FUNDAMENTALS OF SUSTAINABLE AGRICULTURE

EDITOR

Prof. Dr. Korkmaz BELLİTÜRK

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BRIEF CURRICULUM VITAE OF EDITOR

Prof. Dr. Korkmaz Bellitürk is an full Professor of Soil Science and Plant Nutrition Department of Agriculture Faculty at the Tekirdag Namık KemalUniversity, in Tekirdag, Türkiye. He did his undergraduate degree at the Trakya University inTürkiye in 1996 as head of the department, followed by a Ph. D. project on hydrolysis of urea.

He started at the Trakya University in 1996, focusing on plant mineral nutrition, and was a Research Assistant at the Faculty of Agriculture from 1996 till 2007. In 2007, he became Assistant Professor of Soil Science and Plant Nutrition Department, Tekirdag Namık Kemal University, Turkiye. He was assigned to lecture for one week each withinthe context of Erasmus teaching staff mobility at Trakia Democritus University in Greece in 2011 and at the University of Technology and Life Sciences in Poland in 2013, and at University of Bologna-Italy in 2024. From 2014 to 2015, he worked as a postdoc researcher at the University of Vermont in USA, working on soilecology, earthworms and vermicompost. After the postdoc he became Associate Professor of Soil Science and Plant Nutrition Department of Agriculture Faculty at the Tekirdag Namık Kemal University, in Tekirdag, in 2018, where he focused of phytoremediation, plant nutrition, soil and water pollution, soil ecology, organic farming, composting and vermicomposting. He conducts one of the bilateral cooperation projects signed between the Council of Higher Education-Turkiye and Higher Education Commission-Pakistan. The universities involved in the project are Tekirdag Namık Kemal University-Turkiye and University of Agriculture Faisalabad-Pakistan in 2019. He served asproject head and researcher in 29 projects supported by TUBITAK, Trakya University, Tekirdag Namık Kemal University, Nevsehir Hacı Bektas Veli University, Bilecik Seyh Edebali University, TAGEM, University of Agriculture-Faisalabad and Yozgat Bozok University Scientific Research Projects Units. He has 160 articles, 25 book chapters, 1 patent, and 16 books on soil science, ecological management for soil quality, plantnutrition, soil-water pollution, ecologic agriculture, vermicomposting and fertilization topics as research articles and papers presented indomestic and abroad scientific meetings. He has been awarded many projects and scientific publication awards in his field of study. He hasbeen editor-in-chief of the journal Rice Research since 2015. He has onenational patent. He features on ISI's list of highly cited authors in thefield of soil fauna, soil fertility and plant sciences since 2010. Web of Science Researcher JJT-8581-2023.

Dedicated to my family.

PREFACE

Soils are one of the world's most important resources; protection, maintenance, and improvement of this resource is critical to maintaining a quality life on earth. It is the hope that understanding and application of information in this book will help to increase the world's food supply, but at the same time allow the soil resource to be protected for many generations. On the other hand, plants are valuable eresources for all living organisms existing on planet Earth. The world-wide shortage of plant production menacing the survival of many people demands for more and better research, particularly on how to increase food and where it is most needed.

Any major change in environment has a negative impact on the growth and development of plants. It means change in climatic conditions is having a direct or indirect impact on human beings. Climatic change (environmental stress) has a drastic impact on crop yield. Food production for future generations is a main problem because of (1) exponential increase in human population and (2) reduction in farmable land due to environmental pollution, caused by natural and anthropogenic events.

In an era marked by increasing environmental awareness and the urgency of mitigating climate change, sustainable waste management practices have come to the forefront. Traditional methods of waste disposal, such as landfilling and incineration, have significant environmental drawbacks, including the release of greenhouse gases, soil and water contamination, and a heavy reliance on natural resources. Consequently, the need for more responsible and eco-friendly approaches to waste management has never been more critical. This book contains very valuable sections on these subjects.

With the latest advancement in science and technology, huge amount of biosolid waste is produced throughout the globe and is posing serious threats to human beings, the environment, and agricultural lands.

The global consensus to reduce inputs of agrochemicals, which are perceived as being hazardous in nature, has provided opportunity for the development of novel benign sustainable soil and crop management strategies. One of the strategies is the application of effective microbial product in the form of "Compost and Vermicompost", beneficial for both farmers and ecosystem. Education and awareness are vital components of fostering a culture of sustainability. Sustainability in waste management recognizes that economic viability is essential. This involves exploring economically feasible solutions that balance environmental and social goals. This situation is also very important for soil health. It will definitely be useful for scientists, academicians, researchers as well as graduate and postgraduate students of different universities across the globe.

The present book entitled "Fundamentals of Sustainable Agriculture" comprises 14 chapters contributed by leading experts having authoritative experience both in teaching and research on fundamental and applied aspects of agronomy science.

This book is a practical guide for sustainable agriculture and for the lay reader who is seeking general information about soil-plant-water-environment but who may also wish to pursue in more depth the influence of different agricultural studies on food production. The book provides adequate new insights to students, teachers, and other professionals interested to enrich the subject of knowledge of sustainable agriculture process, and application particularly in the context of Agricultural and Environmental studies, Soil science, Biotechnology, Microbiology, Viticulture, Plant protection, Food science, Waste management, Water management, Animal science, Artificial intelligence, agricultural robotics, Agronomy and field practices in crop and fruit ecosystem.

I would like to offer my thanks to all authors and the other contributors to this book for their efforts. Their collaboration and patience during the preparation of this book is unforgettable. As editor, I am grateful to the authors for their efforts to follow the instructions for manuscript preparation and to meet the editorial standards. The very important, invisibly incorporated contributions of numerous scientists who kindly agreed to referee one or more papers, are gratefully acknowledged. So, I would like to thank the anonymous reviewers for provided suggestions and corrections.

I wish to acknowledge with gratitude my indebtedness to the members of my family for their support and patience during the preparation of this book. Finally, I wish to thank all individuals and departments who helped to produce this work.

The book contains a total of 16 valuable chapters. I hope that, in this book may continue to serve the needs of students and professionals alike interested in the subject of sustainable agriculture. Welcome to a journey of knowledge, understanding, and inspiration. Welcome to “Fundamentals of Sustainable Agriculture” in all aspects.

Prof. Dr. Korkmaz BELLİTÜRK / **EDITOR**

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CHAPTER 1

STRATEGIES TO INCREASE THE EFFICIENCY OF NUTRIENT UPTAKE IN CROPS AND REDUCE LOSSES IN THE ENVIRONMENT

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1. Introduction

Most soils in the world do not provide adequate amounts of nutrients to meet the demands of cultivated plants. This is why it is necessary to apply acidity correctors, when soils are acidic, and fertilizers. But it is also necessary to adopt strategies to increase the efficiency of nutrient absorption by plants and reduce losses in cultivation systems (Brunetto et al., 2023; Paula et al., 2023). Therefore, this chapter will present strategies that can contribute to this, such as: selecting plants that are efficient at absorbing nutrients, mechanisms and interaction with microorganisms in the rhizosphere that can improve plant nutrition, sampling and estimating nutrients in soil and leaves, proposing critical levels of nutrients in soil and leaves, liming soils and, finally, managing fertilization.

2. Selecting plants that are efficient at absorbing nutrients

The selection of cultivars and rootstocks that are more efficient at absorbing nutrients should be prioritized whenever possible, incorporating it into genetic improvement programs (Barreto et al., 2020; Paula et al., 2018). This can be done by estimating kinetic parameters, such as maximum nutrient uptake velocity (Vmax), which reflects the maximum capacity for ion uptake or transport across the membrane, being reached when all transporters are saturated, and is often associated with maximum influx (Imax). Km (Michelis-Mentel constant) represents the concentration of ions when the absorption rate reaches half of Vmax. The Km value is directly linked to the affinity between the ion and the transporter: the lower the Km, the higher the affinity, allowing the plant to exploit lower nutrient concentrations in the soil. Cmin defines the minimum concentration of an ion in the soil solution at which the plant can no longer absorb it, representing its extraction limit capacity (Paula et al., 2018, 2023). Details on the methodology for estimating kinetic parameters can be found in Brunetto et al. (2022). Plants that have higher Imax values or lower Km and Cmin values can be grown in soils with low natural fertility or can receive lower doses of fertilizers (Paula et al., 2023; Sete et al., 2020).

3. Mechanisms and interaction with microorganisms in the rhizosphere that can improve plant nutrition

Plants, together with the microbiota that inhabit the rhizosphere, can modify the availability of nutrients, making it possible to absorb less labile or gaseous forms of nutrients, which increases the efficiency of their use by crops. The capacity and intensity of modification of chemical, physical and biological parameters of the rhizospheric soil is determined by the genetic characteristics of the species and the environment (De Conti et al., 2023).

In the modulation of nutrient availability in the rhizosphere, chemical changes stand out, through the increase in the concentration of dissolved organic C (DOC) and the variation in pH, promoted by the exudation of organic compounds and ions by plant roots and environmental microorganisms (De Conti et al., 2018). The reduction in rhizospheric soil pH is frequently reported in various plant species when subjected to P deficiency (Nansahwang et al., 2022). The reduction in pH is due to the efflux of protons and exudation of organic acids by the roots, increasing the solubility of inorganic forms of nutrients via desorption of elements retained in the solid phase and solubilization of precipitated forms. Microorganisms that inhabit the rhizosphere can also exude organic acids, contributing to a reduction in pH. The great biological activity in the rhizosphere promotes the release of substantial amounts of CO_2, which can also contribute to the acidification of the rhizosphere.

Exudation consists of the release by roots of a wide range of compounds into the rhizosphere, including sugars, organic acids, amino acids, secondary metabolites and structural carbohydrates. Root exudates are involved in a series of biotic interactions with other plants, microorganisms in the rhizosphere and abiotic components of the soil, including nutrients. More specifically, root exudates can be an important source of carbon (C) for bacteria and fungi, as they can represent 21-33% of the plant's net photo assimilates, being a source of carbon (Pausch & Kuzyakov, 2018).

The increase in the concentration of organic anions in the rhizosphere solution favors the desorption of P retained in the solid phase, through the ligand exchange reaction, increasing the bioavailability of P. This desorptive capacity of P is proportional to the exuded concentration and the number of carboxylic groups of these organic compounds, with tricarboxylates being the strongest and monocarboxylates the weakest in displacing P from the solid phase to the soil solution (Hinsinger, 2001; Oburger et al., 2009). A higher concentration of ligands in the rhizospheric soil increases the chelation of metals that precipitate P ions, increasing their availability (Nansahwang et al., 2022).

4. Sampling and estimating nutrients in soil and leaves

Determining the nutritional needs of crops is a constant challenge in the agricultural sector. Although the mineral elements required for adequate plant nutrition are the same for all plants, the quantities needed vary greatly from one crop to another. On the other hand, a significant part of the world's agricultural activity is based on the exploitation of soils located in tropical and subtropical regions, such as Brazil, whose land is naturally acidic and poor in terms of fertility. According to Von Uexkull & Mutert (1995), America has the highest proportion of soils with these characteristics, which means that 41% of areas have soils with an acid reaction, while Asia, Africa, Europe and Oceania have, respectively, 26, 17, 10 and 6% of soils with a pH below 5.5. This is mainly due to the weathering process that these regions underwent during the period of soil formation (pedogenesis). As a result, practices such as liming and fertilization are essential to enable farming. However, the only way to effectively manage the various types of fertilizer is to know the limitations of the soil and the nutritional requirements of the crops (Natale et al., 2023). In this way, the use of soil analysis and plant tissue analysis are essential tools for improving soil fertility, meeting the nutritional demands of plants, rationalizing the application of fertilizers and reducing environmental impacts, according to the suggestions presented at the 1st and 2nd Technical Meeting on liming and fertilization in fruit trees (Brunetto et al., 2020; Hahn & Brunetto, 2022). Any recommendation of lime or fertilizer without the support of a soil analysis is risky, to say the least, and can lead to nutritional imbalances in the soil, resulting in possible damage to the producer and/or the environment.

Another important tool for farmers is foliar analysis. Especially in the case of perennial crops, such as fruit trees, it is an accurate method of diagnosing, along with soil analysis, the needs of orchards and monitoring the benefits of liming and fertilizer application (Natale & Rozane, 2018). It is important to note that crops, such as perennials, continue to exploit practically the same volume of soil for several years. In this situation, chemical (acidity) or physical (soil compaction) impediments can occur which reduce the efficiency of fertilizers. Therefore, the only way to determine whether the crop is taking advantage of the nutrient applied is to diagnose the crop's nutritional status using foliar analysis (Natale et al., 2022).

When it comes to soil analysis, you need to follow a few simple but essential steps so that the results are representative of the area being assessed. There is a saying in laboratories: "*the result of the soil or leaf analysis is no better than the sample*". This means that any errors made during sampling cannot be corrected in the laboratory, no matter how good the available methods or equipment are. Therefore, you can't be too careful at this stage. When planting orchards, for example, the procedure is the same as for annual crops, i.e. sampling the entire area randomly and representatively. In general, 20 points should be collected, mixed and a sample of around 300 g of soil taken to be sent to the laboratory for analysis. Sampling should be carried out at least 90 days before planting, separating areas that are homogeneous in terms of soil color and type, slope, fertilizer management and previous cultivation. Sampling should be carried out in the 0-20 and 20-40 cm layers separately, as fruit trees have a wide and deep root system. In orchards in production, sampling should be carried out annually, or at the end of each harvest, in the fertilized zone of the plants (crown projection), taking soil samples from around 20 plants per homogeneous plot (same cultivar, age, productivity, soil type, management and fertilization). Every 2-3 years, the inter-row of the orchard should be sampled, separately from the row, in order to correct the acidity of the soil, if necessary (Natale & Rozane, 2024). The soil sample should be sent to the laboratory to be subjected to the analytical process, which makes it possible to determine the concentrations of nutrients in the soil and also the acidity.

Research and agricultural practices show that the use of tools such as soil and leaf analysis, which are relatively inexpensive, allows for the rational application of correctives and fertilizers. This improves crop productivity, the quality of the harvested products, increases the cost:benefit ratio and reduces the environmental impacts of the activity in the field.

5. Proposition of critical nutrient levels in soils and leaves

The nutritional status of plants has traditionally been diagnosed based on chemical analyses of each element individually, using the critical level (CL) or the sufficiency range (SR). Both interpretations assume that nutrients, with the exception of the one being studied, are not a constraint to productivity, and that they do not interact significantly when present at adequate levels. However, since the analytical results of plant tissue are limited in a closed compositional space, there must be some resonance effect (Parent et al., 2013), because of the variation in composition within the critical content ranges (Parent, 2011). Thus, the use of CL and SR and even of Diagnosis and Recommendation Integrated System (DRIS) to interpret the plant's nutritional status is limited, mainly due to the occurrence of interactions between nutrients

(Parent, 2011), requiring a multi-nutrient analysis rather than the use of simple or binary relationships.

Due to the interaction between nutrients in plant tissue, there is a need to change the paradigm of future research, replacing the concept of the Law of the Minimum, which establishes that limitation of productivity occurs due to insufficient content of a given element, with the concept of nutrient balance, in which groups of elements must be balanced to improve plant performance (Parent et al., 2013). An extensive literature review was carried out by (Rozane et al., 2015) on the evolution of criteria for predicting the nutritional status of tropical fruit trees.

We would point out that the assessment of nutritional status by CL and SR depends on the indication of reference values for nutrients, established in calibration experiments, in which genetic and environmental characteristics and interactions between elements are controlled (Bhargava & Chadha, 1988). For this reason, the results obtained in this way must be used to evaluate crops growing under the same conditions used in the experiment, which makes the process extremely restrictive for large-scale use in agriculture. In addition, the reference values are not definitive and are subject to periodic revisions as a result of the introduction of new genetic materials, new management or cultivation techniques, variations in environmental conditions, which would regularly require the installation of calibration experiments, which are costly and generally of medium to long duration, especially in the case of perennial plants (Rozane et al., 2015).

An alternative to calibration experiments would be to use information from nutritional monitoring, such as those carried out for various crops (Lima Neto et al., 2022; Rozane et al., 2020; Squizani et al., 2023) obtained from commercial plots. As a dynamic way of updating the CL and SR, these data aggregate information from wide environmental variation; however, they cannot be used to determine response curves, such as those obtained in calibration experiments to establish the CL or SR.

Finally, it should be emphasized that no statistical or computational tool is capable of replacing or surpassing the robustness and quality of a database, and it should not be forgotten that from a physiological point of view, the importance of interactions does not outweigh each nutrient's own function (Natale & Rozane, 2024). It can therefore be inferred that maximum production depends on the balance between nutrients in the plant, characterized by well-defined proportions (relationships) between these elements.

The interpretation of the results of the soil analysis (concentrations and fertility attributes) and leaf analysis [contents of the essential elements, usually indicated in elemental form: N, P, K, Ca, Mg and S for the macronutrients, expressed in g kg^{-1} and, B, Cl, Cu Fe, Mn, Mo, Zn, (as well as Ni, Co and Se) for the micronutrients, determined in mg kg^{-1}], which you want to study, need to be compared with standards, which should be obtained from high-yielding crops.

