*, 125759.

Ntow, W. J., Tagoe, L. M., Drechsel, P., Kelderman, P., Gijzen, H. J., & Nyarko, E. (2008). Accumulation of persistent organochlorine contaminants in milk and serum of farmers from Ghana. *Environmental research*, *106*(1), 17-26.

Olufunmilayo, E. O., Gerke-Duncan, M. B., & Holsinger, R. D. (2023). Oxidative stress and antioxidants in neurodegenerative disorders.

Antioxidants, *12*(2), 517.

Özkara, A., Akyıl, D., & Konuk, M. (2016). Pesticides, environmental pollution, and health. İçinde *Environmental health risk-hazardous factors to living species*. IntechOpen.

Parte, S. G., Mohekar, A. D., & Kharat, A. S. (2017). Microbial degradation of pesticide: A review. *African journal of microbiology research*, *11*(24), 992-1012.

Parween, T., Bhandari, P., Sharma, R., Jan, S., Siddiqui, Z. H., & Patanjali, P. K. (2018). Bioremediation: A Sustainable Tool to Prevent Pesticide Pollution. Içinde M. Oves, M. Zain Khan, & I. M.I. Ismail (Ed.), *Modern Age Environmental Problems and their Remediation* (ss. 215-227). Springer International Publishing.

Pell, M., Stenberg, B., & Torstensson, L. (1998). Potential denitrification and nitrification tests for evaluation of pesticide effects in soil. *Ambio*, 24-28.

Pérez, D. J., Menone, M. L., Camadro, E. L., & Moreno, V. J. (2008). Genotoxicity evaluation of the insecticide endosulfan in the wetland macrophyte Bidens laevis L. *Environmental Pollution*, *153*(3), 695-698.

Pérez Rodríguez, M., Melo, C., Jiménez, E., & Dussán, J. (2019). Glyphosate bioremediation through the sarcosine oxidase pathway mediated by Lysinibacillus sphaericus in soils cultivated with potatoes. *Agriculture*, *9*(10), 217.

Petsas, A. S., & Vagi, M. C. (2018). Photocatalytic degradation of selected organophosphorus pesticides using titanium dioxide and UV light. *Titanium Dioxide-Material for a Sustainable Environment*.

Pimmata, P., Reungsang, A., & Plangklang, P. (2013). Comparative bioremediation of carbofuran contaminated soil by natural attenuation, bioaugmentation and biostimulation. *International Biodeterioration & Biodegradation*, *85*, 196-204.

Polaka, S., Raji, S., Singh, A., Katare, P., & Tekade, R. K. (2024). Connecting link between pesticides and Parkinson's disease. *Public Health and Toxicology Issues Drug Research, Volume 2*, 735-754.

Prashar, P., & Shah, S. (2016a). Impact of Fertilizers and Pesticides on Soil Microflora in Agriculture. Içinde E. Lichtfouse (Ed.), *Sustainable*

Agriculture Reviews (C. 19, ss. 331-361). Springer International Publishing.

Prashar, P., & Shah, S. (2016b). Impact of Fertilizers and Pesticides on Soil Microflora in Agriculture. Içinde E. Lichtfouse (Ed.), *Sustainable Agriculture Reviews* (C. 19, ss. 331-361). Springer International Publishing.

Qi, S. Y., Xu, X. L., Ma, W. Z., Deng, S. L., Lian, Z. X., & Yu, K. (2022). Effects of organochlorine pesticide residues in maternal body on infants. *Frontiers in Endocrinology*, *13*, 890307.

Qian, L., Qi, S., Cao, F., Zhang, J., Zhao, F., Li, C., & Wang, C. (2018). Toxic effects of boscalid on the growth, photosynthesis, antioxidant system and metabolism of Chlorella vulgaris. *Environmental Pollution*, *242*, 171-181.

Riskuwa-Shehu, M. L., & Ijah, U. J. J. (2018). Rhizospheric Microbe-Plant Exudate Formulation for Enhanced Restoration of Contaminated Agricultural Soil. Içinde V. Kumar, M. Kumar, & R. Prasad (Ed.), *Phytobiont and Ecosystem Restitution* (ss. 231-252). Springer Singapore.

Romero, E., Fernández-Bayo, J., Díaz, J. M. C., & Nogales, R. (2010). Enzyme activities and diuron persistence in soil amended with vermicompost derived from spent grape marc and treated with urea. *Applied Soil Ecology*, *44*(3), 198-204.

Rose, M. T., Cavagnaro, T. R., Scanlan, C. A., Rose, T. J., Vancov, T., Kimber, S., Kennedy, I. R., Kookana, R. S., & Van Zwieten, L. (2016). Impact of herbicides on soil biology and function. *Advances in agronomy*, *136*, 133-220.

Sagarkar, S., Nousiainen, A., Shaligram, S., Björklöf, K., Lindström, K., Jørgensen, K. S., & Kapley, A. (2014). Soil mesocosm studies on atrazine bioremediation. *Journal of environmental management*, *139*, 208-216.

Sanchez-Hernandez, J. C., del Pino, J. N., & Domínguez, J. (2015). Earthworm-induced carboxylesterase activity in soil: Assessing the potential for detoxification and monitoring organophosphorus pesticides. *Ecotoxicology and Environmental Safety*, *122*, 303-312.

Sanchez-Hernandez, J. C., Morcillo, S. M., del Pino, J. N., & Ruiz, P. (2014).

Earthworm activity increases pesticide-sensitive esterases in soil. *Soil Biology and Biochemistry*, *75*, 186-196.

Sarailoo, M., Afshari, S., Asghariazar, V., Safarzadeh, E., & Dadkhah, M. (2022). Cognitive impairment and neurodegenerative diseases development associated with organophosphate pesticides exposure: A review study. *Neurotoxicity Research*, *40*(5), 1624-1643.

Shakir, S. K., Irfan, S., Akhtar, B., Rehman, S. U., Daud, M. K., Taimur, N., & Azizullah, A. (2018). Pesticide-induced oxidative stress and antioxidant responses in tomato (Solanum lycopersicum) seedlings. *Ecotoxicology*, *27*, 919-935.

Sharma, R., Walia, A., Putatunda, C., & Solanki, P. (2023). Impact of pesticides on microbial diversity. İçinde *Current Developments in Biotechnology and Bioengineering* (ss. 427-458). Elsevier.

Simon-Delso, N., Amaral-Rogers, V., Belzunces, L. P., Bonmatin, J. M., Chagnon, M., Downs, C., Furlan, L., Gibbons, D. W., Giorio, C., Girolami, V., Goulson, D., Kreutzweiser, D. P., Krupke, C. H., Liess, M., Long, E., McField, M., Mineau, P., Mitchell, E. A. D., Morrissey, C. A., … Wiemers, M. (2015). Systemic insecticides (neonicotinoids and fipronil): Trends, uses, mode of action and metabolites. *Environmental Science and Pollution Research*, *22*(1), 5-34.

Singh, T., & Singh, D. K. (2017). Phytoremediation of organochlorine pesticides: Concept, method, and recent developments. *International Journal of Phytoremediation*, *19*(9), 834-843.

Soliman, M. (2012). Effects of UV-light, temperature and storage on the stability and biological effectiveness of some insecticides. *Journal of Plant Protection Research*.

Stipičević, S., Mendaš, G., Dvoršćak, M., Fingler, S., Galzina, N., & Barić, K. (2017). Dissipation dynamics of terbuthylazine in soil during the maize growing season. *Archives of Industrial Hygiene and Toxicology*, *68*(4), 336-342.

Sun, S., Sidhu, V., Rong, Y., & Zheng, Y. (2018). Pesticide pollution in agricultural soils and sustainable remediation methods: A review. *Current Pollution Reports*, *4*, 240-250.

Takkar, S., Shandilya, C., Agrahari, R., Chaurasia, A., Vishwakarma, K., Mohapatra, S., Varma, A., & Mishra, A. (2022). Green technology:

Phytoremediation for pesticide pollution. İçinde *Phytoremediation technology for the removal of heavy metals and other contaminants from soil and water* (ss. 353-375). Elsevier.

Tang, Q., Zhao, Z., Liu, Y., Wang, N., Wang, B., Wang, Y., Zhou, N., & Liu, S. (2012). Augmentation of tribenuron methyl removal from polluted soil with Bacillus sp. Strain BS2 and indigenous earthworms. *Journal of Environmental Sciences*, *24*(8), 1492-1497.

Tarla, D. N., Erickson, L. E., Hettiarachchi, G. M., Amadi, S. I., Galkaduwa, M., Davis, L. C., Nurzhanova, A., & Pidlisnyuk, V. (2020). Phytoremediation and bioremediation of pesticide-contaminated soil. *Applied Sciences*, *10*(4), 1217.

Tejada, M., García, C., Hernández, T., & Gómez, I. (2015). Response of soil microbial activity and biodiversity in soils polluted with different concentrations of cypermethrin insecticide. *Archives of environmental contamination and toxicology*, *69*, 8-19.

Tiwari, B., Sindhu, V., Mishra, A. K., & Singh, S. S. (2020). Carbon catabolite repression of methyl parathion degradation in a bacterial isolate characterized as a Cupriavidus sp. LMGR1. *Water, Air, & Soil Pollution*, *231*, 1-14.

Tiwari, J., Kumar, S., Korstad, J., & Bauddh, K. (2019). Ecorestoration of polluted aquatic ecosystems through rhizofiltration. İçinde *Phytomanagement of polluted sites* (ss. 179-201). Elsevier.

Torrens, F., & Castellano, G. (2014). Molecular classification of pesticides including persistent organic pollutants, phenylurea and sulphonylurea herbicides. *Molecules*, *19*(6), 7388-7414.

Tu, C., Teng, Y., Luo, Y., Sun, X., Deng, S., Li, Z., Liu, W., Xu, Z. (2011). PCB removal, soil enzyme activities, and microbial community structures during the phytoremediation by alfalfa in field soils. *Journal of Soils and Sediments*, *11*, 649-656.

Turkyilmaz, M., & Kucukcongar, S. (2024). Investigation of Endosulfan removal and metabolite formation by Photocatalysis process under UV-C light source using Taguchi Experimental Design Program. *International Journal of Environmental Analytical Chemistry*, *104*(3), 704-717.

Vanitha, T. K., Suresh, G., Bhandi, M. M., Mudiam, M. K. R., & Mohan, S. V.

(2023). Microbial degradation of organochlorine pesticide: 2, 4-Dichlorophenoxyacetic acid by axenic and mixed consortium. *Bioresource Technology*, *382*, 129031.

Wang, C. K., & Shih, Y. H. (2016). Facilitated ultrasonic irradiation in the degradation of diazinon insecticide. *Sustainable Environment Research*, *26*(3), 110-116.

Wang, G., Li, X., Zheng, J., Li, X., Bai, L., Yue, W., & Jiang, L. (2022). Isolation of a diazinon-degrading strain Sphingobium sp. DI-6 and its novel biodegradation pathway. *Frontiers in Microbiology*, *13*, 929147.

Wang, X., Li, Z., Yao, M., Bao, J., & Zhang, H. (2020). Degradation of carbofuran in contaminated soil by plant–мicroorganism combined technology. *Journal of the Serbian Chemical Society*, *85*(1), 111-123.

Wend, K., Zorrilla, L., Freimoser, F. M., & Gallet, A. (2024). Microbial pesticides – challenges and future perspectives for testing and safety assessment with respect to human health. *Environmental Health*, *23*(1), 49.

Willett, K. L., Ulrich, E. M., & Hites, R. A. (1998). Differential Toxicity and Environmental Fates of Hexachlorocyclohexane Isomers. *Environmental Science & Technology*, *32*(15), 2197-2207.

Wu, X., Ding, Y., Wang, R., Rensing, C., Li, Y., & Feng, R. (2019). Differences in the uptake and bioconcentration of dichlorodiphenyltrichloroethane by eight vegetable cultivars and their health risk assessments. *Chemosphere*, *215*, 596-604.

Xie, H., Gao, F., Tan, W., & Wang, S. G. (2011). A short-term study on the interaction of bacteria, fungi and endosulfan in soil microcosm. *Science of the Total Environment*, *412*, 375-379.

Yadav, I. C., Devi, N. L., Syed, J. H., Cheng, Z., Li, J., Zhang, G., & Jones, K. C. (2015). Current status of persistent organic pesticides residues in air, water, and soil, and their possible effect on neighboring countries: A comprehensive review of India. *Science of the Total Environment*, *511*, 123-137.

Yan, D., Zhang, Y., Liu, L., & Yan, H. (2016). Pesticide exposure and risk of Alzheimer's disease: A systematic review and meta-analysis. *Scientific reports*, *6*(1), 32222.

Yang, L., & Zhang, Z. (2019). Degradation of six typical pesticides in water by

VUV/UV/chlorine process: Evaluation of the synergistic effect. *Water research*, *161*, 439-447.

Zhang, W., Chen, W. J., Chen, S. F., Lei, Q., Li, J., Bhatt, P., ... & Chen, S. (2023). Cellular response and molecular mechanism of glyphosate degradation by Chryseobacterium sp. Y16C. *Journal of Agricultural and Food Chemistry*, *71*(17), 6650-6661.

Zhang, W., Jiang, F., & Ou, J. (2011). Global pesticide consumption and pollution: With China as a focus. *Proceedings of the international academy of ecology and environmental sciences*, *1*(2), 125.

Zhang, X., Hao, X., Huo, S., Lin, W., Xia, X., Liu, K., & Duan, B. (2019). Isolation and identification of the Raoultella ornithinolytica-ZK4 degrading pyrethroid pesticides within soil sediment from an abandoned pesticide plant. *Archives of Microbiology*, *201*(9), 1207-1217.

Zhao, H., & Kong, C. H. (2018). Elimination of pyraclostrobin by simultaneous microbial degradation coupled with the Fenton process in microbial fuel cells and the microbial community. *Bioresource technology*, *258*, 227-233.

CHAPTER 5

NANOSELENIUM EFFECT OF THE ON THE AQUATIC ORGANISM

Dr. Ayşegül ERGENLER[1*] Prof. Dr. Funda TURAN[2] ,
Prof. Dr. Tolga DEPCİ[3]

[1 ,*]Faculty of Marine Science and Technology, İskenderun Technical University, 31200 İskenderun, Hatay, Turkey. ORCID ID: 0000-0001-9186-3909 . E-mail: aergenler@gmail.com
[2] Faculty of Marine Science and Technology, İskenderun Technical University, 31200 İskenderun, Hatay, Turkey. ORCID ID: 0000-0002-0257-6009
[3] Petroleum and Natural Gases Engineering, Faculty of Engineering and Natural Sciences, İskenderun Technical University, 31200 İskenderun, Hatay, Türkiye.ORCID ID: 0000-0001-9562-8068

1.INTRODUCTION

Subsequently is projected that by 2050, the global population would continue to increase and reach a total of nine billion people. This is going to exert further pressure on the food manufacturing sector in order to fulfill the increasing demand. The aquarium sector, which is experiencing rapid growth, has constantly played a major role in enhancing world food supply and ensuring food security.However, the long-term viability of the sector is being undermined by the rising expenses of nutrients, as conventional nutritious components become scarcer and more expensive. In response, endeavors have been undertaken to cultivate the capacity to dismantle and use present elements in order to accomplish the objectives of the blue economy. Nanonutrient compounds has the potential to become the primary source of nutrients in the future(Boyd et al., 2020; Khalil et al., 2023).

Nanotechnology is an emerging and expanding technological advancement that is being used in the field of aquaculture. Specifically, nanoparticles and emulsion-based systems have been used in the creation of water materials, avoiding and taking care of diseases, and purification of water. Nanoparticle technology in aquaculture may greatly enhance the effectiveness of using inputs like as medications, vaccines, pelleted nutrition, and gene transfer. Nevertheless, the dimensions of nanomaterial particles have the potential to enhance the mobility, bioavailability, and efficacy of other chemicals in comparison to larger bulk materials. Several experts have undertaken investigations on the advantageous impacts of these nano-scale dietary supplements. The study demonstrated enhancements in the growth performance, food intake, immunological response, and physical attributes of Nile tilapia (*Oreochromis niloticus*), Asian trout (*Lates calcarifer*), rainbow trout (*Oncorhynchus mykiss*), African trout (*Clarias gariepinus*), silver trout (*Hypophthalmichthys molitrix*), and slender gray whale (*Liza ramada*) had comparable effects to nanonutrients (Younus et al., 2020; Khalil et al., 2023).
Nanonutrients are used in the aquaculture by either incorporating them into the feed of organisms or by directly introducing them into the environment where the organisms are cultivated. The efficacy of dietary supplements in aquatic animals is depending to their chemistry and sizes. Ultrafine nanoparticles (NPs) possess distinct characteristics and exhibit extended presence in blood vessels, hence enhancing their availability for biological processes. In addition to nano-

scale variants of some elements like selenium, copper, and iron, the use of nutritional supplements such as chitosan, the antibiotic kana and butyrate of sodium has shown considerable potential in enhancing the productivity of aquarium cultivation.Nanotechnology may greatly transform the fisheries and aquaculture sectors by introducing innovative instruments for quick illness diagnostics. This advancement will improve the capacity of cultivable organisms to absorb medications, such as hormones, vaccinations, and critical nutrients. Metal nanoparticles, including Fe, FeO, Se, Zn, ZnO, Cu, and MgO, have a significant impact on aquaculture operations. Nanoparticles have shown significant potential in managing infections and enhancing immune and developmental functions in aquaculture. Nevertheless, the overutilization of NPs might lead to a rise in their presence in the environment, especially in aquatic environments (Ahmed et al., 2024).

The use of Zinc (Zn) nanoparticles has been shown to effectively alleviate zinc shortage in fish. Research has shown that the use of zinc oxide nanoparticles in fish diet enhances hematological indicators, protein synthesis, and metabolic activity. Studies have shown that nanoparticles of Chromium (Cr) may improve growth metrics, boost immunity, and decrease levels of cortisol and insulin. Studies have shown that the use of silica (Si) nanoparticles may improve the assimilation of nutrients and boost the metabolic rate in fish. Additionally, they have antibacterial characteristics that aid in the prevention of gut wall damage and the maintenance of a healthy gut environment.Ahmad and colleagues (2022). Iron (Fe) nanoparticles are often used as supplements in fish feed owing to their diminutive dimensions and extensive surface area. These nanoparticles demonstrate potent immune reactions against germs and stimulate elevated protein levels in fish. The addition of iron nanoparticles to the feed of Oreochromis niloticus has been discovered to yield substantial advantages. These include enhanced growth, improved immune response, increased phagocytosis activity, reduced mortality rate, higher protein and lipid content, elevated muscles focus, modified red and white blood cell counts, raised antioxidant capacity, and reinforced disease resistance.Overall, nanoparticles have shown considerable promise in improving the uptake of nutrients, metabolic function, immune response, and the prevention of gastrointestinal problems in fish (El-Shenawy et al., 2019). Silver (Ag) nanoparticles have potent antibacterial properties in fish farming by inducing bacterial dysfunction or mortality via the liberation of Ag + ions. They have the ability to attach to cytochrome and nucleic acids, which hinders the process of bacterial cell division. Silver nanoparticles have efficacy against antibiotic-resistant bacteria, including Staphylococcus aureus, Edwardesiella tarda, and cyanobacterial species. The silver nanoparticles produced from Rhizophora mucronata have shown effectiveness against Pseudomonas fluorescens, Proteus species, and Flavobacterium species. In addition, they have antifungal activities that are similar to those of Amphotericin B. Furthermore, they have shown effectiveness against the influenza A virus (Ayala-Núñez et al., 2009). Gold nanoparticles, consisting of the element Au, has strong antibacterial characteristics and have the capability to alter the structure of bacterial cells. Consuming a meal containing gold nanoparticles may improve the immune system's defense of fish. Zinc oxide (ZnO) nanoparticles have a harmful effect on bacterial immunity and may cause bacterial mortality by damaging their cell membrane. Titanium dioxide (TiO2) nanoparticles has bactericidal capabilities and may effectively clean water in fish culture. This use promotes a more resilient aquatic habitat and increases the immune system of fish (Thangapandiyan and Monika, 2020)

Table 1: The impact of various nanomaterials on the development of fish when included into their nutritional supplements

Nanoparticles	Fish species	Suitable range	Impacts	References
Titanium-di-oxide (TiO_2)	Rainbow trout	-	Increased weight loss	Ramsden et al., (2009)
Zinc oxide (ZnO)	*Cirrhinus mrigala*	15 mg/100 gm	The survival rate rises along with increased digestion and growth rate. Additionally, there is an expansion of red blood cells and a decrease in the amount of white blood cells.	Rajan and Rohini (2021)

Silver (Ag)	Rainbow trout	-	Increased weight loss	Dobrochna et al., (2018)
Gold (Au)	Rainbow trout	-	Contains the capacity to generate reactive oxygen species (ROS)	Farkas et al., (2010)
Cupper (Cu)	*Cyprinus carpio*	2.19 to 2.91 mg/kg	Rising levels of hemoglobin, blood cells, albumin, and globulin. There was an increase in both body protein and lipid. Rapid pace of development and enhanced immune system	Dawood et al., (2020)
Silica(Si)	*Oreochromis niloticus*	2 mg/kg	Reduced feed conversion rate (FCR), increased growth rate, enhanced a rise in weight, enhanced liver and kidney function.	Bashar et al., (2021)
Iron (Fe)	*Clarias barachus*	40 mg/kg	Accelerated growth rate, raised dissolved oxygen levels, elevated pH levels, higher survival rate, heightened metabolism,	Akter et al., (2018)

			abundant fat and protein content, and expanded weight gain.	
Selenium (Se)	*Labeo rohita*	0.5 mg^{-1} mg	The growth rate is elevated, digestibility is increased, the quantity of blood cells improves, longevity ratio is elevated, and the nutritional value is heightened.	Ahmad et al., (2022)
	Cyprinus carpio	1 mg/kg	Enhanced development, accelerated metabolism, improved survival rate, and raised strength.	Ashouri et al., (2015)
	European sea bass	0.5–1 mg/kg	The individual shows significant weight growth, a low feed conversion ratio (FCR), strong immune response, and elevated levels of hemoglobin, white blood cells, and red blood cells.	Abd El-Kader et al., (2021)

Nanotechnology is continuously advancing and its uses are becoming more diverse and specialized, offering great promise to improve animals overall generally. Selenium (Se) is a necessity for people and animals. It is required for the synthesis of selenoproteins, which are important for optimum development, resilience, defense mechanisms, the regulation of thyroid metabolism, as well as reproductive. Inadequate fish nutrition may result in reduced growth performance, impaired reproduction, limited immunological function, and diminished antioxidant ability. There are three different types of selenium available: inorganic, organic, and nano. Organic selenium (Se) and nano-Se exhibit reduced toxicity, increased stability in chemicals, and enhanced bioavailability in comparison to inorganic forms of Se. As a result, they are very advantageous for the cultivation of fish. A comparison indicates that the presence of Se nanoparticles improves the growth efficiency, immunology, and antioxidant defense in Cyprinus carpio. Selenium acts as a micronutrient that is extensively researched for its role in stress management. It is shown to be more effectively used by fish when they are under stressful situations. Adding to selenium (Se) in commercial diets may be essential to fulfill the increased demands of fish when they are under stress. Moreover, Se impacts the activation of genes associated with the stimulation of development, immunological reply, and antioxidant protection (Abdollahi-Mousavi et al., 2024). In addition, Aquaculture encounters several stresses that negatively impact the well-being of aquatic animals, resulting in a decrease in their biological and physiological capabilities. Stress factors disturb the equilibrium of antioxidants, leading to the oxidation of lipids and damage to DNA and cells. Selenium is recognized for its function in the formation of selenoproteins, which aid in the synthesis of glutathione peroxidase enzymes. The use of Se nanoparticles is proposed as a potent antioxidants reagent in aquaculture. (Dawood et al., 2021).This rewiew goal of study was to knowledge the aquatic organism to about nanoselenium, which is a nanonutrient (Fig:1)

Figure 1: A schematic representation illustrating several applications of selenium nanoparticles (modified to from Sarkar et al., 2015).

Harsij et al., (2020) The researchers conducted a study to examine how meals containing various combinations of three antioxidants (nano-selenium (NanoSe), vitamin C, and vitamin E) may protect rainbow trout (Oncorhynchus mykiss) from the harmful effects of sublethal ammonia concentration. In addition, the subjects were provided with three different experimental diets: T1 (0.1 mg/kg NanoSe, 100 mg/kg vitamin C, and 30 mg/kg vitamin E) and 100 mg/kg vitamin C. The study had four treatment groups: T1 (30 mg/kg vitamin E), T2 (0.2 mg/kg NanoSe, 200 mg vitamin C, and 60 mg/kg vitamin E), T3 (0.3 mg/kg NanoSe, 300 mg/kg vitamin C, and 90 mg/kg vitamin E), and a control group that received a baseline diet. The experiment lasted for 40 days. It was discovered that fish that were given T2 and T3 meals exhibited considerably greater final weight, body weight increase, specific growth rate, protein efficiency rate, and lipid efficiency rate in comparison to the T1 and control group. Additionally, it was shown that all dietary regimens that received supplements had decreased rates of food conversion in comparison to the control group. Additionally, it was shown that serum catalase exhibited a noteworthy decline alone in the T3 therapy group, but a reduction in superoxide dismutase activity was reported across all T1, T2, and T3 groups. Similarly, the researchers saw a substantial reduction in the concentration of malondialdehyde in the blood serum of fish that were given meals with added supplements. Additionally, it was discovered that the levels of blood total protein rose in T1 and declined in T2 and T3. Meanwhile, the levels of triglycerides increased in the T2 and T3 treatments. Additionally, it was discovered that the levels of total immunoglobulin, serum lysozyme, and albumin exhibited a considerable rise at T2 and T3. Furthermore, literature research indicates that the enhancement in growth performance seen in diets supplemented with antioxidants may be attributed to the advantageous impact of antioxidants on fish development when subjected to stressful situations. Selenium (Se) is a crucial element of the deiodinase enzyme. It is found in several studies where it indirectly influences the release of growth hormone from the pituitary gland in all vertebrates, including fish (Harsij et al., 2020). Cotter et al. (2008) observed an augmentation in thyroid hormone activity in fish that were provided with a diet supplemented with selenium, resulting in improved growth and feed efficiency. The use of selenium nanoparticles improved the rate of development in O. niloticus (Adam et al. 2023), Carassius auratus gibelio (Zhou et al. 2009), Oncorhynchus mykiss (Hunt et al. 2011), and Dicentrarchus labrax (Betancor et al. 2012). In a similar manner, Ibrahim et al. (2021) discovered that the addition of either bulk selenium (Bulk-Se) or nano-selenium (nano-Se) enhanced the growth performance, feed consumption efficiency, and biological parameters of Nile tilapia. The present study observed improvements in growth performance and feed conversion ratio, which can be attributed to several factors. Firstly, the enhancement of gastrointestinal tract morphology and histology by nano-Se led to improved metabolism and nutrient assimilation. Secondly, selenium plays a crucial role as a functional cofactor in the synthesis of endogenous digestive enzymes, resulting in improved nutrient digestion and enhanced growth performance and feed efficiency. Thirdly, selenium enhances protein digestibility and utilization by increasing the quantity and activity of intestinal microbes and digestive protease activity. The inclusion of nano-Se in fish diets resulted in an increase in mucosal length and breadth, as well as an increase in the number of goblet cells in the intestinal epithelium of fish. Additionally, it led to enhanced cell proliferation and protein synthesis. This leads to an increase in the surface area of the digestive tract, which improves the absorption of nutrients in the intestines. Selenium plays an important role as a component of co-enzymes in activating the gut microbiome and intestinal enzymes. This improves the structure and absorption capacity of the digestive tract, resulting in improved performance and feed efficiency in animals. Furthermore, vitamin E enhances the protein content inside the cells of the digestive tract, hence promoting the absorption and assimilation of nutrients (Dawood et al., 2020).Furthermore, Durigon et al. (2019) found no enhancement in growth metrics (weight, total length, standard length, specific growth rate, and total weight gain) among the various treatments and the control diet. The disparities between past and present findings may be ascribed to several variables, such as variations in experimental circumstances, fish species, and disparities in the chemical forms used. It should be noted that regular selenium is not readily absorbed by organisms, unlike nanoselenium particles.

1.1.Toxicity of Nanoselenium nanoparticles

Selenium nanoparticles are crucial for the creation of nutritionally balanced aquafeed. However, excessive administration may lead to toxicity and hinder the normal physical and cellular processes in fish organisms. The presence of selenium (Se) in water and ecosystems is mostly derived from natural, commercial, and agricultural processes. Increasing concerns are arising over the toxicity of selenium in aquatic environments and its impact on food chains. Excessive levels of selenium have been shown to cause toxicology and oxidative damages in aquatic species. Nanoparticles of selenium (Se) may enter fish either by their gills or by being ingested orally and then absorbed through the intestines. This can result in the production of methyl-selenide, which contributes to the generation of superoxide radicals. Additionally, it hinders the activity of cysteine proteins, which play a role in antioxidant processes. Developed Se nanoparticles may have detrimental effects on animals and people, leading to severe toxicity (Dawood et al., 2021; El-Sharawy et al., 2021). There is little research on the effects of Se nanoparticles on the health and productivity of aquatic animals. Significant harm to the the gills liver histology, and metabolic indicators in P. hypophthalmus has been seen as a result of administering large amounts of Se nanoparticles. The presence of Se nanoparticles in goldfish led to an elevation in MDA levels and GPx in seminal plasma, as well as DNA damage in sperm. Additionally, there was a rise in spermatocyte and spermatid count (Kumar et al., 2018).

Conclusions

The growing prevalence of nanotechnology may be ascribed to its potential uses in medicine delivery and enhancing nutrition. Nanomaterials with antibacterial, antioxidant, and growth-promoting characteristics provide notable benefits in the field of aquaculture. These compounds have a high level of bioavailable and may easily pass through the barriers in the intestines. As a result, they help with many genetic, dietary, and cellular functions such as respiration, antioxidation, and defense. Particles of selenium have been shown to concentrate on dangerous bacteria, leading to improved intestinal immunity and digesting capacity. This, in turn, enhances the behavior and generation of aquatic animals. Additional investigation is necessary to have a thorough comprehension of the exact method that Se nanoparticles affect the behavior of aquatic animals.

REFERENCES

Abd El-Kader, M. F., Fath El-Bab, A. F., Abd-Elghany, M. F., Abdel-Warith, A. W. A., Younis, E. M., & Dawood, M. A. (2021). Selenium nanoparticles act potentially on the growth performance, hemato-biochemical indices, antioxidative, and immune-related genes of European seabass (Dicentrarchus labrax). *Biological trace element research*, *199*, 3126-3134.

Abdollahi-Mousavi, S. E., Keyvanshokooh, S., Mozanzadeh, M. T., & Ghasemi, A. (2024). Efficacy of nutritional selenium nanoparticles on growth performance, immune response, antioxidant capacity, expression of growth and immune-related genes, and post-stress recovery in juvenile Sobaity seabream (Sparidentex hasta). *Fish & Shellfish Immunology*, 109452.

Adam, A. H., Verdegem, M., Soliman, A. A., Zaki, M., Khalil, R. H., Nour, A. E. M., ... & Khalil, H. S. (2023). Effect of dietary bile acids: Growth performance, immune response, genes expression of fatty acid metabolism, intestinal, and liver morphology of striped catfish (Pangasianodon hypophthalmus). Aquaculture Reports, 29, 101510.

Ahmad, N., Hussain, S. M., Azam, S. M., Shahzad, M. M., Noureen, A., Yaqoob, R., ... & Ahmad, S. (2022). Effects of Se nanoparticles supplementation on growth performance, hematological parameters and nutrient digestibility of Labeo rohita fingerling fed sunflower meal based diet. *Brazilian Journal of Biology*, *84*, e253555.

Ahmed, M. T., Ali, M. S., Ahamed, T., Suraiya, S., & Haq, M. (2024). Exploring the aspects of the application of nanotechnology system in aquaculture: a systematic review. Aquaculture International, 1-30.

Ali, M. S., Haq, M., Roy, V. C., Ho, T. C., Park, J. S., Han, J. M., & Chun, B. S. (2023). Development of fish gelatin/carrageenan/zein bio-nanocomposite active-films incorporated with turmeric essential oil and their application in chicken meat preservation. *Colloids and Surfaces B: Biointerfaces*, *226*, 113320.

Ashouri, S., Keyvanshokooh, S., Salati, A. P., Johari, S. A., & Pasha-Zanoosi, H. (2015). Effects of different levels of dietary selenium nanoparticles on growth performance, muscle composition, blood biochemical profiles and antioxidant status of common carp (Cyprinus carpio). *Aquaculture*, *446*, 25-29.

Ayala-Núñez, N. V., Lara Villegas, H. H., del Carmen Ixtepan Turrent, L., & Rodríguez Padilla, C. (2009). Silver nanoparticles toxicity and bactericidal effect against methicillin-resistant Staphylococcus aureus: nanoscale does matter. *Nanobiotechnology*, *5*, 2-9.

Bashar, A., Hasan, N. A., Haque, M. M., Rohani, M. F., & Hossain, M. S. (2021). Effects of dietary silica nanoparticle on growth performance, protein digestibility, hematology, digestive morphology, and muscle composition of Nile tilapia, Oreochromis niloticus. *Frontiers in Marine Science*, *8*, 706179.

Bashar, A., Hasan, N. A., Haque, M. M., Rohani, M. F., & Hossain, M. S. (2021). Effects of dietary silica nanoparticle on growth performance, protein digestibility, hematology, digestive morphology, and muscle composition of Nile tilapia, Oreochromis niloticus. Frontiers in Marine Science, 8, 706179.

Betancor, M. B., Caballero, M., Terova, G., Saleh, R., Atalah, E., Benítez-Santana, T., ... & Izquierdo, M. (2012). Selenium inclusion decreases oxidative stress indicators and muscle injuries in sea bass larvae fed high-DHA microdiets. British Journal of Nutrition, 108(12), 2115-2128.

Boyd, C. E., D'Abramo, L. R., Glencross, B. D., Huyben, D. C., Juarez, L. M., Lockwood, G. S., ... & Valenti, W. C. (2020). Achieving sustainable aquaculture: Historical and current perspectives and future needs and challenges. *Journal of the World Aquaculture Society*, *51*(3), 578-633.

Cotter, P. A., Craig, S. R., & McLean, E. (2008). Hyperaccumulation of selenium in hybrid striped bass: a functional food for aquaculture?. *Aquaculture Nutrition*, *14*(3), 215-222.

Dawood, M. A., Basuini, M. F. E., Yilmaz, S., Abdel-Latif, H. M., Kari, Z. A., Abdul Razab, M. K. A., ... & Gewaily, M. S. (2021). Selenium nanoparticles as a natural antioxidant and metabolic regulator in aquaculture: a review. *Antioxidants*, *10*(9), 1364.

Dawood, M. A., Eweedah, N. M., Moustafa, E. M., El-Sharawy, M. E., Soliman, A. A., Amer, A. A., & Atia, M. H. (2020). Copper nanoparticles mitigate the growth, immunity, and oxidation resistance in common carp (Cyprinus carpio). *Biological trace element research*, *198*, 283-292.

Dawood, M. A., Koshio, S., Zaineldin, A. I., Van Doan, H., Moustafa, E. M., Abdel-Daim, M. M., ... & Hassaan, M. S. (2019). Dietary supplementation of selenium nanoparticles modulated systemic and mucosal immune status and stress resistance of red sea bream (Pagrus major). Fish physiology and biochemistry, 45, 219-230.

Dawood, M. A., Zommara, M., Eweedah, N. M., Helal, A. I., & Aboel-Darag, M. A. (2020). The potential role of nano-selenium and vitamin C on the performances of Nile tilapia (Oreochromis niloticus). Environmental Science and Pollution Research, 27, 9843-9852.

Dobrochna, A., Jerzy, Ś., Teresa, O., Magda, F., Małgorzata, R., Yuichiro, M., & Kacper, M. (2018). Effect of copper and silver nanoparticles on trunk muscles in rainbow trout (Oncorhynchus mykiss, Walbaum, 1792). *Turkish Journal of Fisheries and Aquatic Sciences*, *18*(6), 781-788.

Durigon, E. G., Kunz, D. F., Peixoto, N. C., Uczay, J., & Lazzari, R. (2018). Diet selenium improves the antioxidant defense system of juveniles Nile tilapia (Oreochromis niloticus L.). Brazilian Journal of Biology, 79, 527-532.

Eissa, E. S. H., Baghdady, E. S., Gaafar, A. Y., El-Badawi, A. A., Bazina, W. K., Abd Al-Kareem, O. M., & Abd El-Hamed, N. N. (2022). Assessing the influence of dietary Pediococcus acidilactici probiotic supplementation in the feed of European sea bass (Dicentrarchus labrax L.)(Linnaeus, 1758) on farm water quality, growth, feed utilization, survival rate, body composition, blood biochemical parameters, and intestinal histology. Aquaculture Nutrition, 2022, 1-11.

Eissa, E. S. H., Bazina, W. K., Abd El-Aziz, Y. M., Abd Elghany, N. A., Tawfik, W. A., Mossa, M. I., ... & Khalil, H. S. (2023). Nano-selenium impacts on growth performance, digestive enzymes, antioxidant, immune resistance and histopathological scores of Nile tilapia, Oreochromis niloticus against Aspergillus flavus infection. *Aquaculture International*, 1-25.

El-Sharawy, M. E., Hamouda, M., Soliman, A. A., Amer, A. A., El-Zayat, A. M., Sewilam, H., ... & Dawood, M. A. (2021). Selenium nanoparticles are required for the optimum growth behavior, antioxidative capacity, and liver wellbeing of Striped catfish (Pangasianodon hypophthalmus). *Saudi Journal of Biological Sciences*, *28*(12), 7241-7247.

El-Shenawy, A. M., Gad, D. M., & Yassin, S. A. (2019). Effect of Iron Nanoparticles on the Development of Fish Farm Feeds. *Alexandria Journal of Veterinary Sciences*, *60*(1).

Farkas, J., Christian, P., Urrea, J. A. G., Roos, N., Hassellöv, M., Tollefsen, K. E., & Thomas, K. V. (2010). Effects of silver and gold nanoparticles on rainbow trout (Oncorhynchus mykiss) hepatocytes. *Aquatic Toxicology*, *96*(1), 44-52.

Harsij, M., Kanani, H. G., & Adineh, H. (2020). Effects of antioxidant supplementation (nano-selenium, vitamin C and E) on growth performance, blood biochemistry, immune status and body composition of rainbow trout (Oncorhynchus mykiss) under sub-lethal ammonia exposure. *Aquaculture*, *521*, 734942.

Hunt, A. O., Berkoz, M., Ozkan, F., Yalin, S., Ercen, Z., Erdogan, E., & Gunduz, S. G. (2011). Effects of organic selenium on growth, muscle composition, and antioxidant system in rainbow trout. Israeli Journal of Aquaculture-Bamidgeh, 63(562), 10.

Ibrahim, M. S., El-gendy, G. M., Ahmed, A. I., Elharoun, E. R., & Hassaan, M. S. (2021). Nanoselenium versus bulk selenium as a dietary supplement: Effects on growth, feed efficiency, intestinal histology, haemato-biochemical and oxidative stress biomarkers in Nile tilapia (Oreochromis niloticus Linnaeus, 1758) fingerlings. Aquaculture Research, 52(11), 5642-5655.

Khalil, H. S., Maulu, S., Verdegem, M., & Abdel-Tawwab, M. (2023). Embracing nanotechnology for selenium application in aquafeeds. *Reviews in Aquaculture*, *15*(1), 112-129.

Khan, K. U., Zuberi, A., Nazir, S., Ullah, I., Jamil, Z., & Sarwar, H. (2017). Synergistic effects of dietary nano selenium and vitamin C on growth, feeding, and physiological parameters of mahseer fish (Tor putitora). *Aquaculture Reports*, *5*, 70-75.

Kumar, N., Krishnani, K. K., & Singh, N. P. (2018). Comparative study of selenium and selenium nanoparticles with reference to acute toxicity, biochemical attributes, and histopathological response in fish. *Environmental Science and Pollution Research*, *25*, 8914-8927.

Mansour, A. T. E., Goda, A. A., Omar, E. A., Khalil, H. S., & Esteban, M. Á. (2017). Dietary supplementation of organic selenium improves growth, survival, antioxidant and immune status of meagre, Argyrosomus regius, juveniles. Fish & Shellfish Immunology, 68, 516-524.

Rajan, M. R., & Rohini, R. (2021). Impact of different quantity of Zinc oxide nanoparticles on growth and hematology of Mrigal Cirrhinus mrigala. *Journal of Water and Environmental Nanotechnology*, *6*(1), 62-71.

Ramsden, C. S., Smith, T. J., Shaw, B. J., & Handy, R. D. (2009). Dietary exposure to titanium dioxide nanoparticles in rainbow trout,(Oncorhynchus mykiss): no effect on growth, but subtle biochemical disturbances in the brain. *Ecotoxicology*, *18*, 939-951.

Sarkar, B., Bhattacharjee, S., Daware, A., Tribedi, P., Krishnani, K. K., & Minhas, P. S. (2015). Selenium nanoparticles for stress-resilient fish and livestock. Nanoscale research letters, 10, 1-14.

Srinivasan, V., Bhavan, P. S., Rajkumar, G., Satgurunathan, T., & Muralisankar, T. (2016). Effects of dietary iron oxide nanoparticles on the growth performance, biochemical constituents and physiological stress responses of the giant freshwater prawn Macrobrachium rosenbergii post-larvae. Int J Fish Aquat Stud, 4(2), 170-182.

Thangapandiyan, S., & Monika, S. (2020). Green synthesized zinc oxide nanoparticles as feed additives to improve growth, biochemical, and hematological parameters in freshwater fish Labeo rohita. *Biological trace element research*, *195*, 636-647.

Younus, N., Zuberi, A., Mahmoood, T., Akram, W., & Ahmad, M. (2020). Comparative effects of dietary micro-and nano-scale chitosan on the growth performance, non-specific immunity, and resistance of silver carp Hypophthalmichthys molitrix against Staphylococcus aureus infection. *Aquaculture International*, *28*, 2363-2378.

Zhou, X., Wang, Y., Gu, Q., & Li, W. (2009). Effects of different dietary selenium sources (selenium nanoparticle and selenomethionine) on growth performance, muscle composition and glutathione peroxidase enzyme activity of crucian carp (Carassius auratus gibelio). Aquaculture, 291(1-2), 78-81.

CHAPTER 6

OATS WITH ITS PRODUCTION AND TRADE FROM PAST TO PRESENT

Assist. Prof. Dr. Fevzi ALTUNER[1]
Prof. Dr. Tamer ERYİGİT[2]
Emir Kulal ALTUNER[3]

[1] Van Yuzuncu Yil University, Gevas Vocational School, Department of Plant and Animal Production. Van-Türkiye. Orcid ID: 0000-0002-2386-2450
Corresponding author: faltuner@gmail.com
[2] Van Yuzuncu Yil University, Gevas Vocational School, Department of Plant and Animal Production. Van-Türkiye. Orcid ID: 0000-0001-5069-8206
[3] Van Yuzuncu Yil University, Institue of Science, Field Crops Main Sience Branch. Master's Student. Van-Türkiye. Orcid ID: 0009-0006-6506-4461

INTRODUCTION

As the global population continues to rise rapidly, the need for sustainable food sources, particularly through the diversification of plant-based options, has become increasingly urgent (Springmann et al., 2018). The market for plant-based protein sources is experiencing significant growth and is projected to reach $15.6 billion by 2026, reflecting a 7.2% increase (Wang et al., 2022). Currently, around 60% of the calories required for human nutrition worldwide are provided by grains such as wheat, rice, corn, barley, rye, and oats (Sruthi and Rao, 2021).