However, the interpretation of the nutritional diagnosis goes far beyond the values, and it must be considered that the right balance includes the characteristics of each genotype, as well as the soil and climate conditions in which the crops are being managed.

Considering that each production factor works best when the other factors are close to their optimum, without forgetting that the optimum of each factor cannot be considered in isolation, the integrative nutritional assessment of all nutrients should be carried out using multivariate methods, since they are compositional data, and the CND can be used (Parent & Dafir, 1992). This method expresses the nutritional status better than an isolated nutritional index due to the fact that the levels of the elements are expressed by the analytical results of the organ evaluated, which are limited in a closed compositional space, delimited only by the measurement unit, in which all the nutrients interact.

The "Frontier Line" (LF) method (Webb, 1972) is another example of a methodology that applies the concept of database analysis to describe the relationship between productivity and fertility attributes (Evanylo & Sumner, 1987), because they have different units of measurement (pH; mass/volume; loads/volume), which makes it difficult to evaluate all the information together. LF is based on the assumption that plants have a maximum response (representing the best performance) to production factors in a given situation. If it is possible to establish the relationship between a single growth factor and yield or quality, then optimizing this factor should allow for the best crop performance.

6. Liming soils

The acid reaction of the soil is undoubtedly the most perverse environmental condition for the growth of the root system of agricultural crops. This situation is frequently observed in tropical and subtropical areas of the world, and particularly in Brazil, due to the intense weathering that took place during pedogenesis. As a result of this characteristic, there is poverty in exchangeable bases, low cation exchange capacity (CEC), high concentrations of exchangeable aluminum (toxic), high levels of manganese, high P fixation capacity, an environment unsuitable for microbial life, among others (Natale et al., 2023).

The quickest and most economical way to correct soil acidity is through liming. The most commonly used materials are limestones (usually calcium and magnesium carbonates), which are ground rocks whose constituents neutralize acidity and provide two essential elements: Ca and Mg. The main benefits of liming are adding Ca and Mg to the soil and all the reflexes of the increased availability of these nutrients; reducing aluminum saturation, manganese toxicity and eventually iron; reducing the leaching of K, Ca and Mg; reducing the fixation of P; raising the pH with a consequent increase in the availability of nutrients such as N, P, K, S, Mg, Ca, B, Mo, Se; raising the microbiological activity of the soil; improving the use of applied fertilizers; increasing crop productivity as a result of one or more of the benefits mentioned (Natale et al., 2012a; Natale et al., 2012b). In addition, due to the residual effect, the action of limestone can last for years or crops, making liming an investment that is amortized over time.

There are several limestone recommendation methods in use around the world. In Brazil, in the states of Santa Catarina (SC) and Rio Grande do Sul (RS), the dose of lime is calculated using the SMP method, which evaluates the pH variation in a buffer solution. There is a correlation between the SMP Index and the soil's potential acidity (H+Al), since the lower the SMP pH, the more acidic the soil. The dose is then established using a table that relates: SMP pH x pH in water x dose of lime (CQFS-RS/SC, 2016). Depending on the value of this index, the doses of lime Total Neutralization Power (TNP 100%) are calculated so that the soil in the 0-20 cm layer reaches reference values of 5.5; 6.0 or 6.5, according to the crop's requirements. For example, the reference pH for citrus is 6.0. So, if the soil analysis shows an SMP index of 5.8, the corresponding dose to raise the reference pH to 6.0 can be found in the table in the manual, which in this case will be 4.2 t ha^{-1}. In the case of fruit trees, the procedures have been adapted for various species, according to the suggestions presented at the 1st and 2nd Technical Meeting on Liming and fertilization in fruit trees (Brunetto et al., 2020; Hahn & Brunetto, 2022).

In São Paulo and other Brazilian states, the method used is base saturation (V%), which advocates raising the V% to values suitable for each crop, the formula for which is (Raij et al., 1996)**:**

$$CL(t\ ha^{1}) = \frac{(V_2 - V_1) \times CEC}{TNP \times 10}$$

where: CL = liming requirement, given in tons of lime per hectare; V_2 = is the base saturation indicated for the crop; V_1 = is the base saturation revealed by soil analysis; CEC = is the cation exchange capacity of the orchard soil; TNP = Relative Total Neutralizing Power of the lime to be used.

Once the corrective dose has been calculated, it is important to note that common limestones have low solubility and need time to react and fulfill their role of neutralizing acidity. The above dose calculation is for incorporation in the 0-20 cm layer. If there is suitable equipment and physical condition in the soil, it is recommended to be up to 30 cm, increasing the dose by 50%. In pastures, at the start of the no-till system or during the implementation phase of fruit orchards, preference should be given to limestone with a course granulometry (TNP less than 60%), due to its greater residual effect. Liming should preferably be carried out on the whole area, following the guidelines mentioned above.

In the case of the need to reapply lime in consolidated no-till areas, where there will be no incorporation, in planted pastures or in orchards in the production phase, incorporation of the corrective is not recommended, as there could be severe damage to the root system of the fruit trees, as well as spreading pathogens present in the area. Therefore, the application can be made in the total area and/or located in the area where the fruit tree is fertilized (crown projection). This decision should be made by checking the results of the soil analysis for each site; however, in either situation, the application should be superficial, without incorporation (Natale et al., 2012). The type of limestone recommended for established crops (orchards already formed, pastures and no-till systems) is also completely different, i.e., it is suggested to use limestone with fine granulometry (TNP greater than 80%), due to the greater ease with which the particles of the corrective can travel through the soil profile (Silva et al., 2007; Corrêa et al., 2018).

7. Fertilizer management in soils

Fertilizer application is considered one of the essential agricultural practices for improving productivity and the quality of harvested products, especially in tropical and subtropical areas of the world. Considering that macro and micronutrient deficiencies are relatively simple to correct, when fertilization becomes necessary this problem should be removed from the list of factors that can contribute to low yields. However, it is no longer reasonable these days, with the rapid rise in energy and raw material costs, to sin by excess, especially in developing countries.

7.1 Fertilizer doses

Fertilizer application becomes necessary when the crop's nutrient requirement is greater than the soil's capacity to meet this demand, which is almost a rule in tropical and subtropical regions. This necessarily means knowing the availability of nutrients in the area, which can be obtained through soil analysis for fertility purposes. Brazil's Corrective and Fertilizer Recommendation Manuals are generally regional or state-based, such as the CQFS-RS/SC (2016) for RS and SC, Pauletti et al. (2017) used in Paraná and Cantarella et al. (2022) in the state of São Paulo. Thus, adjustments to the quantities of fertilizer to be used are important to avoid wasting inputs, reduce production costs, reduce the country's dependence on imports, reduce the potential risks of environmental pollution and avoid damaging the quality of the products harvested.

7.2 Timing of fertilizer application

7.2.1 Time of application of primary macronutrients in annual species

The supply of P and K to annual species such as maize, wheat, soybeans and most vegetables is usually carried out together with the sowing of the crop, with the fertilizer being deposited a few centimeters below and a few centimeters next to the seeds. This improves the use of these nutrients because they are available close to the plant roots and because the main mechanism for supplying plants with both elements is diffusion, which occurs over short distances in the soil.

On the other hand, the management of N is different, as it is a nutrient that can cause major losses in the system, due to its chemical characteristics that allow for losses through volatilization, leaching and denitrification. N is supplied annually in practically all crops, excluding some legumes. Another factor to consider is the climatic conditions at the time of nitrogen fertilization, prioritizing periods with mild temperatures and, if possible, it is recommended to fertilize before irrigation or rain. In addition, due to the dynamics of the nutrient, it is recommended to supply N in installments. Around 20-30%, for example, should be supplied at sowing, given the low demand of annual crops at this stage of development and the possible losses in the system. The rest of the dose should be spread over 1 or 2 times in the later vegetative stages, depending on the dose, the crop cycle and the producer's operational capacity.

7.2.2 Time of application of primary macronutrients in perennial species

Perennial species include fruit trees, perennial fodder crops and forest essences. For these crops, full fertilization of the recommended dose of P and K is usually carried out in late winter and early spring. This season is favorable because it coincides with rising temperatures and the start of the crop's budding and growth cycles, which increases the plants' demand for and absorption of nutrients.

Nitrogen fertilization, as with annual crops, should be spread out over time. Normally, the first fertilization is carried out together with the supply of P and K, at the time mentioned above. After that, the rest of the recommended dose is applied in installments, according to the needs of the crop and the phenological stages of the plant. In pastures, for example, the number of applications can be higher (3-4), depending on the plant's growth cycles and cuts/grazing. In fruit trees, it can be according to the phenological stages of the plant, with one of the nitrogen fertilizations being carried out at flowering, which is when the plant's demand for N is the greatest, or at other phenological stages that are important for the crop.

7.2.3 Time of application of primary macronutrients according to source

The timing of the application of mineral sources of primary macronutrients has been described in the previous two sections, as they are soluble sources and quickly made available to the plants. On the other hand, organic fertilization has a different dynamic, as the nutrients, with the exception of K, are in organic forms. Because of this, organic fertilizers need to be mineralized through the action of microorganisms before they can be made available and absorbed by plants. These reactions take time and are beneficial to the production system, as they create a synchronous condition between mineralization and absorption by plants. However, in order for this to happen, fertilization needs to be carried out before the time of greatest crop demand. In the case of annual crops, organic fertilization should be carried out a few days before or on the date of sowing/transplanting the crop. For perennial crops, fertilization should be carried out at the time of greatest demand, which is usually late winter/early spring, when the plants begin their growth cycle. In both cases, it is recommended to supply 100% of the dose in the periods described.

7.3 Delivery methods

The way in which fertilizers, whether macro or micronutrients, are applied plays a fundamental role in their bioavailability and, consequently, in their absorption and efficiency of use by plants. The right choice of application technique is decisive in reducing losses through leaching, volatilization or adsorption in the soil, factors that directly affect the amount of nutrients available to the crop.

How nutrients are supplied varies according to the crop, planting system, climatic conditions and economic constraints. In grain crops, which are grown in a row, fertilizers are normally applied in the planting line. In the conventional system, fertilizers are incorporated into the soil, while in the no-till system they are applied superficially.

In perennial crops, such as fruit trees, including grapevines, the supply of phosphorus (P) and potassium (K) is divided between pre-planting and maintenance fertilization (Brunetto et al., 2016). In pre-planting fertilization, it is recommended applying phosphate and potassium fertilizers in the total area, followed by incorporation, ensuring that the soil is prepared for the initial development of the plants. Maintenance fertilization aims to replace the nutrients exported by the fruit and/or lost to the environment (Brunetto et al., 2016). In this type of fertilization, the fertilizers are applied on the projection of the plant canopy, in bands, optimizing absorption by the roots (Brunetto et al., 2016). We point out that fertigation can be a suitable strategy for supplying N in particular to crops such as fruit trees and vegetables (Kulmann et al., 2023).

7.4 Nutrient sources

7.4.1 Organic fertilizer sources

Animal waste can be applied to the soil as a source of nutrients, reducing the external purchase of fertilizers. Organic fertilizers generally have a lower concentration of nutrients than mineral fertilizers. In addition, there are differences in the origin of the manure due to feeding and variations in the age of the animals, as well as in the management of the areas. The concentrations of nutrients in different animal waste can be found in the literature (Rogeri et al., 2016; Demirbas et al., 2017). It is important to note that nutrient concentrations are directly related to the dry matter mass of the manure. Thus, solid fertilizers such as poultry litter and waste compost tend to have higher amounts of nutrients than liquid organic fertilizers.

Another relevant issue is that part of the nutrients can be in organic forms such as N and P, which need to be mineralized in order to be used by the plants. For this reason, the efficiency of use of organic fertilizers for N and P is variable and can vary from 20% to 80% for subsequent crops depending on the element and the type of organic fertilizer (CQFS-RS/SC, 2016). The K in organic fertilizers is fully present in mineral form, i.e. readily available at the time of application, unlike N and P. The fraction of the nutrient that is not released in the first crop constitutes the residual effect, which will potentially fertilize the next crop.

The composition of organic fertilizers varies which can be different from plant demand. This is due to the addition of compounds to the feed or the concentration of elements to the detriment of others. When applied to the soil alone, they can cause an accumulation of some nutrients and a lack of others. One way of improving use efficiency would be to complement organic fertilization with mineral fertilizers in order to achieve a balanced application of nutrients.

7.4.2 Mineral fertilizers

Mineral fertilizers are used as a source of N, P and K in particular, which are the three macronutrients routinely applied to crops. In general, they are relatively simple products, produced from materials extracted from nature or from industrial production, such as ammonia or urea. The availability of fertilizers has been a current concern, as the world's reserves of raw materials (P and K) are finite, and extraction costs are increasing. For this reason, rational use through soil analysis and expected production is fundamental for conscious use. The different sources of mineral fertilizers can be found in the literature (MAPA, 2018; Alcarde, 2007; Novais et al., 2007).

The quality of fertilizers depends on physical, chemical and physicochemical characteristics that influence their performance, especially in terms of application and efficiency in supplying nutrients to plants (Alcarde, 2007). The main physical characteristics of these fertilizers are: granulometry, consistency, fluidity and density, while the chemical characteristics are the number and concentration of nutrients, chemical form, acidifying and alkalizing power, presence of undesirable elements and compounds. The physical-chemical characteristics include solubility, hygroscopicity, clumping and salt content.

The application of mineral fertilizers is easier due to the standardization of the product. In addition, the amount of fertilizer applied is lower per unit area, due to the higher concentration of nutrient(s). On the other hand, when mineral fertilizer is applied, few elements are added, unlike organic fertilizers which have several nutrients in their composition.

In addition to the higher concentration of nutrients, the high solubility characteristic of mineral fertilizers, whose application to the soil, under humid conditions, releases the nutrients into the soil solution. Thus, soon after rainfall, there is a peak in availability, which can cause leaching, as is often the case with nitrogen.

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CHAPTER 2

GROUNDWORK FOR UNDERSTANDING THE PRINCIPLES AND IMPORTANCE OF SUSTAINABLE AGRICULTURE

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1.1. Introduction

Sustainable agriculture represents a transformative approach to food production and land management, addressing the pressing need to balance human demands with environmental stewardship. The global population rising and projected to reach almost 10 billion by 2050 (World Bank, 2018). The consequency is the demand for food, fiber, and fuel intensifies will arise too. This surge in demand places immense pressure on natural resources, necessitating a shift from conventional agricultural practices to more sustainable methods that ensure long-term productivity and ecosystem health.

Defining Sustainable Agriculture

Sustainable agriculture is defined as an integrated system of plant and animal production practices that meet current food and fiber needs without compromising the ability of the next generations to meet their own needs. This holistic approach encompasses environmental health, economic profitability, and social equity. It seeks to create a balance where agricultural activities do not deplete resources, harm the environment, ensuring that farming remains viable and always productive over the long term.

Historical Context

The historical evolution of agriculture provides critical insights into the need for sustainable practices. Traditional agricultural methods, which were labor-intensive and relied heavily on natural processes, gradually gave way to modern, industrialized farming. The Green Revolution of the mid-20th century was a watershed moment, ushering in high-yield crop types, synthetic fertilizers, and pesticides. While these innovations dramatically enhanced food production, they also had unforeseen repercussions, such as soil degradation, water pollution, and biodiversity loss.

The shift from traditional to factory agriculture has been accompanied by a growing recognition of the environmental and social costs associated with intensive farming practices. Nutrient depletion, soil erosion, and contamination of water bodies with agricultural runoff are just a few examples of the negative impacts. These challenges underscore the urgent need to adopt sustainable agricultural practices that can mitigate these effects and promote long-term resilience.

Principles of Sustainable Agriculture

Several key principles underpin sustainable agriculture, each contributing to a more resilient and productive farming system:

1. Integrated Pest Management (IPM) combines biological, cultural, physical, and chemical techniques to manage pests in an environmentally and economically sustainable manner. IPM preserves ecological balance and protects beneficial creatures by reducing the usage of chemical pesticides.
2. Crop Rotation and Diversity: Composting, which involves crop rotation and plant species diversification, can improve soil health, reduce pest and disease attack pressure, and increase biodiversity. Crop rotation disrupts pest life cycles and improves soil structure and fertility, while diversity in planting can create more resilient ecosystems.
3. Agroforestry: Integratingforest trees and shrubs into agricultural landscapes provided multiple benefits, including improved soil fertility, soil property, enhanced water retention, and increased biodiversity and functionality. Agroforestry systems can also sequester carbon, contributing to climate change mitigation.
4. Organic Farming: Organic farming practices avoid synthetic inputs (such as chemical fertilizers and pesticides), instead relying on natural processes and materials. This approach

promotes soil health, reduces pollution, and enhances biodiversity.

5. Conservation Tillage: Reducing or doing away with tillage promotes water infiltration, decreases erosion, and preserves soil structure. Carbon sequestration and soil health can be enhanced by conservation tillage techniques like no-tillage or reduce-tillage farming.
6. Water Management: Sustainable agriculture depends on the efficient use of water. Water conservation and climatic variability resistance can be enhanced by practices including drip irrigation, rainwater gathering, and the use of drought-resistant agricultural cultivars.

Challenges Facing Sustainable Agriculture

Despite the clear benefits, several challenges hinder the widespread adoption of sustainable agricultural practices:

1. Climate Change: Changes in the growing seasons, the frequency and intensity of extreme weather events, and the dynamics of pests and diseases are just a few of the major threats that climate change presents to agriculture. Sustainable practices can enhance resilience, but adapting to these changes requires ongoing innovation and investment.
2. Resource Depletion: The depletion of natural resources, such as soil nutrients and freshwater, threatens the long-term viability of agriculture. Sustainable practices aim to conserve and regenerate these resources, but achieving this balance requires careful management and planning.
3. Socio-Economic Barriers: Economic and social factors, such as access to markets, financial resources, and education, can influence the

adoption of sustainable practices. Smallholder farmers, in particular, may face challenges in accessing the tools and knowledge needed to implement sustainable methods.

4. Policy and Governance: The effective policies and governance structures are essential for promoting sustainable agriculture. This includes creating incentives for sustainable practices, supporting research and development, and ensuring that agricultural policies align with environmental and social goals

Role of Innovation and Technology

Innovation and technology are a crucial role in advancing sustainable agriculture. Precision agriculture such as using data and technology to optimize farming practices, reducing waste and improving efficiency. Biotechnology offers potential solutions for developing crop varieties that are more resilient to pests, diseases, and climate change. Solar and wind energy are examples of renewable energy sources that help lower the carbon footprint of agricultural operations.

Real-world examples and case tudies illustrate the successful implementation of sustainable agricultural practices. For instance, agroforestry projects in Africa have improved soil fertility and increased crop yields, while organic farming initiatives in Europe have enhanced biodiversity and reduced pollution. These examples demonstrate the tangible benefits of sustainable agriculture and provide valuable lessons for broader adoption.

1.2. Historical Context of Sustainable Agriculture

The history of agriculture is a testament to human ingenuity and adaptability. From the civilization dawn, humans have continuously evolved their farming practices to address the food growing demands, fiber, and fuel. This journey, however, has not been without its challenges. The historical context of sustainable agriculture provides a comprehensive understanding of how agricultural practices have developed over time and the pressing need for sustainable methods today.

Early Agricultural Practices

Around 10,000 years ago, during the Neolithic Revolution, when people moved from wandering hunter-gatherers to permanent farming communities, agriculture was born. Early agricultural practices were largely sustainable, relying on natural processes and local resources. Crop rotation, intercropping, and the application of organic fertilizers (compost and manure) were all prevalent practices. These techniques supported natural pest management and soil fertility maintenance.

Ancient civilizations, including those in Mesopotamia, Egypt, and the Indus Valley, developed sophisticated irrigation systems to support agriculture in arid regions. The Nile, Tigris, and Euphrates rivers provided the necessary water for crops, and the annual flooding of these rivers deposited nutrient-rich silt onto the fields, enhancing soil fertility. These early practices were inherently sustainable, as they worked in harmony with natural cycles.

The Agricultural Revolution

The Agricultural Revolution of the 18th century marked a significant shift in farming practices. Agricultural production rose as a result of inventions like Jethro Tull's seed drill and crop rotation schemes like the Norfolk four-course system. These advancements allowed for more efficient use of land and resources, leading to higher yields and supporting population growth.

However, the Agricultural Revolution also introduced practices that began to strain the environment. The increased use of plowing and monoculture (growing a single crop over a large area) led to soil erosion and nutrient depletion. While these practices boosted short-term productivity, they set the stage for long-term environmental challenges.

The Industrial Revolution

Agriculture saw additional transformations throughout the nineteenth century's industrial revolution. Mechanization, with the advent of tractors and other machinery, transformed farming by making it less labor-intensive and more efficient. The early twentieth century saw the introduction of synthetic fertilizers and chemical insecticides, which enhanced crop yields while reducing pest and disease losses.

While these advancements significantly boosted food production, they also had profound environmental impacts. The widespread use of chemical inputs led to water pollution, soil degradation, and loss of biodiversity. The reliance on monoculture and intensive farming practices exacerbated these issues. It is leading to a greater understanding of the need for more sustainable ways.

The Green Revolution

The Green Revolution began in the mid-twentieth century, and was marked by the widespread adoption of high-yielding crop types, synthetic fertilizers, and enhanced irrigation techniques. The Green Revolution, led by scientists such as Norman Borlaug, sought to alleviate hunger and improve food security in poor countries.

While the Green Revolution succeeded in significantly increasing food production, it also highlighted the limitations of intensive farming practices. The heavy reliance on chemical inputs and water-intensive crops led to environmental degradation, including soil salinization, water scarcity, and loss of genetic diversity. These challenges underscored the need for a more balanced approach to agriculture that could sustain productivity while preserving environmental health.

Emergence of Sustainable Agriculture

In response to the negative impacts of industrialized agriculture, the concept of sustainable agriculture began to gain traction in the latter half of the 20th century. This movement was influenced by several key developments:

1. Environmental Awareness: The environmental movement of the 1960s and 1970s, exemplified by publications like Rachel Carson's "Silent Spring," heightened awareness about the environmental consequences of chemical pesticides and industrial farming methods. This period saw a growing recognition of the need to protect natural resources and promote environmental sustainability.
2. Organic Farming: The organic farming movement, which emerged in the early 20th century, advocated for farming practices that avoided synthetic inputs and focused on soil health and biodiversity. Organic farming emphasized the use of natural fertilizers, crop rotations, and biological pest control, laying the foundation for modern sustainable agriculture.
3. Agroecology: The field of agroecology, which integrates principles of ecology into agricultural practices, gained prominence as a scientific approach to sustainable farming. Agroecology emphasizes the importance of biodiversity, natural pest control, and soil health. It promotes farming systems that mimic natural ecosystems, enhancing resilience and sustainability.

Policy and Institutional Support

The late 20th and early 21st centuries saw increasing policy and institutional support for sustainable agriculture. Governments, international organizations, and non-governmental organizations (NGOs) began to recognize the significance of sustainable practices for ensuring food security and environmental sustainability. Key milestones include:

- The 1990 U.S. Farm Bill: This legislation provided a formal definition of sustainable agriculture and outlined goals for enhancing environmental quality, economic viability, and social equity in farming. It marked a significant step towards institutionalizing sustainable agriculture practices.
- United Nations Initiatives: The United Nations has played an important role in promoting sustainable agriculture through initiatives such as the Sustainable Development Goals (SDGs). which include targets for sustainable food production and land management. The Food and Agriculture Organization (FAO) has also been instrumental in advocating for sustainable agricultural practices globally.

Modern Developments

Today, sustainable agriculture continues to evolve, driven by advances in technology, research, and policy. Key trends include:

- Precision Agriculture: The usage of data and technology to optimize farming practices, reduce waste, and improve efficiency is becoming increasingly important in sustainable agriculture. Precision agriculture involves the use of sensors, GPS, and data analytics to monitor and manage crops more effectively, enhancing productivity while minimizing environmental impact.
- Climate-Smart Agriculture: This strategy focuses on modifying agricultural methods to prevent and adapt to climate change, ensuring resilience and sustainability in the face of environmental difficulties. Climate-smart agriculture encourages methods such as conservation tillage, agroforestry, and drought-tolerant crop types.
- Regenerative Agriculture: Regenerative agriculture goes beyond sustainability to actively restore and enhance ecosystems. This technique relies heavily on practices like cover cropping, no-tillage farming, and agroforestry. Regenerative agriculture strives to improve

soil health, boost biodiversity, and sequester carbon, so helping to mitigate climate change.

The historical context of sustainable agriculture highlights the dynamic interplay between technological advancements, environmental awareness, and policy support. From early traditional practices to modern innovations, the journey of sustainable agriculture reflects a growing recognition of the need to balance productivity with ecological and social responsibility. As we move forward, sustainable agriculture will remain critical to safeguarding future generations' food security and environmental health.

1.3. Principles of Sustainability

Sustainability is a multidimensional idea that seeks to strike a balance between economic growth, environmental conservation, and social fairness to preserve the well-being of present and future generations. The principles of sustainability provide a framework for integrating these three dimensions into policies, practices, and behaviors. This essay explores the core principles of sustainability, their historical development, and their application in various contexts.

1. Intergenerational Equity

Intergenerational equality is a fundamental idea of sustainability that emphasizes the importance of meeting current needs without jeopardizing future generations' ability to meet their own. This concept was popularized by the Brundtland Report in 1987, which defined sustainable development as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs"(Gerasimova, 1987). Intergenerational equity requires that we manage resources responsibly, ensuring that future generations inherit a world with sufficient natural resources and a stable environment.

2. Intragenerational Equity

Intragenerational equity focuses on fairness and justice within the current generation. It addresses the disparities in resource distribution and access to opportunities, aiming to reduce poverty and inequality. This principle is crucial for achieving social sustainability, as it ensures that all individuals and communities have the means to improve their quality of life. Policies that promote intragenerational equity include fair trade, social protection programs, and inclusive economic growth strategies (UNDP, 2015).

3. Precautionary Principle

Precautionary principles argue for taking preemptive action in the face of uncertainty to protect the environment and human health. It implies that the absence of complete scientific confidence should not be used as an excuse to put off measures to avert environmental harm. This principle is especially pertinent in the face of growing environmental problems like climate change and biodiversity loss. The precautionary principle encourages the adoption of preventive measures and the development of sustainable technologies (COEC, 2000).

4. Polluter Pays Principle

The polluter pays principle states that people who cause environmental damage must shoulder the expense of controlling and mitigating that damage. This principle is grounded in the idea of internalizing environmental costs, ensuring that the price of goods and services reflects their true environmental impact. Implementing the polluter pays principle can incentivize businesses to adopt cleaner production methods and reduce pollution. Examples include carbon pricing, environmental taxes, and extended producer responsibility programs (OECD, 2024).

5. Sustainable Use of Resources

The sustainable use of resources principle emphasizes the need to use natural resources efficiently and responsibly to ensure their availability for future generations. This princips advocate for the conservation of biodiversity, the sustainable management of ecosystems, and the reduction of waste and pollution. Practices such as sustainable agriculture, forestry, and fisheries are essential for maintaining the health of natural systems and supporting long-term economic and social well-being (FAO, 2014).

6. Integration of Environmental, Economic, and Social Goals

Sustainability requires the integration of economic, environmental, and social goals into decision-making processes. This principle recognizes that these dimensions are interconnected and that achieving sustainability necessitates a holistic approach. Policies and practices should aim to create synergies between these goals, ensuring that economic development does not come at the expense of environmental health or social equity. Integrated planning and management frameworks, such as the Sustainable Development Goals (SDGs), exemplify this principle(Armida, 201 C.E.; FAO, 2014, 2017, 2018; Hernandez & Manu, 2018; Lagiman, 2020; Lesmana et al., 2024; Raharjo, 2015; Sundari et al., 2023; UNDP, 2015; Wahyuningsih, 2018).

7. Participation and Governance

Effective governance and public participation are critical for achieving sustainability. This principle highlights the significance of including all stakeholders, such as governments, corporations, civil society, and local communities, in decision-making processes. Transparent, inclusive, and accountable governance structures can enhance the legitimacy and effectiveness of sustainability initiatives. Participatory approaches, such as community-based resource management and collaborative planning, empower stakeholders to contribute to sustainable development.

Historical Development of Sustainability Principles

The principles of sustainability have evolved over time, influenced by various environmental, social, and economic challenges. The concept of sustainability can be traced back to early conservation movements in the 19th and early 20th centuries, which advocated for the protection of natural resources and the preservation of wilderness areas. The milestones in the development of sustainability principles include:

- **The Brundtland Report (1987)**: This groundbreaking report by the World Commission on Environment and Development presented the concept of sustainable development and emphasized the need for a global approach to sustainability (Gerasimova, 1987).
- **The Rio Earth Summit (1992)**: The United Nations Conference on Environment and Development (UNCED) in Rio de Janeiro produced major texts such as Agenda 21 and the Rio Declaration, which laid forth principles for sustainable development and provided structures for international collaboration.
- **The Millennium Development Goals (MDGs) and Sustainable Development Goals (SDGs)**: Both set global targets for addressing poverty, inequality, and environmental degradation. The SDGs, in particular, provide a comprehensive framework for integrating sustainability principles into national and international policies.

Application of Sustainability Principles

The principles of sustainability are applied in various contexts, from local community initiatives to global policy frameworks. Examples of their application include:

- **Sustainable Agriculture**: Crop rotation, organic farming, and agroforestry are all examples of practices that improve resource sustainability and food security. These practices integrate environmental, economic, and social goals by improving soil health, increasing biodiversity, and supporting rural livelihoods.

- **Corporate Sustainability**: Businesses are increasingly adopting sustainability principles to reduce their environmental footprint and enhance social responsibility. Corporate sustainability strategies may include reducing greenhouse gas emissions, implementing circular economy practices, and promoting fair labor standards.
- **Urban Planning**: Sustainable urban planning aims to create livable, resilient, and inclusive cities. Principles such as green infrastructure, sustainable transportation, and energy-efficient buildings are integrated into urban development plans to reduce environmental impact and improve quality of life.
- **Climate Change Mitigation and Adaptation**: The principles of sustainability guide efforts to address climate change by promoting low-carbon technologies, enhancing resilience to climate impacts, and ensuring that climate policies are equitable and inclusive.

The principles of sustainability offer a comprehensive framework for dealing with the difficult issues of sustainable development. By integrating environmental, economic, and social goals, these principles guide policies and practices that promote long-term well-being and resilience (Sundari & Bellitürk, 2023). Principles of sustainability offer a comprehensive framework for dealing with the difficult issues of sustainable development.

1.4. Challenges and Opportunities in Sustainable Agriculture

Sustainable agriculture is critical to providing food security, conserving natural resources, and combating climate change. However, its implementation faces numerous challenges and presents significant opportunities. This essay explores these challenges and opportunities in detail, providing a comprehensive understanding of the current landscape of sustainable agriculture.

Challenges in Sustainable Agriculture

1. Climate Change

Climate change is a major danger to agriculture globally. Increased temperatures, changed precipitation patterns, and more frequent extreme weather events can all diminish agricultural yields and disrupt farming operations. For instance, prolonged droughts can lead to water scarcity, while intense storms can cause soil erosion and crop damage (FAO, 2017). Adapting to these changes requires innovative approaches and resilient agricultural practices.

2. Resource Depletion

The depletion of natural resources, such as soil nutrients and freshwater, is a critical challenge for sustainable agriculture. Intensive farming practices have led to soil degradation, reducing its fertility and productivity. Over-extraction of groundwater for irrigation has resulted in declining water tables in many regions (Bengston et al., 2023). Sustainable agriculture must focus on conserving and regenerating these resources to ensure long-term viability.

3. Economic Constraints

Economic barriers can hinder the adoption of sustainable practices. Transitioning to sustainable agriculture often requires significant upfront investments in new technologies, infrastructure, and training. Smallholder farmers, who constitute a large portion of the agricultural workforce in developing countries, may lack the financial resources to make these investments (Zerssa et al., 2023). Additionally, market structures and policies may not always support sustainable practices, making it difficult for farmers to achieve economic viability (Sundari et al., 2023; Sundari, Sulistyowati, et al., 2022).

4. Technological Gaps

Access to advanced technologies is unevenly distributed, particularly between developed and developing countries. Many farmers in developing regions lack access to modern tools and techniques that can enhance sustainability, such as precision agriculture, improved irrigation systems, and climate-resilient crop varieties (Ingersoll, 2012). Bridging this technological gap is crucial for widespread adoption of sustainable practices.

5. Policy and Governance Issues

Effective policies and governance structures are essential for promoting sustainable agriculture. However, inconsistent policies, lack of enforcement, and inadequate support for sustainable practices can impede progress. In some cases, subsidies and incentives favor conventional farming methods over sustainable ones (Arshad, Ashraf, et al., 2020; Arshad, Qamar, et al., 2020; Ashraf et al., 2021; FAO, 2020; Khan et al., 2022; Sundari et al., 2021). Strengthening policy frameworks and ensuring their alignment with sustainability goals is necessary for driving change.

6. Social and Cultural Barriers

Social and cultural factors can also influence the adoption of sustainable agriculture. Traditional farming practices and resistance to change can hinder the implementation of new methods. Additionally, gender disparities in access to resources and decision-making power can affect the participation of women in sustainable agriculture (Fróna et al., 2019). Addressing these social and cultural barriers is essential for inclusive and effective agricultural development.

Opportunities in Sustainable Agriculture

1. Technological Innovations

Technological advancements offer significant opportunities for enhancing sustainability in agriculture. Precision agriculture, which uses data and technology to optimize farming practices, can improve resource efficiency and reduce environmental impact. Innovations such as drones, sensors, and satellite imagery enable farmers to monitor crop health, soil conditions, and water usage in real-time (FAO, 2017). These technologies can help farmers make informed decisions and increase productivity while minimizing resource use.