Oats, belonging to the Poaceae family, thrive particularly well in cool and humid climates (Kim et al., 2021a). They come in various types, including black, red, yellow, and white, making oats the sixth most produced grain globally, following wheat, corn, rice, barley, and sorghum (Mert, 2020; Martin-Diana et al., 2021; Kamal et al., 2022).

Avena sativa L., commonly known as oat, is a versatile grain utilized in human food, animal feed, herbal remedies, and cosmetics, possessing unique characteristics that set it apart from other grains (Varma et al., 2016). Cultivated for over 2000 years, oats have been integral to human agriculture (Sang and Chu, 2017). Rich in carbohydrates, digestible dietary fiber, protein, lipids, phenolic compounds, vitamins, and minerals, oats are highly valued for their nutritional content (Joyce et al., 2019). The antimicrobial properties of oats lend themselves to the management and treatment of various health issues, including cardiovascular diseases, diabetes, obesity, celiac disease, cancer, and inflammatory disorders. As awareness of these benefits grows, cultivation has expanded to support trends in healthy eating, industrial applications, and scientific research (Paudel et al., 2021).

The concept of superfood refers to foods that enhance the body’s resistance due to their nutrient and antioxidant content. Examples include spinach, tomatoes, broccoli, garlic, blueberries, and salmon (Yuanqing et al., 2021). Functional grains, which include oats, lentils, chickpeas, amaranth, flaxseeds, and wild rice, are also recognized for their nutrient-rich grains (Wilson et al., 2017). While these grains vary in composition, they generally provide more protein, vitamins, minerals, and dietary fiber than staple grains like white rice, wheat, and barley (Kim et al., 2021b). Regular consumption of these functional grains can help address the issue of inadequate nutrition in today's fast-paced lifestyle (Bai et al., 2018; Li et al., 2018; Wing et al., 2018; Khan et al., 2020).

When comparing the functional content of oats with wheat, barley, and white rice, oats stand out with a higher protein content than white rice and comparable levels to wheat and barley. They feature lower starch content, higher fat and dietary fiber levels, and a significant amount of β-glucan compared to barley (Table 1).

Table 1. Functional contents of oats and some cereals (Maheshwari et al.2019)

Herbs	**Protein (%)**	**Fat (%)**	**Starch (%)**	**Total dietary fiber (%)**	**β-glucan content in grain (g/100 g)**
Wheat	7-22	2-5	68	11.5-15.5	0.5-1
Barley	14.2	2.4	54.2	13.1	2-20
White Rice	6.3	0.7	80.1	1	0.13
Oat	9-17	5-12	27-50	13-30	3-8

Oats are widely recognized for their rich content of high protein, vitamins, and minerals, making them a highly valuable grain. They contain a considerable amount of protein and lipids, alongside essential amino acids like lysine and between 2-6% β-glucan (Saccomanno et al. 2017; Nogala-Kalucka et al. 2020). Unlike many field crops where protein levels can vary inversely, the lysine content in oats remains relatively constant (Klose et al. 2012). Notably, globulin makes up 70-80% of its protein, with a comparable quantity of prolamin present (Gell et al. 2017). Oat grains typically contain 5-12% fat, predominantly unsaturated fatty acids, which is higher than that found in other cereals. About 95% of this fat consists of oleic, palmitic, and linoleic acids (Maheshwari et al. 2019; Nogala-Kalucka et al. 2020; Capurso et al. 2021). Additionally, oats are rich in polyphenols, antioxidants (Kim et al. 2021a; Martin-Diana et al. 2021; Altuner et al. 2021), and alkaloids (Kim et al. 2021a; Martin-Diana et al. 2021). Oat bran is particularly noteworthy for its high content of proteins, β-glucan, saponin, albumin, prolamins, and glutelins. Consuming whole oat grain can yield significant health benefits (Tieri et al. 2020). With a digestibility rate of 90-94% due to high protein, β-glucan, and dietary fiber (Kumar et al., 2021), oats are extensively used in the food industry, incorporated into various products and beverages (Basri et al., 2020; Brückner-Gühmann et al., 2019; Guo et al., 2020; McGorrin, 2019).

Research has shown that the high β-glucan content in oats can provide protective benefits against chronic diseases (Kamal et al., 2022). Moreover, the USA Drug Administration has recognized the positive impact of oat-derived β-glucan on cholesterol and heart health (Yang et al., 2023).

Oats have long been a staple in the diets of draft and pack animals due to their high protein content. However, the advent of mechanization in agriculture led to a significant decline in oat cultivation. Over a span of approximately 70 years, as horses were replaced by machines, global oat production areas shrank by about 60%. Currently, oats are grown in roughly 2%-5% of total cultivated land in some countries, stabilizing production at around 25 million tons. In oat-producing countries, about 25% of the harvest is allocated for human consumption, while the majority is used for animal feed. Recently, there has been a growing recognition of oats as a functional food, which has enhanced their commercial value (Strychar et al., 2011). The production of oats is heavily influenced by ecological and climatic factors, but advancements in breeding high-yielding varieties offer potential for increased output (Krattinger and Keller, 2022; Mel and Malalgoda, 2022).

This study aims to compile data on the cultivation area, yield, production, and trade of oats, emphasizing their rising importance in the functional and healthy food market. Additionally, a partial evaluation of oat production and trade in Türkiye is included.

OATS PRODUCTION IN THE WORLD

The changes in oat planting area, yield, and production data between 1961 and 2022 reveal notable trends. In 1961, the global harvest area for oats was 38.3 million hectares, with a yield of 1296.1 kg/ha, resulting in a production of 49.6 million tons. Since then, the harvest area has progressively declined. For instance, by 1965, it decreased by approximately 23.2% to 29.4 million hectares. This downward trend continued into subsequent years, with the area shrinking further by 15.6% in 1980 (to 24.7 million hectares), 16.6% in 1990 (to 20.7 million hectares), and 21.2% in 1995 (to 16.3 million hectares). By 2000, the area had plummeted by 22.7% to 12.6 million hectares, and by 2010, it reached 8.9 million hectares—a drop of 20.9% compared to the previous period. Post-2010, the harvested area stabilized between 9 and 9.5 million hectares, maintaining these levels through 2022. The most significant reductions in harvest areas occurred during the periods between 1961-1985, which saw a total decrease of 35.2%.

While the harvested area has diminished, oat yield has seen a significant upward trend over the years. Between 1961-1985, yield increased by 47.7%, with further increases of 60.0% between 1961-2000 and a remarkable 114.1% between 1961-2022, reaching 2774.9 kg/ha. Calculating the rate of increase from 1961 to 2023 yields a growth rate of 89.8%.

Table 2. Oat area harvested, yield and production data for the period between 1961-2022 (FAOSTAT, 2024).

Periods	Area Harvested (ha)	Change (%)	Yield (kg/ha)	Change (%)	Production (ton)	Change (%)
1961	38260751		1296.1		49588769	
1965	29386814	-23.2	1543.4	19.1	45356066	-8.5
1970	30677761	4.4	1708.4	10.7	52411105	15.6
1975	29269587	-4.6	1551.7	-9.2	45418289	-13.3
1980	24697330	-15.6	1677.6	8.1	41433288	-8.8
1985	24781851	0.3	1913.7	14.1	47425037	14.5
1990	20679705	-16.6	1930.3	0.9	39917119	-15.8
1995	16302668	-21.2	1716.0	-11.1	27975843.5	-29.9
2000	12595871	-22.7	2073.3	20.8	26114484.3	-6.7
2005	11351905	-9.9	2076.0	0.1	23566010.8	-9.8
2010	8981037	-20.9	2141.5	3.2	19233197.9	-18.4
2015	9692363	7.9	2347.8	9.6	22755504.9	18.3
2020	9800337	1.1	2583.7	10.0	25321359.6	11.3
2021	9617498	-1.9	2356.0	-8.8	22659155.1	-10.5
2022	9508645	-1.1	2774.9	17.8	26385330	16.4
2023*	8364000	-12.0	2460.0	-11.3	20542000	-22.1
1961-1985		-35.2		47.7		-4.4
1961-2000		-67.1		60.0		-47.4
1961-2022		-75.2		114.1		-46.8
1961-2023*		-78.1		89.8		-58.6

*:USDA, (2024).

World oat production has seen a significant decline from 1961 to 2022, mirroring the reduction in harvested areas. In 1961, global oat production stood at 49.6 million tons. By 1985, this figure fell by 4.4% to 47.4 million tons. This relative decrease was influenced by a 14.5% increase in production in 1985 compared to the previous period in 1980. The most notable drop occurred in 1995, with a staggering decline of 29.9%, bringing production down from 39.9 million tons to 27.9 million tons, largely due to reduced harvested areas during that time. Overall, oat production plummeted by 47.4% between 1961 and 2000, and by 46.8% from 1961 to 2022. By 2022, production had decreased to 26.4 million tons. From 1961 to 2023, the decline in production reached 58.6%. After significant drops between 1990 and 1995, there were increases in production during the years 2015, 2020, and 2022, which mitigated the overall decline. Between 2000 and 2022, stable harvested areas contributed to periodic increases in production, attributed primarily to improvements in yield.

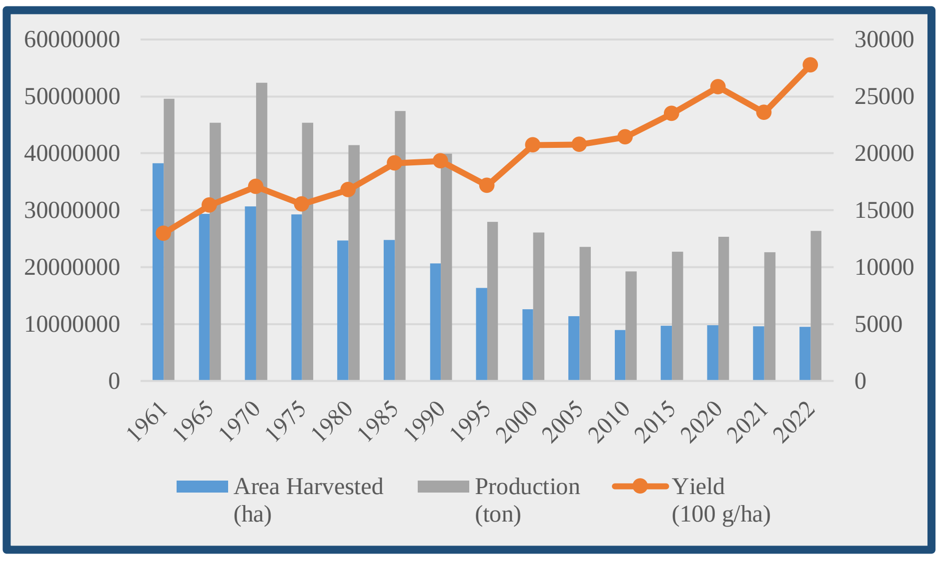


Figure 1. World oat area harvested, yield and production graph between 1961-2022

The graph of oat planting area, yield and production data is shown in Figure 1. Accordingly, the world oat harvest area and production amount have had a similar fluctuation course between 1961-2022. The harvest area, which had the highest amount in 1961, was at 29-30 million hectares between 1965-1975. It decreased to 24-25 million hectares in the 1980-1985 periods and remained in between. The harvest area decreased continuously between 1990-2005, decreasing from 20 million hectares to 11 million hectares. After that, the harvest area did not undergo any serious change (Figure 1).

World oat production followed a fluctuating course between 40-50 million tons between 1961-1990. The gradual increase in unit area yield ensured that the production amount was maintained at a certain level even though the harvest area decreased. The production amount has been decreasing continuously since 1995 and reached its lowest point (19.2 million tons) in 2010. After that, it will remain at 22-26 million tons during the 2015-2022 periods.

LEADING COUNTRIES IN OAT PLANTATION AND PRODUCTION ACCORDING TO PERIODS

The top ten countries leading in oat production according to 2023 data are shown in Table 3. Accordingly, the total world planting area in 2023 is 8.4 million hectares. The European Union has 2.3 million hectares and Russia has 1.8 million hectares, and the plantings of these two groups constitute 49.1% of the total planting area. These are followed by Canada, Australia and Brazil. The top ten countries in oat planting area constitute 90% of the total planting. Others have a share of 10% in planting.

Table 3. Leading unions and countries in oat planting area and production in 2023 (USDA, 2024a)

Country	Area Harvested (1000 Ha)	Ratio (%)	Country	Production (MT)	Ratio (%)	Yield (MT/Ha)
European Union	2310	27.6	European Union	6810	33.1	2.95
Russia	1800	21.5	Russia	3500	17.0	1.94
Others	840	10.0	Canada	2636	12.8	3.20
Canada	823	9.8	Others	1943	9.5	2.31
Australia	700	8.4	Brazil	1220	5.9	1.74
Brazil	510	6.1	Australia	1100	5.4	2.16
China	405	4.8	United Kingdom	850	4.1	2.10
United States	336	4.0	United States	828	4.0	2.46
Argentina	285	3.4	Argentina	610	3.0	2.14
Kazakhstan	190	2.3	China	600	2.9	3.16
United Kingdom	165	2.0	Chile	450	2.2	2.73
World	8364	100		20547	100	2.46

According to 2023 data, the total oat production in the world is 20.6 million tons. The European Union has the highest oat production in the world with 6.8 million tons and a share of 33.1%. The top ten countries in production are led by the European Union, followed by Russia and Canada. The production of these three groups and countries constitutes 63.9% of the total production. Others constitute 9.5% of the total production with 1.9 million tons.

According to the 2023 yield values, Canada, China and the European Union have the highest yields (3200, 3160 and 2950 kg/ha, respectively). High unit area yields provide higher production from a smaller area. Brazil has the lowest yield (1740 kg/ha) and Russia is second in low yield. Especially Russia's low yield has caused the production amount obtained from the unit area to be 1/3 less than Canada, China and the European Union.

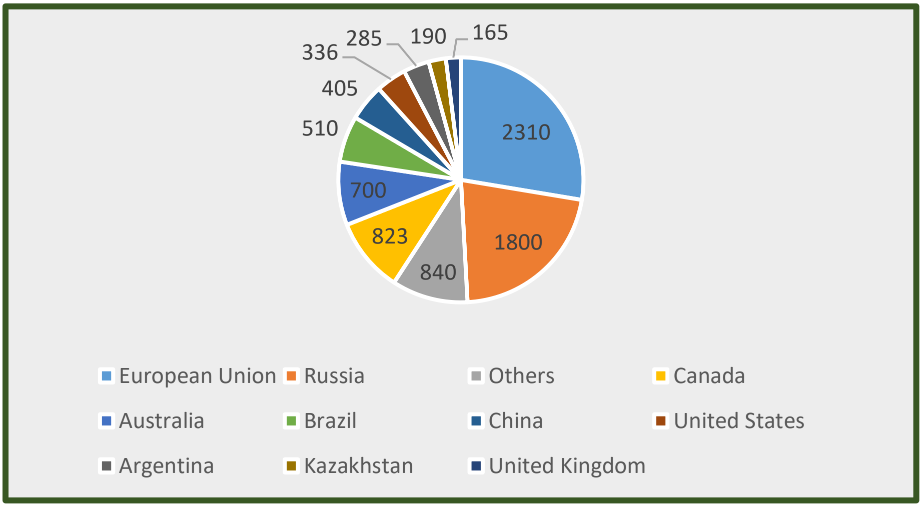


Figure 2. Top ten groups and countries chart in 2023 oat planting area

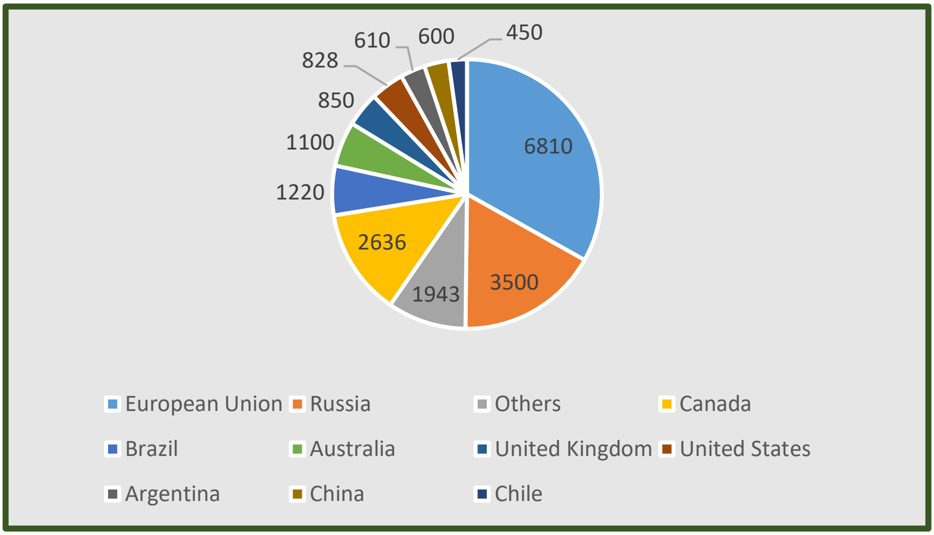


Figure 3. Top ten groups and countries in oat production in 2023

The top ten countries in 2023 oat planting area are shown in Figure 2 and the top ten countries in production amount are shown in Figure 3. Accordingly, it is seen that the European Union and Russia constitute 50% of the planting areas. The lowest value among the top ten countries in the planting area graph belongs to the United Kingdom with a share of 0.165 million hectares and 2%. Others, which are outside the top ten countries, constitute 0.84 million hectares and 10% of the planting area (Figure 2).

In 2023 oat production, the European Union constitutes 50% of the production with 6.8 million tons and Russia with 3.5 million tons. These are followed by Canada (13%) with 2.6 million tons and Brazil (6%) with 1.2 million tons. Others, which are outside the top ten countries, constitute 9% of the production with 1.9 million tons. Among the ten leading countries in world oat production, Chile has the lowest production with 0.45 million tons (2%). The fact that the United Kingdom has a share of 2% in the planted area and 4% in production is due to the relatively high unit area yield. Although Kazakhstan is among the top ten countries with a share of 2% with a planted area of 0.19 million hectares, it is not among the top ten countries in production due to low yield (Figure 3).

Table 4. Top ten countries in oat production by year (FAOSTAT, 2024)

2022		2015		2010		2000		1990		1980	
Countries	Prod. (1000 ton)	Countries	Prod. (1000 ton)	Countries	Prod. (1000 ton)	Countries	Prod. (1000 ton)	Countries	Prod. (1000 ton)	Countries	Prod. (1000 ton)
Canada	5226.5	Russia Fed.	4535.6	Russia Fed.	3219.6	Russia Fed.	6002.3	USSR	15551.0	USSR	13907.0
Russia Fed.	4530.0	Canada	3452.5	Canada	2451.4	Canada	3403.3	USA	5189.0	USA	6659.4
Australia	1734.9	USA	1299.6	Poland	1516.5	USA	2165.1	Canada	2692.0	Germany	3239.7
Poland	1500.8	Australia	1198.0	USA	1188.1	Finland	1412.8	Poland	2118.8	Canada	2911.4
Brazil	1296.3	Poland	1219.6	Australia	1161.6	Sweden	1137.7	Germany	2105.3	Poland	2244.8
Finland	1221.7	Finland	979.6	Spain	1024.7	Australia	1118.0	Finland	1661.8	France	1930.7
UK	1107.0	UK	799.0	Finland	809.7	Germany	1087.2	Sweden	1584.2	Sweden	1566.7
Spain	867.9	Spain	790.4	UK	685.3	Poland	1070.2	Australia	1529.8	Finland	1258.3
USA	836.9	Sweden	744.7	Germany	598.0	China	1012.0	China	890.0	Australia	1128.3
Germany	754.7	France	597.1	Sweden	559.3	Spain	953.7	France	839.5	China	877.0
Top Ten Countries Total	19076.7		15616.2		13214.3		19362.3		34161.4		35723.3
World Total Production	26385.3		22755.5		19233.2		26114.5		39917.1		41433.3
Top Ten/World (%)	72.3		68.6		68.7		74.1		85.6		86.2
World Total Area Harvested	9508.6		9692.4		8981.0		12595.9		20679.7		24697.3

The changes in oat production in the top ten countries in certain periods from 1980 to 2022 are shown in Table 4. Accordingly, in 1980, the USSR had 33.6% of world oat production (41.4 million tons) with 13.9 million tons. During this period, the USSR and the USA met 49.6% of world oat production with 20.6 million tons. The top ten countries had an 86.2% production share in the world with 35.7 million tons.

In 1990, the USSR had 39% of world oat production (40 million tons) with 15.6 million tons. The USSR and the USA met 52% of world oat production with 20.7 million tons during this period. The top ten countries had 85.6% of world oat production with 34.2 million tons.

In 2000, it is seen that the USSR's oat production decreased significantly compared to the previous decade and decreased to 6 million tons. During this period, the USSR and the USA's oat production accounted for only 36% of the world oat production (26.1 million tons). Due to the general decrease in production in these two countries and the top ten countries, which provided half of the world's oat production in the previous decade, the world oat yield also decreased by 15 million tons. During this period, the top ten countries provided 74.1% of the production. As of this period, the share of the top ten countries in world oat production decreased by 10%.

In 2010, world oat production continued to decrease compared to 2000 and decreased to 19.2 million tons. During this period, the Russian Federation ranked first with 3.2 million tons, Canada with 2.6 million tons and the USA with 1.5 million tons. The production amount of the top ten countries, with 13.2 million tons, constituted 68.7% of the world oat production. Compared to the previous period (2000), oat production decreased by 2.8 million tons in the Russian Federation compared to the USSR and by 1 million tons in the USA. This decrease also occurred in some of the top ten countries.

In 2015, world oat production was 22.8 million tons and the production of the top ten countries was 15.6 million tons. The share of the top ten countries in world oat production is 68.6%. The Russian Federation is in third place with 4.5 million tons, Canada is 3.5 million tons and Poland is 1.3 million tons. The USA has fallen one place compared to the previous ten-year period and has fallen to fourth place with 1.2 million tons.

In 2022, world oat production increased by around 4 million tons compared to the previous period and reached 26.4 million tons. The production amount of the top ten countries is 19.1 million tons and its share in world oat production is 72.3%. During this period, the Russian Federation ranked third with 5.2 million tons, Canada 4.5 million tons, and the USA 1.7 million tons. Compared to the previous period, production increased by approximately 0.7 million tons in the Russian Federation, 1.1 million tons in Canada, and 0.3 million tons in the USA. With the increases in the other countries in the top ten and in other countries not included in the ranking, production increased by 3.9 million tons.

When oat production in the countries ranked first in the 2010-2022 period is examined, their share in world oat production was over 85% in the 1980 and 1990 periods. However, since 2000, their shares first decreased to 74.1%, 68.7%, and 68.6%, and increased again to 72.3% in 2022.

OAT TRADE FROM PAST TO PRESENT

World oat export, import quantities and values for certain periods between 1961-2022 are given in Table 5. Accordingly, in 1961, world oat imports were 1.2 million tons and import value was 68.3 million USD, while exports were 1.3 million tons and export value was 60.4 million USD. In 1990, imports increased to 2.2 million tons, import value to 288.8 million USD, exports to 2 million tons and export value to 245.5 million USD. In 2015, imports increased to 3.4 million tons, import value to 853.2 million USD, and exports to 3.2 million tons and 745.8 million USD. In 2020, imports reached their highest level at 3.8 million tons, with an import value of 992.2 million USD, and exports rose to 3.7 million tons and an export value of 907.8 million USD, and 2021 remained around this level. In 2022, imports reached 3.5 million tons, with an import value of 1.2 billion tons, and exports reached 3.5 million tons and an export value of 1.2 billion USD.

Table 5. World oat import and export quantities and values by year (FAOSTAT, 2024)

Periods	Import Quantity (ton)	Import Value (1000 USD)	Export Quantity (ton)	Export Value (1000 USD)
1961	1211979	68319	1274955	60421
1965	1571466	104693	1748595	92392
1970	1572537	106945	1509656	83707
1975	1232063	178302	1189194	141653
1980	1292918	243072	1493807	220263
1985	1487116	210009	1573981	178673
1990	2163882	288797	2063428	245487
1995	2369520.42	323764	2392869	304770
2000	2555130.84	290752	2727943.31	279257
2005	2677051	407886	2603610	368021
2010	2674731.8	577599	2759290	577817
2015	3371747.45	853248	3160620.76	745812
2020	3836364.71	992175	3710985.85	907802
2021	3773068.13	1047228	3735699.42	1023809
2022	3453696.72	1213115	3522274.01	1198799

The world oat import, export and related values graph between 1961-2022 is shown in Figure 4. According to this graph, world oat import reached around 1.6 million tons in the four-year period between 1961 and 1965, started to increase partially and maintained this level until 1970. However, it is understood that imports decreased to 1961 levels in the next five-year period in 1975 and fell to 1.2 million tons. After this, there was a partial increase in the periods of 1980 and 1985 and this increase reached 2.2 million levels in 1990. This increasing trend in imports continued until 2010 and was fixed at 2.7 million tons in this period. It is seen that oat imports exceeded 3 million tons in 2015 and reached 3.4 million tons and 3.8 million in 2020. After this year, imports started to decline and decreased to 3.5 million tons in 2022.

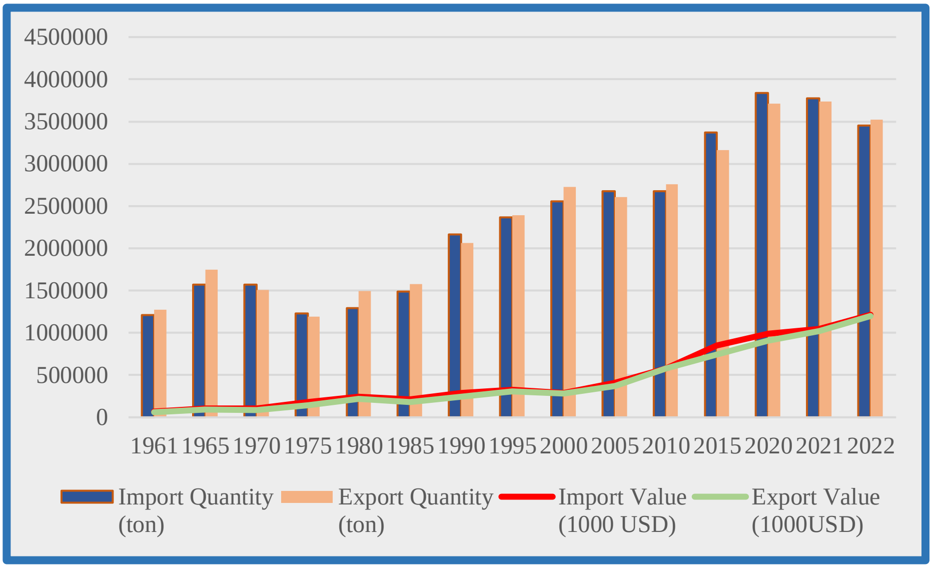


Figure 4. World oat import, export quantities and values between 1961-2022 (FAOSTAT, 2024)

Between 1961-2022, oat export transactions, similar to import transactions, had a partial increase between 1961-1970 and then started to decline again in 1970. Export transactions entered an upward trend between 1980-2000 and reached 2.6 million tons in 2000. Between 2000-2010, world oat exports stagnated, but reached 3.2 million tons by 2015. Export transactions, which were at 3.7 million tons in 2020 and 2021, decreased to around 3.5 million tons in 2022.

World oat import and export values between 1961-2022 had a similar course between 1961-2000 and followed a mild course, reaching from 92.4 million USD to 279.3 million USD. From 2005 to 2022, there was a more aggressive increase from 368 million USD to 1.2 billion USD.

LEADING COUNTRIES IN WORLD OAT TRADE

The oat export and import amounts for the five leading countries in the world between 1990 and 2022 are summarized in Table 6.

In 1990, global oat exports totaled 2.06 million tons, with 1.8 million tons (86.7%) coming from the top five exporting countries: Canada (1.7 million tons), Finland (111.3 thousand tons), Sweden (81.7 thousand tons), Australia (72.8 thousand tons), and France (53.1 thousand tons). The leading importers in the same year were the USA, USSR, Algeria, Japan, and Switzerland, with a combined import of 1.7 million tons. The USA led imports with 1.03 million tons, followed by the USSR at 384 thousand tons and Algeria at 134.09 thousand tons. Overall, the five main importing countries represented 78.5% of the world's total imports of 2.2 million tons.

By 2000, the UK replaced France as the fifth-largest exporting country. During this year, total global oat exports rose to 2.7 million tons, with the top five countries exporting 2.4 million tons, or 88.7% of the total. Canada maintained its leading position with 1.5 million tons of exports. On the import side, global figures reached 2.6 million tons, with the top five countries accounting for 80.2% of this, importing a total of 2 million tons. The USA continued to dominate with an import share of 1.7 million tons.

Table 6. Export and import quantities of the world and the top five countries between 1990-2022 (FAOSTAT, 2024)

2022				2010			
Countries	**Export (ton)**	**Countries**	**Import (ton)**	**Countries**	**Export (ton)**	**Countries**	**Import (ton)**
Canada	1257823.3	USA	1312826.0	Canada	1544055.0	USA	1579712.0
Australia	587229.1	Germany	475861.9	Finland	320306.0	Germany	259668.0
Finland	225519.7	China	390001.2	Australia	207718.0	Spain	111366.0
Sweden	224900.0	Netherlands	327506.9	Sweden	102398.0	Belgium	95746.0
UK	193553.8	Belgium	181565.6	France	85524.0	Mexico	74532.0
Top 5 Total	2489028.0		2687761.5		2260001.0		2121024.0
World	3522274.0		3453696.7		2759290.0		2674731.8
Top 5/World (%)	70.7		77.8		81.9		79.3
2000				**1990**			
Countries	**Export (ton)**	**Countries**	**Import (ton)**	**Countries**	**Export (ton)**	**Countries**	**Import (ton)**

Canada	1510347.0	USA	1730201.0	Canada	611016.0	USA	1034278.0
Sweden	445641.0	Germany	111250.0	Finland	423290.0	USSR	384000.0
Finland	229366.0	Japan	81718.0	Sweden	352324.0	Algeria	134095.0
Australia	138639.0	Italy	72769.0	Australia	236700.0	Japan	81577.0
UK	96140.0	Russian Fed.	53121.7	France	166568.0	Switzerland	63756.0
Top 5 Total	2420133.0		2049059.7		1789898.0		1697706.0
World	2727943.3		2555130.8		2063428.0		2163882.0
Top 5/World (%)	88.7		80.2		86.7		78.5

In 2010, global oat exports reached 2.8 million tons, with the top five exporting countries accounting for 81.9% of the total, equivalent to 2.3 million tons. The leading exporters were Canada (1.5 million tons), Finland (475.9 thousand tons), Australia (207.7 thousand tons), Sweden (102.4 thousand tons), and France (855 thousand tons). During the same year, global oat imports totaled 2.7 million tons, with the top five importing nations capturing 79.3% of this market, which amounted to 2.1 million tons. The primary importers included the USA (1.6 million tons), Germany (259.7 thousand tons), Spain (111.4 thousand tons), Belgium (95.8 thousand tons), and Mexico (74.5 thousand tons).

By 2022, world oat exports increased to 3.5 million tons, with the top five countries comprising 64.3% of this total at 2.3 million tons. Canada continued to lead exports (1.3 million tons), followed by Australia (587.2 thousand tons), Finland (225.5 thousand tons), Sweden (224.9 thousand tons), and the UK (193.6 thousand tons). In terms of imports during this period, total figures also stood at 3.5 million tons, with the leading countries representing 77.8% of the market, totaling 2.7 million tons. The top importers were the USA (1.3 million tons), Germany (475.9 thousand tons), China (390 thousand tons), the Netherlands (327.5 thousand tons), and Belgium (181.6 thousand tons).

From 1990 to 2022, Canada consistently held the highest share in oat exports, with its shares ranging from 29.6%-34.1% in 1990 to 35.7%-50.5% in 2022. Meanwhile, the USA dominated oat imports during the same period, with its shares fluctuating from 47.8%-60.9% in 1990 to 38.0%-48.8% in 2022.

TÜRKİYE OAT PRODUCTION AND TRADE

Oat production in Türkiye ranks third after wheat, barley, and rye (Karaman et al., 2020). The country holds the 13th position in global oat production, contributing 1.7%, just behind Belarus (USDA, 2024b). Oats are primarily cultivated in the Central Anatolia Region, which accounts for 65% of the production and includes provinces like Ankara, Sivas, and Konya. The Marmara Region, including Kocaeli, Canakkale, and Balıkesir, follows as the second key area for oat farming (Anonymous, 2023).

Data from 2005 to 2023 show that the planting areas in 2005 (1.33 million da), 2021 (1.37 million da), 2022 (1.38 million da), and 2023 (1.38 million da) were consistently close in size. However, 2023 yielded the highest production at 410 thousand tons, attributed to an increase in yield from 203 kg/da in 2005 to 297 kg/da in 2023—a notable 31.6% increase over the span.

The lowest values for both planting area and yield during this period occurred in 2010, with the lowest yield after 2005 recorded in 2021, resulting in a significant drop in production to 276 thousand tons, despite the cultivation area being at its peak.

Table 7. Oat planting area, yield and production values in Türkiye between 2005-2023 (TUIK, 2024a)

Periods	Planted Area (da)	Yield (kg/da)	Production (ton)
2005	1330000	203	270000
2010	883900	233	203870
2015	1034570	242	250000
2020	1132633	278	314528
2021	1369490	208	276000
2022	1376551	266	365000
2023	1382118	297	410000

Table 8. Türkiye's oat export and import values for the 2005-2023 period (TUIK, 2024b)

Periods	Export (USD)	Import (USD)
2023	189452	2
2020	124381	8687
2015	1700	673828
2005	9255	788548

The values related to export and import transactions in Türkiye between 2005-2023 are shown in Table 8. Accordingly, the lowest export transaction was in the 2015 period (1700 USD), and the highest export transaction was in the 2023 period (189.5 thousand USD).

According to the import transactions between certain periods between 2005 and 2023, the lowest imports were in 2023 (2 USD), and the highest imports were in 2005 (788.5 thousand USD).

CONCLUSION

Oats have historically played a significant role in animal nutrition, particularly for horses that were essential in rural areas and on battlefields. However, after the 1930s, the rise of mechanization in agriculture led to a decline in oat cultivation, as machinery replaced animals for labor. This resulted in oat production hitting a significant low by the 2010s, stabilizing at around 22-25 million tons. Initially, despite large cultivation areas, production was limited due to the prevalence of low-yielding varieties. The introduction of new high-yielding varieties through breeding efforts improved yields per unit area.

In recent years, the recognition of oats as a healthy diet and functional food has been on the rise, largely due to their rich content of dietary fiber, β-glucan, protein, and antioxidants. Research indicates that oats positively impact chronic conditions such as cholesterol management, diabetes, anemia, colon cancer, and cardiovascular diseases. Additionally, their low gluten content makes them suitable for celiac patients, further expanding their application in health-focused diets.

This shift from conventional animal nutrition to a focus on human health has spurred interest in oats across various sectors, including alternative food, cosmetics, and pharmaceuticals. There’s an optimism that by developing new oat varieties that can adapt to diverse ecological conditions, production levels can increase to meet growing demand.

REFERENCES

Altuner, F., Tuncturk, R., Oral, E., Tuncturk, M., 2021. Evaluation of pigment, antioxidant capacity and bioactive compounds in microgreens of wheat landraces and cereals. Chilean journal of agricultural research, 81(4), 643-654.

Anoymous, 2023. National Grain Council Grain Yield and Forecast Report-Oats. http://www.uhk.org.tr/tr/wp-content/uploads/2023/07/uhk2022-7_temmuz_ayc.pdf. (Accessed date, 25.10.2024).

Bai, S.,Yu, H., Wang, B., Li, J., 2018. Retrospective and perspective of rice breeding in China. J. Genet. Genom. 45, 603–612.

Basri, M. S. M., Jais, N. M., Sulaiman, A., Nor, M. Z. M., Shah, N. N. A. K., Ariffin, S. H., 2020. Optimizing the processing factor and formulation of oat-based cookie dough for enhancement in stickiness and moisture content using response surface methodology and superimposition. Processes, 8(7), 797.

Brückner-Gühmann, M., Benthin, A., Drusch, S., 2019. Enrichment of yoghurt with oat protein fractions: Structure formation, textural properties and sensory evaluation. Food Hydrocolloids, 86, 146–153.

Capurso, C., 2021. Whole-grain intake in the mediterranean diet and a low protein to carbohydrates ratio can help to reduce mor-tality from cardiovascular disease, slow down the progression of aging, and to improve lifespan: A review. Nutrients, 13, 2540.

FAOSTAT, 2024. Oats trade-production. https://www.fao.org/faostat/en/#data/TCL (Accessed date: 02.10.2024)

Gell, G., Kovacs, K., Veres, G., Korponay-Szabo, I.R., Juhasz, A., 2017. Characterization of globulin storage proteins of a low prola-min cereal species in relation to celiac disease. Scientific Reports, 7, 39876.

Guo, X. N., Gao, F., Zhu, K. X., 2020. Effect of fresh egg white addition on the quality characteristics and protein aggregation of oat noodles. Food Chemistry, 330, Article 127319.

Joyce, S.A., Kamil, A., Fleige, L., Gahan, C.G.M., 2019. The Cholesterol-Lowering Effect of Oats and Oat Beta Glucan: Modes of Action and Potential Role of Bile Acids and the Microbiome. Frontier Nutition, 6, 171.

Kamal, N., Tsardakas Renhuldt, N., Bentzer, J., Gundlach, H., Haberer, G., Juhasz, A., 2022. The mosaic oat genome gives insights into a uniquely healthy cereal crop. Nature, 606, 113–119.

Karaman, R., Akgün, I., & Türkay, C. (2020). Alternative food source in human nutrition: Oat. Turkish Journal of Science and Engineering, 2(2), 78-85.

Khan, A., Ahmad, M., Ahmed, M.. Iftikhar Hussain, M., 2020. Rising atmospheric temperature impact on wheat and thermotolerance strategies. Plants, 10, 43.

Kim, I. S., Hwang, C. W., Yang, W. S., Kim, C. H., 2021a. Multiple antioxidative and bioactive molecules of oats (*Avena sativa* L.) in human health. Antioxidants, 10(9), 1454.

Kim, S., Kim, T., Jeong, Y., Park, S., Park, S., Lee, J., Yang, K., Jeong, J., Kim, C., 2021b. Synergistic effect of methyl jasmonate and abscisic acid co-treatment on avenanthramide production in germinating oats. International Journal Molecule Science, 22, 4779.

Klose, C.; Arendt, E.K., 2012. Proteins in oats; their synthesis and changes during germination: A review. Critical Revies on Food Science Nutrition, 52, 629–639.

Krattinger, S. G., Keller, B., 2022. Oat genome — sequence of a superfood. Nature Plants, 8, 602–603.

Kumar, L., Sehrawat, R., Kong, Y., 2021. Oat proteins: A perspective on functional properties. Lebensmittel-Wissenschaft and Technologie, 152, Article 112307.

Li, G.; Zhu, F., 2018. Quinoa starch: Structure, properties, and applications. Carbohydr. Polymer, 181, 851–861.

Maheshwari, G., Sowrirajan, S., Joseph, B., 2019. β-Glucan, a dietary fiber in effective prevention of lifestyle diseases—An insight. Bioact. Carbohydrate Dietary Fibre, 19, 100187.

Martín-Diana, A.B., García-Casas, M.J., Martínez-Villaluenga, C., Frías, J., Peñas, E., Rico, D., 2021. Wheat and oat brans as sources of polyphenol compounds for development of antioxidant nutraceutical ingredients. Foods , 10, 115.

Mel, R., Malalgoda, M., 2022. Oat protein as a novel protein ingredient: Structure, functionality, and factors impacting utilization. Cereal Chemistry, 99(1), 21–36.

Mert, I.D., 2020. The applications of microfluidization in cereals and cereal-based products: An overview. Critical Revies on. Food Science Nutrition, 60, 1007–1024.

Nogala-Kalucka, M., Kawka, A., Dwiecki, K., Siger, A., 2020. Evaluation of bioactive compounds in cereals. Study of wheat, barley, oat and selected grain products. Acta Sci. Pol. Technol. Aliment, 19, 405–423.

Paudel, D., Dhungana, B., Caffe, M., Krishnan, P., 2021. A review of health-beneficial properties of oats. Foods, 10(11), 2591.

Saccomanno, B., Chambers, A.H., Hayes, A., Mackay, I., McWilliam, S.C., Trafford, K., 2017. Starch granule morphology in oat endosperm. Journal of Cereal Science, 73, 46–54.

Sang, S., Chu, Y., 2017. Whole grain oats, more than just a fiber: Role of unique phytochemicals. Molecule Nutrition Food Resource, 61, 1600715.

Springmann, M., Clark, M., Mason-D'Croz, D., Wiebe, K., Bodirsky, B. L., Lassaletta, L., 2018. Options for keeping the food system within environmental limits. Nature, 562(7728), 519–525.

Sruthi, N. U., Rao, P. S., 2021. Effect of processing on storage stability of millet flour: A review. Trends in Food Science & Technology, 112, 58–74.

Strychar, R., Webster, F. H., Wood, P. J., 2011. World oat production, trade, and usage. *Oats:* Chemistry and Technology, 77-94.

Tieri, M., Ghelfi, F., Vitale, M., Vetrani, C., Marventano, S., Lafranconi, A. Godos, J., Titta, L., Gambera, A., Alonzo, E.,. 2020. Whole grain consumption and human health: An umbrella review of observational studies. Internetional Journal Food Science Nutrition, 71, 668–677.

TÜİK, 2024a. Crop Production Statistics. Oats. biruni.tuik.gov.tr/medas/?kn=92&locale=tr. (Accessed date: 10.10.2024).

TÜİK, 2024b. Foreign Trade Statistics, Foreign Trade According to SITC Rev4 Classification(SITC Rev4)-Oats.

biruni.tuik.gov.tr/disticaretapp/disticaret.zul?param1=3&param2=0&sitcrev=4&isicrev=0&sayac=5807. (Accessd date: 04.10.2024).

USDA, 2024a. United States Department of Agriculture Foreign Agricultural Service. Oats World as of December 2023. PSD Online (usda.gov) (Accessed date 16.09.2024)

USDA, 2024b. Production-Oats. U.S. Department of Agriculture. https://fas.usda.gov/data/production/commodity/0452000. (Accessed date: 25.10.2024)

Varma, P., Bhankharia, H., Bhatia, S., 2016. Oats: A Multi-Functional Grain. Journal Clinical Preview Cardiololgy, 5, 9–17

Wang, Y., Tuccillo, F., Lampi, A. M., Knaapila, A., Pulkkinen, M., Kariluoto, S., 2022. Flavor challenges in extruded plant-based meat alternatives: A review. Comprehensive Reviews in Food Science and Food Safety, 1–32.