2. Climate-Smart Agriculture

Climate-smart agriculture (CSA) focuses on adapting agricultural practices to mitigate and adapt to climate change. CSA promotes practices such as conservation tillage, agroforestry, and the use of drought-resistant crop varieties. These practices enhance resilience to climate impacts, improve soil health, and increase carbon sequestration (Bengston et al., 2023). CSA also emphasizes the importance of integrating climate considerations into agricultural planning and policy-making.

3. Sustainable Intensification

Sustainable intensification aims to increase agricultural productivity on existing farmland while minimizing environmental impact. This approach involves optimizing inputs, such as water and fertilizers, and adopting practices that enhance soil health and biodiversity. Sustainable intensification can help meet the growing demand for food without expanding agricultural land, thereby reducing pressure on natural ecosystems.

4. Agroecology

Agroecology applies ecological principles to agricultural systems, promoting biodiversity, natural pest control, and soil health. Agroecological practices, such as intercropping, crop rotation, and polycultures, create resilient farming systems that can adapt to changing environmental conditions. Agroecology also emphasizes the importance of local knowledge and community involvement in sustainable agriculture.

5. Policy and Institutional Support

Strengthening policy frameworks and institutional support for sustainable agriculture is crucial for driving change. Policies that provide incentives for sustainable practices, such as subsidies for organic farming or payments for ecosystem services, can encourage farmers to adopt these methods. Additionally, international cooperation and partnerships can facilitate the exchange of knowledge and resources, supporting the global transition to sustainable agriculture.

6. Market Opportunities

Growing consumer demand for sustainably produced food presents significant market opportunities for farmers. Organic, fair trade, and locally sourced products are increasingly popular, providing farmers with premium prices and access to niche markets. Developing value chains that support sustainable practices can enhance economic viability and create new income opportunities for farmers.

7. Education and Capacity Building

Education and capacity building are essential for promoting sustainable agriculture. Training programs, extension services, and knowledge-sharing platforms can equip farmers with the skills and information needed to implement sustainable practices. Empowering farmers through education can also foster innovation and encourage the adoption of new technologies and methods.

8. Community-Based Approaches

Community-based approaches to sustainable agriculture emphasize the importance of local involvement and collective action. Initiatives such as community-supported agriculture (CSA) and farmer cooperatives can enhance resource sharing, reduce costs, and improve access to markets. These approaches also strengthen social networks and build resilience within farming communities.

Sustainable agriculture faces numerous challenges, including climate change, resource depletion, economic constraints, technological gaps, policy issues, and social barriers. However, it also presents significant opportunities for innovation, resilience, and economic growth. By leveraging technological advancements, promoting climate-smart practices, supporting sustainable intensification, and strengthening policy frameworks, sustainable agriculture can contribute to food security, environmental conservation, and social equity. Addressing these challenges and seizing these opportunities requires a collaborative effort from governments, businesses, researchers, and communities to create a more sustainable and resilient agricultural system for the future.

1.5. Regenerative Agriculture

Regenerative agriculture is a comprehensive approach to farming that focuses on repairing and improving the health of agricultural ecosystems. Unlike conventional agricultural techniques, which frequently harm soil and ecosystems, regenerative agriculture seeks to promote soil health, biodiversity, and ecosystem services. This approach not only supports sustainable food production but also contributes to climate change mitigation and resilience.

Core Principles of Regenerative Agriculture

1. Soil Health Improvement

At the heart of regenerative agriculture is an emphasis on soil health. Healthy soil serves as the foundation for productive and resilient agricultural systems. Cover cropping, decreased tillage, and the application of organic amendments (for example, compost and manure) assist to develop soil organic matter, improve soil structure, and boost microbial activity (Bellitürk et al., 2022; Bellitürk & Eryüksel, 2018). These practices increase the soil's ability to retain water and nutrients, reducing the need for synthetic fertilizers and irrigation. Compost and vermicompost are the best suggestion to apply to grow plant well (Bellitürk & Sundari, 2024).

2. Biodiversity Enhancement

Regenerative agriculture promotes biodiversity at multiple levels, including crop diversity, livestock integration, and habitat restoration. Crop rotation and polycultures (growing multiple crops together) reduce pest and disease pressure and improve soil health. Integrating livestock into farming systems through practices like rotational grazing can enhance nutrient cycling and soil fertility (Bellitürk & Sundari, 2024; Sundari et al., 2023; Sundari, Asyiah, et al., 2022; Wiyanto et al., 2023). Additionally, restoring natural habitats such as hedgerows, wetlands, and woodlands supports wildlife and increases ecosystem resilience.

3. Ecosystem Services

Regenerative agriculture enhances ecosystem services, which are the benefits that humans derive from natural ecosystems. These services include pollination, water purification, carbon sequestration, and climate regulation. By improving soil health and increasing biodiversity, regenerative practices enhance these services, contributing to the overall sustainability of agricultural systems (Cotton, 2024). For example, healthy soils can sequester significant amounts of carbon, helping to mitigate climate change.

4. Minimal Soil Disturbance

Reducing soil disturbance is a key principle of regenerative agriculture. Practices such as no-till or reduced-till farming minimize soil erosion, maintain soil structure, and protect soil organisms. These practices help to preserve soil organic matter and reduce the release of carbon dioxide from the soil

(Kalamdhad et al., 2012). Minimal soil disturbance also supports the development of healthy root systems, which are essential for plant growth and resilience.

5. Water Management

Effective water management is crucial for regenerative agriculture. Practices such as rainwater harvesting, efficient irrigation systems, and maintaining soil cover help to conserve water and improve water use efficiency. Healthy soils with high organic matter content have better water-holding capacity, reducing the need for irrigation and increasing resilience to drought[5]. Additionally, practices that reduce runoff and erosion help to protect water quality in surrounding ecosystems.

6. Holistic Management

Regenerative agriculture adopts a holistic approach to farm management, considering the interconnections between different components of the farming system. This approach involves adaptive management practices that respond to changing environmental conditions and feedback from the ecosystem. Farmers practicing regenerative agriculture often use holistic planned grazing, agroforestry, and permaculture principles to create integrated and resilient farming systems.

Benefits of Regenerative Agriculture

1. Climate Change Mitigation

Regenerative agriculture has the potential to significantly alleviate climate change by sequestering carbon in soils and lowering greenhouse gas emissions. Practices such as cover cropping, agroforestry, and improved grazing management increase soil organic carbon levels and enhance carbon sequestration. Additionally, reducing the use of synthetic fertilizers and pesticides lowers emissions associated with their production and application.

2. Enhanced Soil Fertility and Productivity

By improving soil health, regenerative agriculture enhances soil fertility and productivity. Healthy soils with high organic matter content provide a stable supply of nutrients to plants, reducing the need for external inputs. This leads to more resilient crops that can better withstand environmental stresses such as drought and pests. Over time, regenerative practices can increase crop yields and improve the economic viability of farming operations.

3. Biodiversity Conservation

Regenerative agriculture supports biodiversity conservation by creating diverse and resilient ecosystems. Practices such as crop rotation, polycultures, and habitat restoration provide habitats for a wide range of species, including beneficial insects, birds, and soil organisms. Increased biodiversity enhances ecosystem stability and resilience, making agricultural systems more adaptable to changing environmental conditions.

4. Improved Water Quality and Availability

Regenerative practices that improve soil health and reduce erosion help to protect water quality in surrounding ecosystems. Healthy soils with high organic matter content have better water infiltration and retention, reducing runoff and the risk of water pollution. Furthermore, methods such as rainwater collecting and efficient irrigation systems increase water usage efficiency and availability, promoting sustainable water management.

5. Economic and Social Benefits

Farmers and communities may profit both economically and socially from regenerative agriculture. By reducing reliance on synthetic inputs and improving soil health, regenerative practices can lower production costs and increase farm profitability. Additionally, regenerative agriculture supports rural livelihoods by creating jobs and promoting community resilience.

Engaging in regenerative practices can also enhance farmers' knowledge and skills, fostering innovation and empowerment.

While regenerative agriculture offers numerous benefits, it also faces challenges. Transitioning to regenerative practices requires significant changes in farm management and may involve initial costs and risks. Farmers may need access to education, training, and financial support to adopt regenerative practices successfully. Additionally, market structures and policies may need to be adjusted to support regenerative agriculture and reward farmers for ecosystem services.

Despite these challenges, there are significant opportunities for advancing regenerative agriculture. Increasing consumer demand for sustainably produced food, growing awareness of environmental issues, and supportive policies can drive the adoption of regenerative practices. Collaboration among stakeholders, including farmers, researchers, policymakers, and investors, is essential for scaling up regenerative agriculture and realizing its full potential.

Regenerative agriculture represents a transformative approach to farming that prioritizes soil health, biodiversity, and ecosystem services. By adopting regenerative practices, farmers can enhance the sustainability and resilience of agricultural systems, mitigate climate change, and improve their economic viability. The Hexa-Helix model, which integrates the efforts of media, civil society, business, academia, government, and investors, provides a comprehensive framework for promoting regenerative agriculture. Through collective action and shared responsibility, we can create a more sustainable and resilient agricultural system for future generations.

1.6. Hexa-helix in Sustainable agriculture

The Hexa-Helix model is an advanced framework that integrates six key sectors: media, civil society, business, academia, government, and investors. This model emphasizes the importance of collaboration among these diverse stakeholders to drive innovation and achieve sustainable development goals. In the context of sustainable agriculture, the Hexa-Helix model provides a comprehensive approach to addressing complex challenges and leveraging opportunities. Here's an in-depth exploration of each sector's role within the Hexa-Helix model:

1. Media

The media has a significant influence on public perception and behavior. In the Hexa-Helix model, the media is responsible for disseminating information about sustainable agriculture, raising awareness about environmental and social issues, and promoting positive change. Media outlets can highlight success stories, report on research findings, and provide a platform for diverse voices and perspectives.

By collaborating with other helices, the media can amplify the impact of sustainable agriculture initiatives. For example, media campaigns can raise awareness about the benefits of sustainable farming practices, encourage consumers to make sustainable choices, and hold industry and government accountable for their actions. Social media platforms can also facilitate direct communication between stakeholders, fostering transparency and engagement.

2. Civil Society

Civil society, which includes non-governmental organizations (NGOs), community groups, and advocacy organizations, is critical to supporting sustainable agriculture. These organizations raise awareness about environmental and social issues, advocate for policy changes, and support grassroots initiatives. Civil society can also act as a bridge between other helices, facilitating communication and collaboration among stakeholders.

In the context of sustainable agriculture, civil society organizations can work with farmers to implement sustainable practices, with governments to advocate for supportive policies, and with industry to promote corporate social responsibility. They can also engage with academia to conduct participatory research and with media to raise public awareness about sustainable agriculture.

3. Business

The agricultural industry, including farmers, agribusinesses, and food companies, is a crucial player in the Hexa-Helix model. The industry is responsible for implementing sustainable practices, adopting new technologies, and driving innovation in agricultural production and supply chains. To be sustainable, agriculture must strike a balance between economic viability, environmental stewardship, and social responsibility.

Industry stakeholders can collaborate with academia to develop and test new technologies, such as precision agriculture tools, drought-resistant crop varieties, and sustainable pest management strategies. They can also work with government agencies to create policies and incentives that promote sustainable practices. Additionally, industry players can engage with civil society and consumers to understand market demands for sustainably produced food and to promote sustainable consumption patterns.

4. Academia

Academia plays a pivotal role in advancing sustainable agriculture through research, education, and innovation. Universities and research institutions conduct fundamental and applied research to develop new technologies, practices, and policies that enhance agricultural sustainability. They also provide education and training to equip future generations of farmers, scientists, and policymakers with the knowledge and skills needed to implement sustainable practices.

In the context of sustainable agriculture, academic institutions collaborate with other helices to conduct interdisciplinary research, develop sustainable farming techniques, and disseminate knowledge. For example, research on agroecology, soil health, and climate-smart agriculture can inform policy decisions and guide industry practices.

5. Government

Government agencies and policymakers play a critical role in creating an enabling environment for sustainable agriculture. They develop and implement policies, regulations, and incentives that support sustainable practices and address environmental and social challenges. Governments can also facilitate collaboration among different helices by providing funding, infrastructure, and platforms for stakeholder engagement.

In the Hexa-Helix model, governments work closely with academia to support research and innovation, with industry to promote sustainable business practices, and with civil society to ensure that policies are inclusive and equitable. For example, government programs that provide subsidies for organic farming, support for smallholder farmers, and investments in sustainable infrastructure can drive the adoption of sustainable agriculture.

6. Investors

Investors play a crucial role in the Hexa-Helix model by providing the financial resources needed to support sustainable agriculture initiatives. Investment in sustainable agriculture can take various forms, including venture capital, impact investing, and public-private partnerships. Investors can fund research and development, support the scaling of sustainable technologies, and finance infrastructure projects that enhance agricultural sustainability.

By collaborating with other helices, investors can help drive innovation and ensure that sustainable agriculture initiatives are economically viable. For example, investors can work with academia to fund research on new agricultural technologies, with industry to support the commercialization of sustainable products, and with government to leverage public funds for large-scale projects. Additionally, investors can engage with civil society to ensure that their investments align with social and environmental goals and with media to promote transparency and accountability.

Opportunities and Challenges

The Hexa-Helix model offers numerous opportunities for advancing sustainable agriculture. By fostering collaboration among diverse stakeholders, the model can drive innovation, enhance knowledge sharing, and create synergies that amplify the impact of sustainable practices. For example, partnerships between academia and industry can lead to the development of cutting-edge technologies, while collaboration between government and civil society can result in more inclusive and effective policies.

However, the Hexa-Helix model also faces challenges. Coordinating efforts among multiple stakeholders with different priorities and perspectives can be complex and time-consuming. Ensuring that all voices are heard and that power dynamics do not marginalize certain groups is essential for achieving equitable outcomes. Additionally, securing adequate funding and resources to support collaborative initiatives can be a significant barrier.

The Hexa-Helix model provides a comprehensive framework for promoting sustainable agriculture by integrating the efforts of media, civil society, business, academia, government, and investors. By fostering collaboration and leveraging the strengths of each sector, the model can drive innovation, enhance sustainability, and address the complex challenges facing agriculture today. Embracing the Hexa-Helix model requires a commitment to multi-stakeholder engagement, inclusive decision-making, and a holistic approach to sustainability. Through collective action and shared responsibility, we can create a more sustainable and resilient agricultural system for future generations.

1.7. Sustainable Pillars of Agriculture

Sustainable agriculture is built upon three main pillars: environmental health, economic profitability, and social equity. These pillars provide a comprehensive framework for developing agricultural systems that are productive, resilient, and equitable. Here’s an in-depth exploration of each pillar and its significance in sustainable agriculture:

1. Environmental Health

Environmental health is a cornerstone of sustainable agriculture. It focuses on preserving and enhancing the natural resources and ecosystems that agriculture depends on. Key aspects of this pillar include:

- **Soil Health**: Maintaining and improving soil fertility is crucial for sustainable agriculture. Practices such as crop rotation, cover cropping, reduced tillage, and organic amendments help to build soil organic matter, improve soil structure, and enhance microbial activity[1]. Healthy soils are more productive and resilient, supporting long-term agricultural productivity.
- **Water Management**: Efficient use and conservation of water resources are essential for sustainable agriculture. Techniques such as drip irrigation, rainwater harvesting, and maintaining soil cover help to reduce water usage and improve water retention in soils[2]. Protecting water quality by minimizing runoff and preventing pollution is also critical.
- **Biodiversity**: Promoting biodiversity within agricultural systems enhances ecosystem resilience and productivity. Practices such as agroforestry, intercropping, and maintaining natural habitats support a diverse range of species, including beneficial insects, pollinators, and soil organisms[3]. Biodiversity contributes to natural pest control, pollination, and nutrient cycling.
- **Climate Change Mitigation**: Sustainable agriculture aims to reduce greenhouse gas emissions and increase carbon sequestration. Practices such as conservation tillage, cover cropping, and agroforestry help to sequester carbon in soils and

vegetation[4]. Reducing the use of synthetic fertilizers and pesticides also lowers emissions associated with their production and application.

2. Economic Profitability

Economic profitability ensures that agricultural practices are financially viable for farmers and contribute to the broader economy. This pillar focuses on:

- **Productivity and Efficiency**: Sustainable agriculture seeks to optimize productivity and resource use efficiency. Precision agriculture technologies, such as GPS-guided equipment and remote sensing, enable farmers to apply inputs more accurately and efficiently[5]. This reduces waste and lowers production costs.
- **Market Access and Fair Trade**: Ensuring that farmers have access to markets and receive fair prices for their products is essential for economic sustainability. Fair trade practices and certification schemes can help to ensure that farmers are compensated fairly for their labour and products[6]. Developing local and regional markets can also reduce transportation costs and support local economies.
- **Diversification**: Diversifying crops and income sources can enhance economic resilience. Mixed farming systems that integrate crops, livestock, and agroforestry can provide multiple streams of income and reduce financial risk[7]. Diversification also helps to spread labour and resource use more evenly throughout the year.
- **Investment and Innovation**: Investing in research, development, and innovation is crucial for advancing

sustainable agriculture. Public and private investments in agricultural research can lead to the development of new technologies, practices, and crop varieties that enhance sustainability[8]. Supporting farmer education and training programs can also promote the adoption of innovative practices.