Wilson, D.W., Nash, P., Buttar, H.S., Griffiths, K., Singh, R., De Meester, F., Horiuchi, R., Takahashi, T., 2017. The role of food antioxidants, benefits of functional foods, and influence of feeding habits on the health of the older person: An overview. Antioxidants , 6, 81.

Wing, R.A., Purugganan, M.D., Zhang, Q., 2018. The rice genome revolution: From an ancient grain to Green Super Rice. Natural Reviews. Genetic, 19, 505–517.

Yang, Z., Xie, C., Bao, Y., Liu, F., Wang, H., Wang, Y., 2023. Oat: Current state and challenges in plant-based food applications. Trends in Food Science & Technology, 134, 56-71.

Yuanqing, H.,Pengyao, Y., Yangyang, D., Min, C., Rui, G., Yuqing, D., Haihui, Z., Haile, M. 2021. The preparation, antioxidant activity evaluation, and iron-deficient anemic improvement of oat (*Avena sativa* L.) peptides–ferrous chelate. Frontier Nutrition, 8, 687133.

CHAPTER 7

CURRENT APPROCHES OF AGRICULTURAL BIODIVERTSITY IN TERMS OF CLIMATE CHANGE

Ceren Ayşe BAYRAM[1]*. Hasret GÜNEŞ[2]

[1] Adıyaman University Kahta Vocational School Department of Plant and Animal Production, Turkey cbayram@adiyaman.edu.tr - ORCID: 0000-0002-1570-273X (*Corresponding Author)
[2] Adıyaman University Faculty of Agriculture Department of Plant Protection, Turkey hasretgunes@adiyaman.edu.tr - ORCID: 0000-0003-3155-2695

Introduction

The concept of agricultural biodiversity is very important for the food industry, which is one of the current topics today with sustainable ecosystems. Current solutions and recommendations regarding biodiversity in agricultural production should be developed by taking into account both climate change and sustainable agricultural practices. The diversity of plants is increased, management changes in production systems. Thus, biodiversity makes it more resistant to climatic conditions and pests. Today's climate changes are increasing day by day and agricultural production systems are having to adapt to factors and environmental conditions such as sudden changes in weather events. Monoculture farming is based on growing only one type of a crop at one time on a same agricultural area. One of the most important known disadvantages of monoculture agriculture is that it reduces biodiversity and disrupts the balance in the ecosystem. Thus, integrating the concept of biodiversity into agricultural production areas can increase resilience in crop production. Sustainable agricultural practices such as agroforestry, crop rotation practices, use of cover crops and use of local plant species and varieties in crop production will improve the health of production areas. In addition, these practices will protect water resources and support agricultural productivity and safe food and safe life actions in the future. leads to production.

1. Definitions of Agroecosystem, Biodiversity, Agrobiodiversity and Climate Change

1.1. Agroecosystem

Agroecosystem means the combination of agriculture and ecosystem. An agroecosystem is a managed ecosystem that typically aligns with the area of a farm, where its ecosystem functions are appreciated by humans as agricultural products and services. Consequently, it is a collaborative creation of nature and humans (Anonymous, 2023a). Abiotic components of agro-ecosystems encompass climatic factors (temperature, relative humidity, wind and sun light) and soil (available water and other soil factors). Biotic factors consist of parasitic and herbivorous pests, competition between crops and other plants, and beneficial (symbiotic) relationships among organisms, such as those between belowground organisms and pollinators (Anonymous, 2024).

Agroecosystems are man-made, which lack the natural diversity but they are very stable and efficient ecosystems in terms of productivity.

1.2. Biodiversity

Last studies indicate that the concept of agricultural biodiversity was a significant topic from the 1970s to the present day. Biodiversity is an important environmental resource that encompasses all forms of life on Earth and must be protected and enhanced. Due to its significant services in areas such as climate, water and nutrient cycles, medicine, agriculture, industry, health, and biotechnology, biodiversity holds great importance for human life (Atik, et al., 2010). Biodiversity arises as a result of how living things naturally evolve and adapt. Biodiversity refers to the diversity and variability of living organisms, their interactions with one another and their environment, as well as the complex ecological structures they inhabit (Koyuncu, 2021). It functions at various levels and angles in farms, with the role of increasing stability and productivity, especially by increasing system resilience.

Biodiversity forms the foundation of ecosystem functioning (Harrop and Pritchard, 2011). Biodiversity can be considered at three main levels (Hayırsever Topçu, 2012). They are ecological diversity, organismal diversity, and genetic diversity each forming a hierarchy of elements (Heywood, 1995).

Ecological biodiversity is the combination of the ecosystem and functional diversity. Ecosystem diversity refers to the variety of ecosystems in a given area and the interactions between these ecosystems (Polat, 2017). Functional diversity is the range of roles that species play in an ecosystem and the diversity of ecological functions. Organismal diversity refers to the variety of living organisms within a particular ecosystem, region, or the entire planet (Slowinski and Guyer, 1989). It encompasses the full range of biological species, including animals, plants, fungi, bacteria, and other microorganisms. Organismal diversity is essential for ecosystem stability, resilience, and productivity. It provides ecosystem services such as pollination, nutrient cycling, and climate regulation, which are vital for human well-being and the health of the planet (Chorshanbiyev, 2024). Genetic diversity is the variety of genetic characteristics within a species and the distribution of these variations (Vellend and Geber, 2005).

Biodiversity, particularly in agricultural contexts, plays a vital role in environmental stability and productivity. It functions at several levels and aspects, particularly on farms, where its main role is to enhance system resilience, increasing stability and productivity. Despite challenges in measuring biodiversity trends, ongoing efforts aim to develop appropriate indicators for better conservation and management. These definitions highlight the breadth of the concept and its importance to ecosystems.

1.3. Agricultural Biodiversity

Agricultural biodiversity (agrobiodiversity), is a subset of biodiversity specific to the agricultural context. It encompasses the variety and variability among living organisms which are animals, plants, and microorganisms important to food and agriculture (Heywood, 1999), including the ecological complexes they are part of agricultural areas host unique biological diversity, which forms the basis of human activities (Clergue et al., 2009).

Agrobiodiversity includes units such as cultivars, pure lines, and strains, and habitats like agroecosystems (e.g., farmers' fields) (Heywood, 1999), which are not typically considered part of biological diversity. Agrobiodiversity is a result of deliberate human interaction with natural ecosystems, often leading to significant modifications. Agroecosystems, therefore, vary according to cultural and management systems (Heywood, 1999), in addition to their physical and biological components. Agrobiodiversity is essential as it is not merely a subset of biodiversity but an extension of it (Heywood, 1999). It includes elements that are not always accepted as part of biological diversity, such as artificial diversity and introduced species. However, some argue that introduced species cannot fulfill the full range of societal values that native biodiversity does (Angermeier, 1994). Agrobiodiversity arises from the interplay between the environment, genetic resources, and the management systems and practices employed by various culturally diverse populations. As a result, land and water resources are utilized in multiple ways for production. Agricultural biodiversity encompasses the diversity of genetic resources (varieties, breeds) and species used in the production of food, feed, fiber, fuel, and medicine. It also includes the diversity of non-harvested species that support production (soil microorganisms, predators, pollinators) and the diversity of species that support agricultural ecosystems in the broader environment (agricultural, rural, forest, and aquatic ecosystems) (FAO, 1999; Agnoletti and Santaro, 2022).

1.4. Climate Change

The United Nations Framework Convention on Climate Change defines "climate change" as a change in climate that is directly or indirectly attributed to human activities that alter the composition of the global atmosphere, in addition to natural climate variability observed over comparable time periods (Liu et al., 2021). When climate change issues in the world are examined, temperature increase and then the effects of greenhouse gases come first. Various climatic events such as drought, fire and excessive rainfall can be listed as the effects of climate change. According to the climate change and agriculture evaluation report published by the General Directorate of Agricultural Reform of the Ministry of Agriculture and Forestry (Anonymous, 2023), it was reported that the Mediterranean Basin, which is very important in terms of agricultural production, is among the regions expected to be affected by climate change in the world. Climate change threatens the survival of all living things in the ecosystem and becomes an ecological problem (Botkin et al., 2007, Meyerse and Bull, 2002). This issue, which must be taken precautions in agricultural production, also negatively affects biodiversity. Climate change threatens agricultural production through biotic and abiotic threats. For this study, biotic threats negatively affect biodiversity.

The aim of this study was to examine and compile national and international scientific studies conducted between 2004 and 2024 to investigate the impacts of climate change on agricultural biodiversity. The main sections used in preparing this study include: Global Issues Related to Biodiversity, Key Questions for Understanding the Use and Conservation of Agricultural Biodiversity, Dynamics of Biodiversity, Interactions Between Biodiversity Components, Farm Indicators of Diversity and Sustainability.

2. Dynamics of Biodiversity

Understanding biodiversity dynamics is crucial for effective conservation and management strategies. It enables scientists and policymakers to anticipate how ecosystems might react to disturbances, identify key factors driving biodiversity loss, and implement measures to bolster resilience and sustainability in natural systems. Biodiversity dynamics are influenced by both abiotic and biotic factors, including those related to species characteristics. Abiotic factors encompass the physical and chemical elements that impact organismal life and shape biological diversity within ecosystems. Key abiotic factors include climate, soil properties (such as pH, texture, and nutrient content), topography, the water cycle, and natural disasters, all of which play significant roles in shaping biodiversity dynamics.

Climate is particularly pivotal, influencing species diversity through factors like temperature, precipitation, humidity, and wind patterns. Climate change, in turn, can disrupt the distribution of species and populations across ecosystems, thereby altering biodiversity dynamics. Soil properties such as nutrient availability and drainage status also exert profound effects on plant distribution and community structure, further impacting biodiversity.

Additionally, topographic features like terrain shape and slope dictate microclimatic conditions and vegetation distribution, contributing to biodiversity variations across landscapes. Water availability, rainfall patterns, and the presence of aquatic habitats like rivers and lakes are critical abiotic factors influencing biodiversity in ecosystems. Natural disasters, including floods, fires, hurricanes, and other catastrophic events, can lead to significant ecosystem changes, further influencing biodiversity dynamics.

Biotic factors in biodiversity dynamics involve interspecific interactions, species diversity, genetic diversity, producers, competition, symbiosis, and predation. Interactions among species create ecological niches that support diverse species assemblages, contributing to overall biodiversity. High species diversity often indicates robust ecosystem health and resilience, allowing ecosystems to adapt to environmental shifts over time. Genetic variation within species enhances resilience to environmental stressors and facilitates evolutionary adaptation. Habibullah et al., (2022) stated in their study that a large number of species are under threat with climate change, and it is seen that we face significant risks in terms of food production and nutrition with the loss of these species.

3. Global Issues Related to Biodiversity

Examining global issues related to biodiversity, several factors affecting the diversity of life on Earth emerge. They are;

a) Extreme weather events due to climate change impact the distribution and populations of species in ecosystems.
b) Human activities such as urbanization and infrastructure development lead to habitat loss or degradation.
c) Introduction of invasive species disrupts ecosystems and can outcompete native species, reducing biodiversity.
d) Pollutants like chemicals, heavy metals, and plastics in agricultural areas have detrimental effects on wildlife and ecosystem health.
e) Changes in land use, such as mining and urban expansion, alter natural ecosystems and contribute to biodiversity loss.
f) Overexploitation of natural resources like water, forest products, and fisheries can lead to depletion and degradation of ecosystems.
g) Inadequate enforcement of environmental laws poses a significant challenge to biodiversity conservation.
h) Insufficient funding and resources for biodiversity conservation and management limit the effectiveness of conservation efforts.

Addressing these factors collectively and finding solutions are crucial for the conservation of biodiversity and the promotion of sustainable management practices.

4. Key Questions for Understanding the Use and Conservation of Agricultural Biodiversity

4.1. Why biodiversity matters?

Preserving agricultural diversity is crucial. Supporting and protecting people who provide inputs for evolution and ensuring the preservation of ecosystem capacity are essential steps. Maintaining variety among species is critical for agricultural development and biological resilience. Additionally, restoring agricultural lands and promoting farmer knowledge and experience are vital strategies.

4.2. What is needed to conserve good diversity?

If the goal is conservation, the objectives are as follows:

- Enhancing "in situ" conservation
- Increasing crop development and productivity
- Using a participatory approach

• Ensuring equitable access to knowledge, resources, technology, etc.
• Regulating property and compensation for farmers involved in the conservation of agricultural biodiversity

4.3. What is farmers' knowledge about genetic resources and their benefits for local communities?

Genetic resources are of great importance to local communities (Harrop and Pritchard, 2011). These resources can be used to increase the amount of nutrients and limit different climatic conditions by breaking various agreements and genetically diversifying plant varieties. Additionally, genetic diversity can be added to local cultures and their preservation, while economically it can support local economies, increasing the diversity of the market. The use of systems resistant to diseases and pests, the use of chemical pesticides, new management techniques, and adaptation to challenges such as climate change are also allowed. Therefore, the management and conservation of genetic change is critical for both management and production, as well as cultural, economic and sustainability.

4.4. How to encourage farmers' participation in genetic improvement for "in-situ" conservation?

Protecting the natural habitats of species is one of the best ways to protect biodiversity. National parks and natural protected areas are such places where the protection of naturally existing species parts is created and the protection of biodiversity is broken. division by preventing loss of genetic improvement in in situ conservation (Polat, 2017). This protection zone is designated as the primary duty in conventions regarding the protection of biodiversity.

5. Interactions Between Biodiversity Components

Plant and soil biodiversity is recognized to provide a wide range of ecological functions, from local to global (Liu et al., 2023). Microorganisms and plants may communicate in numerous ways, ranging from symbiosis to disease (Baldrian et al., 2023). But in all ecosystems on Earth, one of the most fundamental ways that plants and soil biodiversity interact involves the breakdown of litter, which controls the amount of carbon and plant nutrients that enter the soil and directly affects plant growth (García-Palacios et al., 2021).

When weighed against their equivalents above ground, subsurface communities typically support a much wider diversity of organisms. While the factors governing this diversity are still largely unknown, an increasing amount of recent studies have provided helpful information in understanding how these factors operate. Both direct and indirect trophic interactions, as well as those occurring within the food pyramid, have the potential to influence soil biodiversity. Large-bodied invertebrates in the soil can also affect the diversity of smaller organisms by altering the soil environment and promoting dispersal (Wardle, 2006).

According to Fierer and Lennon (2011), soils have a surprisingly high biodiversity, both in terms of species and extent. As of now, estimates suggest that only about 10% of the total species diversity is known for the majority of soil organism groups (Geisen et al., 2019). This great diversity of soil life can probably be explained by a high degree of functional specialization (Wurst and Van der Putten, 2007).

In some tropical forests, apicomplexans can account for up to 50% of all protists, leading to theories suggesting that protists play a significant role in controlling animal biodiversity. Soils also frequently contain phototrophic protists, which are important carbon fixers (Oliverio et al., 2020). Protists are the group in soil biodiversity that increases more with an increase in plant diversity. Protist populations are shaped by plants (Coleman et al., 2024). However different management techniques lead to species loss, desertification, increased greenhouse gas levels, and loss of biodiversity as a result of pollution, soil erosion, and urbanization, with negative consequences on ecosystem services and functions (Koch et al., 2013).

6. Effects of climate change on the level of biodiversity in soil

Soil, much more than the rest of the land, is essential for the functioning of the climate system. Almost 25 percent of greenhouse gas emissions come from land use, including agriculture and forestry (Köse, 2022). But several variables, such as changing land uses and climate change, are putting pressure on the world's soil. Soil is under pressure from temperature increases, prolonged droughts, and flood (Leal Filho, 2023). Drought and global warming have a detrimental impact on biodiversity as well as on the Earth. Since there is a positive relationship between biodiversity and ecosystem functioning, biodiversity loss has an impact on Earth's ecosystems (Gore et.al, 2021). Although soils support a significant proportion of the biodiversity that underpins important ecosystem processes, studies examining the link between soil biodiversity and ecological functioning affected by drivers of global change are still rare (Berlinches de Gea et al., 2023).

The ability of soil biodiversity to suppress disease-causing soil organisms and provide clean air, water, and food (Gore et.al, 2021; El Mujtar, 2019) is leading to greater recognition that soil biodiversity is good for human health. On the other hand, harmful land use practices and global climate change are having an impact on subsurface life forms. This is also reducing soil biodiversity and undermining some of these benefits (Pascual et al., 2015). Research supports the idea that soil biodiversity can be maintained and even partially restored (Gore et. al, 2021) through sustainable management practices. Although it has not received much attention, maintaining soil ecology and biodiversity through improved management techniques can benefit human health (Wall et al., 2015).

The dynamic interaction of bacteria, fungi, protozoa, insects, worms, and other invertebrates and vertebrates with the fauna and flora below the soil surface results in a network of biological activities known as soil biodiversity (Adhikari and Hartemink, 2016). Soil biodiversity enhances topsoil vegetation, as it breaks down plant wastes and strengthens soil resilience. According to Bach et al. (2020), the soil system probably accounts for more than 25 percent of total biodiversity. Moreover, high species diversity supports soil health and fertility. Critical ecosystem processes such as nutrient and carbon cycling additionally the management of pests and diseases are driven by soil biota (Geisen et al., 2019). As shown by Hu et al. (2016) and Hol et al. (2015) plant pathogenic fungal development and density are suppressed more strongly by a greater diversity of bacteria than by a lower diversity. Research indicates that the temporal stability and multifunctionality of ecological systems are improved by soil biodiversity (Wagg et al., 2021).

7. Plant health biodiversity relationship

The application of natural and sustainable soil management techniques is crucial for the conservation and enhancement of soil biodiversity functions. By identifying microbes that are likely beneficial for favorable soil species to thrive, it may be possible to produce microbial-based products that can directly impact soil communities to promote plant growth and health (Del Duca et al., 2024). Both the preservation of plant biodiversity and the creation of new opportunities for the application of sustainable agroecological techniques in crop production are imperative (Llauradó Maury et al., 2020).

Compared to diversified ecosystems, low-species ecosystems are generally better at producing biomass, breaking down plant matter, capturing high concentrations of nutrients, and remaining stable over time. The way ecosystems function and the interaction of biodiversity is often context-specific (Cappelli et al., 2022). Moreover, the supply of ecosystem services and functions, such as soil carbon storage, pollination, and pest and pathogen mitigation, are promoted and balanced by biodiversity (van der Plas, 2019). The biodiversity of agricultural systems were reduced, and they are vulnerable to pests and diseases in addition to stresses like drought (Liang et al., 2017; Savary et al., 2019). The relationship between soil microbial diversity and plant health was the subject of recent studies. Increasing research in biodiversity science has revealed the links between diversity and many aspects of ecological balance, as well as the importance of plant-soil interactions for sustainable agricultural methods (Manning et al., 2019; Thakur et al., 2021).

As the scale of time and space increases, biodiversity becomes more significant in ecosystem functioning (Isbell et al., 2018). Spontaneous fluctuations in environmental conditions affect stress levels, which is probably why the persistent character of diversity and complementary interactions become more important (Steudel et al., 2013). Plant health and the environmental conditions necessary for sustainable agriculture can both be significantly improved by biodiversity. Live microorganisms in soil support plant growth for crop diversity, biotechnological uses, and sustainable agriculture while also contributing to biodiversity (Rana et al., 2020).

8. Conclusion and Recommendation

Agricultural biodiversity is the cornerstone of sustainable agricultural systems, especially in the context of climate change. It encompasses the diversity and variability among living organisms (plants, animals, and microorganisms) that are critical to food production and ecosystem health. The increasing impacts of climate change, such as temperature fluctuations, extreme weather events, and changing precipitation patterns, pose significant challenges to agricultural biodiversity. Monoculture agriculture, where modern agricultural practices are intensively applied, reduces biodiversity and ecosystem resilience. Therefore, integrating biological diversity into agricultural systems, especially with local variety richness, is important for agricultural sustainability by increasing resilience to climate change parameters.

Biodiversity contributes to the stability and productivity of agricultural systems by improving soil health, water management, and pest control. Sustainable farming practices such as agroforestry, crop rotation, cover cropping, and the use of native plant varieties can support these benefits, making agricultural ecosystems more resilient to climate change. Genetic diversity in crops and livestock further supports adaptation to changing environmental conditions, reduces dependence on chemical inputs, and increases food security.

The development and management of climate-resilient agricultural systems are fundamental to supporting biodiversity. This includes diversified agricultural systems, genetic diversity, sustainable soil management, research, policy initiatives, and farmer participation. Sustainable soil management requires regular monitoring and support through organic practices, which improve soil structure and reduce reliance on chemical inputs.

Research and dissemination are vital for expanding communication between system applications and biodiversity, and for leveraging improved solutions. Investing in biodiversity research, training, and extension services for farmers on sustainable agricultural practices, biodiversity conservation, and climate adaptation solutions is essential. Corporate and institutional governance should include the development of policies and financial incentives for farmers who adopt biodiversity-friendly practices such as agroforestry and organic agriculture. It should also establish and conserve policies that serve as reservoirs for genetic diversity and ecosystems with high biodiversity.

Finally, departmental dissemination and information sharing are crucial for preserving biodiversity. Integrating traditional and local knowledge into biodiversity conservation strategies and encouraging collaborative networks between farmers, researchers, policy practitioners, and conservationists can enable knowledge sharing, resource pooling, and optimal exploitation. With these recommendations, agricultural systems can be made more resilient to climate change, leading to sustainable food production and the protection of biodiversity for future generations.

References

Adhikari, K., & Hartemink, A. E. (2016). Linking soils to ecosystem services—A global review. *Geoderma*, *262*, 101-111.

Agnoletti, M., & Santoro, A. (2022). Agricultural heritage systems and agrobiodiversity. *Biodiversity and Conservation*, *31*(10), 2231-2241.

Angermeier, P.I. 1994. Does biodiversity include artificial diversity? Conservation Biol. 8:600–602.

Anonymous, 2023. Tarım ve Orman Bakanlığı Tarım Reformu Genel Müdürlüğü, İklim değişikliği ve tarım değerlendirme raporu. https://www.tarimorman.gov.tr/trgm/belgeler/ıklım%20degısıklıgı%20ve%20tarım%20degerlendırme%20raporu.pdf

Anonymous, 2023 a. https://dicoagroecologie.fr/en/dictionnaire/agroecosystem/

Anonymous, 2024. https://www.coursehero.com/file/p3gp79l1/a-Deserts-ISO-90012015-T%C3%9CV-R-01-100-1934918-Republic-of-the-Philippines-CENTRAL/

Atik, A. D., Öztekin, M., & Erkoç, F. (2010). Biyoçeşitlilik ve Türkiye'deki Endemik Bitkilere Örnekler. Gazi University Journal of Gazi Educational Faculty (GUJGEF), 30(1).

Bach, E. M., Ramirez, K. S., Fraser, T. D., & Wall, D. H. (2020). Soil biodiversity integrates solutions for a sustainable future. *Sustainability*, *12*(7), 2662.

Baldrian, P., López-Mondéjar, R., & Kohout, P. (2023). Forest microbiome and global change. *Nature Reviews Microbiology*, *21*(8), 487-501.

Berlinches de Gea, A., Hautier, Y., & Geisen, S. (2023). Interactive effects of global change drivers as determinants of the link between soil biodiversity and ecosystem functioning. Global Change Biology, 29(2), 296-307.

Botkin DB, Saxe H, Araiyo MB, Betts R, Bradshaw RHW, Cedhagen T, Chesson P. Dawson TP, Etterson JR, Faith DP, Ferrier S, Guisan A, Hansen AS , Hilbert DW, Loehle C, Margules C, New M, Sobel MJ, Stockwell DRB. 2007. Forecasting the effects of global warming on biodiversity. Bioscience. 57:227-236.

Cappelli, S. L., Domeignoz-Horta, L. A., Loaiza, V., & Laine, A. L. (2022). Plant biodiversity promotes sustainable agriculture directly and via belowground effects. *Trends in Plant Science*, *27*(7), 674-687.

Chorshanbiyev, F., Abdullayev, O., Khalilova, K., Kodirova, M., Xalimjanov, A., Rakhimov, U., & Rakhimov, J. (2024). Study on Species and Age Structure of Forests: Optimization of Forest Stand Completeness. In E3S Web of Conferences (Vol. 497, p. 03015). EDP Sciences.

Clergue, B., Amiaud, B., Pervanchon, F., Lasserre-Joulin, F., Plantureux, S. (2009). Biodiversity: Function and Assessment in Agricultural Areas: A Review. In: Lichtfouse, E., Navarrete, M., Debaeke, P., Véronique, S., Alberola, C. (eds) Sustainable Agriculture. Springer, Dordrecht. https://doi.org/10.1007/978-90-481-2666-8_21

Coleman, D. C., Geisen, S., & Wall, D. H. (2024). Soil fauna: Occurrence, biodiversity, and roles in ecosystem function. In Soil microbiology, ecology and biochemistry (pp. 131-159). Elsevier.

Del Duca, S., Mocali, S., Vitali, F., Fabiani, A., Cucu, M. A., Valboa, G., ... & Landi, S. (2024). Impacts of Soil Management and Sustainable Plant Protection Strategies on Soil Biodiversity in a Sangiovese Vineyard. *Land*, *13*(5), 599.

El Mujtar, V., Muñoz, N., Mc Cormick, B. P., Pulleman, M., & Tittonell, P. (2019). Role and management of soil biodiversity for food security and nutrition; where do we stand?. Global food security, 20, 132-144.

FAO. 1999. Agricultural Biodiversity, Multifunctional Character of Agriculture and Land Conference, Background Paper 1. Maastricht, Netherlands. September 1999.

Fierer, N., & Lennon, J. T. (2011). The generation and maintenance of diversity in microbial communities. *American journal of botany*, *98*(3), 439-448.

García-Palacios, P., Crowther, T. W., Dacal, M., Hartley, I. P., Reinsch, S., Rinnan, R., ... & Bradford, M. A. (2021). Evidence for large microbial-mediated losses of soil carbon under anthropogenic warming. Nature Reviews Earth & Environment, 2(7), 507-517.

Geisen, S., Vaulot, D., Mahé, F., Lara, E., de Vargas, C., & Bass, D. (2019). A user guide to environmental protistology: primers, metabarcoding, sequencing, and analyses. *BioRxiv*, 850610.

Geisen, S., Wall, D. H., & van der Putten, W. H. (2019). Challenges and opportunities for soil biodiversity in the anthropocene. Current Biology, 29(19), R1036-R1044.

Gore, M. L., Lute, M. L., Ratsimbazafy, J. H., & Rajaonson, A. (2016). Local perspectives on environmental insecurity and its influence on illegal biodiversity exploitation. PloS One, 11(4), e0150337.

Habibullah, M. S., Din, B. H., Tan, S. H., & Zahid, H. (2022). Impact of climate change on biodiversity loss: global evidence. *Environmental Science and Pollution Research*, *29*(1), 1073-1086.

Harrop, S. R., & Pritchard, D. J. (2011). A hard instrument goes soft: The implications of the Convention on Biological Diversity's current trajectory. *Global environmental change*, *21*(2), 474-480.

HAYIRSEVER TOPÇU, F., 2012. Biyolojik Çeşitlilik Özleşmesi: Müzakereden Uygulamaya. Marmara Avrupa Araştırmaları Dergisi, 20 (1): 57-97.

Heywood, V. (1999). Trends In agricultural biodiversity. *Perspectives on new crops and new uses*, 2-14.

Hol, W. G., Garbeva, P., Hordijk, C., Hundscheid, M. P., Gunnewiek, P. J. K., Van Agtmaal, M., ... & De Boer, W. (2015). Non-random species loss in bacterial communities reduces antifungal volatile production. Ecology, 96(8), 2042-2048.

Hu, J., Wei, Z., Friman, V. P., Gu, S. H., Wang, X. F., Eisenhauer, N., ... & Jousset, A. (2016). Probiotic diversity enhances rhizosphere microbiome function and plant disease suppression. MBio, 7(6), 10-1128.

Isbell, F., Cowles, J., Dee, L. E., Loreau, M., Reich, P. B., Gonzalez, A., ... & Schmid, B. (2018). Quantifying effects of biodiversity on ecosystem functioning across times and places. Ecology Letters, 21(6), 763-778.

Koch, A., McBratney, A., Adams, M., Field, D., Hill, R., Crawford, J., ... & Zimmermann, M. (2013). Soil security: solving the global soil crisis. Global Policy, 4(4), 434-441.

Koyuncu, O. (2021). Contributions To Vascular Flora Of Karaağaç (Gediz-Kütahya-Turkey) Village And Its Environs. International Journal of Natural and Engineering Sciences, 15(3), 101–111. Retrieved from https://ijnes.org/index.php/ijnes/article/view/658

Köse, S. (2022). İKlim Değişikliğiyle Mücadelede Yerel Yönetimlerin Rolü ve Yeşil Yeni Düzen (Master's thesis, Marmara Universitesi (Turkey)).

Leal Filho, W., Nagy, G. J., Setti, A. F. F., Sharifi, A., Donkor, F. K., Batista, K., & Djekic, I. (2023). Handling the impacts of climate change on soil biodiversity. *Science of The Total Environment*, *869*, 161671.

Liang, X. Z., Wu, Y., Chambers, R. G., Schmoldt, D. L., Gao, W., Liu, C., ... & Kennedy, J. A. (2017). Determining climate effects on US total agricultural productivity. Proceedings of the National Academy of Sciences, 114(12), E2285-E2292.

Liu, S., Plaza, C., Ochoa-Hueso, R., Trivedi, C., Wang, J., Trivedi, P., ... & Delgado-Baquerizo, M. (2023). Litter and soil biodiversity jointly drive ecosystem functions. Global Change Biology, 29(22), 6276-6285.

Liu, W. Y., Huang, Y. H., & Lin, C. C. (2021). Analyzing direct and indirect effects of climate change trend on the number of visitors toward national forest parks: A case of Taiwan. *Journal of Hospitality and Tourism Management*, *48*, 10-22.

Llauradó Maury, G., Méndez Rodríguez, D., Hendrix, S., Escalona Arranz, J. C., Fung Boix, Y., Pacheco, A. O., ... & Cuypers, A. (2020). Antioxidants in plants: A valorization potential emphasizing the need for the conservation of plant biodiversity in Cuba. *Antioxidants*, *9*(11), 1048.

Manning, P., Loos, J., Barnes, A. D., Batáry, P., Bianchi, F. J., Buchmann, N., ... & Tscharntke, T. (2019). Transferring biodiversity-ecosystem function research to the management of ‘real-world’ecosystems. In Advances in ecological research (Vol. 61, pp. 323-356). Academic Press.

Meyers LA, Bull JJ. 2002. Fighting change with change; adaptive variation in an uncertain world. Trends in Ecology & Evolution. 17:551-557.

Oliverio, A. M., Geisen, S., Delgado-Baquerizo, M., Maestre, F. T., Turner, B. L., & Fierer, N. (2020). The global-scale distributions of soil protists and their contributions to belowground systems. Science advances, 6(4), eaax8787.

Pascual, U., Termansen, M., Hedlund, K., Brussaard, L., Faber, J. H., Foudi, S., ... & Jørgensen, S. L. (2015). On the value of soil biodiversity and ecosystem services. *Ecosystem Services*, *15*, 11-18.

Polat, N. (2017). Biyoçeşitlilik ve önemi. *Terme’nin biyoçeşitlilik ve doğal ortam özellikleri içinde*, 3-14.

Rana, K. L., Kour, D., Kaur, T., Devi, R., Yadav, A. N., Yadav, N., ... & Saxena, A. K. (2020). Endophytic microbes: biodiversity, plant growth-promoting mechanisms and potential applications for agricultural sustainability. Antonie Van Leeuwenhoek, 113, 1075-1107.

Savary, S., Willocquet, L., Pethybridge, S. J., Esker, P., McRoberts, N., & Nelson, A. (2019). The global burden of pathogens and pests on major food crops. Nature ecology & evolution, 3(3), 430-439.

Slowinski, J. B., & Guyer, C. (1989). Testing the stochasticity of patterns of organismal diversity: an improved null model. *The American Naturalist*, *134*(6), 907-921.

Steudel, B., Hector, A., Friedl, T., Löfke, C., Lorenz, M., Wesche, M., & Kessler, M. (2013). Biodiversity effects on ecosystem functioning change along environmental stress gradients. Ecology Letters, 16(4), 568-569.

Thakur, M. P., van der Putten, W. H., Wilschut, R. A., Veen, G. C., Kardol, P., van Ruijven, J., ... & Bezemer, T. M. (2021). Plant–soil feedbacks and temporal dynamics of plant diversity–productivity relationships. Trends in Ecology & Evolution, 36(7), 651-661.

Van der Plas, F. (2019). Biodiversity and ecosystem functioning in naturally assembled communities. *Biological Reviews*, *94*(4), 1220-1245.

Vellend, M., & Geber, M. A. (2005). Connections between species diversity and genetic diversity. *Ecology letters*, *8*(7), 767-781.

Wagg, C., Hautier, Y., Pellkofer, S., Banerjee, S., Schmid, B., & van der Heijden, M. G. (2021). Diversity and asynchrony in soil microbial communities stabilizes ecosystem functioning. elife, 10, e62813.

Wall, D. H., Nielsen, U. N., & Six, J. (2015). Soil biodiversity and human health. *Nature*, *528*(7580), 69-76.

Wardle, D. A. (2006). The influence of biotic interactions on soil biodiversity. Ecology letters, 9(7), 870-886.

Wurst, S., & van der Putten, W. H. (2007). Root herbivore identity matters in plant-mediated interactions between root and shoot herbivores. *Basic and Applied Ecology*, *8*(6), 491-499.

CHAPTER 8

SUSTAINABLE RURAL DEVELOPMENT THROUGH THE IMPLEMENTATION OF THE SMART VILLAGE MODEL: A CASE STUDY IN EASTERN MEDITERRANEAN REGION OF TÜRKİYE

Yavuzkan PAKSOY[1*]. Nazan KOLUMAN (DARCAN)[2]
Melis ÇELİK GÜNEY[3]

[1] Necmettin Erbakan University; Kemal Akman Vocational College, Department of Plant and Animal Production, Konya-Türkiye; yavuzkan7@gmail.com, ORCID: 0000-0002-0935-7693
[2] Cukurova University, Agricultural Faculty, Department of Animal Science, Adana-Türkiye; nazankoluman@gmail.com, ORCID: 0000-0002-1388-2298
[3] Cukurova University, Agricultural Faculty, Department of Animal Science, Adana-Türkiye; melisguneycelik@gmail.com, ORCID: 0000-0002-6825-6884
*corresponding Yavuzkan PAKSOY, Necmettin Erbakan University; Kemal Akman Vocational College, Department of Plant and Animal Production, Konya-Türkiye; yavuzkan7@gmail.com

Introduction

Rural development is essential for improving the quality of life and economic well-being in sparsely populated areas. Traditionally, it has focused on the intensive use of land and natural resources, particularly in agriculture and forestry. However, rural areas face challenges such as poverty, insufficient educational infrastructure, and limited technological accessibility, necessitating innovative solutions. Migration from rural to urban areas poses a significant challenge to sustainable development and environmental health. Immediate action towards sustainability is needed to address climate change and ensure a prosperous future. The European Union reports annual economic losses of around 12 billion euros due to climate-related impacts, potentially rising to 170 billion euros with a 3°C global temperature increase (European Commission, 2021).

The digital transformation adds complexity to creating adaptable, energy-efficient, and resilient communities. While "smartness" can help achieve the United Nations' Sustainable Development Goals (SDGs), challenges like economic growth commitment and governance issues may hinder progress (Jones et al., 2017). Moreover, smart infrastructure is vulnerable to climate change, highlighting the need to integrate climate resilience into smart planning tools for effective governance (Moraci et al., 2018).People migrate to cities seeking better living standards, economic opportunities, and access to services and technology. However, urban areas also face challenges like higher crime rates and poor air quality (OECD, 2020). Governments worldwide are integrating Smart City concepts to promote economic growth, social inclusivity, and sustainability in urban centers.

The rise of smart villages may inadvertently drive urban migration, particularly among the youth seeking better education and economic prospects, potentially causing a new brain drain (Winters, 2011). The COVID-19 pandemic has shifted societal norms, emphasizing remote work and social distancing, which may influence new migration patterns from cities to rural areas (European Commission, 2020).

Climate change, digitalization, and migration are central to sustainable development, affecting both urban and rural areas. Improved connectivity between these areas is crucial. The Smart Village concept addresses rural disparities by leveraging digital and telecommunications technologies, fostering local business support, and enhancing residents' well-being (European Commission, 2017). This aligns with Smart City initiatives in urban settings.

The Smart Village concept, as articulated by Aziiza and Sustano (2020), represents a paradigm shift, leveraging rural cultural heritage for development and re-evaluating cultural diversity in rural planning. Bonenberg et al. (2020) emphasize the competitive advantage of aligning smart village strategies with rural heritage and cultural diversity. Smart City development, according to Mohanty (2017), transcends bureaucratic efficiency, aiming to cultivate communities through ICT infrastructure. Smart Cities optimize urban services, enhance competitiveness, and ensure sustainability through smart infrastructure, buildings, transportation, energy, healthcare, technology, governance, education, and citizen engagement. Guzal (2018) notes that technology in smart villages extends beyond connectivity to include infrastructure investment, business development, human resources, and community building. This integration of technology is crucial for the resilience and effectiveness of the smart village model. Inspired by Smart City principles, the Smart Village model seeks to incorporate advanced technologies into remote regions (Abinash and Josephine, 2018). The goal is to address challenges through ICT and Geographic Information System (GIS) methodologies (Ahlawat, 2017).

This study aims to contribute to the discourse by presenting development models focused on animal and plant production and proposing production and marketing initiatives through women's cooperatives within the smart attraction villages model. The geographical focus is on rural areas in Turkey's Eastern Mediterranean region, enriching the broader context of rural development and smart city initiatives.

Material and Methods

The study was carried out in the rural expanse of the Feke district, situated at a distance of 118 km from the Adana city centre. The altitude of the area is 620 meters. Positioned in the north-eastern sector of the Mediterranean Region, it spans latitudes 36-37° North and longitudes 34-35° East. The overall average elevation stands at 620 meters. According to the latest data from the Turkish Statistical Institute (TUIK) in 2023, the total population of Feke village is recorded as 12,919 people (Figure 1). The research methodology involved conducting interviews with the leaders of 48 villages for a comprehensive analysis.

Feke stands out as the most economically disadvantaged district within the Adana province, marked by a poverty level of 26.3. Notably, it is characterized by a high rate of migration. The challenging topography, featuring rugged and mountainous terrain, directs the predominant agricultural focus towards livestock farming. Animal husbandry, often conducted through small-scale operations centered around sheep and goats, plays a dominant role in the region. Beyond its economic significance, livestock farming serves as a vital source of income for local families and fulfils their protein requirements.

In the forested villages, animal grazing in forest grasslands represents a production method requiring minimal input throughout the day. Additionally, the region boasts natural attractions, with the passage of a branch of the Seyhan River offering opportunities for nature sports such as rafting and trekking. The natural characteristics of the area also position it as a potential hub for ecological farming and eco-tourism.

To be able to define the region and establish a model, we first conducted a SWOT analysis (Anonymous, 2024). A SWOT analysis is a technique that allows you to examine in detail the positive and negative factors related to the work you are undertaking or the project you are initiating, helping you gain an advanced strategic understanding. SWOT consists of the initials of strengths, weaknesses, opportunities and threats. This analysis aims to compare these factors in a detailed manner, resulting in the creation of plans and strategies for the future.

In essence, a SWOT analysis involves placing strengths, weaknesses, opportunities and threats into a four-column table, providing a comprehensive overview of your organization's current state and aiding in the formulation of future plans and strategies.

Shifting the focus to the smart village concept, its infrastructure encompasses physical elements, information and communication technology (ICT) and various services. The physical infrastructure constitutes the tangible, structural entity of the smart village, encompassing buildings, roads, railway tracks, power supply lines and water supply systems. Typically considered the non-smart component of intelligent urban areas, the physical infrastructure provides the foundational framework. In order to establish a smart village model in the region, a survey consisting of 32 questions was conducted in 48 villages to identify opportunities and threats in economic, social and environmental aspects. Subsequently, a model was developed, taking into account the distance of each village to the district center. The survey questions focused on various topics, including the infrastructure of the villages, accessibility, the presence of natural areas, environmental advantages and disadvantages, the existence of endemic plant species and their marketability. Additionally, aspects such as women's participation in the economy, business models suitable for cooperatives, policy implications, migration and expectations were explored. Furthermore, an analysis was conducted on the usage of Information and Communication Technology (ICT), which is a crucial component of the smart village model. A comprehensive search using the keyword "smart village" in SCOPUS revealed literature on 1429 topics. After analyzing these sources, a focused examination was conducted on 25 relevant pieces of literature, marking the completion of the preliminary study on the subject. Subsequently, these documents underwent thorough scrutiny and analysis, focusing on key aspects such as definitions, models and application examples. Through a meticulous process, 19 journal documents emerged as pertinent for the final analysis. Employing the purpose-oriented mapping method, along with a detailed examination of models and application examples, these selected documents were subjected to rigorous scrutiny. The outcomes were then substantiated through meticulous validation processes, ensuring the relevancy and accuracy of the findings in the formulation of the smart village model proposed in this research (Abinash and Josephine, 2018; Ahlawat, 2017; Aziiza and Susanto, 2020; Bonenberg et al., 2020; Fernandez and Peek, 2023; Guzel, 2018; Holmes and Thomas, 2015; Jones et al., 2017; Paniagua, 2022; Paniagua, 2023a; Paniagua, 2023b; Paniagua, 2023c; Patel, 2018; Rahmawati et al., 2018; Rwakihembo et al., 2024; Singh and Zhang and Zhang, 2020; Smith et al., 2023; Viswanadham and Vedula, 2010; Winters, 2011).

The structuring of the model in this study involved several key approaches, starting with an initial interview, an extensive review of relevant literature and an examination of supporting regulations. The literature review was meticulously conducted, focusing on selecting journals that aligned with the model's definition and its practical applications. Following this, an in-depth analysis of local regulations pertaining to the research subject, namely Feke district, was undertaken. For a visual representation of the research methodology, please refer to Figure 2 (Aziiza and Susanto, 2020).

Smart villages embody characteristics such as sustainability, quality of life (QoL), urbanization and smartness. Sustainability considerations encompass various aspects including infrastructure, governance, energy, climate change, pollution, waste management and social, economic, and health-related issues. Quality of life metrics assess the emotional and financial well-being of citizens, while urbanization encompasses technological advancement, infrastructure development, governance efficiency and economic vitality. Smartness, viewed as a goal to enhance economic, social and environmental standards, includes dimensions such as a smart economy, smart people, smart governance, smart mobility and smart living. When re-evaluating the connections between rural and urban areas, the focus should shift towards creating inclusive and participatory networks that prioritize collaboration over hierarchy. This approach ensures that the entire region benefits from both the digital transformation and the move towards environmental sustainability. Figure 3 below presents a simplified yet conceivable representation of these intelligent and sustainable connections (Fernandez and Peek, 2023).

The Smart Village concept has been conceptualized as a transformative paradigm for the development of rural areas in India. This innovative framework was introduced by (Viswanadham and Vedula, 2010) as documented in their seminal work, "Design of Smart Village". The Smart Village model, conceptualized, delineates a systematic ecosystem that encompasses four pivotal dimensions: 1) Institution, 2) Resources, 3) Service Chain and 4) Service Delivery Technologies & Mechanisms (Viswanadham and Vedula, 2010). This structurally comprehensive framework provides a holistic foundation for addressing the intricacies of rural development. In tandem with this model, the Smart Village paradigm identifies seven key focus areas-economy, ICT, people, governance, environment, living and energy-underscoring a nuanced approach to sustainable development (Mishbah et al., 2018). This delineation highlights the multifaceted nature of the challenges and opportunities intrinsic to the smart village development agenda.

The genesis of the Smart Village concept can be traced to the heightened awareness of Information and Communications Technology (ICT), serving as a strategic lever for local economic development (Singh and Patel, 2018). This recognition underscores the instrumental role of technology as a catalyst for transformative change within rural contexts.

Secondary data were sourced from the Ministry of Agriculture and Forest, as well as the Turkish Statistical Institute (TUIK) database for the year 2023.

Approval from the local ethics committee is not deemed necessary for this research.

Results and Discussion

1. SWOT Analyses of Feke District

Following interviews with the headmen of 48 villages, data pertaining to the sustainability of the current regional situation and the outcomes derived from the identification of SWOT analyses have been compiled and are presented in Table 1. Upon scrutinizing the tables outlining internal and external factors influencing the resilience of sustainable livelihoods to climate change and considering existing research, the strategies for enhancing resilience in the SWOT matrix were formulated. The SWOT matrix stands as a critical tool aiding managers in devising four distinct strategy categories: offensive (SO - strengths-opportunities), adaptive (WO - weaknesses-opportunities), conservative (ST - strengths-threats) and defensive (WT - weaknesses-threats) as indicated by (Tohidimoghadam et al., 2023). In the context of the sustainable smart village model in Feke, the matrix presented in Table 1 delineates proposed strategies to address the challenges and capitalize on the opportunities identified in the study.

1.1. Strengths

The region exhibits various strengths that contribute to its overall potential and appeal. Firstly, it possesses significant agricultural potential with ample suitable land and natural resources, providing an opportunity to diversify agricultural products through the adoption of modern farming techniques. Additionally, the area boasts captivating natural beauty and touristic potential, featuring scenic landscapes and abundant natural attractions, positioning it as an attractive destination for agro-tourism. Moreover, the strong social cohesion and adherence to traditional lifestyle practices in the community enhance its cultural appeal, making it enticing for cultural tourism. The availability of diverse water sources and natural wealth further strengthens the region's environmental sustainability potential through responsible resource management. Rich traditional livestock practices, coupled with a diverse range of local livestock breeds, contribute to the region's strength in sustainable and locally focused livestock production. Overall, these strengths create a foundation for the region to capitalize on its agricultural, cultural and environmental assets.

1.2. Weaknesses

The region also faces several challenges and weaknesses that need to be addressed for comprehensive development. Firstly, there is a sensitivity to climate change, posing risks to agricultural activities. A deficiency in technological infrastructure, including limited access to technology, hampers innovation and productivity in various sectors. Insufficient employment opportunities and a lack of essential infrastructure present obstacles to community development, demanding focused efforts in these areas. The tendency of youth migration raises concerns about demographic sustainability, emphasizing the need for incentives to retain the younger population. Challenges associated with input costs and marketing, coupled with uncertainties in the market, require strategic efforts for cost-effectiveness and the development of flexible marketing strategies. Education and skill deficiencies also pose challenges, necessitating training programs to enhance knowledge and skills across various sectors. Addressing these weaknesses is crucial to creating a foundation for sustainable growth and resilience in the face of evolving economic and environmental conditions. There are also specific limitations that may hinder the transition of villages towards smart solutions. One major limitation is the lack of a systematic approach for implementing smart solutions at the municipal level. Often, each municipality independently coordinates its smart development efforts. Decisions regarding the adoption of smart technology and non-technological smart solutions (Hlaváček et al., 2022) are frequently based on considerations of whether they will meet expectations, be financially feasible, and gain acceptance from the local community (Hýllová and Slach, 2018).

1.3. Opportunities

The region presents several promising opportunities that can be leveraged for sustainable development and growth. Firstly, there is the potential for sustainable agriculture and access to organic markets, aligning with the global trend towards environmentally friendly and organic products. Exploring alternative energy sources offers the prospect of environmental sustainability and reduced dependency on traditional energy forms. The region's natural beauty and cultural richness can be utilized to enhance touristic attraction and interaction, contributing to the local economy. Community solidarity and social projects can strengthen bonds within the community and provide avenues for participation in meaningful initiatives. Marketing of local products, including livestock items, creates opportunities for economic growth and local brand recognition. Hosting touristic and cultural events can further boost the region's economy by attracting visitors and fostering cultural exchange. Agriculture-tourism collaboration, through initiatives such as farm tours and interactive experiences, can create diversified income sources. Conservation of local livestock breeds is an opportunity to preserve unique genetic resources and promote sustainable farming practices. Protection of Designation of Origin (PDO) trading for local products can enhance the uniqueness and quality of goods, potentially boosting the local economy. Celebrating and preserving the community's cultural heritage and habituation can attract cultural tourism, contributing to the region's identity. Religious faith can be a unifying force, fostering social cohesion and resilience during challenges. Lastly, the tradition of the family management system provides an opportunity for the sustainable transfer of businesses within families, contributing to the long-term economic stability of the region. Capitalizing on these opportunities requires strategic planning and collaboration across various sectors for holistic and sustainable development.

1.4. Threats

The region faces several potential threats that could impact its development and stability. Firstly, natural disasters and environmental risks pose a significant challenge, requiring preparedness and mitigation measures to safeguard the community and its resources. Market and trade uncertainties introduce risks related to economic activities, demanding adaptable strategies to navigate fluctuating market conditions. Global economic changes may impact the region's economic resilience, necessitating efforts to enhance financial stability. Water scarcity and resource insufficiencies pose threats to agricultural practices and overall sustainability, emphasizing the need for efficient resource management. Market price fluctuations can disrupt economic activities, requiring resilience-building measures to mitigate the impact on local businesses. Livestock diseases and health risks present challenges to the agricultural sector, emphasizing the importance of robust veterinary health measures. Investment and financial challenges may hinder economic growth, requiring strategic financial planning and support. Environmental pressures and regulations, if not addressed thoughtfully, can pose challenges to businesses and practices that are not aligned with sustainability goals. Finally, the lack of employment opportunities and essential infrastructure may contribute to demographic challenges, necessitating focused efforts in these areas for community well-being and retention. Addressing these threats requires a comprehensive and strategic approach, involving collaboration across sectors and proactive measures to build resilience against potential risks (Tohidimoghadam et al., 2023). Reported that to develop a sustainable smart village model in rural areas, it is necessary to design and implement practical programs, based on the assets and experiences of rural regions, to increase resilience against potential crises. In this context, the first essential step is to accurately recognize and understand the dimensions of villagers' sensitivity and resistance, thereby enhancing their threshold of tolerance and flexibility. In our study, a SWOT analysis was conducted to assess the resilience of rural areas against climate change. Similarly, in our research, the region's weaknesses, areas for improvement and strengths were identified not only in the context of the climate crisis but also in economic, social and environmental aspects. This is crucial for the development of a smart village model.

A comprehensive and integrated approach is needed, encompassing economic, social and environmental dimensions. Initiatives focused on sustainable agriculture, tourism, cultural preservation, technological advancement and community engagement can collectively contribute to the overall well-being and resilience of the community. The identified threats should guide strategic planning to implement measures that enhance the community's strengths while addressing its vulnerabilities (Dhraief et al., 2019). This analysis underscores the need for strategic planning that leverages opportunities, addresses threats and capitalizes on the unique strengths of the community. A comprehensive approach should consider the integration of economic, social and environmental factors to foster sustainable development while mitigating potential challenges as similar (Dhraief et al., 2019).

The migration of rural inhabitants is intricately tied to a convergence of social, economic and environmental challenges, including issues such as poverty, underdevelopment and the exacerbating impacts of climate change. These challenges collectively contribute to a cascade of interconnected problems, exacerbated by factors like inadequate basic infrastructure, the underdevelopment of agricultural lands and industrial facilities and the absence of favorable marketing conditions in rural areas. The culmination of these issues compels individuals to seek alternative living arrangements.

Addressing the complexity of this situation requires the adoption of a strategic planning approach that delves into the intricate interplay between existing socio-economic and environmental dynamics. This involves not only addressing immediate problems but also recognizing and harnessing the intrinsic values embedded within local systems. To cultivate sustainable solutions, the planning process must establish achievable goals, acknowledging the diverse and interconnected nature of the challenges at hand. An integrated and holistic strategy becomes paramount, recognizing the necessity for comprehensive measures to counteract the driving forces behind rural migration and promote the development of resilient, thriving communities.

The formulation of rural growth dynamics serves as a reflection of the existing conditions and development challenges within rural areas. Solving these problems requires a comprehensive understanding of sustainable growth and empirical research points to key factors influencing its successful implementation. Chief among these factors is the ability of communities to coexist, exhibit group behavior, engage in collective actions, demonstrate tolerance and build and strengthen social relationships. The effective utilization of these factors translates into the creation of social capital, thereby enhancing competitiveness, increasing income and improving the overall living conditions of rural inhabitants. In essence, the development of a robust system within rural areas holds the potential to positively transform communities by fostering social cohesion, economic prosperity and sustainable living condition.

2.Smart Village: Component and Characteristics

In light of the determined literature and questionnaires, the main headings for the "Smart Village" arrangement in the mountainous and rural areas of the Feke district in Adana are provided below:

2.1. Smart Infrastructure, Internet of Things (IoT), Smart Public Services and Enhanced Living in the Smart Village

The foundation of the Smart Village rests upon the integration of Smart Infrastructure, Internet of Things (IoT) and Smart Public Services, aimed at creating a forward-thinking rural living model. The primary focus is on bolstering information collection and sharing capabilities through sensors and connected devices, with an initial emphasis on enhancing electricity, road and telecommunication-based internet infrastructure. This foundational step is crucial, serving as the bedrock upon which subsequent services can be planned and implemented effectively.

Collaborating with a technology-providing company, the design of the Smart Village aims to craft a next-generation rural living experience that seamlessly blends traditional farming methods with cutting-edge technology. This holistic approach envisions an attractive center where the benefits of digitization enhance efficiency not only in daily life but also in agricultural production, forming the core of the smart village model. The integration of advanced technologies, particularly IoT applications, plays a pivotal role in revolutionizing agricultural practices.

In the Smart Village model, IoT applications extend beyond agriculture to encompass critical aspects of community life. Automation features, such as intelligent irrigation based on meteorological conditions, greenhouse automation and fertilizer management automation, optimize farming processes. Simultaneously, smart technologies enhance the lives of farmers by automating feed production, barn management, poultry facilities, frost protection, milk production, beekeeping and even incorporating health-related tools like pedometers and early warning systems. This not only streamlines agricultural operations but also contributes significantly to environmental cleanliness and the preservation of public health.

Expanding beyond agriculture, the Smart Village incorporates a comprehensive range of public services to ensure the well-being and convenience of its residents. This includes smart healthcare facilities, educational institutions equipped with advanced technologies, social spaces for community interaction, shopping facilities and streamlined governance services. Hospitals and schools are integrated with IoT applications to enhance efficiency and provide a higher standard of service. Social areas are designed to foster community engagement and well-being and shopping facilities embrace digitization for a more convenient and connected experience. Governance services leverage smart technologies to enhance accessibility and streamline administrative processes, making citizenship processes more accessible to residents.

2.1.1. Sustainable Practices & Biodiversity Conservation: In the Smart Village, a strong emphasis is placed on sustainable practices and the conservation of biodiversity. This includes promoting organic farming methods, preserving natural habitats and implementing measures to safeguard the diversity of plant and animal species. By adopting eco-friendly agricultural practices, the Smart Village aims to maintain a harmonious balance between human activities and the surrounding ecosystem, contributing to the overall well-being of the environment.

2.1.2. Community Awareness & Education: To enhance environmental consciousness and promote responsible practices, the Smart Village actively engages in community awareness and education programs. Workshops, training sessions and informational campaigns are conducted to educate residents, farmers and stakeholders about the importance of sustainable agriculture, waste reduction and the overall ecological impact of their activities. By fostering a sense of environmental responsibility, the Smart Village strives to create a community that actively participates in preserving the environment.

2.1.3. Innovative Technologies for Waste Management: The Smart Village leverages innovative technologies for efficient waste management, incorporating advanced methods such as smart waste sorting and recycling systems. Through these technologies, the village ensures that waste materials are sorted at the source, facilitating the recycling process and minimizing the environmental footprint. This forward-thinking approach aligns with the overarching goal of creating a cleaner and more sustainable environment within the Smart Village.

2.1.4. Eco-Friendly Infrastructure Development: In line with the commitment to environmental sustainability, the Smart Village focuses on developing eco-friendly infrastructure. This includes energy-efficient buildings, green spaces and the integration of renewable energy sources. By incorporating eco-friendly elements into the village's infrastructure, the Smart Village not only reduces its ecological impact but also provides a model for sustainable development that can be replicated in other regions.

2.1.5. Monitoring and Evaluation Systems: To continuously assess and improve its environmental initiatives, the Smart Village implements robust monitoring and evaluation systems. These systems track key environmental indicators, allowing for data-driven decision-making and the adjustment of strategies to maximize positive environmental outcomes. Regular assessments ensure that the Smart Village remains adaptive and responsive to emerging environmental challenges.

2.2. Smart Transportation in Smart Village

Smart Transportation is a cornerstone of the Smart Village's commitment to creating a sustainable, efficient and technologically advanced mobility system. With a focus on reducing environmental impact and enhancing overall accessibility, the Smart Village employs innovative technologies to transform transportation within the community.

2.2.1. Electric and Autonomous Vehicles: The Smart Village embraces electric and autonomous vehicles as key components of its smart transportation network. Electric vehicles contribute to a significant reduction in greenhouse gas emissions, promoting cleaner air and a healthier environment. Autonomous vehicles enhance safety and efficiency, providing residents with convenient and reliable transportation options.

2.2.2. Integrated Mobility Platforms: An integrated mobility platform serves as the backbone of the Smart Village's transportation system. This platform seamlessly connects various modes of transportation, including buses, electric shuttles and bike-sharing services. Residents can access real-time information, plan routes and make transportation decisions through user-friendly mobile applications.

2.2.3. Smart Traffic Management: Utilizing advanced sensors and data analytics, the implementation of smart traffic management systems in Smart Villages represents a significant step forward in urban planning and infrastructure development. By optimizing traffic flow, reducing congestion and enhancing road safety, these systems not only improve the daily commute for residents but also contribute to a more sustainable and liveable environment. The integration of adaptive traffic signals and real-time traffic updates further underscores the commitment to efficiency and innovation, ultimately enhancing the overall quality of life in Smart Villages.

2.2.4. Last-Mile Connectivity: Addressing the challenge of last-mile connectivity, the Smart Village introduces solutions such as electric scooters and bike-sharing programs. These options provide residents with convenient and sustainable transportation choices for short-distance travel, contributing to reduced traffic congestion and improved air quality.

2.2.5. Environmental Sustainability: Smart Transportation in the Smart Village prioritizes environmental sustainability by promoting eco-friendly modes of transport. The integration of electric vehicles and the encouragement of cycling and walking not only reduce carbon emissions but also foster a healthier living environment.

2.2.6. Community Engagement for Sustainable Mobility: Community engagement plays a vital role in promoting sustainable mobility practices. The Smart Village conducts awareness campaigns, educational programs and incentives to encourage residents to choose eco-friendly transportation options. By fostering a culture of responsible mobility, the community actively contributes to the overall sustainability goals of the Smart Village.

2.2.7. Accessibility and Inclusivity: Smart Transportation ensures accessibility for all residents, including individuals with mobility challenges. The village adopts universal design principles, making transportation infrastructure inclusive and accommodating for everyone. This commitment to inclusivity enhances the quality of life for all community members.

2.2.8. Collaboration with Technology Providers: The Smart Village collaborates with technology providers, transportation experts and local authorities to stay at the forefront of smart transportation innovations. Partnerships facilitate the integration of cutting-edge technologies, ensuring that the transportation system remains adaptive, efficient and aligned with evolving mobility trends.

2.3. Economic Empowerment, Fight Against Poverty, and Improved Human Resource Capacity in the Smart Village

The Smart Village is committed to fostering economic empowerment, combating poverty and enhancing the capacity of its human resources, thereby creating a robust foundation for sustainable community development.

2.3.1. Economic Empowerment & Poverty Alleviation: A central tenet of the Smart Village's vision is to empower its residents economically and address the challenges of poverty. Through strategic initiatives, the village aims to create a conducive environment for entrepreneurship, small-scale businesses and agro-tourism. By promoting economic diversity and providing support for local ventures, the Smart Village seeks to generate employment opportunities and increase income levels, contributing significantly to poverty alleviation.

2.3.2. Agricultural Innovation for Economic Growth: At the heart of the economic empowerment strategy lies agricultural innovation. The Smart Village leverages cutting-edge technologies, including precision farming and smart agricultural practices, to enhance productivity and the quality of agricultural outputs. The integration of value chains and the promotion of organic farming contribute not only to economic growth but also to the creation of sustainable livelihoods for farmers, breaking the cycle of poverty.

2.3.3. Improving Human Resource Capacity: Recognizing the pivotal role of its human capital, the Smart Village places a strong emphasis on enhancing the skills and capacities of its residents. This involves investing in education and vocational training programs tailored to the needs of the community. By equipping individuals with relevant skills, the Smart Village not only increases employability but also nurtures a workforce capable of driving innovation and contributing to the overall economic development of the region.

2.3.4. Technology-Driven Skill Development: In line with the smart living ethos, the Smart Village embraces technology-driven skill development programs. These initiatives leverage online learning platforms, workshops and skill-sharing networks to empower residents with digital literacy and specialized skills. By ensuring that the workforce is adept at utilizing modern technologies, the Smart Village positions its residents to thrive in a rapidly evolving economic landscape.

2.3.5. Collaboration for Economic Growth: Collaboration forms a cornerstone of the Smart Village's approach to economic empowerment. Partnerships with local businesses, governmental agencies and non-profit organizations facilitate the implementation of impactful economic development projects. By fostering collaboration, the Smart Village creates a network of support that accelerates economic growth, job creation and poverty reduction.

2.3.6. Inclusive Economic Policies: The Smart Village implements inclusive economic policies that prioritize the inclusion of marginalized communities and individuals. Special attention is given to gender equality, ensuring that economic opportunities are accessible to all residents. Through these inclusive policies, the Smart Village seeks to create an equitable economic landscape that benefits the entire community.

2.3.7. Women's Cooperative-Based Business Model: Recognizing the vital role of women in community development, the Smart Village introduces a dedicated initiative centered around women's cooperative-based business models. This initiative aims to empower women by providing them with opportunities to actively participate in economic activities, fostering entrepreneurship and promoting gender inclusivity. By establishing and supporting women's cooperatives, the Smart Village not only contributes to economic growth but also addresses gender equality concerns, creating a more balanced and inclusive economic environment. Through collaborative efforts and targeted support, this innovative approach strives to enhance the economic landscape and social fabric of the Smart Village.

While some services are slated for central provision, mayors operating at the municipal level must craft local strategies to ensure effective governance and transparency in municipal management. Conversations with mayors have underscored their acknowledgment of the positive impacts and cost savings linked to incorporating smart technologies into public infrastructure. These technologies encompass areas such as intelligent lighting, energy management, and leveraging the Internet of Things (IoT) for maintaining municipally managed buildings (Philip and Williams, 2019). Municipalities in rural areas are also grappling with a notable challenge-their diminishing competitiveness relative to suburban and urban regions. Addressing this challenge may entail fostering innovation and entrepreneurship (Hardilla and Muladi, 2016), potentially through endeavors like technology incubators, bolstering support for startups and small enterprises (Kovács and Zoltán, 2017) and exploring local development prospects.

2. Suggested Smart Village Framework

The proposed Smart Village Framework for Feke district in Adana envisions transforming rural communities using advanced technologies (Figure 4). Key elements include IoT for precision farming, robust infrastructure, smart building solutions, and advanced agricultural technologies to boost productivity and resilience. In Smart Living, the framework enhances access to public facilities, collaborates with NGOs, strengthens village institutions, integrates educational and health services, promotes digital literacy, cultural activities, and mobility. Smart Governance focuses on integrating central and local governance, using digital participation platforms, e-Government services, and digital infrastructure to foster informed citizenry. Smart Economy promotes local business models, agro-tourism, smart farming, processing, marketing opportunities, and smart retail solutions for economic sustainability. Smart Environment advocates sustainable resource use, zero pollution, smart energy solutions, food security, and climate adaptation with eco-friendly farming techniques. This comprehensive framework aims to create a thriving, resilient rural ecosystem through technology, collaboration, and sustainability.

However, as Paniagua (2023) suggests, the universal nature of innovation may present challenges when applied to local materials, requiring adaptable solutions to address emerging social needs. In some European nations like Spain, rural transformations focus more on material rejuvenation than population changes. In sparsely populated areas, the emphasis is on restoring homes for new virtual experiences and social movements. The research highlights the importance of material renewal in creating adaptable, smart rural environments that periodically thrive with renewed urban-rural dynamics.

Conclusion

The Smart Village initiative aims to improve living standards, promote environmental sustainability, and create a model for advanced rural communities. The trend of reverse migration to rural areas, driven by COVID-19 lockdowns and natural disasters, presents an opportunity for smart village development. Key innovations include advanced agricultural technologies, renewable energy, diverse non-agricultural activities (agro-tourism, bioenergy, cultural events), and a robust ICT network.

Acknowledgment

The authors extend sincere appreciation to all the respondents whose invaluable contributions were pivotal to the success of this research. Their willingness to share information and dedicate precious time greatly enriched the study. Additionally, the support of the Scientific Research Coordination Unit at Çukurova University, under project number FBA-2021-13011, is gratefully acknowledged.

Funding

This study was financed by Scientific Research Coordination Unit at Cukurova University (Project No: FBA-2021-13011).

Author Contributions

Conceptualization, N.K.; writing-original draft preparation, N.K. and Y.P.; writing-review and editing, N.K.; Y.P. and M.Ç.G. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article.

Conflicts of Interest

The authors declare no conflict of interest.

References

Abinash, P. and J. Josephine (2018). Internet of Things (IoT) for Smart Village (International Conference on Advancements in Engineering, Technology and Sciences (ICAETS)), 813– 819.

Ahlawat, J. (2017). Smart Villages, Information Communication Technology and Geographical Information System (International Journal of Current Trends in Science and Technology), 7(8): 20232–20238.

Anonymous (2024). SWOT Analyses. https://www.economist.com. acc date: 02/02/2024

Aziiza, A.A. and T.D. Susanto (2020). The Smart Village Model for Rural Area (Case Study: Banyuwangi Regency). IOP Conf. Ser.: Mater. Sci. Eng. 722 012011.

Bonenberg, W., Qi, L. Zhou, M. and X. Wei (2020). Smart Village as a Model of Sustainable Development. Case Study of Wielkopolska Region in Poland doi: 10.1007/978-3-030-20151-7_22. In book: Advances in Human Factors in Architecture, Sustainable Urban Planning and Infrastructure.

Dhraief, MZ, Dhehibi, B., Daly Hassen, H., Zlaoui, M., Khatoui, C., Jemni, S. and M. Rekik (2019). Livelihoods strategies and household resilience to food insecurity: a case study from rural Tunisia. Sustainability 11(3): 907. https://doi.org/10.3390/su11030907.

European Commission (2017). EU Action for Smart Villages; Secretariat-General of the European Commission: Brussels, Belgium.

European Commission (2020). European Commission Report on the Impact of Demographic Change; Secretariat-General of the European Commission: Brussels, Belgium.

European Commission (2021). Forging a Climate-Resilient Europe-The New EU Strategy on Adaptation to Climate Change; Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions. COM, 82 Final; European Commission: Brussels, Belgium.

Fernandez, C.G. and D. Peek (2023). Connecting the Smart Village: A Switch towards Smart and Sustainable Rural-Urban Linkages in Spain, Land 2023, 12(4): 822, https://doi.org/10.3390/land12040822.

Guzal, D. (2018). Intelligent Development of the Countryside – The Concept of Smart Villages: Assumptions, Possibilities and Implementation Limitations, Economic and Regional Studies (Sciendo) 11(3): 32–49.

Hardilla, D. and N. Muladi (2016). Xmart village maturity assessment model. In: Uslu, F. (Ed.), 2016. Proceedings of 3rd International Conference on Social Sciences and Humanities (SOCIOINT 2016). Istanbul, Ocerint, 29–36.

Hillis, K. (1999). Digital Sensations: Space, Identity, and Embodiment in Virtual Reality; Elecronic Mediations Series, 1; University of Minnesota Press: Minneapolis, MN, USA, 1999.

Hlaváček, P., Hruška, V., Barták, M., Domín, M., Hartych, M., Holcová, D., Kopáček, M.,

Kopácková, L., Lupták, L., Olšová, P., Raška, P., Skalník, V. and R. Vaibar (2022). Koncept Chytreho Venkova. Jan Evangelista Purkyne University, Ústínad Labem. 373–389. https://doi.org/10.15201/hungeobull.68.4.4.

Holmes, J. and M. Thomas (2015). Introducing the Smart Villages Concept (International Journal on Green Growth and Development vol. 1) no. 2, 151–154.

Hýllová, L. and O. Slach (2018). The Smart City is landing. On the geography of policy mobility. GeoScape 12(2): 124–133. https://doi.org/10.2478/geosc-2018-0013.

Jones, P., Wynn, M., Hillier, D. and Comfort, D. (2017). He Sustainable Development Goals and Information and Communication Technologies. Indones. J. Sustain. Account. Manag. 1, 1–15.

Kovács, J.K. and E.S. Zoltán (2017). Rural enterprise hub supporting rural entrepreneurship and innovation – case studies from Hungary. Eur. Countrys. 9(3): 473–485.

https:// doi.org/10.1515/euco-2017-0028.

Mishbah, M.B., Purwandri, B., and D.I. Sensuse (2018). Systematic Review and Meta-Analysis of Proposed Smart Village Conceptual Model: Objectives, Strategies, Dimensions, and Foundation 2018 International Conference on Information Technology Systems and Innovation (ICITSI), 127–133.

Mohanty, S.P. (2017). Everything You Wanted to Know About Smart Cities (USA). IEEE Consumer Electronics Magazine.

Moraci, F., Errigo, MF, Fazia, C., Burgio, G. and S. Foresta (2018). Making Less Vulnerable Cities: Resilience as a New Paradigm of Smart Planning. Sustainability, 10, 755.

Organisation for Economic Co-operation and Development (OECD) (2020). European Commission (EC). Highlights-Cities in the World: A New Perspective on Urbanisation; OECD Centre for Entrepreneurship, SMEs, Regions and Cities: Paris, France, 2020.

Paniagua, A. (2022). The Histories of New (Geo) Politics of Smart Villages Communities in a Global World. A Contribution to Geographical Debate. In Smart Cities and Smart Communities: Empowering Citizens through Intelligent Technologies; Patnaik, S., Sen, S., Ghosh, S., Eds.; Springer Nature: Singapore, 2022; 69–79.

Paniagua, A. (2023a). Smart and Novelty Villages as the Quality Place of Virtuality. Sustainability 2023, 15, 11702. https://doi.org/10.3390/su15151170.

Paniagua, A. (2023b). Some considerations for research on smart and novelty villages in global rural areas. Agric. Rural. Stud. 2023, 1, 1.

Paniagua, A. (2023c). Conceptualizing New Materialism in Geographical Studies of the Rural Realm. Land 2023, 12, 225.

Philip, L., and F. Williams (2019). Healthy ageing in smart villages? Observations from the field. Eur. Countrys. 11(4): 616–633. https://doi.org/10.2478/euco-2019-0034.

Rahmawati, D., Sulistyarso, H., Ariastita, P.G., Yusuf, M., and D.A. Paramasatya (2018). Smart Kampung for Surabaya Smart City: Criteria Redefined (IOP Conf. Series: Earth and Environmental Science 202), 1–7.

Rwakihembo, G.D.M, Faggioni, F., and M.V. Rossi (2024). The Dimensions of Digital Sustainable Development in Smart Villages: A Case Study Analysis. In: Visvizi, A., Troisi, O., Corvello, V. (eds) Research and Innovation Forum 2023. RIIFORUM 2023. Springer Proceedings in Complexity. Springer, Cham. https://doi.org/10.1007/978-3-031-44721-1_13.

Smith, H., Medero, G.M., De Narvaez, S.C., and W.C. Mera (2023). Exploring the relevance of ‘smart city’ approaches to low-income communities in Medellín, Colombia. GeoJournal 88, 17–38.

Singh A., Patel, M. (2018). Achieving Inclusive Development Through Smart Village (PDPU Journal of Energy and Management 3 (1): 37–43.

Tohidimoghadam A., PourSaeed, A., Bijani M., and R. Eshraghi Saman (2023). Rural sustainable livelihood resilience to climate change: A strategic analysis. Environmental and Sustainability Indicators 20:100292, 1-9.

TUIK, (2023). https://www.tuik.gov.tr/ acc. Date; 20/09/2023.

Viswanadham, N., Vedula S. (2010). Design of Smart Villages, Indian School of Business, Book, (ISB: The Centre for Global Logistics and Manufacturing Strategies), 22, India.

Winters, J.V. (2011). Why are Smart Cities Growing? Who Moves and Who Stays. J. Reg. Sci., 51, 253–270.

Zhang, X.J., and Z.G. Zhang (2020). How Do Smart Villages Become a Way to Achieve Sustainable Development in Rural Areas? Smart Village Planning and Practices in China. Sustainability 2020, 12, 10510.

CHAPTER 9

NUTRITIONAL CONTENT, VITAMIN, MINERAL, FATTY ACID AND AMINO ACID COMPOSITION OF BLACK CUMIN GROWN IN DIFFERENT REGIONS

Res. Assist. Ramazan AYAŞ[1]

[1] Necmettin Erbakan University, Faculty of Veterinary Medicine, Department of Animal Nutrition and Nutritional Diseases, Konya, Türkiye, ramazanayassci@gmail.com, ORCID No:0000-0002-3400-243X

INTRODUCTION

Black cumin (Nigella Sativa L.) has been cultivated in many parts of the world since ancient times. It is especially widely grown in the Eastern Mediterranean, the Balkans, North Africa, the Middle East, and India (Çakmakçı & Çakır, 2011). Black Cumin is mostly produced in India, Türkiye, Bangladesh, China, Indonesia and Pakistan (Dessie et al., 2020). It is grown in provinces such as Afyon, Konya, and Burdur in Türkiye. In Türkiye, 10,089 tons of black cumin was produced in 2022 and 5,386 tons in 2023 (TÜİK, 2023). Black cumin can be used for different purposes. While it is mostly used as a spice in Türkiye, it is used in the cosmetics, food and pharmaceutical sectors in some countries (Seçmen et al., 2000). There are many studies on the effects of black cumin on human health (Hannan et al., 2021). Black cumin and substances obtained from black cumin are used to treat many diseases. It has been reported that black cumin has an antioxidant effect and that the substance called Thymoquinone from black cumin reduces superoxide, hydrogen peroxide, nitric oxide and oxidative stress (Cobourne-Duval et al., 2016). It has been reported that black cumin strengthens memory when used in Alzheimer's disease (Abulfadl et al., 2018). It has been reported to reduce oxidative stress and increase dopamine levels when used in Parkinson's disease (Ebrahimi et al., 2017). When used in ischemic stroke, it has been reported that black cumin reduces cerebral edema and infarction (Soleimannejad et al., 2017). It has been reported to increase neuron density when used in traumatic brain injuries (Gülşen et al., 2016). It has been reported to reduce depression when used for anxiety and depression (Beheshti et al., 2018). It has been reported to increase anticonvulsant activity when used in epilepsy (Bepari et al., 2016). It has been reported that when used in Schizophrenia, black cumin increases dopamine levels and has an anti-amnesic effect. Black cumin can be used in some toxicity cases. For example, it has been reported that black cumin is used in Acrylamide and arsenic toxicity (Firdaus et al., 2019; Tabeshpour et al., 2020). Black cumin is used in many cancer treatments. For example, when used in breast cancer, it has been reported that it reduces the reproduction of tumor cells and increases apoptosis (Dastjerdi et al., 2016). It has been reported to reduce cell proliferation and prevent metastasis when used in colon cancer (Chen et al., 2017; Hsu et al., 2017). It has been reported that it has an inhibitory effect on proliferation and metastasis when used in bladder cancer (Zhang et al., 2020).

Black cumin can be used in the treatment of obesity, diabetes, and hypertension. It has been reported that when used against obesity, it reduces serum cholesterol, LDL and triglyceride concentrations and increases HDL concentrations (Ahmad et al., 2017). It has been reported to reduce blood glucose levels when used against diabetes (Widodo et al., 2016), It has been reported that it reduces cholesterol levels, systolic and diastolic blood pressure when used against hypertension (Hussain et al., 2017). Black cumin has a liver protective effect. It has been reported that it reduces ALT, AST and ALP concentrations when used in ibuprofen-induced hepatotoxicity (Husna et al., 2017). Black Cumin has a lung protective effect. It has been reported that when used in lung fibrosis, it reduces the Inflammatory index and fibrosis score (Abidi et al., 2017). Black cumin has a stomach-protective effect. It has been reported that when used in gastric ulcers, it reduces acid secretion and accelerates ulcer healing (Aleem et al., 2020;Manjegowda et al., 2017). The use of black cumin has a positive effect on reproductive performance. Reproductive organs are susceptible to oxidative stress (Hannan et al., 2021). The reduction of oxidative stress by black cumin increases reproductive performance. Black cumin affects wound healing. It has been reported to have an antimicrobial effect and increases epithelization when used in treating skin injuries (Okasha et al., 2018;Kumandaş et al., 2020). Black cumin affects bone development and healing of bone damage (Ezirganli et al., 2016).

As mentioned above, black cumin seed is used successfully in the treatment of many diseases. The reason why black cumin is so effective against diseases is due to the substances it contains. The nutritional content of black cumin varies depending on the type of black cumin, the region where it is grown, the harvest season, the amount of rainfall and fertilization. The distribution of studies on the nutritional content of black cumin used in the current study by country is given in Table 1 and Figure 1.

Table1: Origin of black cumin used in studies

Origin of Black Cumin	Number of Studies
Türkiye	5
Saudi Arabia	4
Egyp	4
Iran	4
Pakistan	3
Tunisia	3
India	3
Bangladesh	2
Morocco	2
Syria	1
Jordan	1
China	1
Algeria	1
Iraq	1
Germany	1
Malaysia	1
Ethiopia	1

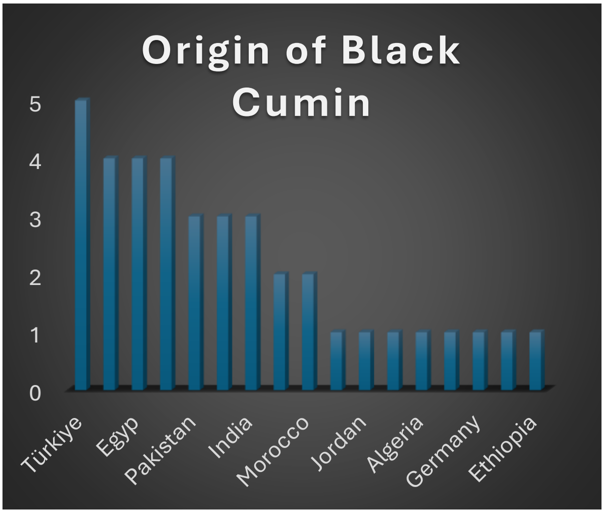
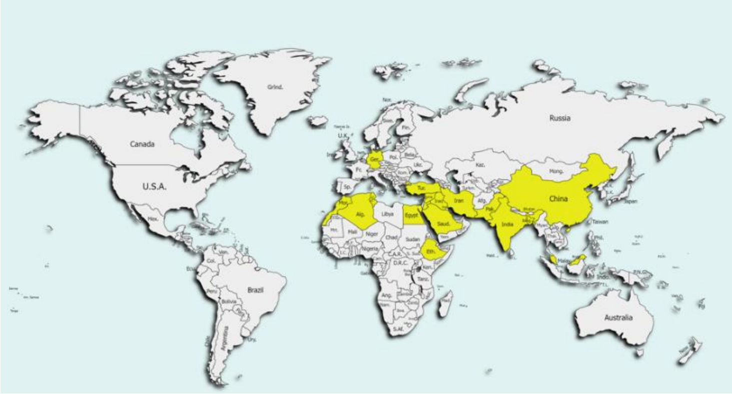


Figure 1: Origin of black cumin used in studies



1. Nutritional Content Of Black Cumin

The nutritional content of black cumin varies depending on factors such as the type of black cumin, the region where it is grown, the harvest season, the amount of rainfall and fertilization. There are many studies on this subject. In the literature review, it was understood that the nutritional content of black cumin samples taken from different regions was different. 22 different data were obtained regarding the dry matter, protein, fat, starch, crude fiber, dietary fiber, ash and total carbohydrate levels of black cumin. The results are shown in Table 2.

Table 2: Black Cumin Nutritional Content (%)

Country	Study	Dry Matter	Proteın	Fat	Starch	Crude Fıber	Ash	Total Carbohydrate
Average	Current study	94,05	22,10	33,53	8,78	6,82	4,98	30,68
İndia	(Shah & Ray, 2003)	93,00	23,00	39,00	15,00	5,40	4,30	-
Saudi Arabia	(Al-Jassir, 1992)	95.6	20.9	38,2	-	7,9	4.4	31.9
Middle East	(Babayan et al., 1978)	94.48	21.26	35,49	-	5.5	3.77	33.96
Pakistan	(Sultan et al., 2009)	93.54	22.80	31.16	-	6.03	4.20	-
Egyp	(Al-Gaby, 1998)	-	16,1	31,4	-	7,05	5,55	-
Pakistan	(Ashraf et al., 2006)	-	19.69	32.70	-	-	5.13	-
Türkiye	(Nergiz & Ötleş, 1993)	93.6	20,2	32		6,6	4	37,4
Tunisia	(Cheikh-Rouhou et al., 2007)	91,35	26,7	28,48	-	-	4,86	40,00
İran	(Cheikh-Rouhou et al., 2007)	95,92	22,6	40,35	-	-	4,41	32,70
Türkiye	(Takruri & Dameh, 1998)	96,17	21,6	40,60	-	8,40	4,50	24,90
China	(Albakry et al., 2022)	94,98	21,07	39,02	-	6,01	3,02	25,86
Egypt	(Atta, 2003)	93	20,8	34,8			3,7	33,7
Pakistan	(Iqbal et al., 2013)	94,11	22,1	31,7	-	-	5,07	25,47
Bangladesh	(Kabir et al., 2019)	92,88	20,3	45,4	-	-	7,39	19,70
Bangladesh	(Mamun & Absar, 2018)	94,5	18,09	32,74	2,55	6,39	4,69	29,18
Saudi Arabia	(Al-Jasass & Al-Jasser, 2012)	97,45	20.61	31.95		10.37	4.51	30.0
Malaysia	(Mohammed et al., 2016)	93,33	19.19	32.26			6.82	35.04
Iran	(Solati et al., 2014)	95,01	23.07	31.72			5.29	34.91
Iran	(Khoddami et al., 2011)	94,6	20.02	37.33			6.72	30.53
Türkiye	(Dandik & Aksoy, 1992)	94,5	21.30	35.50			3.80	34.00
Ethiopia	(Mariod et al., 2012)	91,1	26,1	29,1		8,1	5,7	23,1
Syria	(Mariod et al., 2012)	92,8	25,8	13,2		5,8	4,3	43,7

2. Mineral Content of Black Cumin

There are many studies on the mineral content of black cumin. In the literature review, it was understood that the mineral content of black cumin samples taken from different regions was different. The studies on this subject are shown in Table 3, Table 4 and Table 5.

Table 3: Mineral content of black cumin (ppm)

Country	Study	K	P	Na	Fe	Zn	Ca	Mg	Mn	Cu	Ni	Cr
Average	Current Study	5380	3266	682	189,8	38,7	2531	1383	36,6	14,8	46,5	15,3
Saudi Arabia	(Al-Jassir, 1992)	76	18	7,5	1,5	0,6	0,4	0,3	0,2	0,2	-	-
Pakistan	(Sultan et al., 2009)	8080	5430	176	97,00	62,30	5700	2650	85,3	26	-	-
Pakistan	(Ashraf et al., 2006)	6750	3781,2	4125	104	44,3	2809	1381	125,3	31,7	91,5	28,2
Türkiye	(Vatansev et al., 2013)	-			117,3	41,4	0	0	28,5	30,2	1,4	2,5
Tunus	(Cheikh-Rouhou et al., 2007)	783	48,9	20,8	8,65	8,04	572	235	4,4	1,65	-	-
İran	(Cheikh-Rouhou et al., 2007)	708	51,9	18,5	9,42	7,03	564	260	3,37	1,5	-	-
İndia	(Takruri & Dameh, 1998)	5517	5043	550	102	62	1932	-	-	24	-	-
Jordanian	(Takruri & Dameh, 1998)	4423	5023	419	107	59	1867	-	-	18	-	-
Suriye	(Takruri & Dameh, 1998)	1946	5221	535	91	66	1946	-	-	15	-	-
Türkiye	(Takruri & Dameh, 1998)	1544	5267	440	130	56	1544	-	-	18	-	-
Çin	(Albakry et al., 2022)	-	3580	276	9,5	4,3	8105	2768	-	2,5	-	-
Türkiye	(Nergiz & Ötleş, 1993)	11800	-	853	575		1880		-		-	-
Bangladesh	(Kabir et al., 2019)	14983	4815	448	426	67	3667	3552	31	15	-	-
Bangladesh	(Mamun & Absar, 2018)	5100	915	1000	418	-	5793	2183	-	-	-	-
Saudi Arabia	(Al-Jasass & Al-Jasser, 2012)	8230	-	-	650	25	1600	800	15	9	-	-

Tablo 4: Black cumin vitamin content (ppm)

Country	**Study**	**α-Tacopherol**	**δ-Tacopherol**	**Retinol**	**Vitamin D2**	**Vitamin K1**	**Vitamin K2**
Average	Current study	13,1875	35,285	0,24	1,38	1,85	2,15
Türkiye	(Vatansev et al., 2013)	10,19	2,28	0,18	1,38	1,85	2,15
Egypt	(Saleh, 2014)	10,41	6,95	0,21	-	-	-
India	(Saleh, 2014)	11,39	6,47	0,27	-	-	-
Saudi Arabia	(Saleh, 2014)	9,52	6,09	0,2	-	-	-
Syria	(Saleh, 2014)	5,65	2,76	0,42	-	-	-
Sudan	(Saleh, 2014)	7,04	2,26	0,15	-	-	-

Tablo 5: Black cumin mineral content (ppm)

Country	**Study**	**Thiamine**	**Niacin**	**Pyridoxine**	**Folate**
Average	Current Study	13,66	48,0275	7,378	440,084
İndia	(Takruri & Dameh, 1998)	13	48	4	700
Jordanian	(Takruri & Dameh, 1998)	14	33	15	400
Suriye	(Takruri & Dameh, 1998)	18	-	6	630
Türkiye	(Takruri & Dameh, 1998)	15	48	4	470
Turkiye	(Nergiz & Ötleş, 1993)	8,3	63,11	7,89	0,42

3. Black Cumin Fatty Acid Composition

There are many studies on the fatty acid composition of black cumin. In the literature review, it was understood that the fatty acid composition of black cumin samples taken from different regions was different. The studies on this subject are shown in Table 6.