3. Social Equity

Social equity ensures that the benefits of sustainable agriculture are distributed fairly and that all individuals and communities have access to the resources and opportunities they need to thrive. Key aspects of this pillar include:

- **Access to Resources**: Ensuring that all farmers, including smallholders and marginalized groups, have access to land, water, seeds, and other essential resources is critical for social equity. Policies and programs that support land tenure security, access to credit, and affordable inputs can help to level the playing field.
- **Labor Rights and Working Conditions**: Promoting fair labour practices and improving working conditions for agricultural workers is essential for social sustainability. This includes ensuring fair wages, safe working environments, and access to social protections. Supporting the rights of women and migrant workers is particularly important.
- **Community Engagement and Participation**: Engaging local communities in decision-making processes and ensuring their participation in agricultural development is crucial for social equity. Community-based approaches, such as participatory research and farmer cooperatives, empower individuals and

strengthen social networks. This can lead to more inclusive and effective agricultural practices.

- **Education and Capacity Building**: Providing education and training opportunities for farmers and rural communities is essential for promoting sustainable agriculture. Extension services, farmer field schools, and knowledge-sharing platforms can equip individuals with the skills and information they need to adopt sustainable practices. Education also fosters innovation and empowers farmers to make informed decisions.

The three pillars of sustainable agriculture-environmental health, economic profitability, and social equity-provide a comprehensive framework for developing agricultural systems that are productive, resilient, and equitable. By integrating these pillars into agricultural practices and policies, we can create a more sustainable and just food system that meets the needs of present and future generations. Achieving this vision requires collaboration among all stakeholders, including farmers, researchers, policymakers, businesses, and civil society. Through collective action and shared responsibility, we can build a sustainable agricultural future.

1.8. Conclusion

Sustainable agriculture is essential for addressing the environmental impacts of conventional farming and ensuring food security for future generations. This chapter has highlighted the complexity and ambiguity surrounding the concept of sustainability, emphasizing the need for standardized principles. Through a comprehensive literature review and qualitative analysis, four fundamental principles were identified: integrated management, dynamic balance, regenerative design, and social development. These principles provide a robust framework for guiding sustainable agricultural practices, balancing ecological, economic, and social goals. By adopting these principles, we can make better use of natural and human resources, fostering resilient and sustainable agricultural systems[1].

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CHAPTER 3

THE IMPORTANCE OF PLANT-MICROORGANISM RELATIONSHIPS IN SUSTAINABLE AGRICULTURE

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1. INTRODUCTION

The use of fertilizers in agriculture has increased significantly due to the decrease in agricultural lands, the destruction of forests and the increasing demand for more products to meet the food needs of the world population. In addition to chemical fertilizers, the intensive use of agricultural pesticides pollutes our soil and water resources and threatens the health of living beings through the food chain. For this reason, environmentally and friendly agricultural systems to support plant growth are being investigated. Recently, organic fertilization has been preferred as an alternative method to the use of agricultural pesticides and chemical fertilizers, and the best way for this has been suggested as microbial support (Yayla and Şenol, 2020).

The rhizosphere is the narrow area around the root directly affected by root secretions and root microorganisms. The rhizosphere is a preferred microhabitat for soil microorganisms and some soil animals and can contain about a thousand microbial cells and about thirty thousand prokaryotic species per gram of plant roots. This community is known as the microbiome and has a greater biomass than plant roots. The microbiome community helps the healthy growth of the plant, it allows the plant to benefit more by decomposing the organic matter in the soil, thus increasing nutrient uptake. It also allows the plant to produce more capillary roots, increasing its water absorption capacity and making plants more resistant to pathogens (Odoh, 2017).

Microorganisms can live in the rhizosphere, on the surfaces of root (rhizoplane), or within the root tissue (endophytic microorganisms). Microorganisms in the rhizoplane adhere to the root surface by adsorption and/or fimbriae around the cell. Endophytes form the strongest associations with plants and live in root tissue. Endophyt bacteria are called as Rhizobacteria.

On average, 30-60% of the carbon used by plants in photosynthesis reaches the roots and a large portion of this carbon is exuded to the rhizosphere in the form of root secretions by roots. Root secretions are various volatile, soluble, and particulate materials and consist of high- and low-molecular weight compounds. High-molecular weight compounds are mucilages and ectoenzymes, while low-molecular weight compounds are sugars, organic acids, phenolic compounds and amino acids including phytosiderophores. The composition of microbial community in the rhisozphere change to depending on root morphology, plant species and root exudates. Various microbial interactions in the rhizosphere is shown in Figure 1. While microorganisms in the rhizosphere compete with plants for nutrients and water, they also release available nutrients for plants from various organic substances. Pathogenic microorganisms must succeed in colonizing the rhizosphere before penetrating the root. The colonization of these microorganisms may be inhibited or promoted by some Rhizobacteria. Microorganisms that promote plant growth in the rhizosphere are called ‘plant growth promoting rhizobacteria’ (PGPR). PGPRs have two effects on plants, direct and indirect. Their direct effects include promoting plant growth, while their indirect effects include protecting plants against phytopathogens through their primary and secondary metabolites. PGPRs perform many functions, such as nitrogen fixation, phosphorus and potassium uptake, and antibiotic, enzyme and hormone production. PGPRs include Azotobacter, Bacillus, Azospirillum, Pseudomonas and many subspecies (Bhardwaj et al., 2014).

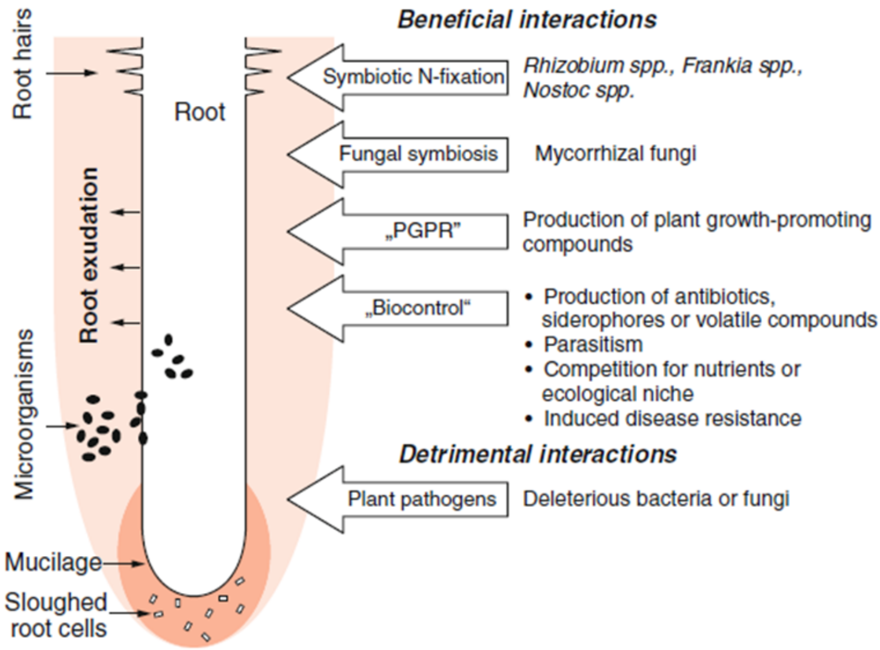

Figure 1. Plant-microorganism interactions in rhizosphere (Blume et al., 2016)

2. BENEFICIAL INTERACTIONS BETWEEN PLANT AND MICROORGANISM

2.1. Symbiotic N_2-fixation

Symbiosis is a relationship between two organisms that benefit from each other. It is usually a long-term relationship and in a symbiotic relationship such as N_2 fixation, the microbial partner has a special structural development. Each N_2-fixing symbiotic relationship involves a N_2-fixing prokaryotic organism (e.g. microsymbionts such as Rhizobium, Klebsiella, Nostoc and Frankia) and a eukaryotic, usually photosynthetic host (e.g. legumes or non-legumes). Although the rate of N_2 fixation varies depending on the host, microsymbiont and environmental conditions, it can reach up to 600 kg N/ha in ecologies such as clover meadows. The main symbionts that fix N_2 symbiotically are:

-Legumes and rhizobia

-Actinorhizal plants and Frankia (an Actinomycete genus)

-The fern Azolla and its microsymbiont Anabaena

- Lichen symbionts involving cyanobacteria

Nodule formation in legumes occurs as a result of interactions between the plant and Rhizobium bacteria. Certain species of bacteria form nodules on plant roots that may or may not be capable of fixing nitrogen. In other words, there is only one type of bacteria that infects a particular group of legumes. These host plants that accept the bacteria are grouped under cross-inoculation groups. A cross-inoculation group describes a legume species that can form active nodules when inoculated with bacteria isolated from nodules of any of a particular group of plants. For example, rhizobium isolated from Medicago (common clover) can form nodules on Melilotus (scented clover) but not on Trifolium species (clover). More than twenty different cross-inoculation groups have been described, resulting in named plant groups for each species within a single Rhizobium genus.

Rhizobium bacteria form nodules in the plant root system in three stages (Figure 2).

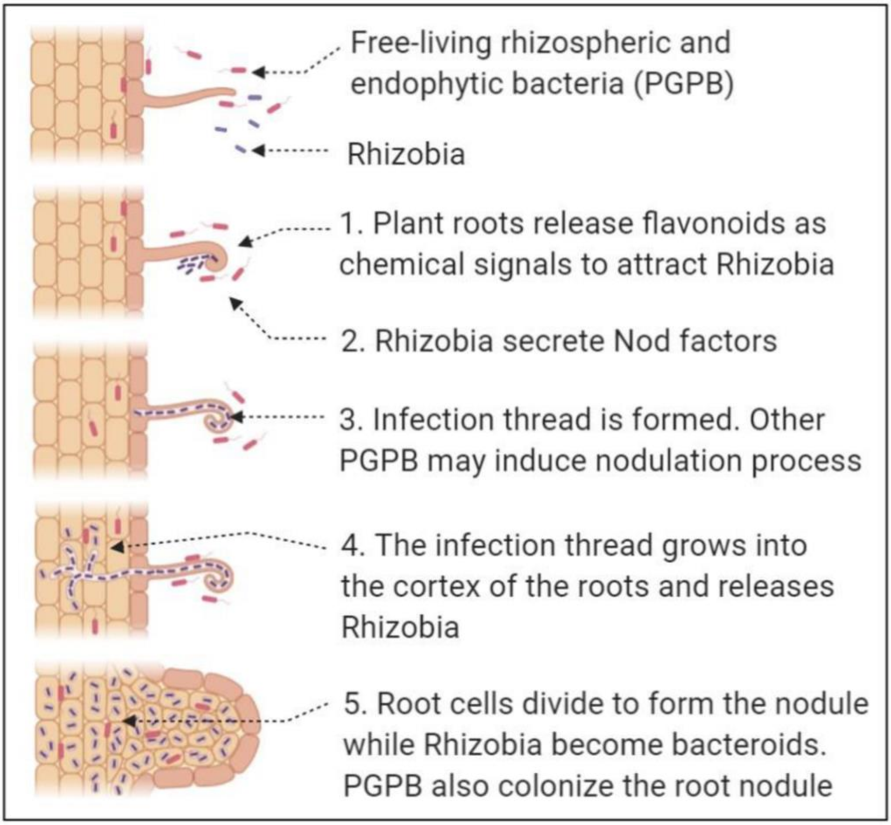

Figure 2. Nodule forming by Rhizobium bacteria on host plant

1. Pre-infection period: During this period, some relationships occur between the plant and the bacteria. The roots of legume plants secrete a type of organic substrate that stimulates the development of microflora in the rhizosphere. If there are rhizobes in the soil, they develop and multiply in the rhizosphere. In infection through capillary roots; the tryptophan secreted by the plant root is converted into the plant hormone indole acetic acid by the rhizobes. This hormone causes the capillary roots to curl. Infection begins with the perforation of the capillary root wall. The secretion of hydrolytic enzymes (polygalacturanase) at the point of infection facilitates this perforation. Thus, bacteria enter through this opened hole.

2. Formation of the infection thread: After the bacteria enter the root cell, a thread-like structure is formed that is thought to be continuous with the wall components of the capillary root. This is called the infection thread. The formation of the infection thread is controlled by the plant. The function of this thread is to carry bacteria from the root meristem cells to the cortex cells. Rhizobiums never remain free in the root. During infection, they remain within the infection thread and then within a peribacteroid membrane formed by the plant. These membranes protect the bacteria from the defense mechanisms of the host plant.

3. Nodule formation: As the infection thread develops towards the base of the root cell, the bacteria divide and multiply within the thread. The multiplying bacteria line up in a single row. When the infection thread reaches the cortex cells, it branches to infect many cells. The infected cells begin to divide and thus form nodules. The infection thread is broken down by the cellulase activity stimulated by the Rhizobium and after the Rhizobiums are free in the cell, they are surrounded by a peribacteroid membrane. After being surrounded by this membrane, the bacteria are called "bacteroids" and can be X, Y, T or irregularly shaped. Bacteroides contain the enzyme nitrogenase.

The pink leghemoglobin found in nodules is responsible for the transport of oxygen within the nodule. Leghemoglobin is only found in nodules. It is not found alone in Rhizobium or in the plant. In pink or red nodules, N_2 fixation is usually actively continuing and they are called "effective" nodules. If the nodule is white or greenish brown, the nodule is inactive or has begun to deteriorate due to aging.

2.2. Mycorrhiza symbiosis

Mycorrhiza, meaning "root fungus", is a mutually beneficial relationship between soil-borne fungi and the roots of higher plants. Mycorrhiza is also defined as a mutualistic lifestyle between plant roots and certain types of fungi. In this relationship, there is a movement of carbon formed by the plant towards the fungus and nutrients gained by the fungus towards the plant. Mycorrhiza infects the roots of approximately 90-95% of plants in the terrestrial ecosystem through its spores. This mutual cooperation constitutes the most widespread symbiotic relationship in nature. Mycorrhizal hyphae transfer nutrients from the soil solution to the roots. With this mechanism, mycorrhiza increases the effective absorptive surface of the plant. In soils poor in nutrients or soils that do not contain enough water, plants can survive with the nutrients taken in by these hyphae. As a rule, mycorrhizal plants are more resistant and combative against stress conditions than non-mycorrhizal plants.

Mycorrhizal fungi vary greatly in structure and function. The main types of mycorrhizae are given in Table 1.

Table 1. Main types and hosts of mycorrhizae (Sylvia et al., 1998).

Mycorrhizal type	**Hosts involved**	**Fungi involved**	**Characteristics structures**	**Characteristics functions**
Ectomycorrhizae	Mostly gymnosperms Some angiosperms Restricted to woodt plants	Mostly asidiomycetes Some Ascomycetes Few Zygomycetes	Hartig net Mantle Rhizomorphs	Nutrient uptake Mineralization of organic matter Soil aggregation
Arbuscular	Bryophytes Pteridophytes Some gymnosperms Many angiosperms	Zygomycetes (Glomales)	Arbuscules Vesicles Auxiliary cells	Nutrient uptake Soil aggregation
Ericaceous	Ericales Monotropaceae	Ascomcyetes Basidiomycetes	Some with hyphae in cell, spme with mantle and net	Mineralization of organic matter

				Transfer between plants
Orchidaceous	Orchidaceae	Basidiomycetes	Hyphal coils	Supply carbon and vitamins to embryo
Ectendomycorrhizae	Mostly gymnosperms	Ascomcyetes	Hartig net with some cell penetration Thin mantle	Nutient uptake Mineralization of organic matter

- Ectomycorrhizae (EM): They form a thick hyphal mantle on the plant root and the hyphae fill the intercellular spaces in the cortex, forming a network (Hartig network). The Hartig network is an interface between the host plant and the fungus where carbohydrates and minerals are exchanged. The thickness, color and structure of the mantle may vary depending on the plant-fungus association. The mantle increases the surface area of the absorbent roots and causes a thin root morphology. Hyphal threads extend from the mantle to the soil. The majority of ectomycorrhizal fungi are taxonomically included in the Basidiomycetes. Ectomycorrhizae are generally found in most gymnosperms, some angiosperms and a limited number of woody plant roots.

-Arbuscular mycorrhizae: The most distinctive feature of arbuscular mycorrhizae (AM) is the emergence of a densely branched arbuscular structure within the root cortex cells. The fungus first grows between the cortex cells, but after a short while it penetrates into the cell and begins to develop there. The general name given to all mycorrhizal fungi that develop inside the cell is endomycorrhizae. In this association, there is no disruption or splitting of the fungus cell wall or the plant cell membrane. As the fungus grows, the host cell membrane expands and covers the fungus like an envelope in a newly created compartment inside the cell. This envelope prevents the plant and fungus cytoplasm from coming into contact with each other and ensures the effective transfer of nutrients between the symbioses.

Other structures formed in some arbuscular mycorrhizal fungi are vesicles, auxiliary cells, and asexual spores. Vesicles are thick-walled, lipid-filled, and usually develop in the spaces between cells. Their primary function is thought to be storage, however, vesicles may also serve as the fungus' reproductive organs. Auxiliary cells are formed in the soil and their functions are not fully known. Asexual spores occur in roots and more commonly in soil. Arbuscular mycorrhizae are taxonomically included in the Glomales order.