Tablo 6: fatty acid composition of black cumin (%)

Country	Study	Saturated fatty acids	Unsaturated fatty acids	Myristic	Myristoleic	Palmitic
				C14:0	C14:1	C16:0
Average	Current study	17,59	82,03	1,06	1,34	12,89
Saudi Arabia	(Al-Jassir, 1992)	16,3	83,7	0,9	0,18	11,9
Pakistan	(Sultan et al., 2009)	16,64	83,36	0,42	2,49	12,07
Iran	(Nickavar et al., 2003)			0,5		12,5
Pakistan	(Ashraf et al., 2006)	-	-	0,29	-	14,77
Türkiye	(Nergiz & Ötleş, 1993)	-	-	1,2	-	11,4
Türkiye	(Vatansev et al., 2013)	6,5	93,5	-	-	5,4
Tunisia	(Cheikh-Rouhou et al., 2007)	22,7	77,3	0,35	-	17,2
Iran	(Cheikh-Rouhou et al., 2007)	25,5	74,5			
Egypt	(Houghton et al., 1995)	15,18	84,82	0,21		12,07
India	(Houghton et al., 1995)	16,57	83,43	0,2		13,15
Syria	(Houghton et al., 1995)	17,66	82,34	0,22		14,64
Bangladesh	(Kabir et al., 2019)	16	84	0,23		13,1
Iraq	(Kaskoos, 2011)	15,1	79,9	0,16		8,51
Tunisia	(Bourgou et al., 2010)	22	78	0,4		14,8
Iran	(Khonche et al., 2019)	-	-	0,63	-	20,27
Germany	(Ramadan & Mörsel, 2002)	-	-	-	-	13
Egypt	(Atta, 2003)			9,8		9,9
Saudi Arabia	(Al-Jasass & Al-Jasser, 2012)	-	-	1	-	10,5
Iran	(Solati et al., 2014)	15,75	84,25	-	-	13,49
Iran	(Khoddami et al., 2011)	20,5	79,5	1,3		15
Morocco	(Gharby et al., 2015)	16,8	82,9	1		13,1
Morocco	(Asdadi et al., 2014)	16,8	82,9	1		13,1
Tunisia	(HAMROUNI-SELLAMI et al., 2008)	24,1	75,9	3,2		12,2
Ethiopia	(Mariod et al., 2012)	17,4	82,6	0,4		13,9
Syria	(Mariod et al., 2012)	16,8	81,2	0,3		13,1

Country	Study	Palmitoleic	Stearic	Oleic	Linoleic	Linolenic
		C16:1	C18 , 0	C18 , 1	C18 , 2	C18 : 3
Average	Current study	0,39	2,92	21,49	56,25	0,79
Saudi Arabia	(Al-Jassir, 1992)	0,30	2,28	23,58	59,34	0,30
Pakistan	(Sultan et al., 2009)	-	2,35	19,65	57,38	1,13
Iran	(Nickavar et al., 2003)		3,40	23,40	55,60	0,40
Pakistan	(Ashraf et al., 2006)	-	2,24	25,65	54,66	0,47
Türkiye	(Nergiz & Ötleş, 1993)	0,10	2,90	21,90	60,80	-
Türkiye	(Vatansev et al., 2013)	-	1,10	23,50	66,50	0,80
Tunisia	(Cheikh-Rouhou et al., 2007)	1,15	2,84	25,00	50,31	0,34
Iran	(Cheikh-Rouhou et al., 2007)		3,69	23,70	49,15	0,32
Egypt	(Houghton et al., 1995)		2,70	23,46	58,00	0,47
India	(Houghton et al., 1995)		2,97	25,67	54,68	0,68
Syria	(Houghton et al., 1995)		2,60	24,51	54,13	0,69
Bangladesh	(Kabir et al., 2019)	0,28	2,47	21,80	57,00	0,46
Iraq	(Kaskoos, 2011)	0,16	2,22	16,60	42,80	0,25
Tunisia	(Bourgou et al., 2010)	0,28	2,90	19,20	58,10	0,41
Iran	(Khonche et al., 2019)	0,94	5,48	5,76	48,29	-
Germany	(Ramadan & Mörsel, 2002)	-	3,16	24,10	57,30	
Egypt	(Atta, 2003)	0,70	3,30	20,10	49,00	2,70
Saudi Arabia	(Al-Jasass & Al-Jasser, 2012)	-	2,04	16,23	68,07	2,16
Iran	(Solati et al., 2014)		2,26	23,52	59,70	0,77
Iran	(Khoddami et al., 2011)		3,04	21,73	55,65	2,24
Morocco	(Gharby et al., 2015)	0,20	2,30	23,80	58,50	0,40
Morocco	(Asdadi et al., 2014)	0,20	2,30	23,80	58,50	0,40
Tunisia	(HAMROUNI-SELLAMI et al., 2008)		6,30	12,70	61,30	1,50
Ethiopia	(Mariod et al., 2012)	0,20	2,90	24,50	55,10	0,20
Syria	(Mariod et al., 2012)	0,20	3,20	23,50	56,50	0,30

4. Amino Acid Composition of Black Cumin

There are many studies on the amino acid composition of black cumin. In the literature review, it was understood that the amino acid composition of black cumin samples taken from different regions was different. The studies on this subject are shown in Table 7.

Table 7: Amino acid composition of black cumin

Country	Average	Saudi Arabia	China	Bangladesh	Egyp	Egypt	Ethiopia	Syria
Study	Current Study	(Al-Jassir, 1992)	(Albakry et al., 2022)	(Kabir et al., 2019)	(Al-Gaby, 1998)	(Michel et al., 2011)	(Mariod et al., 2012)	(Mariod et al., 2012)
Essential Amino Acids (%)								
Leucine	5,72	5, 82	6,00	6	6,92	2,04	6,48	6,86
Valine	4,80	4,61	5,42	4,77	5,1	1,34	6,33	6,01
Lysine	3,64	4,04	3,55	3,86	3,91	1,1	4,64	4,40
Threonine	3,48	3,65	3,68	3,86	3,95	1,21	4,19	3,85
Phenylalanine	3,34	3,61	3,68	3,7	4	1,16	3,79	3,45
İsoleucine	3,65	3,46	4,06	3,69	3,98	1,06	4,49	4,80
Histidine	2,59	3,35	2,58	2,79	2,83	1,05	2,74	2,75
Methionine	1,40	1,65	1,87	1,88	1,45	0,53	1,05	1,35
Tyrosine	2,28	-	3,35	-	-	-	1,50	2,00
Cystine A	0,58	-	0,58	-	-	-	-	-
Total Essential Amino Acids	32,48	30,19	34,77		-	-	-	-
Non-Essential Amino Acids (%)								
Glutamic Acid	20,50	24,74	26,45	23,95	22,44	7,78	21,54	20,87
Arginine	8,35	9,19	9,03	8,9	9,18	3,07	9,12	9,96
Aspartic Acid	8,19	8,94	10,26	9,32	10,05	2,86	7,88	8,01
Glycine	5,29	5,61	5,87	6,11	6,86	1,89	5,58	5,11
Proline	4,82	4,9	5,35	4,88	6,07	1,58	5,33	5,66
Serine	3,44	4,31	3,94	4,5	3,8	1,31	3,44	2,75
Alanine	3,92	3,73	4,32	4,39	4,21	1,47	4,49	4,80
Tyrosine	2,77	3,59	-	3,43	3,35	-	1,50	2,00
Ammonium	4,68	2,84	-		-	-	5,68	5,51
Cystine	1,51	1,96	-		1,17	0,75	1,79	1,85

REFERENCES

Abidi, A., Robbe, A., Kourda, N., Khamsa, S. B., & Legrand, A. (2017). Nigella sativa, a traditional Tunisian herbal medicine, attenuates bleomycin-induced pulmonary fibrosis in a rat model. *Biomedicine & Pharmacotherapy*, *90*, 626-637.

Abulfadl, Y. S., El-Maraghy, N. N., Ahmed, A. A. E., Nofal, S., & Badary, O. A. (2018). Protective effects of thymoquinone on D-galactose and aluminum chloride induced neurotoxicity in rats: biochemical, histological and behavioral changes. *Neurological research*, *40*(4), 324-333.

Ahmad, S., Chughtai, A., Hussain, R., & Iqbal, S. (2017). Physiological and biochemical role of nigella sativa in hyperlipidemic albino rats a comparative study. *Pak. J. Med. Health Sci*, *11*, 195-196.

Al-Jasass, F. M., & Al-Jasser, M. S. (2012). Chemical composition and fatty acid content of some spices and herbs under Saudi Arabia conditions. *The scientific world journal*, *2012*(1), 859892.

Al-Jassir, M. S. (1992). Chemical composition and microflora of black cumin (Nigella sativa L.) seeds growing in Saudi Arabia. *Food Chemistry*, *45*(4), 239-242.

Al-Gaby, A. (1998). Amino acid composition and biological effects of supplementing broad bean and corn proteins with Nigella sativa (black cumin) cake protein. *Food/Nahrung*, *42*(05), 290-294.

Albakry, Z., Karrar, E., Ahmed, I. A. M., Oz, E., Proestos, C., El Sheikha, A. F., Oz, F., Wu, G., & Wang, X. (2022). Nutritional composition and volatile compounds of black cumin (Nigella sativa L.) seed, fatty acid composition and tocopherols, polyphenols, and antioxidant activity of its essential oil. *Horticulturae*, *8*(7), 575.

Aleem, U., Rehman, A., Shah, R., Jan, T., Jan, M., & Jan, R. (2020). Effects of thymoquinone obtained from seeds of Nigella sativa on volume & Acidity of stimulated gastric secretion. *Pak. J. Med. Health Sci*, *14*, 49-50.

Asdadi, A., Harhar, H., Gharby, S., Bouzoubaâ, Z., Yadini, A., Moutaj, R., Hadek, M., Chebli, B., & Hassani, L. M. I. (2014). Chemical composition and antifungal activity of Nigella Sativa L. oil seed cultivated in Morocco. *International Journal of Pharmaceutical Science Invention*, *3*(11), 09-15.

Ashraf, M., Ali, Q., & Iqbal, Z. (2006). Effect of nitrogen application rate on the content and composition of oil, essential oil and minerals in black cumin (Nigella sativa L.) seeds. *Journal of the Science of Food and Agriculture*, *86*(6), 871-876.

Atta, M. B. (2003). Some characteristics of nigella (Nigella sativa L.) seed cultivated in Egypt and its lipid profile. *Food Chemistry*, *83*(1), 63-68.

Babayan, V., Koottungal, D., & Halaby, G. (1978). Proximate analysis, fatty acid and amino acid composition of Nigella sativa L. seeds. *Journal of Food Science*, *43*(4), 1314-1315.

Beheshti, F., Norouzi, F., Abareshi, A., Anaeigoudari, A., & Hosseini, M. (2018). Acute administration of Nigella sativa showed anxiolytic and anti-depression effects in rats. *Current Nutrition & Food Science*, *14*(5), 422-431.

Bepari, A., Parashivamurthy, B., & Niazi, S. K. (2016). Evaluation of the effect of volatile oil extract of Nigella sativa seeds on maximal electroshock-induced seizures in albino rats. *National Journal of Physiology, Pharmacy and Pharmacology*, *7*(3), 273-273.

Bourgou, S., Pichette, A., Marzouk, B., & Legault, J. (2010). Bioactivities of black cumin essential oil and its main terpenes from Tunisia. *South African Journal of Botany*, *76*(2), 210-216.

Cheikh-Rouhou, S., Besbes, S., Hentati, B., Blecker, C., Deroanne, C., & Attia, H. (2007). Nigella sativa L.: Chemical composition and physicochemical characteristics of lipid fraction. *Food Chemistry*, *101*(2), 673-681.

Chen, M. C., Lee, N. H., Hsu, H. H., Ho, T. J., Tu, C. C., Chen, R. J., Lin, Y. M., Viswanadha, V. P., Kuo, W. W., & Huang, C. Y. (2017). Inhibition of NF-κB and metastasis in irinotecan (CPT-11)-resistant LoVo colon cancer cells by thymoquinone via JNK and p38. *Environmental toxicology*, *32*(2), 669-678.

Cobourne-Duval, M. K., Taka, E., Mendonca, P., Bauer, D., & Soliman, K. F. (2016). The antioxidant effects of thymoquinone in activated BV-2 murine microglial cells. *Neurochemical research*, *41*, 3227-3238.

Çakmakçı, S., & Çakır, Y. (2011). çörekotu (Nigella sativa L.): Bileşimi, Gıda Sanayinde Kullanımı ve Sağlık Üzerine Etkileri. *Academic Food Journal/Akademik GIDA*.

Dandik, L., & Aksoy, H. (1992). The kinetics of hydrolysis of Nigella sativa (black cumin) seed oil catalyzed by native lipase in ground seed. *Journal of the American Oil Chemists Society*, *69*, 1239-1241.

Dastjerdi, M. N., Mehdiabady, E. M., Iranpour, F. G., & Bahramian, H. (2016). Effect of thymoquinone on P53 gene expression and consequence apoptosis in breast cancer cell line. *International journal of preventive medicine*, *7*(1), 66.

Dessie, A. B., Abate, T. M., Adane, B. T., Tesfa, T., & Getu, S. (2020). Estimation of technical efficiency of black cumin (Nigella sativa L.) farming in northwest Ethiopia: a stochastic frontier approach. *Journal of economic structures*, *9*, 1-14.

Ebrahimi, S. S., Oryan, S., Izadpanah, E., & Hassanzadeh, K. (2017). Thymoquinone exerts neuroprotective effect in animal model of Parkinson's disease. *Toxicology letters*, *276*, 108-114.

Ezirganli, S., Kazancioglu, H. O., Ozdemir, H., Inan, D. S., & Tek, M. (2016). The effects of Nigella sativa seed extract on bone healing in an experimental model. *Journal of Craniofacial Surgery*, *27*(7), 1905-1909.

Firdaus, F., Zafeer, M. F., Anis, E., Ahmad, F., Hossain, M. M., Ali, A., & Afzal, M. (2019). Evaluation of phyto-medicinal efficacy of thymoquinone against Arsenic induced mitochondrial dysfunction and cytotoxicity in SH-SY5Y cells. *Phytomedicine*, *54*, 224-230.

Gharby, S., Harhar, H., Guillaume, D., Roudani, A., Boulbaroud, S., Ibrahimi, M., Ahmad, M., Sultana, S., Hadda, T. B., & Chafchaouni-Moussaoui, I. (2015). Chemical investigation of Nigella sativa L. seed oil produced in Morocco. *Journal of the Saudi Society of Agricultural Sciences*, *14*(2), 172-177.

Gülşen, İ., Ak, H., Çölçimen, N., Alp, H. H., Akyol, M. E., Demir, I., Atalay, T., Balahroğlu, R., & Rağbetli, M. Ç. (2016). Neuroprotective effects of thymoquinone on the hippocampus in a rat model of traumatic brain injury. *World Neurosurgery*, *86*, 243-249.

HAMROUNI-SELLAMI, I., Elyes Kchouk, M., & Marzouk, B. (2008). Lipid and aroma composition of black cumin (Nigella sativa L.) seeds from Tunisia. *Journal of Food Biochemistry*, *32*(3), 335-352.

Hannan, M. A., Rahman, M. A., Sohag, A. A. M., Uddin, M. J., Dash, R., Sikder, M. H., Rahman, M. S., Timalsina, B., Munni, Y. A., & Sarker, P. P. (2021). Black cumin (Nigella sativa L.): A comprehensive review on phytochemistry, health benefits, molecular pharmacology, and safety. *Nutrients*, *13*(6), 1784.

Houghton, P. J., Zarka, R., de las Heras, B., & Hoult, J. (1995). Fixed oil of Nigella sativa and derived thymoquinone inhibit eicosanoid generation in leukocytes and membrane lipid peroxidation. *Planta medica*, *61*(01), 33-36.

Hsu, H.-H., Chen, M.-C., Day, C. H., Lin, Y.-M., Li, S.-Y., Tu, C.-C., Padma, V. V., Shih, H.-N., Kuo, W.-W., & Huang, C.-Y. (2017). Thymoquinone suppresses migration of LoVo human colon cancer cells by reducing prostaglandin E2 induced COX-2 activation. *World journal of gastroenterology*, *23*(7), 1171.

Husna, M., Sumera, S., Laiba, S., & Anam, A. (2017). THE EFFECT OF CRUDE Nigella sativa OIL AGAINST THE ACUTE TOXICITY OF DICLOFENAC SODIUM AND IBUPROFEN ON THE LIVER OF ALBINO MICE. *Slovenian Veterinary Research/Slovenski Veterinarski Zbornik*, *54*(1).

Hussain, N., Majid, S., Abbasi, M., Hussain, M., Rehman, K., Khan, M., Dar, M., Shaheen, H., & Habib, T. (2017). Use of black seed (Nigella sativa L.) oil in the management of hypertensive and hyperlipidemic individuals of district Muzaffarabad, Azad Kashmir, Pakistan. *Applied Ecology & Environmental Research*, *15*(4).

Iqbal, M. S., Abdul Ghafoor, A. G., Inamullah, I., & Habib Ahmad, H. A. (2013). Genetic variation in yield performance for three years in Nigella sativa L. germplasm and its association with morpho-physiological traits and biochemical composition.

Kabir, Y., Shirakawa, H., & Komai, M. (2019). Nutritional composition of the indigenous cultivar of black cumin seeds from Bangladesh. *Progress in Nutrition*, *21*(1-S), 428-434.

Kaskoos, R. (2011). Fatty acid composition of black cumin oil from Iraq.

Khoddami, A., Ghazali, H. M., Yassoralipour, A., Ramakrishnan, Y., & Ganjloo, A. (2011). Physicochemical characteristics of nigella seed (Nigella sativa L.) oil as affected by different extraction methods. *Journal of the American Oil Chemists' Society*, *88*, 533-540.

Khonche, A., Huseini, H. F., Gholamian, M., Mohtashami, R., Nabati, F., & Kianbakht, S. (2019). Standardized Nigella sativa seed oil ameliorates hepatic steatosis, aminotransferase and lipid levels in non-alcoholic fatty liver disease: A randomized, double-blind and placebo-controlled clinical trial. *Journal of Ethnopharmacology*, *234*, 106-111.

Kumandaş, A., Karsli, B., Kürüm, A., & Çinar, M. (2020). Comparison of the effects of zinc-silver cream and Nigella sativa oil on wound healing and oxidative stress in the wound model in rats.

Mamun, M., & Absar, N. (2018). Major nutritional compositions of black cumin seeds–cultivated in Bangladesh and the physicochemical characteristics of its oil. *International Food Research Journal*, *25*(6), 2634-2639.

Manjegowda, S. B., Rajagopal, H. M., & Dharmesh, S. M. (2017). Polysaccharide of Black cumin (Nigella sativa) modulates molecular signaling cascade of gastric ulcer pathogenesis. *International journal of biological macromolecules*, *101*, 823-836.

Mariod, A. A., Edris, Y. A., Cheng, S. F., & Abdelwahab, S. I. (2012). Effect of germination periods and conditions on chemical composition, fatty acids and amino acids of two black cumin seeds. *Acta Scientiarum Polonorum Technologia Alimentaria*, *11*(4), 401-410.

Michel, C. G., El-Sayed, N. S., Moustafa, S. F., Ezzat, S. M., Nesseem, D. I., & El-Alfy, T. S. (2011). Phytochemical and biological investigation of the extracts of Nigella sativa L. seed waste. *Drug testing and analysis*, *3*(4), 245-254.

Mohammed, N. K., Abd Manap, M. Y., Tan, C. P., Muhialdin, B. J., Alhelli, A. M., & Meor Hussin, A. S. (2016). The effects of different extraction methods on antioxidant properties, chemical composition, and thermal behavior of black seed (Nigella sativa L.) oil. *Evidence-Based Complementary and Alternative Medicine*, *2016*(1), 6273817.

Nergiz, C., & Ötleş, S. (1993). Chemical composition of Nigella sativa L. seeds. *Food Chemistry*, *48*(3), 259-261.

Nickavar, B., Mojab, F., Javidnia, K., & Amoli, M. A. R. (2003). Chemical composition of the fixed and volatile oils of Nigella sativa L. from Iran. *Zeitschrift für Naturforschung C*, *58*(9-10), 629-631.

Okasha, E. F., Bayomy, N. A., & Abdelaziz, E. Z. (2018). Effect of topical application of black seed oil on imiquimod-induced psoriasis-like lesions in the thin skin of adult male albino rats. *The Anatomical Record*, *301*(1), 166-174.

Ramadan, M. F., & Mörsel, J. T. (2002). Characterization of phospholipid composition of black cumin (Nigella sativa L.) seed oil. *Food/Nahrung*, *46*(4), 240-244.

Saleh, A. (2014). Nigella seed oil as alternative to avilamycin antibiotic in broiler chicken diets. *South African Journal of Animal Science*, *44*(3), 254-261.

Seçmen, Ö., Gemici, Y., Görk, G., Bekat, L., & Leblebici, E. (2000). Tohumlu bitkiler sistematiği. *Ege Üniversitesi Fen Fakültesi Kitaplar Serisi*, *116*, 394.

Shah, S., & Ray, K. S. (2003). Study on antioxidant and antimicrobial properties of black cumin (Nigella sativa Linn). *Journal of food science and technology (Mysore)*, *40*(1), 70-73.

Solati, Z., Baharin, B. S., & Bagheri, H. (2014). Antioxidant property, thymoquinone content and chemical characteristics of different extracts from Nigella sativa L. seeds. *Journal of the American Oil Chemists' Society*, *91*, 295-300.

Soleimannejad, K., Rahmani, A., Hatefi, M., Khataminia, M., Ahmadi, M. R. H., & Asadollahi, K. (2017). Effects of nigella sativa extract on markers of cerebral angiogenesis after global ischemia of brain in rats. *Journal of Stroke and Cerebrovascular Diseases*, *26*(7), 1514-1520.

Sultan, M. T., Butt, M. S., Anjum, F. M., Jamil, A., Akhtar, S., & Nasir, M. (2009). Nutritional profile of indigenous cultivar of black cumin seeds and antioxidant potential of its fixed and essential oil. *Pak. J. Bot*, *41*(3), 1321-1330.

Tabeshpour, J., Mehri, S., Abnous, K., & Hosseinzadeh, H. (2020). Role of oxidative stress, MAPKinase and apoptosis pathways in the protective effects of thymoquinone against acrylamide-induced central nervous system toxicity in rat. *Neurochemical research*, *45*, 254-267.

Takruri, H. R., & Dameh, M. A. (1998). Study of the nutritional value of black cumin seeds (Nigella sativaL). *Journal of the Science of Food and Agriculture*, *76*(3), 404-410.

Vatansev, H., Ciftci, H., Ozkaya, A., Ozturk, B., Evliyaoglu, N., & Kiyici, A. (2013). Chemical composition of Nigella sativa L. seeds used as a medical aromatic plant from East Anatolia Region, Türkiye.

Widodo, G. P., Herowati, R., Perangin-Angin, J. M., & Kamlasi, J. (2016). Antihyperglycemic, antioxidant, and pancreas regeneration activities of black cumin (Nigella sativa L.) seeds ethanol extract in alloxan-induced diabetic rats. *International Journal of Pharmacy and Pharmaceutical Sciences*, *8*(5), 37-40.

Zhang, M., Du, H., Wang, L., Yue, Y., Zhang, P., Huang, Z., Lv, W., Ma, J., Shao, Q., & Ma, M. (2020). Thymoquinone suppresses invasion and metastasis in bladder cancer cells by reversing EMT through the Wnt/β-catenin signaling pathway. *Chemico-biological interactions*, *320*, 109022.

CHAPTER 10

EFFECT USE LEVEL OF IMMORTAL (*Helichrysum ssp.*) HERBAL PLANT EXTRACT IN THE PROTECTION OF HISTORICAL WOODEN ARTWORK

Assoc. Prof. Dr. Şule CEYLAN[1]
Prof. Dr. Hüseyin PEKER[2]

[1] Artvin Çoruh Unıversity, Forest Faculty, Forest Industrıal Engineering Department, Artvin, Türkiye. E-mail: sceylan@artvin.edu.tr. ORCID ID: 0000-0001-9515-1829
[2] Artvin Çoruh Unıversity, Forest Faculty, Forest Industrıal Engineering Department, Artvin, Türkiye. E-mail: peker100@artvin.edu.tr. ORCID ID: 0000-0002-7771-6993

1. INTRODUCTION

The factors that cause wood to deteriorate are mainly physical factors (UV, acid rain, wind erosion, etc.), mechanical factors (wear, ruptures, etc.), chemical factors (fires, corrosion, etc.) and biological factors (bacteria, fungi, termites, etc.). sea creatures etc.) are formed. The wooden structure has deteriorated due to outdoor conditions and biological factors and that long-term maintenance and protection procedures have not been carried out on the structure. It has been a matter of curiosity for experts how wooden structures built centuries ago have survived until today, despite being threatened by many negative factors. Horyuji Temple in Japan, which is considered the oldest wooden structure in the world (Cartwright, 2017), 62 historical wooden houses from the 12th century in Bryggen, Norway (UNESCO, 2021), Beyşehir Eşrefoğlu Mosque built during the Seljuk period in Turkey (Uzun, 2018), Göğceli Mosque (Can, 2004) and Afyon Ulu Mosque (Uysal, 1993) are examples of wooden structures that have survived to the present day. When looking at wooden structures that have survived for long periods, a common design approach can be seen. Cutting the wooden structure's direct contact with the soil provides the structure with a long lifespan. Especially historical wooden structures were built on stone or marble and have survived to the present day.

Studies are continuing to increase the performance of herbal protective impregnations and make them more useful in the coming years. Especially tannins obtained from these herbal extracts are used. The fact that tannins are both healthier and less costly than other petroleum derivatives indicates that the value of plant-based preservatives will increase in the coming years (Şimşek,2013). Tomak (2011) applied waste oil impregnation to beech and Scots pine samples and stated that the physical properties of the material could be improved by finding the water absorption rates low and the water repellency efficiency high. Bazyar et al. (2010) found a significantly reduced amount of moisture and low water uptake rates with an 80-106% weight increase in the hot oil treatment of poplar samples with linseed oil. Chen et al. (2020) reported in their study that epoxidized linseed oil/carnauba wax provided excellent water repellency and dimensional stability in the modification process, and that the service life of poplar wood could be extended in this method. He et al. (2019), in the sample of Chinese fir (Abies chensiensis) impregnated with silicone oil, water uptake was reduced and dimensional stability was increased by providing hydrophobicity

The extract of the immortelle plant, which is among the natural organic and medicinal aromatic plants, was prepared at a concentration of (7%) and impregnated on beech (*Fagus orientalis Lipsky*) and ıroko wood (*Milicia excelsa*) to change the water uptake rate (WUR) and the amount of washed substance (AWS). It was tried to determine the usability of this plant species in wooden historical artifacts by researching and determining the effect level of this plant species on wood (indoor/outdoor use, etc.).

2. MATERIAL AND METHOD

Within the scope of the study, the extract of the immortelle plant (*Helichrysum ssp*.) was prepared at a concentration of (7%), and beech (*Fagus orientalis Lipsky*) and ıroko wood (*Milicia excelsa*) wer used as wood species. Care was taken to ensure that the samples were chosen randomly, without cracks, with smooth fibres, without ridges or knots, and without differences in color or density. Then, the samples were prepared according to TS ISO 13061-1 standard.

2.1. Preparation of Test Samples and Impregnation Method

Test samples were prepared according to TS 2470 from the sapwood section, which had no knots, knots, cracks, a smooth fiber structure, was not damaged by fungi or insects, and had no discoloration. Both types of wood were cut into slats and test samples were obtained from the sapwood in the radial direction. The impregnation method was carried out on a vacuum/diffusion basis according to the ASTM D1413-76 standard.

2.2. Preparation of Plant Extract

After the immortelle plant is cleaned, it is placed in distilled water or water at least equivalent to this purity, mixed at certain intervals, heated at a temperature below the boiling point in a refrigerated device for 1 hour, filtered under vacuum in a previously prepared porous capsule, and then several times so that no sample remains in the flask. The process was continued by washing with distilled water and the insoluble part was completely placed in the porous capsule. Finally, the residue was washed with 200 ml of hot distilled water, and after the residue was dehydrated with the help of a pump or another device that would act as a suction device, the porous capsule and its contents were dried by keeping it in an oven set at 103°C for 16 hours, then cooled in a desiccator and weighed with an accuracy of 0.001 g. (Ceylan,2020).

2.3.Water Uptake Rate (WUR) and Amount of Washed Material (AWM)

While the water uptake test was carried out in accordance with the TS 2470-2471/1976 standard, the knitting dimensions were prepared as 20x20x30 mm and the samples were sanded and then conditioned (at 20±20C/65±5% relative humidity) to 12% moisture content. Both control and impregnated samples were kept in distilled water at room temperature for 6, 24, 48, 72 and 96 hours (Rowel et al. 1985). At the end of each period, measurements were made and water intake amounts were determined.

3. FINDINGS AND DISCUSSION

3.1. Solution (Extract) Feature

Table 1. Solution Properties

Plant Extract/ Concentration	Solvent	Degree (°C)	pH		Density (g/ml)	
			İB	İA	İB	İA
7%	Methanol	22°C	7.56	7.61	0.923	0.923

İB:İmpregnation Before **İA:**İmpregnation After

There was no change in pH and density of solution properties after impregnation and impregnation are given in Table 1.

3.2. Retention

The retention level of immortelle plant extract on beech/ıroko wood is given in Table 2.

Table 2. Amount of Retention **(%)**

Wood Type	Vacuum/ Dıffussıon	Solvent	Degree (°C)	Retention (%)	
				Mean	HG
Beech Wood	30/30 Minute	Methanol	22°C	3.05	A
Iroko Wood				2.82	B

The highest retention value in beech wood was achieved at 7% solution concentration (3.05 %). As the concentration increased, the retention level decreased.

Var et al. (2019) found the highest retention value in red pine wood treated with geothermal water as 2.773% in the SJ-5 40.9ºC treatment, while the lowest value was 2.565% in the SJ-1 23.0ºC treatment.

3.3. Water Uptake Rate (WUR) Properties

Water intake rate is given in Table 3 according to time periods.

Table 3. Water Uptake Rate (%)

Odun Türü	**Vacuum/ Dıffusıon**	**Solvent**	**Water Uptake (%)**				
			6 Hours	24 Hours	48 Hours	72 Hours	96 Hours
Beech Wood	30/30 Minute	Methanol	38.43	54.73	61.27	82.64	72.39
Iroko Wood			31.43	39.48	56.17	55.43	64.13

The highest water uptake rate was determined as 72 hours (82.64 %) in beech wood, and the lowest water uptake rate was determined as 6 hours (31.43 %) in iroko wood. It can be said that especially the anatomical structure of iroko wood, wood type, water resistance properties in the external environment and the effect of immortelle plant extract are effective on the water uptake rate. Kılıc et al. (2002) reported in their study that the amount of water uptake was high in fir and poplar wood.

3.4. Amount of Washed Material (AWM)

The amount of washed substance is given in Table 4 according to time periods.

Table 4. Washed Material (%)

Odun Türü	**Vacuum/ Dıffusıon**	**Solvent**	**Washed Material (%)**				
			6 Hours	24 Hours	48 Hours	72 Hours	96 Hours
Beech Wood	30/30 Minute	Methanol	27.01	49.41	56.64	78.18	69.42
Iroko Wood			19.78	31.66	52.12	54.46	59.55

In terms of the amount of washed material, the highest value was 72 hours (78.18%) in beech wood, and the lowest value was 6 hours (19.78%) in iroko wood. It can be said that wood type, anatomical structure, impregnation method, concentration, plant extract type and solvent properties are effective on the washed substance. Venkatasamy (2002) impregnated Eucalyptus wood in Kenya with the CCA structure and determined the pH interaction with the amounts of chromium, copper and arsenic removed from the wood. They found that in the remediation process, washing was largely present in the first 12 days and that washing was reduced on the 21st day.

4. CONCLUSION

There are medicinal and aromatic plant species with significant production potential in our country. In terms of the future of humanity, it is imperative that these products be evaluated in all areas. Especially in sectors such as food, spices, pharmacology, etc., its use on wooden materials will seriously increase the level of human/environmental health. In this sense, we can say that the immortelle plant has a positive effect on both types of wood, both on the adhesion level and against the effects of water, on the wooden material to be used in the restoration of wooden historical artifacts. The study has shown that the immortelle plant can be used as a surface impregnation material for wood, as it is natural, can be recycled economically and can be a new area of use in the woodworking industry. It can be used especially in children's toys, interiors and many other areas.

REFERENCES

Cartwrıght, M., (2017). Horyuji - World History Encyclopedia.

Uzun, S., (2018). Tarihi ahşap yapı taşıyıcı sistemlerinin incelenmesi ve boğaziçi örneği: Amcazade Hüseyin Paşa yalısı, Yüksek Lisans Tezi, İstanbul Teknik Üniversitesi

Can, Y., (2004). Samsun yöresinde bulunan ahşap camiler. İstanbul: Etüt Yayınları

Şimşek, U.B. (2013). Bitkisel ve Kimyasal Koruyucularla Emprenye Edilen Sarıçam Odununun Bazı Fiziksel ve Biyoloji Özellikleri, Yüksek Lisans, Karadeniz Teknik Üniversitesi, Trabzon, 91.

Tomak, E.D., Yıldız, Ü.C. (2012). Bitkisel Yağların Ahşap Koruyucu Bir Madde Olarak Kullanılabilirliği, Artvin Çoruh Üniversitesi Orman Fakültesi Dergisi 13(1):142-157.

Bazyar, B., Parsapajouh, D. ve Khademieslam, H., (2010). An Investigation on Some Physical Properties of Oil Heat Treated Poplar Wood, Paper Prepared for the 41st Annual Meeting, Biarritz, France.

Chen, J., Wang, Y., Cao, J., Wang, W., (2020). Improved water repellency and dimensional stability of wood via ımpregnation with an epoxidized linseed oil and carnauba wax complex emulsion. Forests 11(3): 271.

He, Z., Qu, L., Wang, Z., Qian, J., Yi, S., (2019). Effects of zinc chloride–silicone oil treatment on wood dimensional stability, chemical components, thermal decomposition and its mechanism. Scientific Reports 9(1): 1-7.

TS ISO 13061, (2021). Odunun fiziksel ve mekanik özellikleri – Kusursuz küçük ahşap numunelerin deney yöntemleri - Bölüm 1: Fiziksel ve mekanik deneyler için nem muhtevasının belirlenmesi.

TS 2470, (1976). Odunda fiziksel ve mekaniksel deneyler için numune alma metotları ve genel özellikler, Ankara.

TS 2471 (1976) Odunda, fiziksel ve mekaniksel deneyler için rutubet miktarı tayini, Ankara.

ASTM, (1986), D1413-76 Standard method of testing wood preservatives by laboratory soil block culture, American Society for Testing and Materials, Philadelphia, USA.

Ceylan, Ş., (2020). Çiriş Bitki (Antioksidan/Antibakteriyel) özütünün Ahşap Endüstrisinde (Mobilya/İnşaat) Kullanılabilme Olanakları, Artvin Çoruh Üniversitesi BAP Projesi Koordinatörlüğü, Proje No: 2017.M82.02.02, Artvin.

Rowell, R.M., Banks, W.B. (1985). Water Repellency and Dimensional Stability of Wood. Department of Agriculture, Forest Service, Forest Products Laboratory, Gen. Tech. Rep. FPL-50, Madison, WI, U.S.

Var A. (2001). Ahşap Malzemede Su Alımının Parafin Vaks / Bezir Yağı Karışımıyla Azaltılması, Süleyman Demirel Üniversitesi Orman Fakültesi Dergisi, Seri: A, Sayı: 2, Sayfa: 97-110.

Kılıç, A., Hafızoğlu, H. (2002). Metil Metakrilat İle Muamele Edilen Bazı Ağaç Türlerinin Boyut Stabilizasyonunun Artırılması, ZKÜ Bartın Orman Fakültesi Dergisi Cilt:4 Sayı:4.

Venkatasamy, R., (2002). The Effects of pH Leaching of Copper-Chrome-Arsenate (CCA) From Pressure-Treated, Kenyan-Grown Eucalyptus saligna ve Acacia mearnsii: Initial Findings, The International Research Group on Wood Preservation 33rd Annual Meeting in Cardiff, Wales, UK, IRG/WP 02-30298.

CHAPTER 11

THE RELATIONSHIP BETWEEN ARBUSCULAR MYCORRHIZAL FUNGUS (GLOMUS SPP.) AND DROUGHT AND ITS MECHANISM OF ACTION IN CORN (ZEA *MAYS L.*)

Assoc. Prof. Dr. Timuçin TAŞ[1], Assoc. Prof. Dr. Orkun BABACAN[2]
Assoc. Prof. Dr. Arzu MUTLU[3]

[1] Balıkesir University Kepsut Vocational School Department of Veterinary. Balikesir/Türkiye, E-mail: timuçin.tas@balikesir.edu.tr ORCİD NO: 0000-0002-2144-9064
[2] Balıkesir University Kepsut Vocational School Department of Veterinary. Balikesir/Türkiye, E-mail: orkun.babacan@balikesir.edu.tr ORCİD NO: 0000-0003-0258-1825
[3] Harran University, Faculty of Agriculture, Akçakale Vocational School, Şanlıurfa/Türkiye, E-mail: amutlu@harran.edu.tr , Orcid No: 0000-0001-8992-8371)

INTRODUCTION

According to data for 2024, the global population stands at 8.123.828 billion and continues to grow daily. In 1650, the world population was between 450-550 million, in 1750 it was 700-800 million, in 1850 it ranged from 1 to 1.2 billion, and in 1900 it was between 1.5 and 1.6 billion. In the last century, the world population has increased sevenfold (Anonymous, 2024). Developments in health and technology, innovations in agriculture, increases in food supply, and the fact that 80% of inventions occurred in the last century have reduced early mortality and significantly increased the population. Meeting the food demands of this large population has necessitated optimizing yields from unit areas. With the increase in population, human and animal activities, industrial waste, and emissions of greenhouse gases (such as water vapor, CO2, CO, CH4, O3) and toxic gases (from volcanic eruptions) are rapidly polluting the environment and ecology. The consequences of these negative impacts include global warming, climate change, water scarcity, and drought. It is necessary to implement plans and strategies to prevent the food crisis we are currently experiencing and which will intensify in the future.

Drought will be a significant abiotic stress factor contributing to future food crises. Drought is one of the most intense environmental challenges impacting plant development and yield. It causes a decrease in transpiration rates, disruptions in active transport and membrane permeability, and limited absorption of water and nutrients by plants. These changes in plant cells adversely affect nutrient metabolism, photosynthesis, and respiration (Pavithra and Yapa, 2018). Lack of water directly disrupts plant growth and development and leads to the inhibition of photosynthesis (Wu et al., 2013). This is as a result of decreased CO_2 uptake. because of stomatal closure and the disruption of the structure of protective cells necessary to keep stomata open (Pinheiro and Chaves, 2011).

Grains, which are fundamental to human and animal nutrition and serve as raw materials for many food industries, must be prioritized in planning for future drought scenarios. Among grains, corn, second only to wheat in production, is of strategic importance. Corn is an important raw material for the production of ethanol, corn syrup, and animal feed, as well as being supreme food source for humans (Begum et al., 2019).

Increasing the adaptation capacity of corn, which is grown in open and unprotected environments, and identifying its tolerance mechanisms to abiotic stresses such as water scarcity are critical strategic steps (Elliott et al., 2014). Adapting corn to new environments is vital, and efforts must be accelerated to develop its tolerance to climate change. Additionally, efforts to enhance food output to guarantee food security in the future must be directed and increased (Elliott et al., 2014). Being a C4 plant, corn uses CO2 more efficiently for photosynthesis and has better water use efficiency compared to C3 plants. However, despite these abilities, corn cannot survive without water (Braga, 2021).

When experiencing drought stress, grains like corn employ a series of drought avoidance and/or tolerance mechanisms, including osmotic adjustment, stomatal conductivity and photosynthesis regulation, production of antioxidants and detoxifying substances, or controlling water absorption and movement within their tissues (Ruiz-Lozano et al., 2012b; Candar-Çakır et al., 2016). Despite these physiological and biochemical efforts, corn is particularly sensitive to drought stress. Drought stress during any vegetative or generative development stage (seedlings, anthesis-silking, milk and dough stages) leads to significant decreases in yield (Daryanto et al., 2016).

Corn plants undergo various physiological and biochemical changes to cope with drought. These changes aim either to keep the plant alive or to increase grain yield, based on the length and intensity of the drought stress. However, the plant's intensive efforts may not be sufficient on their own. Therefore, corn plants require supportive partners. Recent studies was declarated that arbuscular mycorrhizal fungi (AMF) inoculated into drought-stressed corn plants can be beneficial partners (Santana et al., 2023).

The symbiotic relationship between plants and AM fungi is estimated to have originated over 450 million years ago (Strullu-Derrien et al., 2018). This evolutionary process has also led to the formation and colonization of other beneficial soil organisms (Brundrett and Tedersoo, 2018). Arbuscular mycorrhizal fungi (AMF), fundamental partners for plants, are well-known soil microorganisms with significant effects on ecosystems. They can help plants by improving phosphorus and micronutrient uptake, resulting in faster biomass development (Bennett and Groten, 2022), and by mitigating the detrimental effects of water stress, thus aiding plant growth and development (Bahraminia et al., 2020).

A study has reported that under water stress conditions, AMF inoculation increases the biomass, chlorophyll concentration, gas exchange, and transpiration rate of corn plants. It also improves root hydraulic conductivity, gas exchange, osmotic regulation, water stress, and photosynthetic activities (Ghorchiani et al., 2018).

AMF, one of the most prevalent microbial groups in soils, have the ability to enhance plant water and nutrient use efficiency (Zhao et al., 2015), reduce stress caused by high temperatures and drought (Diagne et al., 2020), regulate biotic and abiotic stress (Mathur and Jajoo, 2020), improve soil physical and microbiological conditions (Zhang et al., 2022), reduce heavy metal uptake by plants (Yu et al., 2021), and even increase organic carbon reserves in the soil (Lu et al., 2018).

There is significant evidence that AMF can enhance host plant tolerance to drought stress (Asrar et al., 2012; Lazcano et al., 2014). The tolerance of AMF-associated plants to water stress can be explained by increased root volume and the development of external hyphae. These hyphae enhance the ability to explore and absorb soil moisture, thereby increasing turgor pressure in the plant's leaves. This osmotic regulation improves stomatal conductance, water use efficiency and plant nutrition while reducing oxidative harm caused by reactive oxygen species (ROS) (Hashem et al., 2018).

Differences in ecosystems, host plants, soil physical and chemical properties, and AMF species are some of the reasons for variability among AMF types (Moebius-Clune et al., 2013; Horn et al., 2017). Additionally, low pH, phosphorus (P), and water capacity in the soil increase AMF populations, while higher levels reduce them (Xu et al., 2018). Similarly, high electrical conductivity (EC) and high levels of $Ca2+$, $Mg2+$, $K+$, and $Na+$ have been shown to reduce AMF sporulation (Sanchez-Lizarraga et al., 2018).

AMF alleviate drought stress by either directly absorbing water or facilitating its transport through their hyphae (Augé et al., 2007). Additionally, AM fungi have been declarated to enhance nutrient absorption (Michalis et al., 2013), root hydraulic conductivity (Bárzana et al., 2014), plant gas exchange (Habibzadeh et al., 2013), soil water holding capacity, osmotic balance (Aroca et al., 2007), and antioxidant activity (Bompadre et al., 2014).

This review discusses mycorrhizas, their types, the characteristics of AMF, and their contributions to plants. It also provides information on the mechanisms and behaviors of AMF in relation to corn, particularly under drought conditions.

1. Mycorrhiza and Its Classification

Mycorrhiza refers to fungi that form a symbiotic association with the roots of specific plants. The term "mycorrhiza" is derived from Greek words: *mykes* (fungus) and *rhiza* (root), and it was first dclarated by Frank (1885). Additionally, "mycorrhiza" is used to describe the structures formed through the symbiotic relationships between plant roots and specific fungi (Moser and Haselwandter, 1975; Hayman, 1981).

In this type of symbiosis, fungi play a supportive rather than a parasitic role. Once mycorrhizal fungi colonize the root cortex of the plant, they extend their hyphae (fungal threads) into the cortex, integrating into the internal environment. The rapidly growing hyphae inside and outside the root provide water and minerals from the soil and transport organic matter from the plant to the soil. This symbiosis is highly active by nature and supports nutrient cycling and plant vitality within ecosystems. Mycorrhizal fungi are symbiotically present in the roots of a significant portion of higher plants (Brundrett, 2009; Wang and Qiu, 2006).

Mycorrhizal associations, one of the most common symbiotic relationships between soil microorganisms and plants, are found in nearly all terrestrial plants on Earth. About 83% of dicotyledons, 79% of monocotyledons, and all gymnosperms possess this type of symbiotic relationship. Corn (Zea mays) belongs to the monocotyledon class. Very dry or saline, waterlogged soil, or highly fertile or infertile habitats are rare environments where mycorrhizal symbiosis does not occur. Additionally, plants from the Cruciferae and Chenopodiaceae families do not naturally exhibit mycorrhizal associations unless inoculated externally (Harley, 1975; Brundrett, 1991; Marschner, 1995). Examples of such plants include Raphanus sativus (radish), Brassica oleracea (cauliflower), Spinacia oleracea (spinach), and Urtica dioica (nettle).

Mycorrhizal fungi vary greatly in taxonomy, including differences in spore structure, infection patterns in plants, and morphological and physiological structures within the roots. Two major groups of mycorrhizae stand out based on their relationship with root structure: Endomycorrhiza and Ectomycorrhiza. Ectomycorrhiza is commonly found in forest trees and some fruit trees, while Endomycorrhiza is present in nearly all cultivated plants and other fruit trees (Marschner, 1995). Additionally, there is an intermediate group called ectendomycorrhiza that displays characteristics of both groups. Ectomycorrhizae generally appear in the roots of woody plants and, occasionally, in perennial weeds and cereal grasses, characterized by two key structures. The first is the fungal mycelial network surrounding the root surface, known as the Hartig net, and the second is the hyphal structures that penetrate the root cortex from this mycelial network. These fungi extend into the soil and form well-developed hyphae and rhizomorphs around the roots and into the soil (Wilcox, 1971; Peterson and Farquhar, 1994; Marschner, 1995). Endomycorrhizal fungi, on the other hand, live within the cortical cells of the root and develop intercellularly or intracellularly. The most well-known types of Endomycorrhizae, which have only a few species, are Ectomycorrhiza, Orchid Mycorrhiza, and Arbuscular Mycorrhiza (AM) (Smith and Read, 2008; Marschner, 1995). Research on mycorrhizae has particularly focused on Arbuscular Mycorrhiza (AM), which belongs to the endomycorrhizal life forms, due to its significant contributions to plant health (Demir, 1998). The electron microscope image of branching AM fungi within plant roots is illustrated in Figure 1.

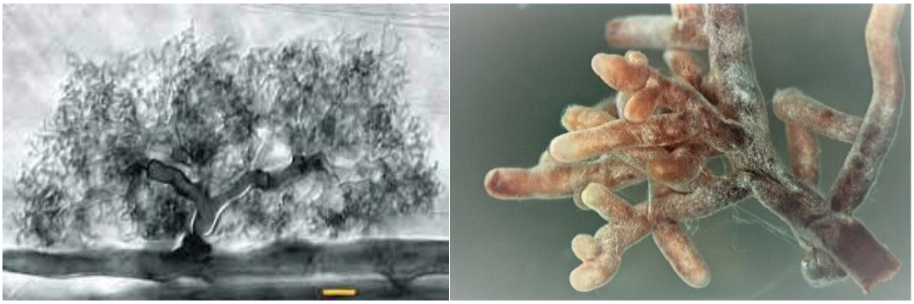


Figure 1: Image of sucking hyphae of AM fungi branching within the root cortex.

1.1. Arbuscular Mycorrhizal Fungi (AMF)

Endomycorrhizal fungi enter plant roots through the epidermis and root hairs, progressing through intercellular spaces and also penetrating root cells.

Inside the cells, they form hyphae, oval structures called vesicles, and specialized branched structures known as arbuscules. These structures are involved in the exchange of nutrient ions between the host plant and the fungus (Almaca et al., 2013).

Initially, endomycorrhizal fungi were referred to as vesicular-arbuscular mycorrhiza (VAM) due to their vesicular and arbuscular structures. However, since not all species possess vesicles, the term "arbuscular mycorrhizal fungi" (AMF) and the abbreviation AMF have become more commonly used (Smith and Read, 2008). Mycorrhizal associations with plants vary greatly in structure and function, but the majority are seen as arbuscular mycorrhizal associations (Smith and Read, 2008).

The taxonomy of AM fungi was classified by Morton and Benny in 1990. The classification is organized as follows (Morton and Benny, 1990):

- **Class:** ZYGOMYCETES
- **Order:** Glomales
  - **Suborder 1:** Glominae
    - **Family 1:** Glomaceae
      - **Genus:** Glomus
    - **Family 2:** Acaulosporaceae
      - **Genera:** Acaulospora, Entrophospora
  - **Suborder 2:** Gigasporineae
    - **Family:** Gigasporaceae
      - **Genera:** Gigaspora, Scutellospora

Arbuscular mycorrhizal fungi (AMF), an important form of endomycorrhizal association, have established symbiotic relationships with almost all terrestrial plants, including crops. This is the most common type of symbiosis among ecto- and endomycorrhizae. Since the early 1950s, research has increasingly focused on AM fungi (Gerdemann, 1968; Mosse, 1973; Bethenfalvay, 1992; Marschner, 1995). Schenck (1991) attributed the interest in AM fungi to their various host-promoting properties.

AM fungi are distinguished by their arbuscules, which function similarly to absorptive hyphae (analogous to haustoria), as well as vesicles that store nutrients and energy, and an extensive mycelium that encases the surrounding soil (Bonfante-Fasolo, 1984; Brown and King, 1991). The germination and growth of AM fungal spores are influenced by various factors, including soil pH, temperature, drought conditions, the levels of minerals and organic matter in the soil, the presence of host plants, and other microorganisms (Kapulnik and Douds, 2000a).

Besides enhancing nutrient absorption, AM fungi boost a plant's resilience to saline and drought stress, heavy metal toxicity, and heat stress. They also encourage the plant to produce growth-enhancing substances such as hormones. Additionally, some mycorrhizal fungi envelop soil aggregates with their mycelium, which helps improve soil structure by secreting enzymes, thereby mitigating soil erosion (Tisdall, 1994).

AM fungi enhance plant growth, particularly in nutrient-poor or marginal soils. This benefit arises from the fungi's superior ability to absorb certain macro and micronutrients from the soil, with phosphorus being particularly notable. In exchange, the fungi receive organic compounds and carbohydrates from the plant. This reciprocal relationship is advantageous to the plant, which gains more from the association with AMF. Both partners gain mutual benefits under specific conditions. (Bolan et al., 1987; Li et al., 1991).

AMF affect plant growth by enhancing root development and absorption capacity, leading to improved nutrient and water uptake and cell renewal in roots. They also promote the absorption of essential nutrients, including N, Ca, Cu, Mn, S, and Zn, in addition to P (Sieverding, 1991; Ortaş, 2002). Under drought conditions, AMF induce the production of healing compounds and hormones such as arginine, isoflavonoids, cytokinins, and gibberellins in roots as a response (Muchovej, 2001).

Many plants struggle to absorb certain nutrients, especially P, due to various environmental and soil-related factors. AMF absorb less soluble or insufficiently available nutrients, particularly P, and make them available to the plant. It has also been reported that AMF increase the host plant's tolerance to soil fungi, nematodes, and obligate pathogens (Demir and Onoğur, 1999). AMF are noted for promoting root renewal, accelerating plant growth, and reducing chemical fertilizer use (Kara and Tilki, 2001).

One study emphasized the importance of AMF, noting their impact on plant biodiversity, their role in controlling nematodes and pathogen fungi, and their contribution to the healthy development of plants in polluted and arid lands (Souza, 2015). AMF are obligate symbiotic organisms that develop extra-radical hyphal networks from germinated spores in the presence of the host plant. These hyphae are great importance part of the mycorrhizal function, serving as a bridge for nutrient transfer between the roots and the soil (Smith and Read, 2008).

1.1.1. Life Cycle of AM Fungi

Arbuscular Mycorrhizal Fungi (AMF) are compulsory biotrophic organisms that live symbiotically in the roots of host plants. As obligate biotrophs, they obtain their nutrients from living cells of the host plant without causing significant harm to it.

AM fungi cannot be cultivated in culture without a host plant. Most species produce spores in the soil, and these spores are capable of germination regardless of the presence of a host plant. These spores can germinate under various soil structures and environmental conditions; however, they cannot produce extensive mycelium or complete their life cycle without the presence of a host plant. The presence of a host plant is essential for complete their life cycle and fulfill their symbiotic functions. (Kapulnik and Douds, 2000a). The infection of corn root regions by AMF spores and the formation of arbuscules in root cells are illustrated in Figure 2.

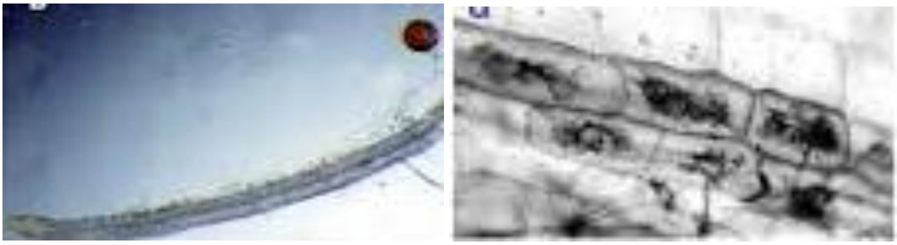


Figure 2: a) Infection of the host plant (corn) with AMF spores b) Arbuscule formation within the cortical root cells

1.1.2. Formation Process, Structure, and Host Plant Relationship of AM Fungi

Arbuscular Mycorrhizal Fungi (AMF), as obligate microorganisms, initially interact with plants in a manner akin to pathogenic fungi before establishing a symbiotic relationship (Dehne, 1982). The process initiates with the development of appressoria on the root surface, which facilitates the fungal hyphae's entry into the host tissue. Once inside, AMF colonize the root cortex either between the cells (intercellularly) or within the cells (intracellularly). This penetration generally occurs in the epidermal cells at the rear of the meristematic zone in young roots, though in some plant species, it can also occur through root hairs. The growing hyphae may exhibit irregular shapes and vary in size, developing either between or within cells. Both intercellular and intracellular connections are frequently observed. During periods of rapid growth, the hyphae lack septa, but they become septate when conditions become less favorable. AM hyphae can proliferate both inside the root and externally (Linderman, 1988; Smith et al., 1992).

Once fungal hyphae penetrate the root cortex, they quickly form arbuscules within the cortical cells. These arbuscules, which are akin to haustoria, appear at the extremities of the hyphae and, in some plant species, may also be observed along the lateral surfaces of the hyphae as they progress through the cells. Arbuscules are transient structures with a lifespan of about 10-12 days. They start to deteriorate from their tips due to the host cell's influence before they fully mature, and are ultimately taken up by the plant. These arbuscules are thinked to play a significant role in the metabolite exchange between the fungus and the plant (Gerdemann, 1968; Dehne, 1982; Bonfante-Fasolo, 1984; Smith et al., 1992; Marschner, 1995).

Vesicular structures of AMF are used for nutrient storage, while arbuscular structures are specialized for nutrient exchange between mycorrhizae and the host plant. In this symbiotic relationship, the fungus is dependent on the host for carbon because it cannot photosynthesize.

Arbuscular mycorrhizal fungi represent the most complex group of mycorrhizal fungi and form structures within and between roots. These fungi are characterized by (1) whorls forming intracellular hyphae, often in the outer layers of the cortical parenchyma, (2) intracellular hyphae, (3) highly branched intercellular hyphae, i.e. arbuscules, and (4) vesicles exhibiting intracellular and intercellular hyphae. hypertrophy.

Arbuscules, which are highly branched structures, typically form within the inner cortex. They are temporary structures created by repeated branching and complete their development within 4 to 5 days. Arbuscules are important loci for nutrient excahnge and continue to function actively for only 4-15 days. Most arbuscular mycorrhizal fungi later form terminal or intermediate vesicles in the root cortex. These vesicles are expanded, thin-walled structures rich in lipids, separated by a septum, and resemble resting spores. Vesicles serve as endophytic storage organs and are rich in lipids (Verma et al., 2008).

Nutrient exchange between AMF and the host plant occurs through the intraradical hyphae of the AM fungus and the root cells of the host plant. Penetrating into root tissues, AMF hyphae form specialized AMF organelles called vesicles and arbuscules. Arbuscules are highly characterized hyphae of AMF and rapidly branch into a tree-like structure after penetrating root cortical cells. The formation of arbuscules changes the structure of stem cells. Research shows that arbuscules are organelles responsible for nutrient transfer. Fungal cell walls become thinner as AMF hyphae penetrate root cortical cells to form arbuscules. Chitin, a primary constituent of the fungal cell wall, is fibrils in extraradical and intercellular hyphae. The plasma membrane of the host cell extends inward to surround the developing arbuscule, forming a sheath around it known as the periarbuscular membrane. The plant cell wall is very close to the periarbuscular membrane and there is a very narrow gap in between. This area is enriched in β-glucan-glycoproteins, hydroxyproline, N-acetylgalactosamine polysaccharides and galactose residues. (Kapulnik and Douds, 2000b).

Soil respiration increases with AMF colonization in roots. AMF respiration also increases the metabolic activities of plant tissues. Enzyme tissue chemistry analyzes have shown that glycolysis, the tricarboxylic acid (TCA) cycle, and the glucose monophosphate cycle occur in intraradical hyphae. The protein content in the roots increases with the formation of mycorrhiza. According to research, the cytoplasmic content of root cells in mycorrhizal roots is greater compared to non-mycorrhizal roots. (Kapulnik and Douds, 2000c).

2. Mechanism of AMF's Influence on Phosphorus (P) Uptake by Host Plants

Numerous studies conducted up to the present day have revealed that plant nutrients are taken up not only by plant roots but also by AM fungi. Phosphorus (P), one of the particularly significant macronutrients, plays an important role in the plant's nutrient acquisition process.

AM fungi have garnered significant attention from researchers across various fields due to their contributions to phosphorus uptake. It has been reported that in more than 90% of natural plant communities, symbiotic AM fungi play a decisive role in the uptake of phosphorus by plants (Smith et al., 1992). Besides their role in phosphorus nutrition, some plant species rely entirely on the presence of AM fungi for their survival.

In addition to phosphorus, AM fungi also have secondary effects on the uptake of micronutrients such as Zn, Cu, Mn, Fe, and Ca, as well as macronutrients like K and N (Hayman, 1982). AM fungi are generally effective in marginal soils with low nutrient levels, as reported by Egboka et al., (2022).

It has been noted that mycorrhizal plants growing in unfertilized and non-cultivated soils are more sensitive to phosphorus uptake compared to mycorrhizal plants growing in fertilized soils, with increased phosphorus content suppressing mycorrhizal formation. Additionally, the potential for using these fungi in the rehabilitation of mining soils and in agricultural practices has been highlighted (Tarafdar and Rao, 1997).

Phosphorus, which is heavily fixed in the soil and limited in plant uptake, is more readily available to plants through AM fungi. The mechanism by which mycorrhizal plants acquire several times more phosphorus compared to non-mycorrhizal plants has been explained by various researchers as follows (Hayman, 1982; Bolan, 1991; Smith et al., 1992):

a) AMF release certain enzymes and acidic fluids that lower the pH around the plant roots, making inorganic phosphates, which are very low in solubility, more available.

b) These fungi take up organic phosphorus compounds that are not readily available to the plant, using them as a nutrient source. They then convert these phosphorus compounds into a more usable form within the hyphal cells and transport them to the plant roots.

c) AMF hyphae create a sponge-like absorptive surface on the plant root surface, collecting phosphorus compounds that have been converted to a usable form by various activities in the soil, and transport these compounds to the plant roots through the hyphae.

AM fungi are in contact with microorganisms in the root, rhizosphere, and soil. These interactions can be either inhibitory or stimulating, with instances of competition as well as mutual benefits. Such interactions can be observed throughout the entire life cycle of the mycorrhizal fungus, from the dynamics of spore populations to the colonization of roots by external hyphae (Fitter and Garbaye, 1994).

3. Relationship Between AM Fungi and Drought

Arbuscular mycorrhiza (AM) synthesizes a hydrophobic protein called glomalin that protects hyphae from desiccation and promotes the aggregation of soil around the root system, enhancing contact between roots and mineral elements and water in the rhizosphere. This property of AM fungi associated with plants increases plant resistance to drought and other environmental stressors (Davies, 2008).

A study conducted by Kara and Tilki (2001) reported that AM fungi enhance the absorption of water and nutrients by plants, thereby increasing the plant's tolerance to high temperatures, high pH, diseases, and pests.

Palta et al. (2010) emphasized the ecological significance of mycorrhizal fungi due to their interactions both inside and outside the roots of their host plants. They also reported that AM fungi, through their extra-matrical (external) hyphae, expand the surface area of plant roots, allowing the plant to better utilize the soil it occupies, and increase the plant's resistance to abiotic stressors, including drought, salinity, and heavy metal toxicity. AM fungi were found to stimulate the production of phytohormones (ABA, Proline) that enhance tolerance in plants.

AM fungi increase drought resistance in corn by causing biochemical changes (such as better osmotic pressure regulation and reduced ABA and Proline secretion), altering root morphology (such as promoting the formation of more new roots for better water uptake), and improving root contact with soil moisture through the formation of more extra-radical hyphae (Xu et al., 2015).

Under abiotic stress conditions, such as drought and high heat, the balance of the symbiotic relationship between AM fungi and the host plant may be disrupted. Nevertheless, both the host plant and the mycorrhizal fungus typically strive to preserve a balanced state (Kapulnik and Douds, 2000b). Chemical analyses of intra-radical hyphae have revealed the presence of lipid and polyphosphate granules. Neutral lipids are also found in large amounts in vesicles and intercellular hyphae, and it is believed that neutral lipids present in spores serve as a carbon reserve (Kapulnik and Douds, 2000a). Additionally, chemical analyses indicate that mycorrhizae contain various chemical components, including sugars, carbohydrates, lipids, amino acids, and fatty acids (Kapulnik and Douds, 2000c).

3.1. Relationship Between Corn and AMF Under Drought Conditions

A multitude of researchs have been carried out globally on the contributions of arbuscular mycorrhizal fungi (AMF) to plants. A significant portion of these studies focuses on vegetable species, medicinal aromatic plants, and corn (Erzurumlu and Kara, 2014). The contributions of AMF to corn include: (i) rapid growth during the corn seedling stage, (ii) reduced phosphorus (P) requirements for corn, (iii) increased tolerance of corn to the pathogen Ustilago maydis (DC) Corda, (iv) improved resilience to abiotic stresses, including drought and extreme temperatures, (v) higher pollen fertility in corn, (vi) improved uniformity of corn emergence, and (vii) increased corn yield (Cervantes-Gámez et al., 2021).

Corn (Zea *mays L.*) is considered a plant that benefits greatly from symbiosis with AMF (Ureta et al., 2020). Various studies have demonstrated that corn is mycotrophic, meaning it benefits from AMF (Cervantes-Gámez et al., 2021). When AMF is inoculated into corn-cultivated soil and a symbiotic relationship is established, increased soil aggregation has been observed (Xu et al., 2015). This increase is more pronounced at the soil surface but decreases with soil depth (Carrillo-Aguilar et al., 2021).

According to Sukmawati et al. (2021), the inoculation of AMF species such as Glomus, Gigaspora, and Acaulospora into corn-cultivated soil increases the number of soil spores compared to non-inoculated treatments and improves leaf area index and plant height. Additionally, it was noted that phosphorus (P) nutrient content increased while AMF spore numbers decreased.

Both natural and exogenous (inoculated) AMF have been reported to enhance corn yield improve morphological traits (Cozzolino et al., 2013; Moreira-Salgado et al., 2017). These positive developments in corn can be attributed to the AMF's role in facilitating greater uptake of nitrogen and phosphorus from the soil and enhancing tolerance to drought stress (Wahid et al., 2020; Saboor et al., 2021). Mena-Echevarría et al. (2013) found that corn inoculated with single or multiple AMF species effectively supports plant development and increases corn yield, with taller plants observed in inoculated treatments compared to non-inoculated ones (Colina-Navarrete et al., 2020).

In corn fields within the same region but different areas, it has been declarated that different AMF species colonize each area due to variations in soil physical and chemical properties (Bueno et al., 2022). Different host and soil structures, as well as abiotic and biotic stress factors, lead to the formation of various AMF species (Cozzolino et al., 2013).

It has been documented that a correlation exists between native AMF species and the edaphic structure of the soil, which positively affects the uptake of phosphorus (P) and nitrogen (N) by the plant, thereby improving corn growth and yield. Additionally, native AMF species help tolerate drought stress due to their hydric properties (Bueno et al., 2022).

In another study, physical and chemical analyses of two contrasting soils used as substrates for corn revealed different arbuscular mycorrhizal fungal (AMF) communities. In the fine-clayey, mixed, superactive, acid-free, and thermal soil, nine native AMF species (Rhizophagus aggregatus, Funneliformis geosporum, Paraglomus occultum, Diversispora aurantia, Diversispora trimurales, Gigaspora kandida, Gigaspora gigantean, Acaulospora mellea, and Septoglomus sp.) were found. In the coarse, mixed, semi-active, and thermal soil, only three of the nine AMF species (Funneliformis geosporum, Paraglomus occultum, and Diversispora aurantia) were present. Furthermore, the natural AMF populations in each soil affected the activity of allochthonous AMF inoculations. It was also reported that fertilization, compared to non-fertilized treatments, more significantly reduced the activity of AMF (native or allochthonous) and, consequently, the stability of soil aggregates. However, further research is needed to determine whether this result applies to all soil types (Gómez-Leyva et al., 2023).

Arbuscular mycorrhizal fungi (AMF) have been shown to increase corn's tolerance to drought (Zhao et al., 2015). Corn subjected to different levels of drought (full irrigation, moderate irrigation, and severe drought) was inoculated with the AMF species Rhizophagus intraradices. As drought severity increased, AMF colonization in the root zone increased, and nitrogen (N) and phosphorus (P) uptake also increased. Additionally, corn plants inoculated with AMF rehydrated more quickly than non-inoculated plants (Birhane et al., 2012).

Quiroga et al. (2017) demonstrated that corn plants inoculated with AMF have increased tolerance to various levels of drought stress by regulating their aquaporins. The study aimed to compare the effects of AMF symbiosis on root aquaporins and their impact on physiological parameters. Compared to drought-tolerant corn varieties, AMF symbiosis had a more positive effect on physiological parameters in drought-sensitive varieties. The measured physiological parameters included biomass, chlorophyll content, cell membrane stability, and soluble dry matter. Notably, aquaporins worked more efficiently in drought-sensitive corn varieties inoculated with AMF. Furthermore, AMF symbiosis is critical for maintaining water availability, plant viability, and yield during drought periods. The formation of spores in corn roots during the seedling the phase is showed in Figure 3.

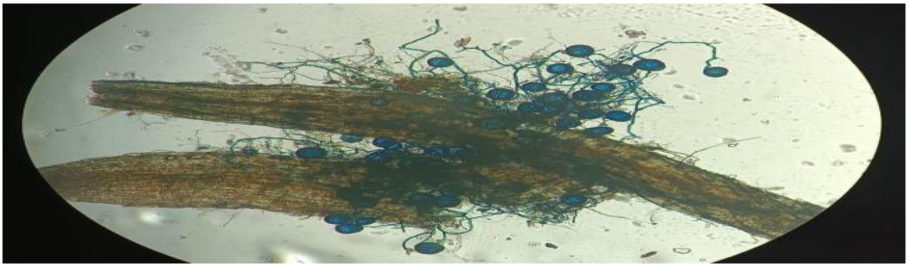


Figure 3: Microscopic image of the symbiosis between AMF (Glomus *iranicum var*.) and maize roots, including AMF spores.

4. CONCLUSION

In the plant-mycorrhizal symbiosis, fungi play a supportive rather than a parasitic role. The rapidly growing hyphae, both inside and outside the plant roots, assist in the uptake of external water and mineral nutrients, while the plant provides organic matter to the fungi. This mutualistic relationship is inherently dynamic and maintains nutrient cycling and plant vitality within the ecosystem. From a different perspective, the advantage of mycorrhizae to the plant is their ability to access soil nutrients more effectively, while the benefit to the fungi is the provision of a living environment, nutrients, and a surface for attachment.

Numerous plants worldwide have been found to form symbiotic partnerships with fungi. Arbuscular mycorrhizal fungi (AMF), in particular, are more prevalent in impoverished soils and areas experiencing biotic or abiotic stress conditions, where they form more spores and establish symbiotic relationships with host plants. In less favorable ecological and soil conditions, AMF play a crucial role by creating additional arbuscular structures within plant roots, thereby enhancing the plant's absorbsion of N, P and micronutrients, as well as improving water absorption. This, in turn, contributes to plant growth and enhances resistance to both abiotic and biotic stresses, including soil-borne pathogens and drought.

Based on this information, for crops of significant importance to human and animal life, such as corn, it is beneficial to inoculate with suitable AMF species, in addition to the naturally occurring soil AMF, to improve resistance to abiotic and biotic factors.

REFERENCES

Almaca, A., Almaca, N. D., Söylemez, S. and Ortaş, İ. (2013). The effects of mycorrhizal species and differentdoses of phosphorus on pepper (Capsicum *annuum L.)* yield and development under field conditions. ***Journal of Food, Agriculture & Environment (JFAE)***, 11(3-4): 647-651.

Anonymous (2024). World population prospects, Available online: https://www.worldometers.info/worldpopulation/#:~:text=8.1%20Billion%20(current)&text=The%20term%20%22World%20Population%22%20refers,currently%20living)%20of%20the%20world (Access date: 24/03/2024).

Aroca, R., Porcel, R. and Ruiz-Lozano, J. M. (2007). How does arbuscular mycorrhizal symbiosis regulateroothydraulicproperties and plasma membran eaquaporins in Phaseolus vulgaris under drought, cold or salinity stresses? ***New Phytologist***, 173 (4): 808–816. https://doi.org/10.1111/j.1469-8137.2006.01961.x

Asrar, A. A., Abdel-Fattah, G. M. and Elhindi, K. M. (2012). Improving growth, flower yield, and water relations of snapdragon (Antirhinum *majus L.*) plants grown under well-watered and water-stress conditions using arbuscular mycorrhizal fungi. ***Photosynthetic,*** 50 (2): 305–316. http://10.1007/s11099-012-0024-8

Augé, R. M., Toler, H. D., Moore, J. L., Cho, K. and Saxton, A.M. (2007). Comparing contributions of soil versus root colonization to variations in stomatal behavior and soil drying in mycorrhizal Sorghum bicolor and Cucurbita pepo. ***Journal of Plant Physiology***, 164 (10): 1289-1299. https://doi.org/10.1016/j.jplph.2006.08.005

Bahraminia, M., Zarei, M., Ronaghi, A., Sepehri, M. and Etesami, H. (2020). Ionomic and biochemical responses of maize plant (Zea *mays L.*) inoculated with Funneliformis mosseae to water-defcit stress. ***Rhizosphere***, 16, 100269. https://doi.org/10.1016/j.rhisph.2020.100269

Bárzana, G., Aroca, R., Bienert, G. P., Chaumont, F. and Ruiz-Lozano, J. M. (2014). New insights into the regulation of aquaporins by the arbuscular mycorrhizal symbiosis in maize plants under drought stress and possible implications for plant performance. ***Molecular Plant-Microbe Interactions***, 27(4): 349-63. http://10.1094/MPMI-09-13-0268-R

Begum, N., Ahanger, M. A., Su, Y., Lei, Y., Mustafa, N.S.A., Ahmad, P. and Zhang, L. (2019). Improved drought tolerance by AMF inoculation in maize (Zea *mays L.*) involves physiological and biochemical implications. ***Plants***, 8, 579. http://10.3390/plants8120579

Bennett, A. E. and Groten K. (2022). The costs and benefits of plant–arbuscular mycorrhizal fungal interactions. ***Annual Review of Plant Biology***, 73:649-672. https://doi.org/10.1146/annurev-arplant-102820-124504

Bethlenfalvay, J.G (1992). Mycorhizae and crop productivity. Mycorhizae in Sustainable Agriculture. ***ASA Special Publication***, number 14, p: 1 - 27.

Birhane, E., Sterck, F.J., Bongers, F. and Kuyper, T.W. (2013). Arbuscular mycorrhizal impacts on competitive interactions between *Acacia etbaica* and *Boswellia papyrifera* seedlings under drought stress. ***Journal of Plant Ecology***, 7(3): 298-308. https://doi.org/10.1093/jpe/rtt031

Birhane, E., Sterck, F.J., Fetene, M., Bongers, F. and Kuyper, T.W. (2012). Arbuscular mycorrhizal fungi enhance photosynthesis, water use efficiency, and growth of frankincense seedlings under pulsed water availability conditions. ***Oecologia,*** 169(4): 895-904.

Bolan, N. S., Robson, A.D. and Barrow N. J. (1987). Effects of vesicular-arbuscular mycorhizae the availability of ıron phosphates to plants. ***Plant and Soil***, 99: 401-410.

Bompadre, M.J., Silvani, V.A., Bidondo, L.F., de Molina, M.D.C.R., Colombo, R.P., Pardo, A.G. and Godeasa, A.M. (2014). Arbuscular mycorrhizal fungi alleviate oxidative stress in pomegranate plants growing under different irrigation conditions. ***Botany***, 92 (3): 187-193. https://doi.org/10.1139/cjb-2013-0169

Bonfante-Fasolo, P. (1984). Anatomy and morphology of va mycorrhizae. pp: 5 - 33 in: VA Mycorrhiza. Ed., C.L.I. Powel and D.J. Bagyaraj. CRC Press. Boca Rafon, Florida/USA

Braga, F.M. (2021). Growth of C3 and C4 plants in response to different CO2 concentrations and competitive arrangements. ***Research, Society and Development***, 10, http://hdl.handle.net/1843/36847

Brown, M.F. and King, E.J. (1991). Morphology and histology of vesicular-arbuscular mycorrhizae. A. anatomy and cytology. In: ***Methods and Principles of Mycorrhizal Research,*** p: 15 21.

Brundrett, M. (1991). Mycorrhizas in naturel ecosystem. ***Advanced in Ecological Research***, 21: 171 - 313.

Brundrett, M.C. (2009). Mycorrhizal associations and other means of nutrition of vascular plants: Understanding the global diversity of host plants by resolving conflicting information and developing reliable means of diagnosis. ***Plant Soil***, 320: 37-77. http://dx.doi.org/10.1007/s11104-008-9877-9

Brundrett, M.C. and Tedersoo, L. (2018). Evolutionary history of mycorrhizal symbioses and global host plant diversity. ***New Phytologist***, 220:1108-1115. https://doi.org/10.1111/nph.14976

Bueno, C.B., dos Santos, R.M., de Souza Buzo, F., de Andrade da Silva, M.S.R. and Rigobelo, E.C (2022). Effects of chemical fertilization and microbial inoculum on bacillus subtilis colonization in soybean and maize plants. ***Frontiers in Microbiology***, 13:901157. http://10.3389/fmicb.2022.901157

Bueno, C.G., Gerz, M., Moora, M., León, D., Gomez-García, D., García de León, D., Fonte, X., Al-Quraishy, S., Hozzein, W.N. and Zobel, M. (2021). Distribution of plant mycorrhizal traits along an elevational gradient does not fully mirror the latitudinal gradient. ***Mycorrhiza***, 31: 149-159. https://doi.org/10.1007/s00572-020-01012-3

Candar-Cakir, B., Arican, E. and Zhang, B. (2016). Small RNA and degradome deep sequencing reveals drought-and tissue-specific micrornas and their important roles in drought-sensitive and drought-tolerant tomato genotypes. ***Plant Biotechnology Journal***, 14(8):1727-1746. http://10.1111/pbi.12533

Carrillo-Aguilar, D.G., Hernández-Ortega, H.A., Franco-Ramírez, A., Vallejo-Jiménez, B., Guzmán-González, S., ManzoSánchez, G. and Sánchez-Rangel, J.C. (2021). Influence of edaphic properties on the abundance of spores and colonization of arbuscular mycorrhizal fungi in banana in two seasons of the year. ***Scientia Fungorum***, 51: e1306. https://doi.org/10.33885/sf.2021.51.1306

Cervantes-Gámez, R.G., Peñuelas-Rubio, O., Araujo-Benard, N., Alicia Fierro-Coronado, R.A., Dora Trejo-Aguilar, D., MaldonadoMendoza, I.E. and Cordero-Ramírez, J.D. (2021). Diversity of arbuscular mycorrhizal fungi associated with volunteer corn plants in transitional soils: natural ecosystem-agricultural use. ***Scientia Fungorum***, 51. e1330. https://doi.org/10.33885/sf.2021.51.1330

Colina-Navarrete, E.; Paredes-Acosta, E.; Gutiérrez-Mora, X. and Vera-Suarez, M. (2020). Effect of nitrogen fertilization in corn (Zea *mays L.*) on populations of mycorrhizal fungi in Babahoyo. ***Journal of Science and Research***, 5: 135-155. http://10.5281/zenodo.4424767

Cozzolino, V., Di Meo, V. and Piccolo, A. (2013). Impact of arbuscular mycorrhizal fungi applications on maize production and soil phosphorus availability. ***Journal of Geochemical Exploration***, 129: 40–44. https://doi.org/10.1016/j.gexplo.2013.02.006

Daryanto, S., Wang, L. and Jacinthe, P.A (2016). Global synthesis of drought effects on maize and wheat production. ***Plos One***, 11(5): e0156362. http://10.1371/journal.pone.0156362

Davies, F.T. (2008). Opportunities from down under: How mycorrhizal fungi can benefit nursery propagation and production systems. ***Combined Proceedings International Plant Propagators' Society***, 58: 539-548.

Dehne, H.W. (1982). Interactions between vesicular-arbuscular mycorrhizal fungi and plant pathogens. ***Phytopathology***, (72): 1115-1119.

Demir, S. (1998). Studies on vesicular-arbuscular mycorrhiza (VAM) formation in some crop plants and ıts role in plant development and resistance. Ege University, Institute of Science, Department of Plant Protection, *PhD Thesis*, 114 p. İzmir/Turkey.

Demir, S. and Onoğur, E. (1999). The importance of vesicular-arbuscular mycorrhiza formation in plants in plant nutrition and plant protection. ***Anatolia Journal***, 9(2): 12-32.

Diagne, N., Ngom, M., Djighaly, P.I., Fall, D., Hocher, V. and Svistoonoff, S. (2020). Roles of arbuscular mycorrhizal fungi on plant growth and performance: Importance in biotic and abiotic stressed regulation. ***Diversity***, 12 (10): 370. https://doi.org/10.3390/d12100370

Egboka, N.T., Fagbola, O., Nkwopara, U.N., Okoli, N.H., Afangide, A.I. and Nwosu, T.V. (2022). Density of arbuscular mycorrhizal fungi and nutrient status of soils in selected land use types and soil depths. ***Sarhad Journal of Agriculture***, 38(2): 633-647. https://dx.doi.org/10.17582/journal.sja/2022/38.2.633.647

Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M. and Gerten, D., et al. (2014). Constraints and potentials of future irrigation water availability on agricultural production under climate change. ***Proceedings of the National Academy of Sciences***. 111, 3239-3244. U.S.A. http://10.1073/pnas.1222474110

Erzurumlu, G.S. and Kara E.E. (2014). Studies on mycorrhiza in Turkey. ***Turkish Journal of Scientific Reviews***, 7 (2): 55-65.

Fitter, A.H. and Garbaye, J. (1994). Interactions between mycorrhizal fungi and other soil organism. ***Plant and Soil***, 159(1): 123-133.

Gerdemann, J.W. (1968). Vesicular-arbuscular mycorhiza and plant growth. ***Annual Review of Phytopathology***. 6: 397-418.

Ghorchiani, M., Etesami, H. and Alikhani, H.A. (2018). Improvement of growth and yield of maize under water stress by co-inoculating an arbuscular mycorrhizal fungus and a plant growth promoting rhizobacterium together with phosphate fertilizers. ***Agriculture, Ecosystems & Environment***, 258: 59–70. https://doi.org/10.1016/j.agee.2018.02.016

Gómez-Leyva, J.F., Segura-Castruita, M.A., Hernández-Cuevas, L.V. and Íñiguez-Rivas, M. (2023). Arbuscular mycorrhizal fungi associated with maize (Zea *mays L.)* in the formation and stability of aggregates in two types of soil. ***Microorganisms***, 11: 2615. https://doi.org/10.3390/microorganisms11112615

Habibzadeh, Y., Pirzad, A., Zardashti, M.R., Jalilian, J. and Eini, O. (2013). Effects of arbuscular mycorrhizal fungi on seed and protein yield under water-deficit stress in mung bean. ***Agronomy Journal***, 105 (1): 79-84. https://doi.org/10.2134/agronj2012.0069

Harley, J.L. (1975). The Mycorhizal associations. ***Encylopedia of Plant Physiology***, 17: 148-186

Hashem, A., Alqarawi, A.A., Radhakrishnan, R., Al-Arjani Al-B.F., Aldehaish, H.A., Egamberdieva D. and Abd_Allah, E.F. (2018). Arbuscular mycorrhizal fungi regulate the oxidative system, hormones and ionic equilibrium to trigger salt stress tolerance in Cucumis sativus L.. ***Saudi***

Journal of Biological Sciences, 25(6): 1102–1114 https://doi.org/10.1016/j.sjbs.2018.03.009

Hayman, D. (1981). Mycorhiza and it's significance in horticulture. ***The Plantsman***, 2(4): 214-224.

Hayman, D. (1982). Influence of soils and fertility on activity and survial vesicular-arbuscular mycorrhizal fungi. ***Phytopathology***, (72): 1119-1126.

Horn, S., Hempel, S., Verbruggen, E., Rillig, M.C. and Caruso, T. (2017). Linking the community structure of arbuscular mycorrhizal fungi and plants: A story of interdependence. ***The ISME Journal***, 11 (6): 1400–1411. https://doi.org/10.1038/ismej.2017.5

Kapulnik, Y. and Douds, D.D. Jr (eds.) (2000a). Arbuscular mycorrhizas: physiology and function. ***Kluwer Academic Publishers***, p: 47-68, Netherlands.

Kapulnik, Y. and Douds, D.D. Jr (eds.) (2000b). Arbuscular mycorrhizas: physiology and function. ***Kluwer Academic Publishers***, p: 85-106, Netherlands.

Kapulnik, Y. and Douds, D.D. Jr (eds.) (2000c). Arbuscular mycorrhizas: physiology and function. ***Kluwer Academic Publishers***, p: 3-18, Netherlands.

Kara, Ö. and Tilki, F. (2001). Mycorrhiza and its use in forestry. Istanbul University, ***Faculty of Forestry Journal***, 51 (1): 127-139.

Lazcano, C., Barrios-Masias, F.H. and Jackson, L.E., (2014). Arbuscular mycorrhizal effects on plant water relations and soil greenhouse gas emissions under changing moisture regimes. ***Soil Biology and Biochemistry***, 74: 184–192. https://doi.org/10.1016/j.soilbio.2014.03.010

Li, X. L., Marschner, H. and George, E. (1991). Extension of the phosphorus depletion zone in VA mycorrhizal white clover in a calcareous soil. ***Plant and Soil***, 135: 41-48.

Linderman, R.G. (1988). Mycorrhizal interactions with the rhizosphere microflora: The mycorrhizosphere effect. ***Phytopathology***, 78 (3): 366-370.

Lu, X., Lu, X. and Liao, Y. (2018). Effect of tillage treatment on the diversity of soil arbuscular mycorrhizal fungal and soil aggregate-associated carbon content. ***Frontiers in Microbiology***, 9:2986. http://10.3389/fmicb.2018.02986

Marschner, H. (1995). Mycorrhizas. Mineral nutrition of higher plants (Second Edition), Academic Press. pp.566-595.

Mathur, S. and Jajoo, A. (2020). Arbuscular mycorrhizal fungi protect maize plants from high temperature stress by regulating photosystem II heterogeneity. ***Industrial Crops and Products***, 143, 111934. https://doi.org/10.1016/j.indcrop.2019.111934

Mena-Echevarría, A., Fernández, K., Olalde, V. and Serrato, R. (2013). Differences in the response of corn (Zea *mays L*.) to inoculation with glomus cubense (Y. Rodr. & Dalpé) and with a conglomerate of arbuscular mycorrhizal fungal species (AMF). ***Tropical Crops***, 34 (2): 12-15.

Michalis, O., Ioannides, I.M. and Ehaliotis, C. (2013). Mycorrhizal inoculation affects arbuscular mycorrhizal diversity in watermelon roots but leads to improved colonization and plant response under water stress only. ***Applied Soil Ecology***, 63: 112–119. https://doi.org/10.1016/j.apsoil.2012.09.013

Moebius-Clune, D.J., Moebius-Clune, B.N., Van Es, H.M. and Pawlowska, T.E. (2013). Arbuscular mycorrhizal fungi associated with a single agronomic plant host across the landscape: Community differentiation along a soil textural gradient. ***Soil Biology and Biochemistry***, 64: 191–199. https://doi.org/10.1016/j.soilbio.2012.12.014

Moreira-Salgado, F.H., Sousa-Moreira, F.M., Siqueira, J.O., Barbosa, R.H., Paulino, H.B. and Carbone-Carneiro, M.A. (2017). Arbuscular mycorrhizal fungi and colonization stimulant in cotton and maize. ***Ciência Rural***, 47(6): e20151535. https://doi.org/10.1590/0103-8478cr20151535

Morton, J.B. and Benny, G.L. (1990). Revised classification of arbuscular mycorrhizal fungi (Zygomycetes): a new order, glomales, two new suborders, Glominae and Gigasporinae and two new families Acaulosporaceae and Gigasporaceae with Emendation of Glomaceae. ***Mycotaxon***, 37: 471-284.