Although the term vesicular-arbuscular mycorrhizae (VAM) is used to describe symbiotic associations formed by all fungi in the Glomales order, the abbreviation AM is preferred because a large suborder lacks the ability to grow vesicles in roots.

The occurrence of arbuscular mycorrhizal symbiosis in most herbaceous and woody plants indicates that host specificity is generally absent in this type of mycorrhizae. However, specificity (natural ability to colonize), infectivity (amount of colonization) and effectiveness (plant response to colonization) can vary. The degree of colonization of root systems by arbuscular mycorrhizal fungi, their effects on nutrient uptake and plant development vary greatly.

2.3. Plant Growth Promoting Rhizobacteria (PGPR)

There is a very close relationship between PGPR and their hosts because they have many beneficial effects on plant growth. However, the degree of this relationship varies depending on where and how the PGPR colonizes the host plant. The relationship between PGPR and its host can occur in two different ways: (1) rhizospheric and (2) endotrophic relationships. In rhizospheric relationship, PGPR can colonize in the rhizosphere, root surface and dead cell tissues. Plants change the soil properties in the rhizosphere, facilitating the colonization of PGPR in this region. These changes occur in soil pH, water potential, partial pressure of oxygen and other physical and chemical properties resulting from plant secretions. In endotrophic relationships, PGPR is found in the apoplastic spaces of the host plant cell. The best characterized example of symbiosis related to the colonization of the host plant by endophytes is the legume-rhizobium relationship. This complex and also regular association, which includes chemoattraction, attachment, infection of the microsymbiont and the development of root nodules, has been described in detail in many articles. In many endophytic relationships where special structures such as root nodules are not formed, the infection routes of PGPR and the environmental conditions where the microsymbiont is located are still not very well known. In particular, there is no clear information about the infection routes of the bacteria. In some studies, there is information that the entry point of PGPR into the plant cell is the junctions of the lateral roots. However, Mc Cully (2001) suggested that such entry points are not found in intact plant roots and that this situation is due to the breaks in the lateral root junctions during the removal of the plant roots from the soil. Cellulase and pectinase enzymes secreted by some PGPR endophytic species are also known to aid infection. Some endophytic species can use other organisms as vectors to gain entry into the apoplastic spaces of the plant.

The ways in which PGPR is effective in obtaining nutrients from the host plant can be grouped under five headings:

1. Biological N_2 fixation
2. Increasing the availability of nutrients in the rhizosphere
3. Increasing root surface area
4. Increasing other beneficial symbioses of the host and
5. Increasing plant growth through the combination of the above 4 modes of action

PGPRs fixing N_2 for the host plant

The most studied and researched PGPRs so far are the members of the rhizobia group (Allorhizobium, Azorhizobium, Bradyrhizobium, Mesorhizobium, Rhizobium and Sinorhizobium) that have the ability to fix N_2 for legume plants. The first rhizobium inoculums developed for use in legumes were in the 1890s. Due to the symbiosis between root nodule bacteria and legumes is particularly well investigated, this article will focus more on N_2 fixing communities.

The stimulation of host plant growth by PGPRs with nitrogen fixing ability is due to the nitrogenase activity having *Azoarcus* sp., *Beijerinckia* sp., *Klebsiella pneumoniae*, *Pantoea agglomerans* and Rhizobium sp. While it was previously believed that the beneficial effects of *Azospirillum brasilense* on plant growth in non-legume plants were due solely to the nitrogen it fixes, it is now well established that these effects are mediated by other mechanisms (e.g., phytohormone production, effects on root morphology) (Vessey, 2003). Unlike BNF (biological nitrogen fixation) communities, which generally have low N_2 fixation capacity, the symbiosis between sugarcane and endophytic diazotrophs allows the plant to meet 20-60% of its nitrogen needs from its microsymbionts (Boddey et al., 2001). In particular, *Gluconacetobacter diazotrophicus* has been found to make significant contributions to the nitrogen nutrition of sugarcane under controlled conditions by Sevilla et al. (2001). It has been determined that another N_2-fixing endophytic species of sugarcane, *Herbaspirillum seroepdiaceae*, also infects rice plants and increases the amount of $^{15}N_2$ entering the plant (James et al., 2002).

PGPRs increasing the availability of nutrients in the rhizosphere

There are many publications about the mechanism of action of many PGPRs, which is to increase the availability of nutrients in the rhizosphere and allow plants to benefit more from these nutrients (Rawat et al., 2021; Pan and Cai, 2023; Rajawat et al., 2019; Scavino and

Pedraza, 2013). The ways in which these increases occur are to increase the solubility of unavailable forms of nutrients and/or to produce siderophores that help the transfer possibilities of some nutrients, especially Fe.

Phosphate-Solubilizing Microorganisms (PSMs)

Although soils have a large phosphorus reserve, ironically the amounts available to plants constitute a very small portion of this pool. Plants can only take phosphorus in two available forms, monobasic ($H_2PO_4^-$) and dibasic (HPO_4^{-2}) ions. PSMs are widespread in the rhizosphere. The unavailable forms of phosphorus can be converted into available forms by the secretion of organic acids and phosphatases by these microorganisms (Rawat et al., 2021). Bacteria belonging to the genera Pseudomonas, Enterobacter, and Bacillus (Biswas et al., 2018; Buch et al., 2008), Serratia and Pantoea (Sulbaran et al., 2009), Rhizobium, Arthrobacter, and Burkholderia, and *Rahnella aquatilis* HX2 (Liu et al., 2019; Zhang et al,. 2019), *Leclercia adecarboxylata* (Teng et al., 2019), and fungi like *Penicillium brevicompactum* and *Aspergillus niger* (Rojas et al., 2018; Whitelaw, 1999), and Acremonium, Hymenella, and Neosartorya (Ichriani et al. 2018) are potent PSMs.

PSMs also produce growth-promoting hormones like auxins, cytokines, and gibberellins which promote shoot growth, cell division, cell differentiation, root development, germination, flowering and xylem differentiation (Puri et al. 2020).

Potassium-Solubilizing Microorganisms (KSMs)

Certain bacteria can decompose aluminosilicate minerals and release available potassium (Basak and Biswas, 2009). A wide range of bacteria, namely, *Acidithiobacillus ferrooxidans*, Pseudomonas, Burkholderia, *Bacillus mucilaginosus*, B. *circulans*, B. *edaphicus*, and Paenibacillus spp., have been reported to release potassium in available form potassium-bearing minerals in soils (Liu et al., 2012; Meena et al., 2014, b; Kumar et al., 2015). Inoculation with potassium solubilizing microorganisms (KSMs) has been reported to exert beneficial effects on growth of cotton and rape (Sheng, 2005), cucumber and pepper (Han et al., 2006), wheat (Sheng and He, 2006), and sudan grass (Basak and Biswas, 2010). Application of K-solubilizing bacteria as biofertilizer for agricultural improvement can reduce the use of agrochemicals and support eco-friendly crop production (Sindhu et al., 2010).

PGPRs facilitating iron absorption

Fe, an important trace element required by plants, is found in relatively insoluble forms in the soil solution. Plant roots prefer reduced Fe (Ferri, Fe^{+2}) ions, but ferrous Fe (Fe^{+3}) ions are more abundant in well-aerated soils. Plants generally secrete organic soluble compounds such as chelates and phytosiderophores that bind Fe+3 and ensure its preservation in the soil solution. Chelates direct Fe^{+3} to the root surface, where it is reduced to Fe^{+2} and immediately absorbed by the plant. Phytosiderophores are absorbed along the plasmelemma with Fe^{+3} ions.

It has been proven that some rhizospheric bacteria also form siderophores and that many plants can absorb bacterial Fe^{+3}-siderophore complexes (Kartic et al., 2023). Some researchers have suggested that the contribution of these siderophores to the overall Fe requirement of plants is very small (Glick, 1995), while others have suggested that the contribution is significant and even vital, especially in calcareous soils (Masalha et al., 2000).

PGPRs affecting root development and morphology

Studies have shown that PGPRs, which affect root morphology and increase root surface area, can have a major effect on nutrient uptake. A great deal of evidence for the positive effects of PGPR biofertilization points to bacterial-induced changes in root development and morphology. PGPR inoculations increased root weight (Bertrand et al., 2001). More importantly, increases in root length and root surface area have also been reported (German et al., 2000). Fallik et al. (1994) found that root surface area increased due to the increase in capillary roots after inoculation of maize with *Azospirillum brasilense*. The increase in root length and root surface area, rather than the increase in root weight, is more important in terms of indicating the increase in the affected soil volume.

One of the mechanisms by which microorganisms improve plant growth and stress tolerance is their ability to synthesize metabolites/phytohormones in the rhizosphere or root tissue (Etasami at al., 2015). Microbial phytohormones affected the metabolism of endogenous growth regulators in plant tissue and played a key role in improving root morphology exposed to drought, salinity, extreme temperature and heavy metal toxicity (Sorty et al., 2016). Microorganisms belonging to different genera and species such as Acinetobacter, Pantoea, Pseudomonas, Rhizobium and Sinorhizobium, various isolates of Bacillus, Enterobacter, Brevibacillus Cellulosimicrobium, Mycobacterium, Ochrobactrum and Paenibacillus (Egamberdieva et al., 2017), Mycobacterium species isolated from orchid rhizosphere (Tsavkelova et al., 2007) and Azotobacter, Azospirillum, Cellulomonas and Mycoplana isolated from wheat rhizosphere (Egamberdieva et al., 2009) produced various phytohormones.

Indole-3-acetic acid (IAA) is a phytohormone related to the initiation of root formation, cell division and cell growth. This hormone is widely produced by PGPRs. Studies on this subject have shown that PGPRs producing IAA increase root development and length, resulting in a larger root area, and thus the plant can take more nutrients from the soil (Vessey, 2003).

Ethylene, the only hormone in gaseous form, has numerous effects on plant development and growth as well as a limiting effect on root development. Glick et al. (1998) reported that 1-aminocyclopropane-1-carboxylate (ACC) deaminase activity secreted by some PGPRs reduces ethylene production in host plant roots, thus allowing plant roots to continue elongating.

Increasing other beneficial symbioses of the host: "Helper" bacteria

The benefits of PGPR's may be increased by synergistic or stimulatory effects of a third microorganism present in the rhizosphere. In these cases, the PGPR that assists the other host-symbiont relationship is usually called the "helper" bacterium. The vast majority of studies on this subject are on legume-rhizobium symbioses or plant-fungus symbioses.

There have been many studies on PGPR bacteria that help legume-rhizobium symbiosis. Singh and Subba Roa (1979), who were among the first to work on this subject, reported the positive effects of *A. brasilense* inoculation on nodule number, nodule dry weight and shoot development of soybean. There are many mechanisms for the stimulating effect of PGPR in legume-rhizobium symbiosis. However, the most accepted mechanism is the phytohormone-induced (usually IAA) stimulation of root development (Molla et al., 2001). PGPR stimulates root development and provides more contact sites for infection and nodulation. Burdman et al. (1996) determined that some PGPRs that stimulate legume-rhizobium symbioses can directly affect the development of the symbiosis. These researchers established a relationship between the nodulation-stimulating effect of *Azospirillum brasilense* and increased flavonoid production by the host legume. Flavonoids are the first chemical signals secreted by the host legume to form nod-genes in rhizobia, thus initiating the legume-rhizobium symbiosis (Schultze and Kondorosi, 1998).

Under some conditions, PGPR indirectly increases plant growth by stimulating the interaction between the host plant and beneficial rhizospheric fungi (such as arbuscular mycorrhiza AM). Although it is well known that AMs increase the uptake of various nutrients (especially

P), studies have shown that co-inoculation with some PGPRs may increase the interaction between the plant and its fungal symbiont. Ratti et al. (2001) found that a combination of an AM fungus (*Glomus aggregattum*) and two PGPRs (*Bacillus polymyxa* and *Azospirillum brasilense*) increased the biomass and P content of aromatic palmarosa grass. Similarly, Toro et al. (1997) found that both Enterobacter sp and *Bacillus subtilus* stimulated the growth of AM, *Glomus intraradices*, and consequently increased plant biomass and tissue N and P content. Kim et al. (1998) found that separate inoculations of *Glomus etunicatum* (EM) and the phosphorus-solubilizing PGPR *Enterobacter agglomerans* increased plant P content, but that higher P and N uptake in tomatoes occurred when both organisms were inoculated together. These studies clearly demonstrated that one or more of the helper bacteria had P-solubilizing capacity, but that the bacteria acted together with AM to increase P uptake by the host plant. However, other mechanisms, such as phytohormone production, are undoubtedly responsible for this increase.

Combination of mechanisms of action

Although individual mechanisms of action of PGPR's are given, in many cases a single PGPR may have more than one of these mechanisms of action. Cattelan et al. (1999) identified 22 isolates from the rhizosphere of soybean that were positive for PGPR properties, 6 isolates positive for ACC deaminase production, 4 isolates positive for siderophore production, 3 isolates positive for β-1,3-gluconase production and 2 isolates positive for P solubility. Antoun et al. (1998) examined 266 Rhizobium strains and found that 83% produced siderophores, 58% produced IAA and 54% could solubilize phosphorus. Belimov et al. (2001) isolated 15 bacterial strains from the pea rhizosphere and determined that three of the five Psudomonas isolates that stimulated the development of rapeseed grown in Cd-contaminated soils showed positive properties for ACC-deaminase, phosphorus solubilization and IAA production. These studies show that PGPR may have many mechanisms of action. In addition, these studies revealed that the presence of PGPR with a single mechanism of action in the rhizosphere may create a synergy to stimulate the development of the host plant.

2.4. Biocontrol

Another function of rhizosphere bacteria is to be an effective biological control agent by suppressing the effect of diseases. Rhizosphere bacteria use different mechanisms to protect the plant against pathogens; such as competition, antibiotic production, degradation of fungal cell walls and sequestration of iron by siderophore production (Ramyasmruthi et al., 2012). Enzymes that degrade the cell wall of fungi, such as chitinase, lyase and cellulase, prevent the onset of diseases and their spread. Hydrogen cyanide produced by some bacteria is also effective in suppressing diseases. Again, siderophore produced by bacteria reduces the uptake of iron by fungi. Bacterial siderophores can also increase the systemic resistance of the plant (Audenaert et al., 2002; Saravanakumar et al., 2007). Antibiotics produced by PGPRs are also effective in suppressing pathogens. The synergistic interaction between antibiotics and ISR further increases resistance to pathogens (Jha et al., 2011).

3. CONCLUSION

The ability of microorganisms to promote plant growth under normal and stress conditions and their mutualistic relationships with plants have increased their importance in sustainable agricultural systems. For better performance, these microorganisms need to colonize the rhizosphere and increase their populations. However, there is still a lack of evidence on the consistent performance of rhizosphere microorganisms, especially under field conditions. In some cases, the results obtained in the laboratory do not match the field conditions. It is necessary to develop effective inoculums that can perform better under field conditions. This may be due to the poor quality of the inoculum and/or the inability of the bacteria to compete with the native population. Therefore, the use of such technologies that increase agricultural production is very important to feed the increasing human population. Application of multi-strain bacterial consortia instead of single inoculums may be an effective approach to reduce the detrimental effect of stress on plant growth. Strains that have the ability to protect the plant from diseases by biological control mechanisms can also be included in the formulation. Each strain in the multi-strain consortium can effectively compete with the native rhizosphere population and enhance plant growth with its partners. Knowledge of the interactions between microbial consortia and the plant system can be very effective in improving plant growth in sustainable agricultural soils. When all this information is brought together, it is possible to increase the sustainability and plant productivity of agricultural soils by utilizing and increasing the capacity of the natural and native populations of the soil.

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CHAPTER 4

NATURAL AND HUMAN RESOURCES

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1.1. INTRODUCTION

By developing industry and urbanization, the need for the food supply increased. So, the human forced to use of more land and natural resources such as water and soil for producing the agricultural products. Some of these usages were not according to the rights and rules. So different toxic and chemical materials used to have more products. The ground water usage continued indiscriminately. The more cultivation on the soil without respecting the potential of the soil caused to the soil exhaustion and soil different erosions. In addition, these problems, by increasing the population the farm lands converted to the structure and human residence and agricultural producing was challenged between the two basic problems of reducing agricultural land and increasing the need for food raw materials. This mater caused to destruction the environment and damaged to the microclimate and other environment living beings. Today, seeing these problems further showed the need to use new agricultural methods and technologies that are based on preserving the environment and improving economic and social conditions (Lobao and Meyer, 2001). Sustainable agriculture is a kind of farming that is environmentally friendly. This system can produce agricultural products without any harmful to the natural, microclimate and human resources. Sustainable agriculture helps us, in addition to meeting the daily food needs, let's preserve natural resources for the future generation. As a result of the indiscriminate use of chemical pesticides and fertilizers and negative effects of these materials on the food quality, natural resources pollution by fossil fuels from the use of tractors, endangering human health by using of these chemical materials, soil organic materials and fertility decreasing, sustainable agriculture has special importance for the agriculture. Sustainable agriculture has different methods with different systems that can solve these problems (Kremen et al., 2012).