Moser, M. and Haselwandter, K. (1975). Ecophysiology of mycorrhizal symbiosis. ***Encylopedia of Plant Physiology***, Vol: 12, pp.391-421.

Mosse, B. (1973). Advances in the study of vesicular - arbuscular mycorrhiza. ***Annual Review of Phytopathology***, 11: 429- 454.

Muchovej, R.M. (2001). Importance of mycorrhizae for agricultural crops. University of Florida, Extension Instude of Food Agricultural Sciences, SS-AGR-170.

Ortaş, İ. (2002). Do plants depend on mycorrhizae ın terms of nutrient requirement? International Conference On Sustainable Land Use And Management. Çanakkale/Turkey.

Palta, Ş., Demir, S., Şengönül, K., Kara, Ö. and Şensoy, H. (2010). Arbuscular mycorrhizal fungi (AMF), their relationship with plants and soil, their importance in rangeland improvement. ***Bartın Forestry Faculty Journal***, 12 (18): 87-98.

Pavithra, D. and Yapa, N. (2018). Arbuscular mycorrhizal fungi inoculation enhances drought stress tolerance of plants. ***Groundwater for Sustainable Development***, 7: 490–494. https://doi.org/10.1016/j.gsd.2018.03.005

Peterson, R.L. and Farquhar, M.L (1994). Mycorrhizas - integrated development between root and fungi. ***Mycologia***, 86 (3): 311-326.

Pinheiro, C. and Chaves, M.M. (2011). Photosynthesis and drought: Can we make metabolic connections from available data? ***Journal of Experimental Botany***, 62 (3): 869–882. https://doi.org/10.1093/jxb/erq340

Quiroga, G., Erice, G., Aroca, R., Chaumont, F. and Ruiz-Lozano, J.M (2017). Enhanced drought stress tolerance by the arbuscular mycorrhizal symbiosis in a drought-sensitive maize cultivar is related to a broader and differential regulation of host plant aquaporins than in a drought-tolerant cultivar. ***Frontier Plant Science*** 8:1056. http://10.3389/fpls.2017.01056

Ruiz-Lozano, J.M., Porcel, R., Bárzana, G., Azcón, R. and Aroca, R. (2012). Contribution of arbuscular mycorrhizal symbiosis to plant drought tolerance: state of the art. In book: plant responses to drought stress: from morphological to molecular features, Chapter 13, pp. 335-362, Springer-Verlag, Heidelberg, Germany. http://10.1007/978-3-642-32653-0_13

Saboor, A.; Ali, M.A.; Danish, S.; Ahmed, N.; Fahad, S.; Datta, R.; Ansari, M.J.; Nasif, O.; Habib ur Rahman, M. and Glick, B.R. (2021). Effect of arbuscular mycorrhizal fungi on the physiological functioning of maize under zinc-deficient soils. ***Scientific Reports***, 11: 18468. https://doi.org/10.1038/s41598-021-97742-1

Sanchez-Lizarraga, A.L., Arenas-Montaño, V., Marino-Marmolejo, E.N., Dendooven, L., Velazquez-Fernandez, J.B., DavilaVazquez, G., Rodriguez-Campos, J., Hernández-Cuevas, L. and Contreras-Ramos, S.M. (2018). Vinasse irrigation: Effects on soil fertility and arbuscular mycorrhizal fungi population. ***Journal of Soils and Sediments***, 18: 3256-3270. https://doi.org/10.1007/s11368-018-1996-1

Santana, L.R., da Silva, L.N., Tavares, G.G., Batista, P.F., Cabral, J.S.R. and Souchie, E.L. (2023). Arbuscular mycorrhizal fungi associated with maize plants during hydric deficit. ***Scientific Reports***, 13: 1519. https://doi.org/10.1038/s41598-023-28744-4

Schenck, N.C. (1991). Methods and principles of mycorrhizal research, APS Press, 244 p

Sieverding, E. (1991). Vesicular-arbuscular mycorrhizae management in tropical agrosystems. Technical Cooperation, Federal Rebpublic of Germany, 372 p.

Smith, S.E. and Read, D.J. (2008) Mycorrhizal symbiosis. Third Edition, Academic Press, 73(1): 787p, New York/USA

Smith, S.E., Robson, A.D. and Abott, L.K. (1992). The involvement of mycorrhizas in assement of genetically dependent efficiency of nutrient uptake and use. ***Plant and Soil***, 146: 169-172.

Smith, S.E., Robson, A.D. and Abott, L.K. (1992). The involvement of mycorrhizas in assement of genetically dependent efficiency of nutrient uptake and use. ***Plant and Soil***, 146: 169-172.

Souza, T. (2015). Handbook of arbuscular mycorrhizal fungi, Springer International Publishing, 32-33 p.

Strullu-Derrien, C., Selosse, M.A., Kenrick, P. and Martin, FM. (2018). The origin and evolution of mycorrhizal symbioses: from palaeomycology to phylogenomics. ***New Phytologist***, 220:1012–1030. https://doi.org/10.1111/nph.15076

Sukmawati, S., Adnyana, A., Suprapta, D.N., Proborini, M., Soni, P. and Adinurani, P.G. (2021). Multiplication arbuscular mycorrhizal fungi in Corn (Zea *mays L.*) with pots culture at greenhouse. ***E3S Web of Conferences,*** 226, 00044. http://10.1051/e3sconf/202122600044

Tarafdar, J.C. and Rao, A.V. (1997). Mycorrhizal colonization and nutrient concentration of naturally grown plants on gypsum mine spoils in India. ***Agriculture Ecosysistem and Environment***, 61: 13-18.

Tisdall, J.M. (1994). Possible role of soil microorganisms in aggregation in soils. ***Plant and Soil***, 159 (1): 115-123.

Ureta, C., González, E.J.; Espinosa, A., Trueba, A., Piñeyro-Nelson, A. and Álvarez-Buylla, E.R. (2020). Maize yield in Mexico under climate change. ***Agricultural Systems***, 177: 102697. https://doi.org/10.1016/j.agsy.2019.102697

Verma, N., Chaturvedi, S. and Sharma, A.K. (2008). Mass multiplication of AMF using soilless substrates. ***Mycorrhiza News***, 20:11-15.

Wahid, F., Fahad, S., Danish, S., Adnan, M., Yue, Z., Saud, S., Siddiqui, M.H., Brtnicky, M., Hammerschmiedt, T. and Datta, R. (2020). Sustainable management with mycorrhizae and phosphate solubilizing bacteria for enhanced phosphorus uptake in calcareous soils. ***Agriculture***, 10 (8): 334. https://doi.org/10.3390/agriculture10080334

Wang, B. and Qiu, Y.L. (2006). Phylogenetic distribution and evolution of mycorrhizas in land plants. ***Mycorrhiza***. 16(5): 299-363. http://10.1007/s00572-005-0033-6

Wilcox, HE. (1971). Morphology of ectomycorrhizae in Pinus resinosa. In Mycorrhizae, ed, E. Hacskaylo, 54 - 68. U.S. Dept. Agr. Misc. Publ. pp.1189, 225.

Wu, Q.S., Srivastava, A.K. and Zou, Y.N. (2013). AMF-induced tolerance to drought stress in citrus: A review. ***Scientia Horticulturae***, 164: 77-87. https://doi.org/10.1016/j.scienta.2013.09.010

Xu, J., Liu, S., Song, S., Guo, H., Tang, J., Yong, J.W.H., Ma, Y. and Chen, X. (2018). Arbuscular mycorrhizal fungi influence decomposition and the associated soil microbial community under different soil phosphorus availability. ***Soil Biology and Biochemistry***, 120: 181–190. https://doi.org/10.1016/j.soilbio.2018.02.010

Xu, P., Liang, L.Z., Dong, X.Y. and Shen, R.F. (2015). Effect of arbuscular mycorrhizal fungi on aggregate stability of a clay soil inoculating with two different host plants. Acta Agric. Scand. ***B-Soil Plant Science***, 65: 23-29. https://doi.org/10.1080/09064710.2014.960887

Yu, Z., Zhao, X., Su, L., Yan, K., Li, B., He, Y. and Zhan, F. (2021). Effect of an arbuscular mycorrhizal fungus on maize growth and cadmium migration in a sand column. ***Ecotoxicology and Environmental Safety***, 225, 112782. https://doi.org/10.1016/j.ecoenv.2021.112782

Zhang, S., Meng, L., Hou, J., Liu, X., Ogundeji, A.O., Cheng, Z., Yin, T., Clarke, N., Hu, B. and Li, S. (2022). Maize/soybean intercropping improves stability of soil aggregates driven by arbuscular mycorrhizal fungi in a black soil of northeast China. ***Plant and Soil***, 481: 63-82. https://doi.org/10.1007/s11104-022-05616-w

Zhao, R.; Guo, W.; Bi, N.; Guo, J., Wang, L.; Zhao, J. and Zhang, J. (2015). Arbuscular mycorrhizal fungi affect the growth, nutrient uptake and water status of maize (Zea *mays L.*) grown in two types of coal mine spoils under drought stress. ***Applied Soil Ecology***, 88: 41-49. https://doi.org/10.1016/j.apsoil.2014.11.016

CHAPTER 12

WEED DETECTION IN LETTUCE FIELDS VIA IMAGE PROCESSING

Mert EYİLİ[1]

Assoc. Prof. Dr. Emine KAYA ALTOP[2]

[1]Ondokuz Mayis University, Faculty of Agriculture, Department of Plant Protection, Samsun-TÜRKİYE. merteyili@outlook.com, ORCID: 0000-0002-3997-1838
[2] Ondokuz Mayis University, Faculty of Agriculture, Department of Plant Protection, Samsun-TÜRKİYE. kayae@omu.edu.tr, ORCID: 0000-0002-0987-9352
*Produced from Mert Eyili's completed master's thesis at Ondokuz Mayıs University, Institute of Science and Technology, Department of Plant Protection

INTRODUCTION

Lettuce, classified among leafy vegetables, is an annual plant that grows in temperate climates. It matures within 2-3 months and can be cultivated outdoors or under cover year-round. The optimal temperature range for lettuce cultivation is between 15.5 ºC and 18.3 ºC. When temperatures exceed 18 ºC, vegetative growth shifts to generative development, while lettuce can tolerate cold temperatures down to -4 ºC.

Lettuce can be grown either directly from seeds or through seedlings. If seedlings are to be planted in ridges, rows are spaced 40-80 cm apart using tools like a dibble or lister, with plants spaced 15-20 cm within rows. If planting is done on a flat surface, the same spacing is maintained on 120-130 cm-wide strips, with 3-4 lettuce seedlings planted per strip.

The yield is calculated based on the number of plants in lettuce cultivation. In our country, approximately 7,000-8,000 lettuce heads per decare are obtained, corresponding to 3-4 tons per decare by weight (Ministry of Food, Agriculture and Livestock, 2015).

According to 2018 FAO data, 1,270,138 hectares of land globally yielded 27,256,487 tons of lettuce. China ranks first with 15,541,717 tons, accounting for 57% of total global production, followed by the USA (3,677,323 tons) and India (1,222,323 tons). Turkey ranks eighth with 487,543 tons (FAO, 2018).

In our country, three types of lettuce are produced: curly, head, and iceberg. According to 2019 TUIK data, 499,796 tons of lettuce were produced in Turkey, with 198,491 tons of curly, 215,758 tons of head, and 85,547 tons of iceberg lettuce. With this production volume, lettuce ranks second in the leafy vegetable group after cabbage.

According to TUIK 2019 data, Tokat leads in curly lettuce production (24,454 tons), Adana in head lettuce (49,231 tons), and Ankara in iceberg lettuce (43,363 tons).

Weeds in lettuce cultivation reduce crop quality and lead to yield losses. The effects of weeds on lettuce head hardness, leaf size, nitrate, and carotene content are also relatively known (Shrefler et al., 1996).

Due to these characteristics, weed control should begin early before weed development is complete. However, identifying weeds in the early stages can be challenging. Effective control requires the correct identification of weed species.

Traditionally, weed species identification and density calculation are performed using the frame-throwing method. In lettuce fields, a 1-square-meter frame is thrown diagonally, four times in a 1-decare area, eight times in a 2-10 decare area, and twelve times in an 11-20 decare area. The weed species observed within each frame are documented, and density calculations are subsequently derived based on these records. The economic damage threshold is assessed based on this density, and control timing is determined (Odum, 1971).

Image processing and analysis is a rapidly growing field used in various areas, including medicine, agriculture, manufacturing, transportation, communication systems, and space research. Digital image processing, also known as computer vision, involves obtaining and processing visual information via computers. Its importance stems from our primary reliance on vision, enabling us to gather information without physical interaction and analyze information directly from images or videos. Digital image processing has applications like identifying land types in satellite images, robotic control of Mars rovers, and automatic classification of abnormalities in medical images (Dougherty, 2020).

With advancing technology, weed species identification and density calculation can now be performed digitally. Specialized software, such as "Matlab," can be used to detect weeds in agricultural areas. Images captured by drones are processed using specialized software that applies image segmentation techniques to categorize materials into distinct layers, allowing weeds to be identified. Soil, crop plants, and weeds are each segmented into separate layers. When combined with Artificial Neural Networks (ANN), weed species can also be identified within the weed layer.

ANN is a system that performs learning based on the human brain. It learns from prior examples, where interconnected artificial neurons with different weight values form connections. ANN distributes these values across networks, allowing it to handle incomplete data, make decisions amidst uncertainty, and tolerate encountered errors (Öztemel, 2003).

Teaching ANN to recognize different weed species is possible by loading images of the weed species in various conditions and sizes. Future imaging can then identify weed species through these trained networks. With software support from researchers, it is intended that the Image Processing Technique could lead to a universal control method for all weeds in cultivation areas, potentially eliminating chemical control methods. Systems like eradication or laser-based methods are aimed at destroying weeds.

Considering this, lettuce was chosen for this study due to potential imaging issues stemming from planting methods and the lack of plant protection products against problematic weeds in lettuce fields. The study aims to identify weed populations and densities in lettuce fields using the traditional frame-throwing method and the innovative Image Processing Technique and assess how well these techniques support each other.

Only the Image Processing Technique was used in this study to classify weeds as either narrow- or broad-leaved. Since ANN was not utilized, no species identification was conducted.

THEORETICAL FOUNDATIONS AND LITERATURE REVIEW

Weeds Problematic in Lettuce Cultivation Areas

In a study conducted between 2004-2005 by Işık et al. (2009) on organic lettuce cultivation at the Samsun Black Sea Research Institute, the suppressive effect of summer cover crops on weeds was noted. The predominant weed species in the experimental area were barnyardgrass (*Echinochloa crus-galli* (L.) P.B.) (10%), bindweed (*Convolvulus arvensis* L.) (8%), Bermuda grass (*Cynodon dactylon* (L.) Pers.) (6%), purslane (*Portulaca oleracea* L.) (6%), creeping thistle (Cirsium arvense (L.) Scop.) (5%), redroot pigweed (*Amaranthus retroflexus* L.) (5%), and lamb’s quarters (*Chenopodium album* L.) (5%). Other species had a relative presence of less than 5%.

In a study conducted in Erzurum, the critical time for weed control was calculated to be the 13th day after lettuce planting. The average weed density per square meter was found to be 34, with redroot pigweed (*Amaranthus retroflexus* L.) being the most common weed, followed by lamb’s quarters (*Chenopodium album* L.), creeping thistle (*Cirsium arvense* (L.) Scop.), and green foxtail (*Setaria viridis* (L.) Beauv.) (Kaymakçı, 2007).

In 2017, Soylu et al. conducted a study across 75 lettuce gardens in Hatay province, identifying the most prevalent weed species. Each garden's 1-decare area was framed with a 1-square-meter frame, and the weed species and counts within the frame were recorded to calculate density and occurrence frequency. Species were classified as very common (>50%), moderately common (25-49%), less common (12.5-24%), and rare (<12.5%).

In a study conducted in the Ames area of the United States in 2013-2014 on the same lettuce planting area, the dominant weeds in the soil were yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult.), denseflower pepperweed (*Lepidium densiflorum* Schrad.), lamb's quarters (*Chenopodium album* L.), green foxtail (*Setaria viridis* (L.) Beauv.), Pennsylvania smartweed (*Polygonum pensylvanicum* L.), prickly lettuce (*Lactuca serriola* (L.)), and shepherd's purse (Capsella bursa-pastoris (L.) Medik.). Additionally, potatoes were previously cultivated in this area, which has a slope of 2-6% and a fine loamy soil texture (Kruse & Nair, 2016).

In a 2020 study from Brazil, the impact of different fertilization management systems on weeds in lettuce cultivation areas was assessed through phytosociological analysis. Over 3,000 weed samples representing 25 weed species from 11 families were collected from the examined area. Among the collected samples, 88% were dicotyledonous, and 22% were monocotyledonous weed species. The families Asteraceae, Brassicaceae, and Poaceae were identified as the most abundant weed families. The most common weed species in the region were found to be purple nutsedge (*Cyperus rotundus L.*), gallant soldier (*Galinsoga parviflora Cav.*), Brazilian pusley (*Richardia brasiliensis* Gomes), broadleaf woodsorrel (*Oxalis latifolia* HB & K.), Bermuda grass (*Cynodon dactylon* (L.) Pers.), and Canadian horseweed (*Conyza canadensis* (L.) Cronq.) (de Freitas et al., 2020).

Image Processing Technique

Humans rely on vision to interpret the world around us. We look at objects to identify and classify them and scan for differences, and gain a general sense of the scene with a glance. Humans develop highly refined visual skills, enabling us to instantly recognize a face, distinguish colours, and rapidly process large amounts of visual information.

An image is a single picture representing something, such as a person, animal, outdoor scene, a micro-photograph of an electronic component, or a medical scan. Image processing involves enhancing the pictorial information for human interpretation or making it more suitable for independent machine perception by altering the nature of the image (McAndrew, 2004).

The main tasks in image processing include:

- **Image enhancement:** This involves the subjective improvement of image details, such as edge information.
- **Image restoration:** A type of processing that typically provides objective corrections of blurred images and effects that degrade the image, preserving fidelity to the original.
- **Image detection and prediction:** This type of processing enables the detection of the presence or absence of an object or class of objects in an image scene, as well as the estimation of specific attributes and parameters of the object.
- **Image reconstruction:** This process reconstructs two-dimensional spaces from one-dimensional projections, taken at different angles relative to the object.
- **Image data compression:** This involves encoding information based on redundancy, aiming to reduce data storage/transmission needs while preserving overall accuracy.
- **Spectral estimation in images:** Used to develop power density estimates of two-dimensional spectra for image fields.
- **Image analysis:** Represents image data in an interpretable context, often compatible with automated, machine-based processing (Ekstrom, 2012).

RGB images represent three-dimensional colour data, where each pixel value corresponds to intensity levels across red, green, and blue channels. —Red, Green, and Blue—which we can think of as three distinct layers. RGB is the most commonly used colour space for digital image representation, as it corresponds to the three primary colours that blend to produce an image on monitors or similar devices. Each colour axis is within a 0-1 range, scaled to 0-255 for 24-bit image representation, with each colour channel taking 1 byte. The RGB colour space is based on the visible portion of the electromagnetic spectrum, spanning approximately 400-700 nm in wavelength (Solomon & Breckon, 2011).

Matlab, short for "Matrix Laboratory," can display images as matrices with three colour layers. Each point where these three layers meet forms pixels.

The most crucial factor separating soil from vegetation images is colour. The soil image can be isolated by calculating the pixel values forming the brown colour. Additionally, the area of the isolated soil image can be determined based on pixel count within a 1-square-meter area.

The Image Processing Technique is used in many different fields today. This technique aims to obtain information from images by analyzing existing pictures. It is widely used in food quality evaluation. A 2004 study developed a system incorporating a rechargeable device camera, ultrasound, magnetic resonance imaging, computed tomography, and electrical tomography for image acquisition. Image Processing Technique was used for quality evaluation, classifying object size, shape, colour, and texture characteristics using statistical information and artificial neural networks (Du & Sun, 2004).

Animal husbandry is divided into two parts: small livestock and large livestock. Small livestock includes poultry, sheep, goats, and similar animals. Because small livestock is easier to weigh directly, it can be weighed directly. For large livestock, especially cattle, there are some differences in measurement. Accurate, efficient results depend on the cattle's body length, chest condition, height, and width. Technical information can be used in digital image processing to analyze cattle weight (Pradana et al., 2016).

Evaluating cracks is an essential process in the maintenance of concrete structures. Generally, cracks are manually observed, yielding subjective results that depend on the inspector's experience. Additionally, evaluating hard-to-reach structural elements can be time-consuming, expensive, and often unsafe. In a study conducted in South Korea, drone technology combined with digital image processing was used to assess cracks, overcoming the disadvantages of manual visual inspection (Kim et al., 2017).

In the United Kingdom, a system was developed in 2017 to acquire the necessary data using brain images of 10,000 volunteers, allowing for the measurement of image quality (Alfaro-Almagro et al., 2018).

A study conducted in Turkey noted that identifying rocks requires determining the minerals present in the rock and their percentage composition. It was also added that visual analysis of rocks is challenging and that the primary examination is carried out by observing rock sections under a microscope. However, obtaining results is time-consuming, and the results can vary depending on the observer. In the study, a multilayer artificial neural network (ANN) was used to facilitate the digital identification of rocks. Using single and cross-polarized images, the identification of rock-forming minerals such as muscovite, chlorite, quartz, biotite, and opaque minerals was conducted (Baykan, 2010).

There is a study that uses Image Processing Techniques to detect *Escherichia coli* bacteria in drinking water. Detecting *E. coli* bacteria, a pathogen in drinking water, requires approximately 20-24 hours for visual identification. During this process, a sample from drinking water is transferred to an endo agar medium, and the resulting colour change due to bacterial metabolic activities is observed. In the study, a system and an image-processing-based analysis method were developed to shorten this process. Various planting techniques were also tested. As a result, it was demonstrated that bacterial detection could be achieved within 8-10 hours with the developed method (Değirmenci et al., 2019).

A study on vocal cords aimed to obtain information on the vibrations of the vocal cords; however, due to the high speed of image development and the data volume, manual observation seemed impossible. By comparing the system based on the proposed Gaussian Mixture Model with a pixel-based classification model of deep neural networks, glottis detection and segmentation were performed on vocal cord images captured with an endoscopic camera (Yılmaz et al., 2020).

Image Processing Techniques are also used in various fields such as X-rays and biomedical images in medicine, weather forecasting in geography, restoration of old black-and-white or blurry images, electron microscope images, radar images, night vision systems, face and fingerprint recognition, license plate reading, and product classification.

Image Processing Technique in the Agricultural Sector

In a study conducted in California, multispectral images of leaf reflection in the visible and infrared regions at wavelengths between 384 and 810 nm were used to distinguish between lettuce and weeds. An average crop/weed classification accuracy of 90.3% was achieved. To increase classification accuracy, machine vision was used to determine leaf boundaries (Slaughter et al., 2008).

In quality control systems, potato tubers were classified using Image Processing Techniques and artificial neural networks. In a study conducted using Matlab software, potatoes with shape deformities were detected using morphological processes and the Otsu method and were not included in the classification process (Sabancı et al., 2012).

Sabancı et al. (2014) developed a robot that detects weeds between rows in sugar beet fields using Image Processing Techniques and applies herbicide to the identified weeds. In the size estimation of the Napoleon cherry variety, Image Processing Techniques were used. Images of Napoleon cherries were transferred to Matlab software, and size calibration was performed. Based on the calculations, cherries were classified into categories (Balcı et al., 2016).

In a study conducted by Solak et al. (2017), Image Processing Techniques were used to classify hazelnut fruit. After capturing images of hazelnuts in the study setup, the area and size of the hazelnut fruit were calculated with the help of Image Processing Techniques. Based on the calculated data, they were classified into three different categories: small, medium, and large.

In India, a study was conducted in 2017 to detect and classify leaf diseases using digital image processing techniques. The study consisted of four parts: 1) image processing, 2) segmentation, 3) feature extraction, and 4) disease classification (Prakash et al., 2017).

In a study conducted in China, a system was developed to detect weeds using ground-based machine vision. Various techniques were applied to separate vegetation layers and identify weeds within crops. In images obtained using ground-based machinery, preprocessing, segmentation, feature extraction, and classification techniques from Image Processing Techniques were used. Different colour indices, thresholding, and learning-based classification approaches were developed to separate vegetation from the background. The study highlighted that identifying weeds is challenging in scenarios where crops have similar characteristics to weeds, where leaves overlap in images, due to different lighting conditions, and due to varying growth stages of weeds (Wang et al., 2019). In developed countries like the United States, labor shortages have led to an increase in food production costs, creating a need for robotic weed control in vegetables to avoid manual weeding and enhance crop productivity. However, developing reliable, intelligent robotic systems for real-time weed control in vegetables is challenging, as separating weeds from crops presents several issues. In the study, a new crop signalling technique is presented, aiming to separate crops from weeds in complex natural scenarios using real-time machine vision. A machine-vision-based weeding robot with a micro-jet herbicide spraying system was developed for weed control in lettuce fields (Raja et al., 2020).

MATERIAL AND METHOD

Material

The main material of the study consisted of lettuce plants and the problematic weed populations present. In this context, the study was conducted in 10 different lettuce planting areas: 4 in İpekköy village, 1 in Kayabaşı village, 1 in Bulduklu village, 2 in Karaköprü village, 1 in Ovasaray village in Amasya province, and 1 in Bafra district of Samsun province. The GPS coordinates of the study's locations are specified in Table 1.

Table 1. Label and coordinate information of the locations determined for the study

PROVINCE	VILLAGE	LOCATION NUMBER	LATITUDE	LONGITUDE
AMASYA	İpekköy	1	40;36;3.888199	35;48;7.240600
		2	40;36;4.090999	35;48;6.733099
		3	40;36;4.093699	35;48;7.145300
		4	40;36;4.672599	35;48;4.783800
	Kayabaşı	5	40;34;0.651799	35;45;49.82910
	Bulduklu	6	40;36;5.984700	35;47;58.66929
	Karaköprü	7	40;32;12.10839	35;45;9.294500
		8	40;32;12.54600	35;45;11.62840
	Ovasaray	9	40;31;32.48290	35;44;59.44319
SAMSUN	Bafra	10	41;34;37.19109	35;53;54.00040

Method

The study was conducted in two phases. The first phase involved a conventional method, which is based on identifying species and determining population density through the use of a frame. The second phase utilized an innovative method, regarded as a regional pilot application, which involves detecting weeds using Image Processing Techniques.

Calculation of Population Measurement of Weed Species Diagnosed by the Conventional Method

The ten different locations studied cover 27 decares of lettuce planting area. A 1-square-meter frame was used in the study. In areas up to 1 decare, sampling was performed 4 times; in locations with areas between 2-10 decares, sampling was conducted 8 times, preferably moving along the diagonals of the planting area. Accordingly, a total of 72 sampling instances were reached. Table 2 provides the sizes of the planting areas at the locations and the number of samples taken based on these sizes (Odum, 1971).

Table 2. Size of lettuce planting areas and number of samples taken at locations

Location label	Area (da)	Number of samples
LC 1	3	8
LC 2	2	8
LC3	2	8
LC4	1	4
LC 5	7	8
LC 6	1	4
LC 7	2	8
LC8	3	8
LC 9	4	8
LC10	2	8
Total	**27**	**72**

The weed species remaining within the frame were identified, and these species were counted. For each sampling, the identification and counting of weed species were repeated. Figure 1 shows an example of one of the frames that were thrown.

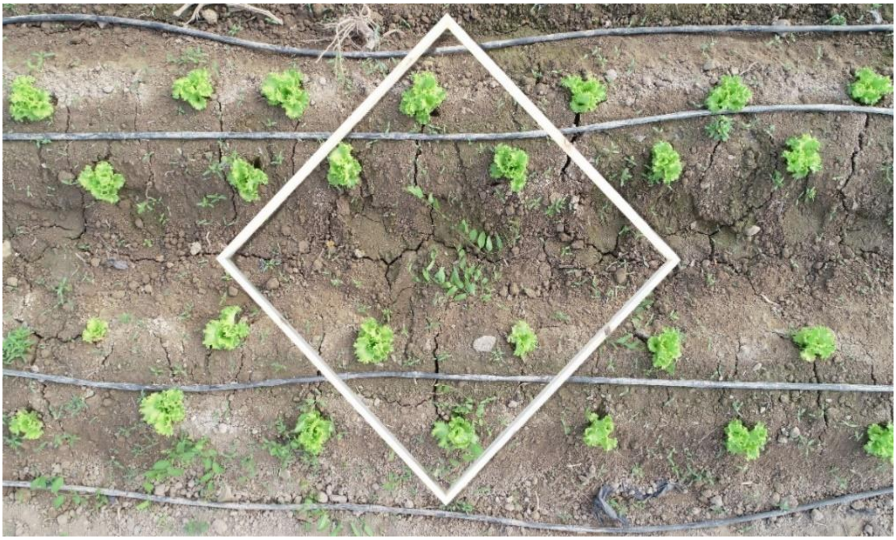


Figure 1. Identification of species and population measurement through frame sampling

The occurrence frequencies and densities of the weed species identified separately at each location were calculated according to the formula provided:

- **RS = M/T x 100**
  RS = Occurrence frequency
  M = Number of locations where the weed species was found during sampling in the region
  T = Total number of locations where sampling was conducted in the region
- **Y (plants/m²) = B/Ç**
  B = Total number of a weed species at a location
  Ç = Total number of frames thrown at the location

The occurrence frequency of a weed species in a region is defined as the ratio of the number of locations found to the total number of locations. All villages studied in Amasya province are located in the Central district. Therefore, the occurrence frequency of a weed species expresses its occurrence frequency in the Central district of Amasya. Since only 1 location was studied in Samsun province, the occurrence frequency is not defined.

The density calculation of a weed species is defined as the total number of that weed species at a location divided by the total number of frames thrown

(Odum, 1971). At this point, the density calculation was performed per-location basis as plants/m².

3.2.2. Detection of Weeds Using Image Processing Method

In the locations where sampling was conducted, images were taken using a drone equipped with a camera capable of capturing photos with a resolution of 20 megapixels and an image size of 5472x3078 pixels. Figure 2 shows example images of the study area taken using the drone.

Figure 2. Aerial images of the planting area for Location 2 (a) and Location 5 (b)

Care was taken to ensure that the rows between the lettuce were not closed due to their density in the areas where the images were taken. Shots were taken in open fields and in closed greenhouse conditions. Different lettuce planting areas were preferred, considering variations such as irrigation systems, soil structure, maturity of the lettuce plants, and types of lettuce.

The obtained images were transferred to a computer environment using the "Matlab" software. Although numerous images were obtained from the examined locations, images containing different conditions were preferred for the transfer to test various scenarios the software could identify (Figure 3 (a)).

Image processing began with the detection of soil, irrigation systems, stones, and other areas excluding vegetation. A colour factor was used to obtain this layer (Figure 3 (b)). Although the colour factor is not a reliable factor for detecting other layers, the absence of vegetation in the studied locations' soil colours or the non-existence of green-coloured soil in nature allows the colour factor to be used confidently in identifying this layer.

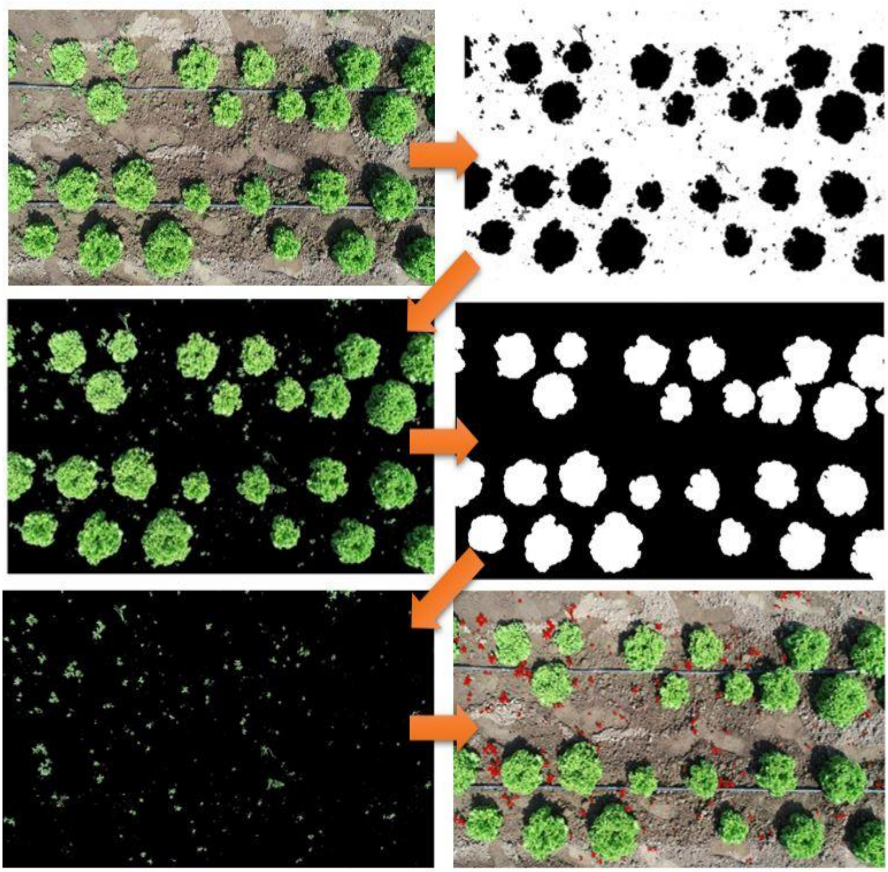


Figure 3. Original image for Location 3 (a), soil detection (b), vegetation layer (c), lettuce plant layer (d), weed layer (e), targeted weeds in the original image (f)

The vegetation layer is obtained by extracting the detected soil layer from the image (Figure 3 (c)).

The separate identification of lettuce plants and weeds within the vegetation layer presents a challenging task for the study. The vegetation image in RGB colour format was converted to L*a*b format. The image segmentation process was performed using the "Graph cut" technique. At this stage, objects with similar characteristics were identified, utilizing colour and shape properties. After the identified lettuce plants were converted to black-and-white format, their interiors were filled, and boundary areas were expanded. This way, the lettuce plant layer was obtained (Figure 3 (d)).

The weed layer remains by extracting the identified lettuce plant layer from the vegetation layer (Figure 3 (e)). The area covered by each weed identified in the weed layer is marked in red at their locations in the original image (Figure 3 (f)).

FINDINGS

Identification of Weed Species in Lettuce Planting Areas Using Conventional Methods, Their Occurrence Frequencies, and Densities

A total of 10 different locations were studied to identify weed species, their occurrence frequencies, and density calculations in lettuce planting areas, including 9 different locations in Amasya province and 1 location in the Bafra district of Samsun province.

The study identified the problematic broadleaf weed species in the lettuce planting areas as follows: the purslane (*Portulaca olerace*a L.) from the Portulacaceae family, lamb's quarters (*Chenopodium album* L.) and redroot pigweed (*Amaranthus retroflexus* L.) from the Amaranthaceae family, bindweed (*Convolvulus arvensis* L.) from the Convolvulaceae family, and wild mustard (*Sinapis arvensis* L.) from the Brassicaceae family. The narrow-leaf weed species identified were the dogtooth grass (*Cynodon dactylon* (L.) Pers.) from the Poaceae family and *Cyperus* spp. from the Cyperaceae family. A total of 7 different weed species from 6 families were identified. The occurrence frequency of *P. oleracea* and *C. album* was 77%, while the lowest occurrence frequency at 11% belonged to *S. arvensis* (Table 3).

Table 3. Weed Species Found in Lettuce Planting Areas in the Central District of Amasya Province and Their Occurrence Frequencies

Family	Weed Species	Occurrence Frequency (%)
Broadleaf Weeds		
Portulacaceae	*Portulaca oleracea*	77
Amaranthaceae	*Chenopodium album*	77
	Amaranthus retroflexus	44
Convolvulaceae	*Convolvulus arvensis*	44
Brassicaceae	*Sinapis arvensis*	11
Narrowleaf Weeds		
Poaceae	*Cynodon dactylon*	66
Cyperaceae	*Cyperus* spp.	22

Table 4. Densities of Weed Species Found at the Locations

Species	Locations										Average
	1	2	3	4	5	6	7	8	9	10	(plants/m²)
***Cyperus* spp.**	-	2	-	-	-	-	-	-	1.5	2.5	0.6
C. dactylon	1	2.5	1	0.5	2	-	-	-	3	3.25	1.32
S. arvensis	-	-	-	-	2	-	-	-	-	4	0.6
C. arvensis	-	-	3	-	3	-	-	0.5	4	5.5	1.6
A. retroflexus	-	0.5	-	-	2.5	-	0.5	-	7	6	1.65
C. album	1.5	2	-	1.5	4.5	0.5	1	1.25	7.5	7	2.67
P. oleracea	12	14.5	4.5	7	-	2	1.5	2	-	-	4.35

When looking at the average population densities across all studied locations, *P. oleracea* was identified as the most problematic species in lettuce planting areas, with a density of 4.35 plants/m², followed by C. album with 2.67 plants/m², *A. retroflexus* with 1.65 plants/m², *C. arvensis* with 1.60 plants/m², *C. dactylon* with 1.32 plants/m², and *S. arvensis* and *Cyperus* species with 0.60 plants/m² (Table 4).

Overall, among the broadleaf weed species, purslane (*P. oleracea*) and lamb's quarters (*C. album*), and among the narrowleaf weed species, dogtooth grass (*C. dactylon*) appear to be significant problems in lettuce planting areas in the Central district of Amasya province, both in terms of occurrence frequency and density.

Image Processing Technique Layers Obtained in Lettuce Planting Areas

Raw Image

At this stage, different images have been chosen to test various factors such as image capture height, sun angle, and the overlap of weeds with the green parts of the lettuce plants. The selected images have been transferred to the Matlab environment. The transferred images must be of size 5472x3078 pixels.

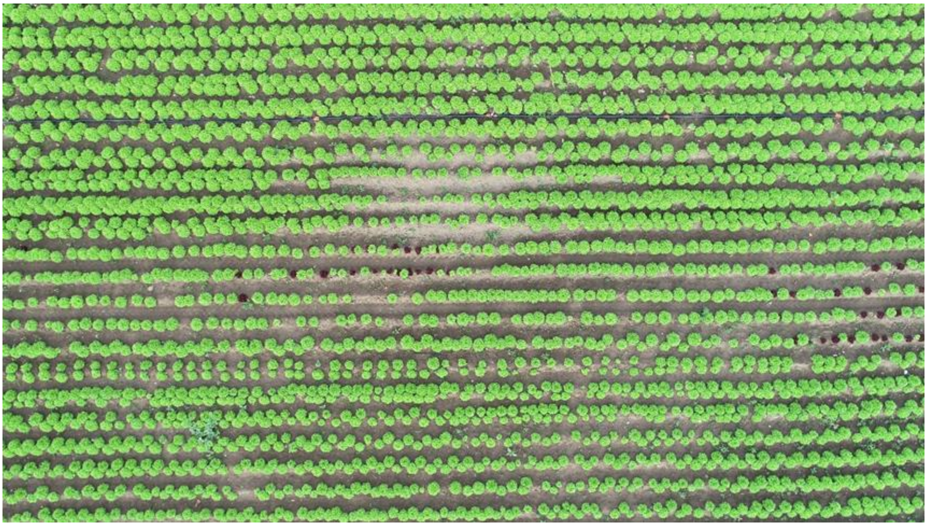


Figure 4. Raw Image of Location 5

The presence of factors such as height, compressed row spacing, the presence of red lettuce, and the overlap of weeds with the green parts of the lettuce plants has been tested in a planting area where it is very difficult to detect with the naked eye (Figure 4).

Figure 5. Raw Image of Location 9

Figure 6. Raw Image of Location 10

Under closed greenhouse conditions, the usability of the unmanned aerial vehicle and the ability to obtain suitable images for the method have been tested (Figure 5). As a result of the observations and evaluations obtained, it has been determined that the proposed method does not work in locations where the weed population is very dense and where weeds frequently overlap with the plant cover (Figure 6).

Soil and Irrigation System Layer

The easiest way to separate the soil and irrigation system from the plant cover is through colour factors. Since there are no brown or black-toned plant samples in lettuce planting areas, the colour factor can be safely used.

The soil and irrigation system have been extracted from the image based on the specified colour range. The identified soil and irrigation system image is converted to a black-and-white image (Appendix 1).

In black-and-white images, the pixel value is either 0 or 1. "0" represents the colour black, or the absence of something, while "1" represents the colour white, or the presence of something. In the black-and-white image created for the soil and irrigation system, the parts where the soil and irrigation system are located are shown as "1," or white colour.

As seen in Figures 7-8-9, parts that do not belong to the plant cover, such as soil, irrigation system, and stone fragments, appear as a whole layer.

Figure 7. Black-and-White Image of Soil and Irrigation System Detected in Location 5

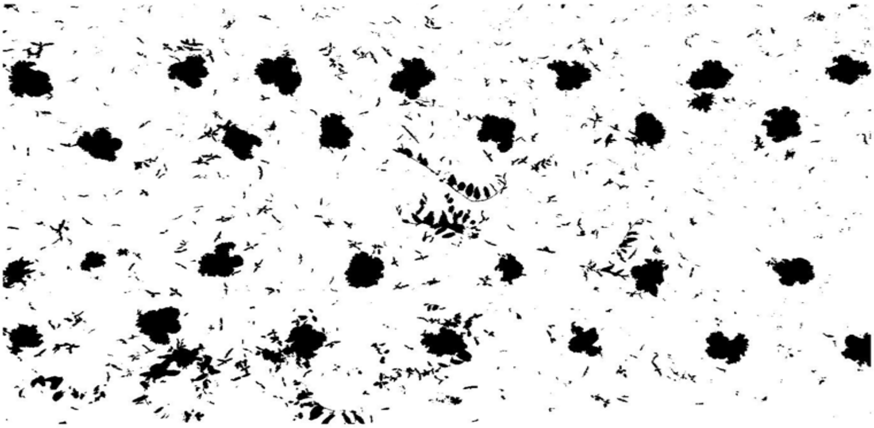


Figure 8. Black-and-White Image of Soil and Irrigation System Detected in Location 9

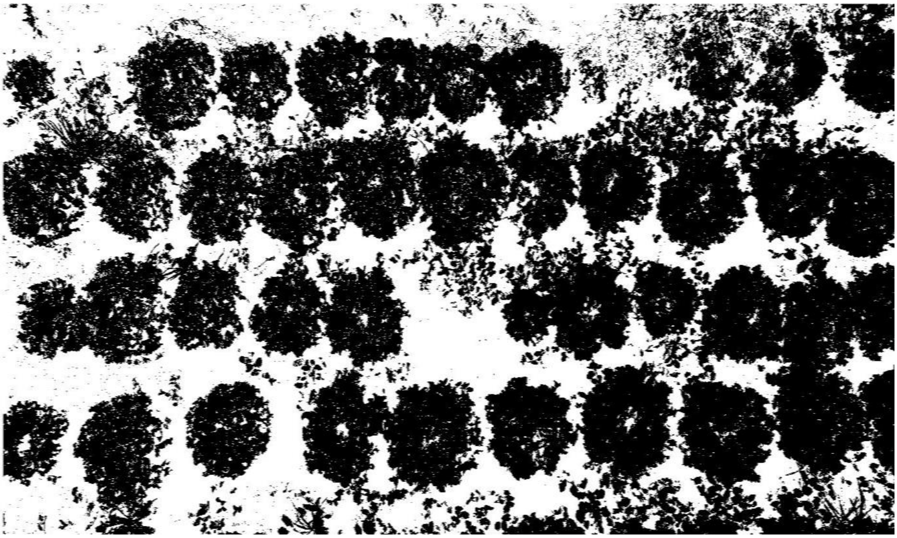


Figure 9. Black-and-White Image of Soil and Irrigation System Detected in Location 10

Vegetation Layer

The value of each pixel indicating the presence of soil and irrigation system, obtained in black-and-white, which has a value of "1", is set to display "0" (representing "absence") in the original RGB image, leaving only the vegetation in the original RGB image (Appendix 2).When examining the obtained vegetation layer in colour format, the success of the soil extraction process becomes clearer. Diseases and damages occurring in lettuce plants can be more easily examined in this part. It is impossible to distinguish between lettuce plants and weeds by colour; however, as seen in the images, the lettuce plants in the same planting areas are homogeneously distributed with a specific shape structure. By utilizing artificial intelligence, the aim is to identify objects that have high similarity in shape and colour to distinguish between lettuce plants and weeds. Losses experienced during cultivation and mistakes made during planting or sowing can also be observed at this stage (Figures 10-11-12).

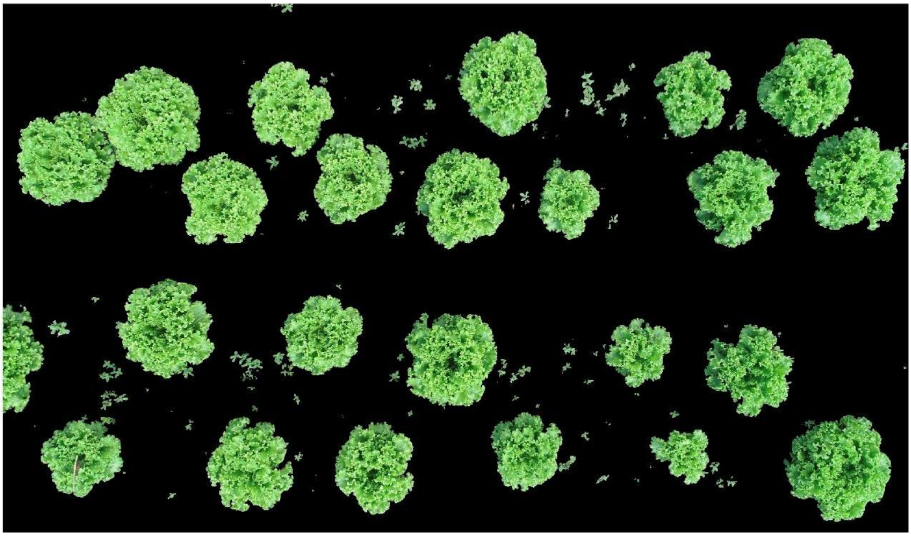


Figure 10. Vegetation Obtained from Location 1

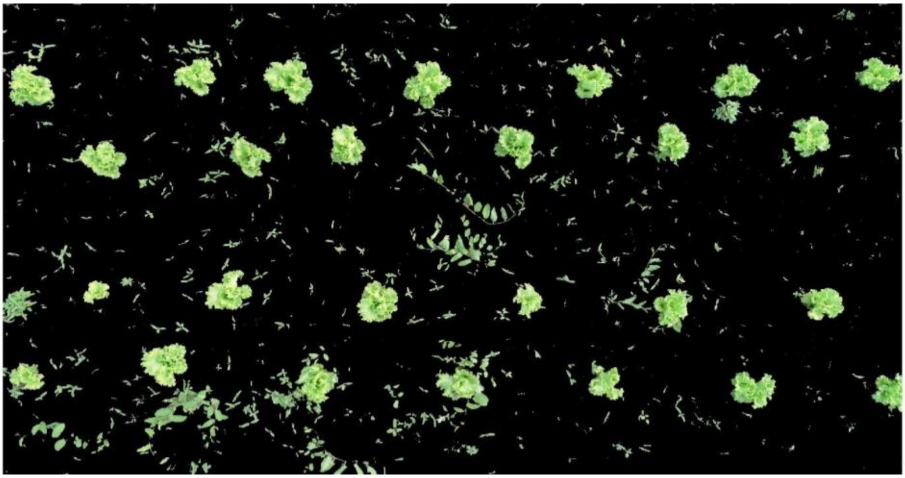


Figure 11. Vegetation Obtained from Location 6

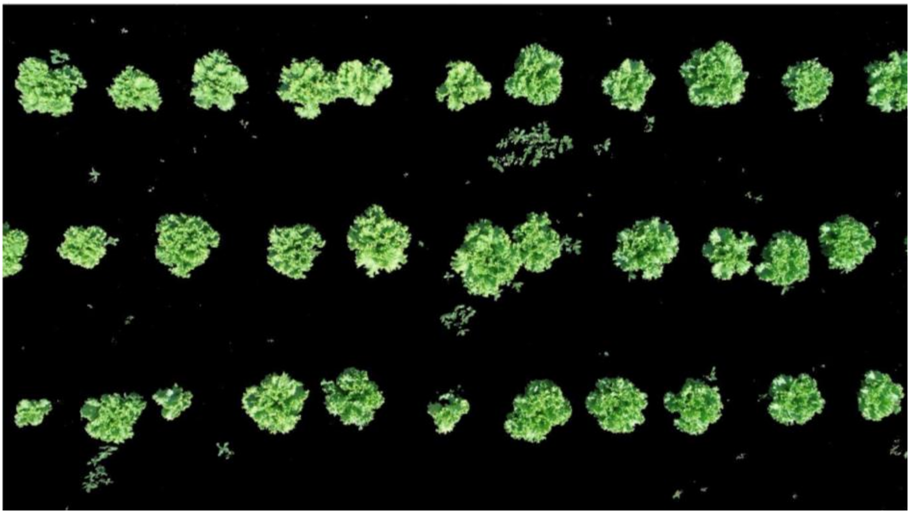


Figure 12. Vegetation Obtained from Location 9

Lettuce Plant Layer

Multiple techniques are applied when detecting lettuce plants. Firstly, the RGB image is converted to the L*a*b colour format. Extracting colours in the L*a*b colour format is more accessible than in the RGB image. It represents colours in a three-dimensional coordinate system: L* (lightness) represents the brightness/lightness coordinate, a* represents the red-green coordinate, and b* represents the yellow-blue coordinate.

After converting to the L*a*b format, image segmentation is performed. Applying the "Graph cut" technique, lettuce plants with similar colour ranges and shapes are brought to the foreground, while dissimilar weeds are pushed to the background. The lettuce plants are then converted to a black-and-white format for further processing. The gaps within the boundary lines of the lettuce plants have been filled. For safety purposes, the boundary area of the lettuce plants has been expanded. Weeds outside the lettuce plants have been removed from the image. Objects below the defined pixel area that might be overlooked have been removed from the image (Appendix 3). The detected lettuce plants in the image are represented in white colour, indicating their presence, i.e., value "1".

In cases such as leaf fertilization, the coordinates of the obtained lettuce plants can be utilized as needed. The area occupied by the lettuce plant can be calculated in this section. Since the yield of the lettuce plant is calculated in terms of the number of heads, the total number of lettuce to be obtained can be easily seen in the lettuce layer section. Since the boundaries of the lettuce plants have been expanded for safety reasons, the boundary lines appear soft rather than sharp. Sometimes, soil accumulations can occur in the centre, and since the software will see these parts as soil, gaps are created. With the given command, these gaps have also been cleared.

Even though the lettuce plant has not yet reached the required maturity, there have been no issues in its detection.

Weed Layer

Every pixel where the value of the lettuce plant is "1" is converted to a value of "0" in the image we refer to as vegetation, thereby extracting it from the image (Appendix 4). As a result, weeds remain in RGB format.

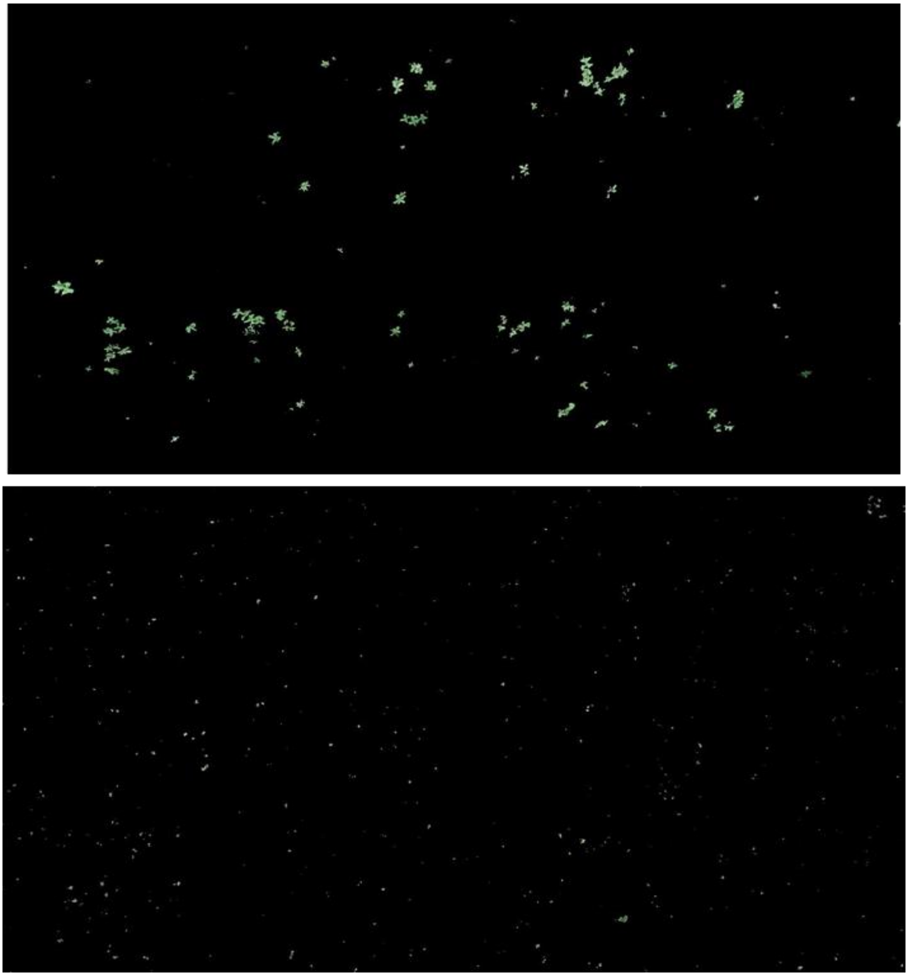


Figure 12. Obtained Weeds from Location 1

It is observed that even weed populations, which are very difficult to see with the naked eye in the images, have been detected (Figure 12).

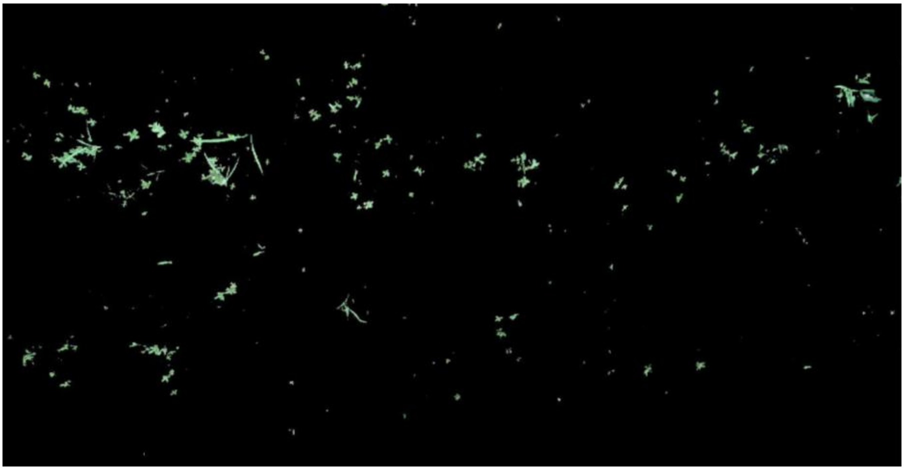


Figure 13. Obtained Weeds from Location 2

In the images, the total area occupied by weeds can be calculated; however, a precise count of weeds cannot be obtained, resulting in the inability to calculate density. Before entering the planting area and without needing a frame, a 1 square meter area can be marked in this section, and weed detection can be performed by examining the image.

In images taken from very high points, successful weed detection has been achieved in areas where it is impossible to identify with the human eye. In images where very dense weed populations are observed and overlap with the green parts of the lettuce plants, the weed population has also been successfully detected (Figure 15). The weed image obtained in RGB colour format is converted to a black-and-white format.

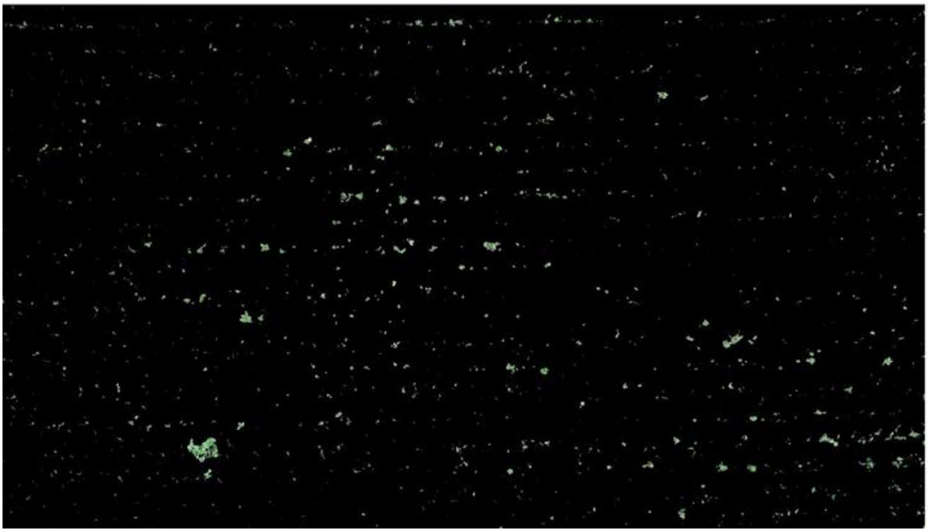


Figure 14. Obtained Weeds from Location 5

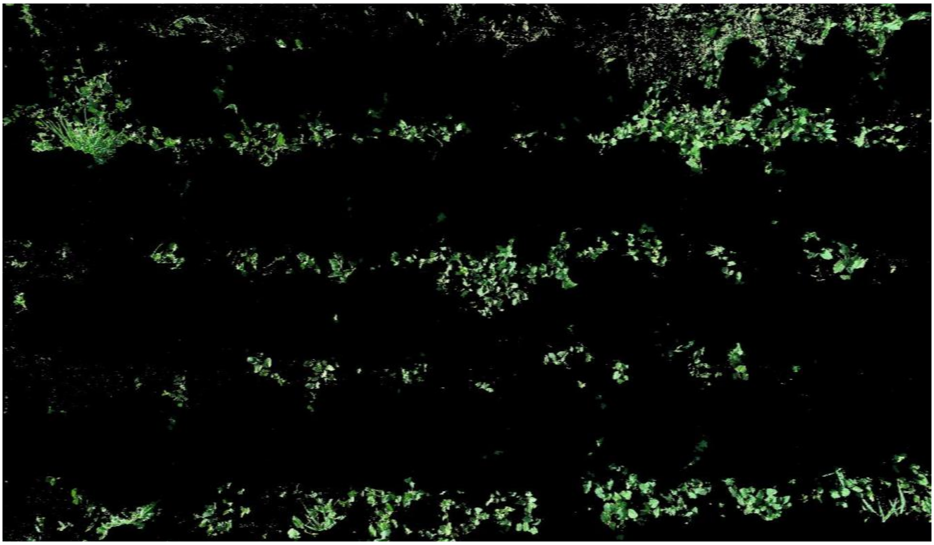


Figure 15. Obtained Weeds from Location 10

Targeted Weed Populations on the Original Image

In the black-and-white format of the weed image, every pixel where weeds are present and has a value of "1" is shown in the original RGB image with R=240, G=0, and B=0. The targeted weeds are marked in red colour in the original image (Appendix 5).

The results indicate that species identification has not been accomplished while the weeds have been detected (Figure 16). It has been observed that in some lettuce planting areas, a single photograph can capture the weed populations present throughout the entire lettuce planting area (Figure 17).

Figure 16. Targeted Weeds from Location 1

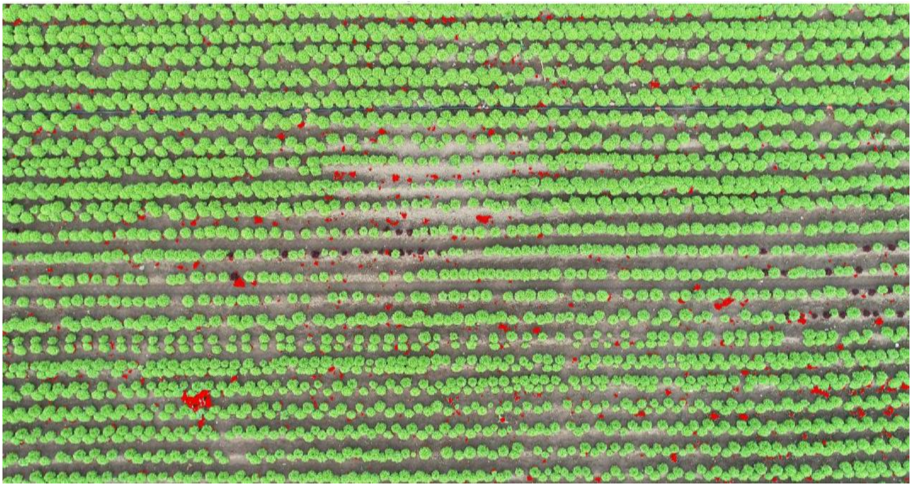


Figure 17. Targeted Weeds from Location 5

Evaluation of Weed Populations Detected by Image Processing Technique

Weeds have been detected using image processing techniques, and their location information and covered areas have been calculated. Weeds that might have been overlooked can also be detected. However, this technique has not achieved species identification for weeds detectable by conventional methods.

When looking at the background of the Image Processing Technique, many weed species that cannot be detected with the naked eye outside the frame area have been identified. Additionally, location and area information for these weed species has been obtained. The success rate of counting weeds using image processing techniques is low. In cases of weeds growing branched, if there is soil accumulation on the stem or if the petiole is thin enough to blend in with the soil appearance, a plant can be perceived as two separate plants. However, the success rate for calculating the areas covered by weeds is very high. The ability to detect weeds even at points where they contact the lettuce plants increases the reliability of the study (Figure 18).

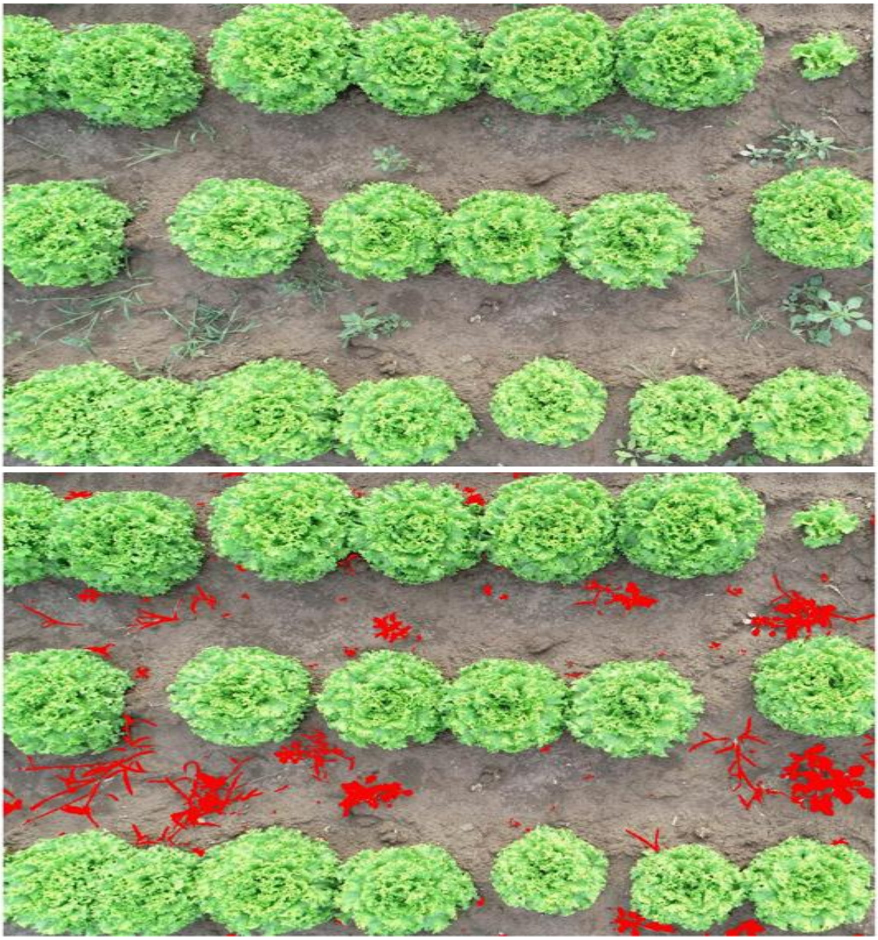


Figure 18. Detection of Overlapping Weeds with Lettuce Plants Using Image Processing Technique

The coverage area of the detected weeds has been calculated using the software. It is thought that with a planned standard control method, energy can be expended only in these areas. The calculated coverage rate of the weeds allows for observing the proportion of energy spent versus the actual amount used in control. The total coverage area and coverage rates of weeds by location are shown in Table 5.

Table 5. Total Image Area in Location, Total Coverage Area of Weeds, and Coverage Rate of Weeds

Location Label	**Total Image Area (Px)**	**Total Coverage Area of Weeds (Px)**	**Coverage Rate of Weeds** (%)
LC 1	13,960,463	116,305	0.83
LC 2	15,301,118	190,890	1.24
LC 3	16,842,816	155,539	0.92
LC 4	16,842,816	92,346	0.55
LC 5	15,070,247	215,863	1.43
LC 6	16,842,816	111,095	0.66
LC 7	16,842,816	499,683	2.97
LC 8	16,842,816	57,295	0.0003
LC 9	16,842,816	667,328	3.96
LC 10	16,842,816	879,364	5.22

Data showing characteristics such as the similarity ratios of the weeds in the region are specified in Table 5. It has been determined that the weeds found in the location are predominantly broadleaf weed species. It is thought that the high similarity ratios obtained from the software could indicate the presence of broadleaf weed species, while the lower similarity ratios might suggest the presence of narrowleaf weed species, indicating that the study should be developed in this direction.

Table 6. Displaying the Number of Weeds Detected, Their Covered Area, Shape Characteristics, Similarity Ratio, and Width Data

Weed	Area	Max. Axis Length	Min. Axis Length	Similarity Ratio (%)
1	3990	114.39	67.03	81
2	2604	323.40	87.80	96
3	2018	81.59	39.45	88
4	2549	183.97	120.58	76
5	2001	187.33	56.69	95
6	10.88	196.29	133.14	74
7	3107	123.27	49.53	92
8	4366	106.40	79.32	67
9	9924	184.77	106.66	82
10	2167	73.14	55.39	65
11	4285	136.21	74.11	84
12	2202	77.79	45.57	81
13	2085	105.50	38.36	93
14	2970	277.39	49.83	98
15	3727	127.53	66.18	85
16	17.86	286.23	176.35	79
17	2739	182.12	57.94	95
18	29.06	278.78	237.31	52
19	2135	85.48	50.58	81

It is possible to separate weeds into narrow-leaf and broadleaf using image processing techniques (Figure 19). However, separate operations are required for each lettuce planting area, and each photo frame making this separation is practically challenging. It is thought that combining neural networks and image processing techniques in software may provide a more practical solution.

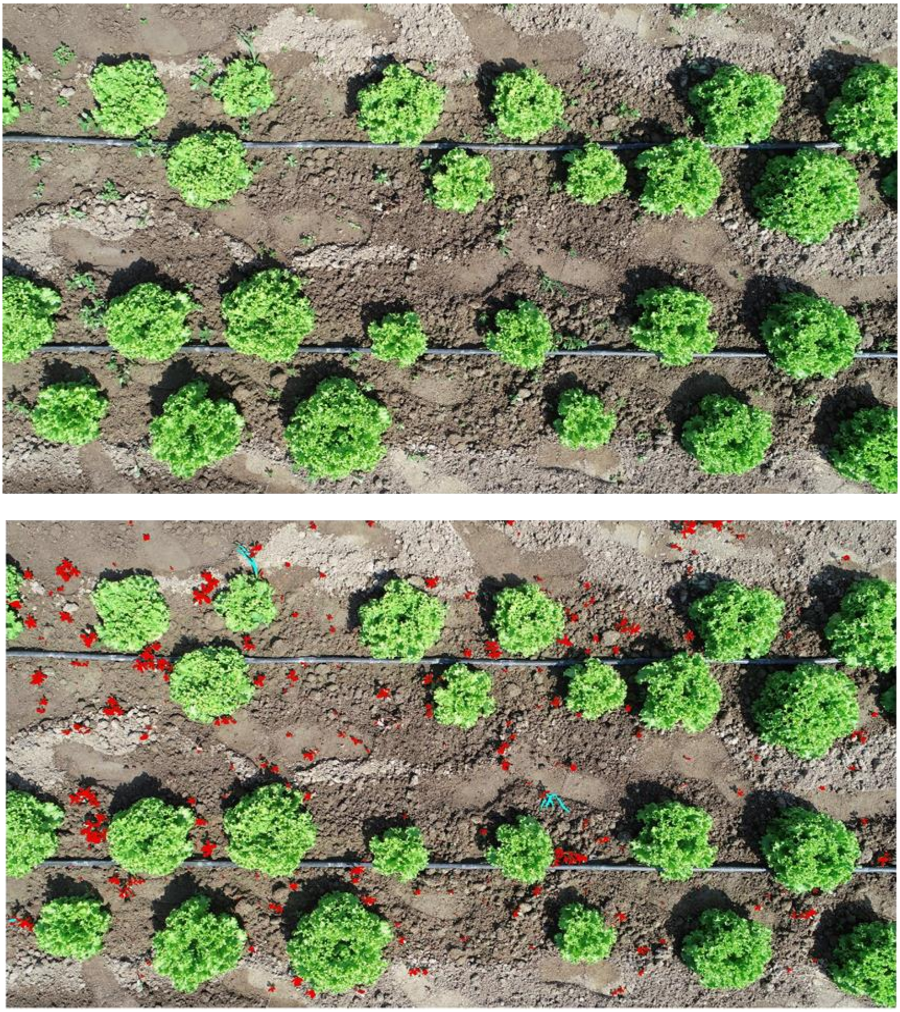


Figure 19. Detection of Narrowleaf and Broadleaf Weeds Using Image Processing Technique

DISCUSSION

In the study conducted by Işık et al. in Samsun, the most prevalent species in lettuce planting areas were found to be barnyard grass (*Echinochloa crus-galli* (L.) P.B.) at a rate of 10% and Canadian thistle (*Cirsium arvense* (L.) Scop.) at 5%, which were not found in the study conducted in Amasya. The field bindweed (*C. arvensis*) at 8%, dogtooth grass (*C. dactylon.*) at 6%, purslane (*P. oleracea.*) at 6%, redroot pigweed (*A. retroflexus*) at 5%, and lamb's quarters (*C. album*) at 5% exhibited similarities in both regions compared to the other identified species.

In a study conducted in Erzurum by Kaymakçı in 2007, high densities of Canadian thistle (*C. arvense.*) and green foxtail (*Setaria viridis* (L.) Beauv.) were noted. However, the presence of these species was not mentioned in the locations studied in Amasya. Additionally, purslane (*P. oleracea*), which had a frequency of 77% in Amasya, was not identified in the conducted research.

In the study by Soylu et al. in 2017, the density of wild oat (*Avena sterilis* L.), which is one of the most prevalent species, was reported to not pose an economic problem in lettuce fields in Amasya. The other species mentioned in the study exhibited similarities in both regions.

Although image processing technology is widely used in the industrial sector, it has not gained the necessary importance in agriculture. Factors such as the high variability in planting areas complicate the implementation of these techniques, and the applications are not adequately prepared for today’s agricultural conditions, which are thought to contribute to this lack of recognition.

Studies conducted in Turkey that utilize image processing technology in agriculture have been observed to generally focus on the classification of harvested crops. Conducting these studies in controlled conditions, such as fields or gardens, eliminates variables and simplifies the processes compared to field conditions. In the studies on weed detection, it has been noted that low-altitude photographs do not cover the entire area or fully include the cultivated crops, resulting in a limited number of detected weed species. Moreover, it has been observed that species identification, location information, and area information of the detected weeds could not be achieved. There are no studies where this technique has been applied to lettuce crops.

Internationally, projects have been reported where weeds found along train tracks are identified, and only those areas are treated, indicating a high success rate due to the absence of variables in these regions. There are also low-altitude weed detection studies in agricultural conditions, but species identification is often impossible for all detected weed species. In aerial surveys of agricultural land, software is currently available only for detecting prohibited plant species.

In a study conducted in the United States by Raja et al. in 2020, troublesome weeds in lettuce gardens were successfully managed using image processing technology and artificial neural networks (ANN). However, species identification for each weed found in the planting area was not performed. The developed spraying system aimed to treat only the points where these weeds were present, using low-altitude photographs for detection.

Generally, in studies using image processing technology, the periodic variations in weed leaf structure, the overlap of green foliage due to field conditions, and variations in green biomass due to nutrient deficiencies or plant diseases complicate species identification of the weeds.

The biggest advantage of conventional methods is that species identification and density calculations can be performed. However, when a system is developed that can apply a standard control method for each species, leading to the eradication or death of weeds, the significance of conventional methods diminishes. Identifying the weeds and their locations becomes the main priority in such cases.

CONCLUSION

According to the results obtained, species identification and density calculations can be achieved using conventional methods, allowing for the determination of when to control weeds as economic damage thresholds are reached.

It has been observed that image processing technology can be confidently used for detecting weeds, location identification, and area calculations. High detection success has been noted even at points where weed green parts overlap or come into contact with lettuce plants. However, because species identification is not possible, the calculation of species density and whether it has reached an economic damage threshold cannot be performed. The identified weeds' detection, location information, and area data can be uploaded to the system, allowing control measures to be conducted only at these points. Additionally, with modifications and applications of the developed software specific to other crops, treatments can be limited to areas where only weeds are present, thereby protecting human and environmental health. However, since there are no registered plant protection products for problematic weeds in lettuce fields, control measures are conducted through cultural and mechanical practices, which increase production costs.

Incorporating ANN can facilitate species-level identification, thereby enhancing the precision of weed detection in agricultural contexts. However, conducting separate studies for each weed species encountered in planting areas over several years is necessary. For high success in species identification for a single weed species, it is essential to take hundreds of photographs under different growing conditions and developmental stages for every weed species encountered in the field. It is generally easier to refer to the remaining vegetation as weeds after teaching about the cultivated plants.

The lettuce plant, with its unique shape and planting style that does not resemble the weeds in our region, enables the application of image processing techniques. Testing has also been conducted on crops such as cabbage and beet, yielding successful results.

Certain adjustments must be made before applying image processing techniques to different lettuce planting areas. Using ANN with constant software that does not change can prevent this issue.

In light of the obtained data, in a weed management system where species identification of weeds is not mandatory, weeds can be eradicated at targeted coordinates. Since energy will not be expended for areas without weeds, costs will be reduced, and environmental health will be protected. It is believed that developing systems that facilitate weed eradication, such as eradication systems or systems that use lasers for burning weeds in conjunction with image processing technology, can yield successful results. Innovative applications should be developed and integrated into the agricultural sector to minimize control costs.

REFERENCES

Alfaro-Almagro, F., Jenkinson, M., Bangerter, N. K., Andersson, J. L., Griffanti, L., Douaud, G., & Vidaurre, D. (2018). Image processing and quality control for the first 10,000 brain imaging datasets from UK Biobank. *NeuroImage*, *166*, 400-424.

Balcı, M., Altun, A. A., & Taşdemir, Ş. (2016). Görüntü işleme teknikleri kullanılarak Napolyon tipi kirazların sınıflandırılması. *Selçuk-Teknik Dergisi*, *15*(3), 221-237.

Baykan, N. (2010). Robotik bir mikroskop sisteminden elde edilen görüntülerin görüntü işleme ve yapay zeka yöntemleri ile analizi. (Doctoral dissertation, Selçuk Üniversitesi Fen Bilimleri Enstitüsü, Konya).

De Freitas, E. M., de Andrade Junior, V. C., Ferreira, E. A., Cristina, D., Grazziotti, F. S., Guimaraes, A. G., & Aker, A. M. (2020). Evaluation of weed changes according to different fertilization management systems, through phytosociological analyzes in lettuce and carrot. *Australian Journal of Crop Science*, *14*(1), 150-160.

Değirmenci, E., Kaloğlu, A. H., Güven, E., Durak, S., & Orbuk, H. (2019). İçme sularında bulunan E. coli bakterilerinin görüntü işleme yöntemleriyle tespiti. *Çukurova Üniversitesi Mühendislik-Mimarlık Fakültesi Dergisi, 34*(3), 235-246.

Dougherty, E. R. (2020). *Digital image processing methods*. New York: CRC Press.

Du, C. J., & Sun, D. W. (2004). Recent developments in the applications of image processing techniques for food quality evaluation. *Trends in Food Science & Technology*, *15*(5), 230-249.

Ekstrom, M. P. (2012). *Digital image processing techniques*. Orlando: Academic Press.

Food and Agriculture Organization of the United Nations. (2020). *FAOSTAT*. http://www.fao.org/faostat/en/#data/QC. (Access date: 15.10.2020).

Denli, N. (2015). Gıda Tarım ve Hayvancılık Bakanlığı. *Marul Yetiştiriciliği*.https://arastirma.tarimorman.gov.tr/alata/.(Access date: 20.10.2020).

Hamouz, P., & Hamouzova, K. (2016). *A handbook of weed seedlings*. České Budějovice: Kurent.

Hilty, J. (2016). Common purslane (*Portulaca oleracea*). http://www.illinoiswildflowers.info/weeds/plants/purslane.htm.(Access date: 20.10.2022).

Isık, D., Kaya, E., Ngouajio, M., & Mennan, H. (2009). Summer cover crops for weed management and yield improvement in organic lettuce (*Lactuca sativa*) production. *Phytoparasitica, 37*(2), 193-203.

Kaymakçı, N. (2007). Marul (*Lactuca sativa* L.)'da yabancı ot kontrolü için kritik periyodun belirlenmesi. (Master's thesis, Atatürk Üniversitesi Fen Bilimleri Enstitüsü, Erzurum).

Kim, H., Lee, J., Ahn, E., Cho, S., Shin, M., & Sim, S. H. (2017). Concrete crack identification using a UAV incorporating hybrid image processing. *Sensors, 17*(9), 2052.

Kruse, R., & Nair, A. (2016). Summer cover crops and lettuce planting time influence weed population, soil nitrogen concentration, and lettuce yields. *HortTechnology, 26*(4), 409-416.

McAndrew, A. (2004). An introduction to digital image processing with MATLAB: Notes for SCM2511 image processing. *School of Computer Science and Mathematics, Victoria University of Technology, 264*(1), 1-264.

Odum, E. P. (1971). *Fundamentals of ecology* (3rd ed.). Tokyo: W. B. Saunders Company.

Öztemel, E. (2003). *Yapay sinir ağları*. İstanbul: Papatya Yayıncılık.

Pradana, Z. H., Hidayat, B., & Darana, S. (2016, September). Beef cattle weight determined using digital image processing. In *2016 International Conference on Control, Electronics, Renewable Energy and Communications (ICCEREC)* (pp. 179-184).

Prakash, R. M., Saraswathy, G. P., Ramalakshmi, G., Mangaleswari, K. H., & Kaviya, T. (2017, March). Detection of leaf diseases and classification using digital image processing. In *2017 International Conference on Innovations in Information, Embedded and Communication Systems (ICIIECS)* (pp. 1-4).

Raja, R., Nguyen, T. T., Slaughter, D., & Fennimore, S. A. (2020). Real-time weed-crop classification and localisation technique for robotic weed control in lettuce. *Biosystems Engineering, 192*, 257-274.

Sabancı, K., Aydın, C., & Ünlerşen, M. F. (2012). Görüntü işleme ve yapay sinir ağları yardımıyla patates sınıflandırma parametrelerinin belirlenmesi. *Iğdır Üniversitesi Fen Bilimleri Enstitüsü Dergisi, 2*, 59-62.

Sabancı, K., & Aydın, C. (2014). Görüntü işleme tabanlı hassas ilaçlama robotu. *Tarım Bilimleri Dergisi, 20*, 406-414.

Shrefler, J. W., Stall, W. M., & Dusky, J. A. (1996). Spiny amaranth (*Amaranthus spinosus* L.), a serious competitor to crisphead lettuce (*Lactuca sativa* L.). *HortScience, 31*(3), 347-348.

Slaughter, D. C., Giles, D. K., Fennimore, S. A., & Smith, R. F. (2008). Multispectral machine vision identification of lettuce and weed seedlings for automated weed control. *Weed Technology*, *22*(2), 378-384.

Solak, S., & Altinişık, U. (2018). Görüntü işleme teknikleri ve kümeleme yöntemleri kullanılarak fındık meyvesinin tespit ve sınıflandırılması. *Sakarya University Journal of Science, 22*(1), 56-65.

Solomon, C., & Breckon, T. (2011). *Fundamentals of digital image processing: A practical approach with examples in MATLAB*. Chichester: John Wiley & Sons.

Soylu, S., Sertkaya, E., Üremiş, İ., Bozkurt, İ. A., & Kurt, Ş. (2017). Hatay ili marul (*Lactuca sativa* L.) ekim alanlarında görülen önemli hastalık etmenleri, zararlı ve yabancı ot türleri ve yaygınlık durumları. *Mustafa Kemal Üniversitesi Ziraat Fakültesi Dergisi, 22*(1), 23-33.

Stubbendieck, J. L. (2003). *Weeds of the Great Plains*. Nebraska Department of Agriculture. P. 564.

Uygur, F. N., Koch, W., & Walter, H. (1986). Çukurova bölgesi buğday-pamuk ekim sistemindeki önemli yabancı otların tanımı. *PLTS, 4*(1). Aichtal: Josef Margraf, Aichtal.

Anonymous, (2022). Ülkemizde yetiştiriciliği ve tüketimi hızla artan sebze: Marul http://www.harmantime.com.tr/haber/ (Access date: 30.08.2022).

Walker, K., Burrows, G., & McMahon, L. (2001). *Bidgee bush: An identification guide to common native plant species of the south western slopes of New South Wales*. Yarralumla: Greening Australia.

Wang, A., Zhang, W., & Wei, X. (2019). A review on weed detection using ground-based machine vision and image processing techniques. *Computers and Electronics in Agriculture*, *158*, 226-240.

Yılmaz, A., Derdiman, Y. S., & Turgay, K. O. Ç. (2018). Ses tellerigörüntülerinde otomatik piksel tabanlı sınıflandırma için performans ölçütlerinin incelenmesi. *Avrupa Bilim ve Teknoloji Dergisi*, 103-110.

APPENDICES

(Appendix 1)

```
matlab
function [BWgreen, maskedRGBImage] = detectPlant(RGB)
I = rgb2lab(RGB);
channel1Min = 9.701;
channel1Max = 98.514;
channel2Min = -66.492;
channel2Max = -7.912;
channel3Min = 11.163;
channel3Max = 66.573;

sliderBW = (I(:,:,1) >= channel1Min) & (I(:,:,1) <=
channel1Max) & ...
           (I(:,:,2) >= channel2Min) & (I(:,:,2) <=
channel2Max) & ...
           (I(:,:,3) >= channel3Min) & (I(:,:,3) <=
channel3Max);

BWgreen = sliderBW;
maskedRGBImage = RGB;
maskedRGBImage(repmat(~BWgreen, [1 1 3])) = 0;
end

[BWgreen, maskedRGBImage] = detectPlant(field);
greenArea = imfill(BWgreen, 'holes');
soil = ~greenArea;
```

(Appendix 2)

```
matlab
[row, col] = find(soil > 0);
for i = 1:length(row)
    field(row(i), col(i), 1) = 0;
    field(row(i), col(i), 2) = 0;
    field(row(i), col(i), 3) = 0;
end
soilRemovedField = field;
```

(Appendix 3)

```
matlab
function [BWlettuceSeparated, maskedImage] =
separateLettuceFromIrrigatedField(RGB)
X = rgb2lab(RGB);

foregroundInd = [5612 546780 726162 1027706 1185986
1250627 1956560 3464764 4345252 4369780 4425260 ...
                 4517588 4536200 5254699 5267123 5350079
5408545 5420857 6072632 6137246 7374442 ...
                 8582597 8776454 8838936 14576136
15629456 15832544 15986338 16078694 16140242 16801661];

backgroundInd = [1052328 1070852 1138618 3752369 4369834
4542278 4813290 4819436 4905638 4981116 5575104 ...
                 5575135 5808024 5829618 6073852 6132526
6132534 6132557 6132573 6132580 6192678 6550403 ...
                 6559637 6578105 6605807 6633509 6651977
6661211 6670445 7915598 8822237 8822240 8831459 ...
                 8831462 8840690 9108254 9113464 11387558
15143128];

L = superpixels(X, 42157, 'IsInputLab', true);
scaledX = prepLab(X);
BWlettuceSeparated = lazysnapping(scaledX, L,
foregroundInd, backgroundInd);
BWlettuceSeparated = imfill(BWlettuceSeparated, 'holes');

radius = 12;
decomposition = 0;
se = strel('disk', radius, decomposition);
BWlettuceSeparated = imdilate(BWlettuceSeparated, se);

maskedImage = RGB;
maskedImage(repmat(~BWlettuceSeparated, [1 1 3])) = 0;
end

function out = prepLab(in)
out = in;
out(:,:,1) = in(:,:,1) / 100;
out(:,:,2:3) = (in(:,:,2:3) + 100) / 200;
end

[BWlettuceSeparated, maskedImage] =
separateLettuceFromIrrigatedField(soilRemovedField);
BWlettuceSeparated = bwareaopen(BWlettuceSeparated,
5000);
```

```
% Note: Values may vary.
```

(Appendix 4)

```
matlab
[row, col] = find(BWlettuceSeparated > 0);
for i = 1:length(row)
    soilRemovedField(row(i), col(i), 1) = 0;
    soilRemovedField(row(i), col(i), 2) = 0;
    soilRemovedField(row(i), col(i), 3) = 0;
end
weeds = soilRemovedField;
```

(Appendix 5)

```
matlab
grayWeeds = rgb2gray(weeds);
binaryWeeds = imbinarize(grayWeeds);
figure, imshow(binaryWeeds);

[row, col] = find(binaryWeeds > 0);
for i = 1:length(row)
    original(row(i), col(i), 1) = 240;
    original(row(i), col(i), 2) = 0;
    original(row(i), col(i), 3) = 0;
end
```

İKSAD
Publishing House
ISBN: 978-625-367-898-2