1.2. SUSTAINBLE AGRICULTURE GOALS

1. Emphasis on local knowledge and traditional agricultural systems with optimal use of agricultural ecological system, local resources and respect for local culture.
2. Production and supply of healthy and diverse food with appropriate quality and quantity without the presence of chemical residues and taking into account the health of the producer and consumer without the use of preservatives and additives.
3. Economic stability of agriculture by creating added value and providing living conditions for producers and their families by providing sufficient income.
4. Preservation of natural resources, plant and animal biodiversity, along with the balance of the ecosystem and reduction of all types of pollution in water, soil and air.
5. Protection of water resources, soil and biological species and optimal use of them and finally preservation of the environment.
6. Maintaining and increasing soil fertility in the long term.
7. Not using artificial growth regulators, including chemical fertilizers and hormones, in plant and animal production.
8. Producing healthy livestock, poultry and aquatic animals and providing favorable living conditions for them.
9. Reducing energy consumption and non-renewable resources.
10. Increasing the income of farmers and producers by producing good and continuous yields and reducing production costs in low yield areas and marketing and searching for appropriate business methods (Ristino and Steier, 2016).

Sustainable agriculture should not be considered only as a collection of different methods, but it should be considered a kind of vision. Modern or commercial agriculture is based on *reductionism*. This view looks at agriculture like an industry and its biological nature is not taken into account and by removing complex biological relationships between biological phenomena, it tries to solve problems in the short term and only aims to achieve the maximum economic benefit (Timmermenn and Felix, 2015).

Sustainable agriculture is a type of agricultural system in which by using of minimal inputs and external artificial and chemical agents, optimal performance can be obtained in such a way as to have minimal negative impact on the environment.

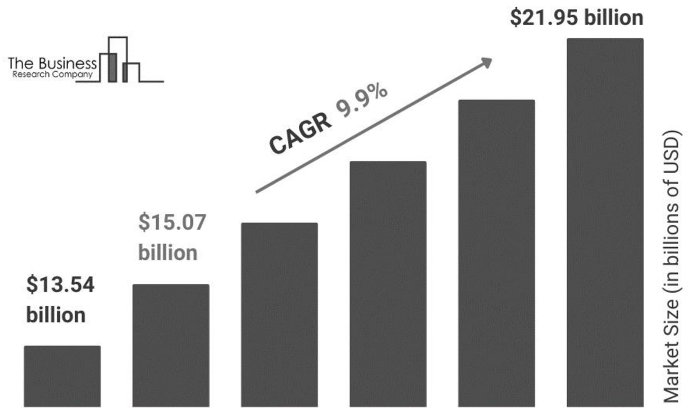

Figure 1: Sustainable agriculture global market report 2024

1.3. SOIL MANAGEMENT IN SUSTAINABLE AGRICULTURE

The soil is one of the important factors for human producing activities on the lands. So, soil has special effects on the agricultural production, agricultural industry and agricultural ecosystems.

Soil has three important functions: food production, biodegradation, establishment of plants. Use of machinery and chemical materials damage soil physical and chemical properties and cause to the weakening and destruction soil microorganisms. As this results soil healthy has more important for the sustainable agriculture. Desirable soil is that one can establish and maintain the plants as physically, supply the plants growth possibility and cause the maximum production during long time that this name is sustainable production (Warner, 2006).

The farming and soil problems in the sustainable agriculture

1.3.1. Soil clumping

Soil drought as the result of water deficiency in hot and dry region and the need to accelerate the next cultivation causes to plant under un-sufficient soil moisture and making soil clumping. Existance of big clumping in the soil prevent to agricultural machineries easy work, so the machineries use of the more fuel and increasing environment, soil and water pollution that is problem for the sustainable agriculture (Warner et al., 2011).

1.3.2. Soil structure destruction

Heavy cultivation on the soil causes to the soil structure destruction. Under this condition the plants cannot be establish sufficiently in the soil and adsorb enough water. As the result of compression will not have desirable growth into the soil and cannot produce enough with high quality. This mater is an important problem for the sustainable agriculture that in addition to the physical problems can cause the other problems such as economical, energy and timing problems (Woodard and Verteramo-Chiu, 2017).

1.3.3. Excessive water consumption effects on the soil

Enough and sufficient water amount for the cultivation is one of the basic factors. Excessive water usage causes to run out the ground water and empty the water channels. So, this mater making erosion problems for the farming land soil. Sinkholes are the other problems that are seen as the result of water excessive consumption. This problem can convert the farming fertile lands to the dry and desert lands that is contradiction for the sustainable agriculture (USDA NASS, 2017).

1.4.CROP ROTATION

The main goal of the crop rotation under sustainable system is the weeds, pests and diseases control. The crop rotation provides the possibility of diverse agricultural operations during different times. So ecosystem stability can be established in the region that causes to the weeds, pests and diseases control. Crop rotation takes off the agronomy systems from the vulnerable state and increases the biological diversity. So, the plants can use of the soil nutrition and water as optimum and continue the growth and fertility during long time. This is according to the sustainable agriculture concept exactly (USDA ERS,2019).

1.5. WATER

Water resources effects on the sustainable agriculture are as three cases: excessive water consumption, water resources drought and water resources pollution. Water quality and quantity influences on the agricultural products. Physical and chemical pollution of the water can continue during long time and changes the region microclimate and biological systems (Smith et al., 2014).

1.6. AIR

Fuel usage in the farms can produce toxics gases such as nitrogen oxides, carbon monoxides, hydrogen sulfides. These gases effects on the soil, water and plants and decreases the adsorbed oxygen by the plants. Fuel effects on the natural resources and environment is one of the important factors that sustainable agriculture is facing to this problem (Smith et al., 2014).

1.7. THREE IMPORTANT FACTORS FOR SUSTAINABLE FARM MANAGEMENT

Energy, farming system and smart agriculture system are the three cases that are important for the sustainable agriculture application and continues. According to these three factors, can be developed the sustainable system and applied the farming running easily.

1.8. FARMING UNDER SYSTEM CONCEPT

Farming systems details are identified by the technical sensitivity to the farming production land diversity, recognizing production limiting and rational decision for the production problems. For the farming system, the production should be enough and sufficient and continues during long time. Under less production can be have system concept, so the sustainable agriculture cannot be maybe in the land. In the regions that have problems as climate or land breadth cannot be apply a farming system because usage energy as physical and human are important. The system needs to the technology, energy and the workforce that accepts the region. Because the system will be evaluating as economical and sociality finally (Shields, 2018).

1.9. CLIMATE CHANGES AND SUSTAINABLE AGRICULTURE

Climate changes is increasing day by day and was accepted as science and politics. Agricultural industry influenced by the climate changes. Climate changes will have wide range as landscape physical changes that cause to apply the different government requirement and markets demands. For the greenhouse gases decreasing and the preparing for future weather planning needs to change the agriculture systems. Weather changes cause to farms lands condition changes (Rosset et al., 2011).

Climate changes effects on the agricultural business and government political should be planed according to the changes to have the best business. Usage of bioenergy and reduce the fossil fuel can prevent the climate changes and world warning.

1.10. RURAL DEVELOPMENT AND FOOD SECURITY

In a country, for sustainable development, rural development and sustainable agriculture are the indispensable factors. Sustainable agriculture influences on the four important topics as economic, social, environment and culture that causes to changes the yield of these cases.

Picture 2: Objectives of sustainable agriculture and rural development

This change can be accepted by the international different organizations. Agriculture and rural development are sustainable when they are friendly for the environment, valuable for the economic, just as society and sufficient for the culture. Sustainable agriculture can be supplied the human food needs in the present and future time (Meyfroidt et al., 2019).

1.11. WORKFORCE IN THE AGRICULTURE

Day laborer are the workers that works in the field, greenhouse and livestock to produce the food and fiber as daily and can have income during the day hours. They are employed in the small or medium agricultural operations. They cannot use of any tools or technology for the work generally. These workers are not constant group for the agricultural works and they work according to the agricultural season and condition. These workers cannot have more guaranty for the agricultural production because they work as money or condition and they do not have any commitment for the organizations. Also, some of these workers are non-native and after the agricultural season come back to their cities and cannot be help in the winter caring and spring preparations (Harper et al., 2009). But Agriculture is a serious work and needs to full-time workers too. So they are indigenous workers that live in the agricultural regions and can work in the agricultural organizations during twelve months and can have important effects on the production. They work as agreement and are constant. But sustainable agriculture needs to have enough experience and attention for the works. So the permanent workers are sufficient for the sustainable agriculture. Continuity is important factor that should be under sustainable agriculture condition. Also, the income level of the workers in rural regions is very important because workers want to have good economic condition. According to this case, if the salary of the workers be constant during the year or if financial situations worsen, the workers will leave the works and cannot continue the task. As the permanent workers can have important effects on the sustainable agriculture, the sustainable agriculture can influence on the continuity of workers. Education for the workers, agriculture methods such as organic agriculture and some agricultural and financial cooperation can help to have sustainable organization and develop the rural agriculture (Goldstein et al., 2019).

1.12. GOVERNMENT AND SUSTAINABLE AGRICULTURE

The governments should be having good policies that can promote the sustainable agriculture.

1.12.1. Improvement support

The government should be established the big companies to regulate and ensure the agricultural standards. These companies must have enough experience in agricultural activities and plight to continue sustainable agriculture system. Smallholder farmers are not sufficient producers for sustainable agriculture and big companies should be replaced as these farmers (Getz et al., 2008).

1.12.2. Subsidy

According to some agreements between the producer companies of farmers such as developing the organic agriculture or reduction the usage of chemical pesticides and fertilizers, the government can supply the subsidies or some financial advantages for the producers.

1.12.3. Research and extension services

The government can help the producers as research and educational activities because the products quality increasing and developing the practices can maybe by using of the technology and new tools and equipment that for this case research and education have the important role. The government can supply this service as financial and information too (Ferguson et al., 2019).

1.12.4. Land tenure reforms

As the result of leasing, inheritance the farm lands are divided to the small parcels or after harvesting the income of the production divided between the heirs or land owner. So this case is big problem for the agriculture development in different village and region. This problem can be prevented by the unification of the land documents and surrender the farm lands to the constant producer such as producer companies or a constant and young farmer.

1.12.5. Government sustainable agriculture policy

Government should be determining special policy for the sustainable agriculture that there are some promotion and advantages cases for the producers. Also, government can be locating the special region for the agriculture products according to the climate condition and water resources and soil fertility state. Government policy for the sustainable agriculture should become as important strategy that cause to develop the agriculture in the country (Engelbert, 2013).

1.13. GOVERNMENT AND PROCEEDING

Local people can help to do the government sustainable agriculture policy and contribute to development the village and distribute the sustainable agriculture processes in the rural region. This process has some stages such as:

1. Important cases organization
2. Important area selection
3. Situation evaluation
4. The future scenarios identification
5. Recommendable policy changes identification

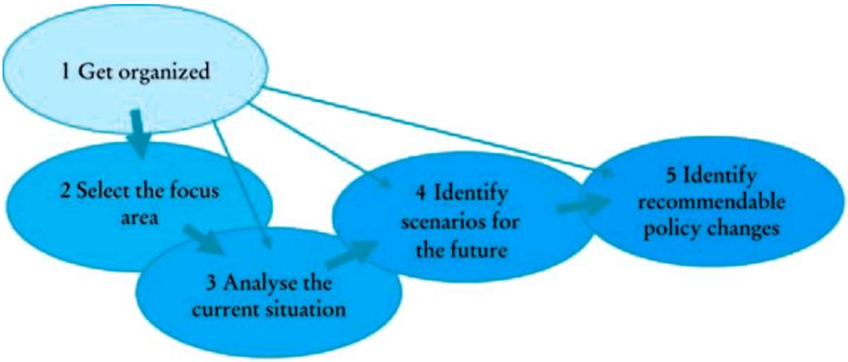

Figure 3: Sustainable agriculture processes stages in the rural region.

The sustainable agriculture processes can be useful in other sectors such as urban developing, health and education (Dumont and Baret, 2017).

1.14. SUSTAINABLE AGRICULTURE POLICY ANALYSIS

For application sustainable agriculture should be increased the agriculture area and agriculture sector development. Also, reduction of greenhouse gases and limitation the climate changing speed is necessary to have food security and successful sustainable agriculture. This cases cannot be supply if there is not sufficient government policy. The government should be having special policy for sustainable agriculture in addition to the social and economic policies. By this way they can guarantied the food security during medium and long time (Delgado, 2010). The climate condition improvement should be key factor to ensure sustainable agriculture growth. So, good policy effects on the climate changing potential. So, the ability to receive the social and economic goals can be reinforced, too. Sustainable agriculture development is gold standard for the agriculture projects because the sufficient development can guaranty the food security and livelihood improvement during long time.

These policies should be converted to the programs and during the determined time to act in the different agriculture regions. These programs should be increased the agriculture production and keep the food resources in sufficient standard level (Belasco, 2017).

1.15. DISCUSSION

Sustainable agriculture will offer good methods for environment and nature resources protection. For this goal, should be used of sufficient technologies and strategies to develop the sustainable agriculture. By this way, there will be standard agriculture in different rural region in the country. Many technologies to use of them for the sustainable agriculture are developing. But these technologies are not enough alone and should be planned and are under goof planning with the government policies. These processes should be applying in the different fields of agriculture such as soil protection, agronomy, livestock and pasture, gardens and fruits-vegetables production, machinery, irrigation, plant protection and use of chemical pesticides and fertilizers and so and so. Agriculture production should be replaced from small lands to the big lands and changed the small farmers management to the big farmer organization or companies. New crops selection should be according to the region climate condition and soil-water-crop match and relationship. The region population and demand should be evaluated. The production should not be more than the soil potential and causes to the soil fatigue. Also soil fertility should be protected. Also, the toxic material usage should be decrease or eliminate, too. The design of new technologies should be according to the different regions demand and rural culture. Also, the sufficient research in different region is necessary. According to the research results, should be sufficient education to the farmers, too. The research results should be accepted for the long period and estimate the different fields action such as social, economic, cultural cases for the sustainable agriculture. Also, for all of the field's action should be cooperation with the government policies. The sustainable agriculture cannot be continuing only with good technologies or lands and resources. The human workforce is necessary for this work, too. The full-time workers are important factors for the sustainable agriculture. The rural region should be lived and possibility of workers accommodation will be provided in the rural regions. For this, The educational, health and social facilities should be provided for the workers and their families. The rural regions should not be convert to the urban regions and the agricultural soil must be protected for the crops and agricultural activities. The sustainable agriculture such as organic farms markets should be develop and the people must be promoted to these protections too. The valuable of the sustainable agriculture products should be determined and have their position in good level in the markets. The quality and quantity of the sustainable agriculture products should be kept as good level and standard state in the markets. Sustainable agriculture is the indispensable case of the agriculture sector because the future food security is depended on the sustainable agriculture if not by the increasing the population and destruction the agriculture lands and natural resources and climate pollution the future generation will have a big problem to supply the needed and healthy food and food security.

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CHAPTER 5

CFD MODELLING OF AMBIENT FACTORS IN EVAPORATIVE COLD STORE FOR APPLE STORAGE

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1.Introduction

Apple fruit is an important fruit with a wide range of producers and consumers, long-term stor-age and export takes first place in the cod stored fruits in Turkey. Granny Smith apple variety is one of the gradually new varieties to grow in Turkey. The fruits of this variety are harvested at the end of October and can be stored for a long time. Apple production amount was 3.62 million tonnes and total losses was 188 550 tonnes as 5.2% of total production In Turkey, product losses are so high (Anonymous, 2021). A total loss was determined as 11.3% product during post-harvest transportation and storage in apples (Skende, 1999). Eris et al. (1992) determined that 25-28% losses occurred for 7 months cold storage in apples. The loss of water during storage of ap-ples is caused by the transpiration of the fruit (Veraverbeke et al.2003). Apples generally lose their quality after harvest. Quality loss is very slow in stored products. When the time to market the product gets longer, the size of this loss becomes important. After harvesting, fruits continue their vital activities by using the energy generated by their respiration in other metabolic events (Karaçalı, 2009; Kaynaş, 1987). The humidity rate in cold rooms should be appropriate for the product. For this reason, humidity rate should be controlled in cold room applications. One of the important process is to prevent water losses and high relative humidity (Karaman et al., 2009). Pekmezci (1975) stated that the storage temperature should be adjusted to 0-4^{o}C depending on the apple varieties, these temperatures should change as little as possible during the storage period and the relative humidity in the storage should be between 85-90% for good apple storage. Chris et al. (2004) also states that the storage possibilities of apples can vary between 1-12 months depending on the variety, ecology and harvest time, and that they can be easily stored between -1^{0}C and + 4^{0}C for 3-6 months. Water loss, which has been defined as a problem in apple preservation for many years, causes an unattractive wrinkled appearance in the fruit when it is more than 6% (Dündar, 1999). Evaporative conditions should be controlled in order to minimize the water loss in fruits during apple storage (Hatfield and Knee, 1988; Lohse and Schone, 1994). Post-harvest ripening of the fruit and development of pests in the warehouse depend on the effects of pre-harvest factors. The recommended conditions for commercial storage of apples range from -0.5° C to 4° C (Ferree and Warrington, 2003). The temperature, which is the most important factor among the storage conditions, must be kept constant at a certain level in order to preserve the quality of the apples. The temperature must be constant in the warehouse, which is constantly monitored with a thermostat, and there must be no dead spots that cannot be cooled. Since the storage conditions of apples are very different, the storage conditions of the variety to be stored should be well known. The optimum storage temperature is between -1^{o}C and 0^{o}C. Varieties that are not sensitive to cold should be stored at temperatures close to freezing point. The optimum temperature for the storage of apples is +4^{o}C for European varieties, -1^{o}C for Golden Delicious and 0-2^{o}C for Starking (Delicious Red) for American varieties (Coşar, 1996; Anonymous, 1998). Koyuncu and Eren (2005) determined that Granny Smith, Imparatore and Idared apple varieties can be stored for 5-6 months at 0^{o}C temperature and 90-95% relative humidity. Uygun (2003) determined taht the Granny Smith apple variety is sensitive to skin browning, skin darkening was ob-served in fruits from the 4th month. CFD is the one the tool used for estimation of ambient factors. A two-dimensional mathematical model and computer software were developed for a cold store. Simulation results were accepted for the distribution of air velocity and temperature. This has shown that CFD is a very powerful tool for design and optimization in cold rooms (Xie et al., 2006). A model was developed to estimate heat and mass transfer in cold store of fruits and vegetables. This method was used to determine the mass transfer of water vapour from packaged fruits and vegetables (Tanner et al., 2002). Air flow in a cold store was determined by using Computational Fluid Dynamics (CFD). Condi-tions of airflow was assumed as permanent and incompressible for CFD modelling. Turbulence was considered using the k-ε model. The forced air circulation of the cooling unit has been mod-elled in accordance with the characteristics of the evaporator air channells and the fan, approximately an associated body strength and resistance. The validity of the model was made by com-paring with the sensor values. The relative error of model was 26% (Hoang et al., 2000). Distribution of air velocity, temperature and humidity for a full and empty cold store were investigated to calculate a three-dimensional CFD model. The validity of the developed model was tested by using measured values of the air velocity and product temperature (Nahor et al., 2004).

A mapping software was used to determine spatial distribution of the air velocity in a cold store. The results can be used to determine weak airflow region in the cold store (Akdemir and Arin, 2005). Ambient factors such as temperature, relative humidity and air velocity of a cold store was determined by Management Zone Analyse (MZA) (Akdemir and Tagarakis, 2014).

2. Materials and Methods

An evaporative cold store was used in this research. Its volume was 68.23 m^3. The power of compressor was 5.25 kW. Condenser capacity was 15 kW (Figure 1).

Figure 1. Cold store (A), evaporator (B), condenser (C)

The ambient temperature and relative humidity were measured by Testo 177 H1 data loggers from 36 points. The variety of the stored apple was Granny Smith (Figure 3). Apples were loaded in cold store within 160 cases (Figure 2).

Figure 2. Granny Smith apple and arrangement of cases

Ansys Fluent 14.0 software was used to determine the distribution of the ambient temperature and the relative humidity for modelling by computational Fluid Dynamic (CFD). A tetrahedral mesh was created and then refined until a converged solution was obtained. The storage ambient temperature and the relative humidity were 2°C and 90%, respectively. Boundary conditions for CFD modelling were given in Table 1.

Table 1. Boundary conditions for CFD modelling

Inlet	surface of fluid inlet
Outlet	surface of fluid outlet
Walls	solid, proof against flow
Convective heat transfer Coefficient	0.24 W/m K (for plastic boxes)
Conductive heat transfer Coef.	0.025 W/m K
Inside / Outside Temperature	28°C and 1°C
H_2O mass fraction value	0.0041432 H_2O for 90% RH
Solution type	Pressure-based-double precision
Flow type	steady state
Turbulence model	k-ε
Density of peach	930 kg/m^3
Specific heat for peach	3.887 kJ/kg°C

The data were measured from 36 different points at 3 levels for 12 points (Figure 3).

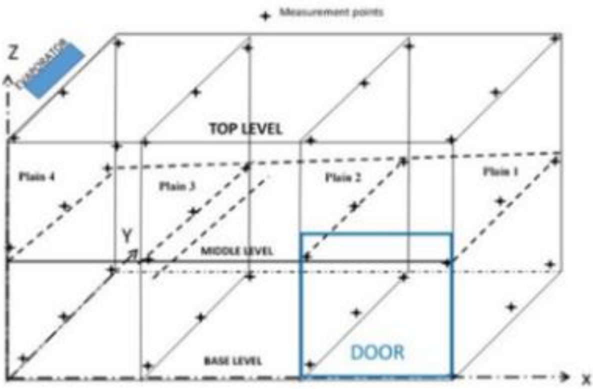

Figure 3. Measurements points of sensors

The Y planes were called as 1, 2, 3, and 4 (Figure 4A) and Z plane were called as top, middle and base in the variance analysis and evaluations (Figure 4B).

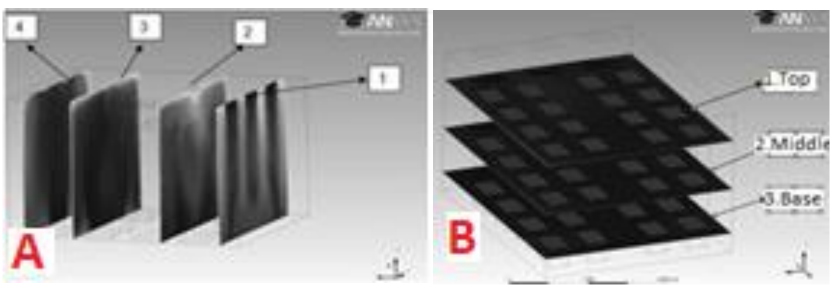

Figure 4. Planes and its codes for *Y* axis (A) and *Z* axis (B)

Differences between models and sensor measurements (Δt, ΔRH), descriptive statistics and variance analyses were calculated. In addition, Relative Error of the CFD model were calculated. CFD Model validated with measurements by using equation given below (Hoang et al., 2000; Nahor et al., 2005; Chourasia and Gosvami 2007; Akdemir and Bartzanas, 2015).

$$\Delta t, \Delta RH = (t_{m,} RH_s - t_{s,RH_s}) \quad (1)$$

$$\%\Delta t, \Delta RH = \left(\frac{t_m,RH_s - t_s,RH_s}{t_s,RH_s}\right).100 \quad (2)$$

$$\overline{E_{CFD}} = \frac{1}{S}\sum_{r=1}^{n} \frac{|RH_{CFD}^r, t_{CFD,}^r - RH_S^r, t_S^r|}{RH_S^r,\ t_S^r}.100 \quad (3)$$

Where;

$\overline{E_{CFD}}$= Relative error (%)

n= Total number of the measurements

r= Indices (0, 1, 2,.., n)

$RH_{CFD,}^r\ t_{CFD}^r$ =CFD model data for relative humidity and ambient temperature

RH_S^r, t_S^r=Measured data for relative humidity and ambient temperature

Estimated results for the ambient temperature and the relative humidity were given in Figure 5 and Figure 6.

CFD model and sensor measurements were compared by using variance analyses. SPSS 17.0 software was used for statistical analyses.

3. Results

3.1. CFD Analyses of Ambient Temperature and Relative Humidity

CFD Models of *Y* planes and *Z* axes (top, medium and base levels) were given in Figure 5 for the ambient temperature and Figure 6 for the relative humidity (%).

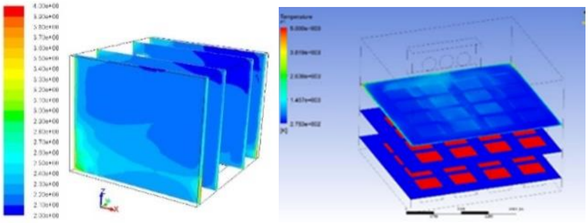

Figure 5. Temperature contours at *Y* axes and *Z* axes

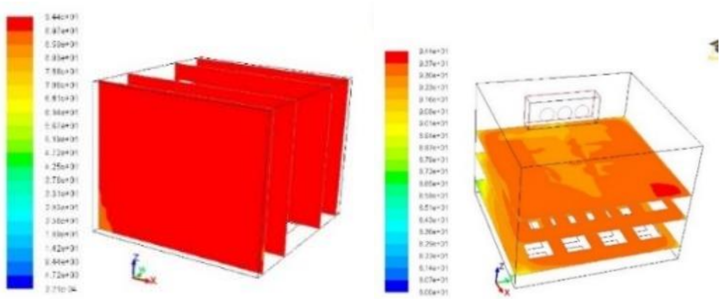

Figure 6. Relative humidity (%) contours at *Y* and Z axes

3.2. CFD Model Validation

Estimated results by CFD model, measured results by sensors and differences between measurements and model estimations for Y axis, levels and measurement points for ambient temperatures were given in Table 2.

Table 2. Estimation of CFD Modelling and sensor measurements for ambient temperatures

Y axis	Levels	Measurement points	t_{CFD} (°C)	t_s (°C)	Δt	RH_{CFD} (%)	RH_s (%)	ΔRH
1	1	1	2.2	3.3	1.1	94.4	93.7	0.7
1	1	2	2.2	3.4	1.2	94.4	95.4	1.0
1	1	3	2.2	3.3	1.1	94.4	95.3	0.9
1	2	1	2.2	3.4	1.2	94.4	91.4	3.0
1	2	2	2.2	3.4	1.2	94.4	94.2	0.2
1	2	3	2.2	3.4	1.2	94.4	95.3	0.9
1	3	1	2.4	3.4	1.0	94.4	95.9	1.5
1	3	2	2.3	3.3	1.0	94.4	97.9	3.5
1	3	3	2.3	3.4	1.1	94.4	95.3	0.9
2	1	1	2.2	3.4	1.2	94.4	95.0	0.6
2	1	2	2.2	3.4	1.2	94.4	95.2	0.8
2	1	3	2.1	3.4	1.3	94.4	96.6	2.2
2	2	1	2.2	3.4	1.2	94.4	95.1	0.7
2	2	2	2.2	3.4	1.2	94.4	94.2	0.2

2	2	3	2.1	3.3	1.2	94.4	95.3	0.9
2	3	1	2.2	3.5	1.3	94.4	95.2	0.8
2	3	2	2.2	3.6	1.4	94.4	94.3	0.1
2	3	3	2.2	3.4	1.2	94.4	95.2	0.8
3	1	1	2.3	3.3	1.0	94.4	94.7	0.3
3	1	2	2.2	3.4	1.2	94.4	95.2	0.8
3	1	3	2.2	3.3	1.1	94.4	95.0	0.6
3	2	1	2.4	3.4	1.0	94.4	95.4	1.0
3	2	2	2.2	3.4	1.2	94.4	95.1	0.7
3	2	3	2.2	3.4	1.2	94.4	95.2	0.8
3	3	1	2.3	3.4	1.1	94.4	94.2	0.2
3	3	2	2.2	3.4	1.2	94.4	95.5	1.1
3	3	3	2.2	3.4	1.2	94.4	95.6	1.2
4	1	1	2.1	3.4	1.3	94.4	96.3	1.9
4	1	2	2.1	3.4	1.3	94.4	95.7	1.3
4	1	3	2.1	3.4	1.3	94.4	95.2	0.8
4	2	1	2.1	3.4	1.3	94.4	94.7	0.3
4	2	2	2.2	3.4	1.2	94.4	94.3	0.1
4	2	3	2.2	3.4	1.2	94.4	95.9	1.5
4	3	1	2.2	3.4	1.2	94.4	93.7	0.7
4	3	2	2.2	3.5	1.3	94.4	95.2	0.8
4	3	3	2.2	3.4	1.2	94.4	94.5	0.1

Descriptive statistics, differences between model estimation and the measured values and absolute error of the model were given in Table 3, Duncan test grouping results in Table 4 for the ambient temperature and in Table 5 for Relative Humidity.

Average of differences between the models and sensor measurement was calculated as 1.19^0C for ambient temperature. Relative error of the CFD model was 27.15%. According to the analysis of variance for the ambient temperature; differences between the CFD model and sensors measurements (F=10176,8, α=0.001), Levels (F=9.50, α=0.005), model/sensor measurement x Levels interaction (F=9.037, α=0.001) and Model/Sensor measurementxY Axisx Levels interactions (F=2.426, α=0.040) were statistically significant. Model estimations were generally less than measured data.

Table 3. CFD model and measurement for temperature

	t_{CFD} (°C)	t_s (°C)	Δt (°C)
Mean	2.21	3.39	1.19
Min.	2.10	3.30	1.00
Max.	2.40	3.60	1.40
SD	0.07	0.06	
CV(%)	3.20	1.69	
Relative error (%)	27.15		

Table 4. Average of ambient temperature for model, sensor measurements, levels, Y Axis and interactions

		LEVELS				
	Y	Top	Middle	Base	Mean	Mean
CFD	***1***	2.20^{b}	2.20^{b}	2.33^{b}	*2.24^{b}*	
	2	2.16^{b}	2.16^{b}	2.26^{b}	*2.17^{b}*	2.21^{B}
	3	2.23^{b}	2.26^{b}	2.23^{b}	*2.24^{b}*	
	4	2.10^{b}	2.16^{b}	2.20^{b}	*2.15^{b}*	
Mean		***2.18***	***2.20***	***2.21***		
Sensor	***1***	3.33^{a}	3.40^{a}	3.36^{a}	*3.36^{a}*	3.39^{A}
	2	3.40^{a}	3.36^{a}	3.50^{a}	*3.42^{a}*	
	3	3.33^{a}	3.40^{a}	3.40^{a}	*3.37^{a}*	
	4	3.40^{a}	3.40^{a}	3.43^{a}	*3.41^{a}*	
Mean		***3.37***	***3.39***	***3.42***		
Total		**2.77^{B}**	**2.80^{B}**	**2.83^{A}**		
		Y Axis				
		1	**2**	**3**	**4**	
CFD		$2,24^{b}$	$2,18^{b}$	$2,24^{b}$	$2,16^{b}$	
Sensor		$3,37^{a}$	$3,42^{a}$	$3,38^{a}$	$3,41^{a}$	
Variables/Interactions				**Duncan group value**		
Level				Sx=0 .003, α = 0.05		
CFD/Sensor x Y Axis				Sx=5.7735e-02,α=0.05		
CFD/Sensor x Y Axis x Level				Sx=0.1, α=0.05		

According to the variance analyses and Duncan test results; levels were grouped in two different groups for ambient temperature (Top level 2.77°C^{B}, middle level 2.80°C^{B} and base level 2.83^{A}.

Descriptive statistics, differences between model estimations and the measured data and absolute error of the model were given in Table 5 for Relative Humidity. Mean difference between the model and measurements for relative humidity was calculated as 3.47. Relative error of the CFD model for the cold store was calculated as 3.70. Model estimations were higher than measured relative humidity values.

Table 5. Descriptive statistics of CFD model and measurement for relative humidity

	RH_{CFD} (%)	RH_{S} (%)	ΔRH (%)
Mean	94.40	95.05	0.94
Min.	94.40	91.40	0.10
Max.	94.40	97.90	3.50
SD	0.00	1.00	
CV(%)	0.00	1.05	
Relative error (%)	3.70		

According to the analysis of variance for the relative humidity; differences between CFD models and sensors measurement (F=15.94, α=0.001) was evaluated as statistically significant.

4. Conclusions

Estimation of the ambient temperature and relative humidity were determined by using CFD was for an evaporative cold store for apple storage. The temperature and the relative humidity results of CFD and sensors were compared. The storage ambient temperature was 2°C and the relative humidity was 90%. Mean difference between the model and measurements was calculated as 1.19°C for ambient temperature and 0.94% for relative humidity. Relative error of the CFD model was calculated as 27.15 for the ambient temperature of the cold store and 3.70

for relative humidity. The developed CFD models were estimated relative humidity successfully.

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CHAPTER 6

MUNICIPAL SOLID WASTE COMPOST: FROM WASTE TO ORGANIC FERTILIZER

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1. INTRODUCTION

Organic matter, defined as the most important component of soil due to its influence on many properties of the soil, is accepted as the most important indicator of soil quality and agricultural sustainability. Soil organic matter (SOM) encompasses all decomposition products that come from plant and animal-based waste materials at various stages of degradation and do not share characteristics with the initial material (Sağlam et al., 1993). The most significant role of organic matter in the soil is to stabilize soil aggregates, increase the soil's water retention and buffering capacities, and ensure the release of plant nutrients during mineralization (Fageria, 2012). Additionally, organic matter affects the physical properties of soils alongside its chemical characteristics, such as being a nutrient source for plants primarily containing N, P, and S, having a high cation exchange capacity (CEC), and providing a high buffering capacity. Particularly, it improves the soil structure and regulates aeration and water conductivity in soils. The development of structure allows for an increase in micro and mesopores in sandy soils, while it increases meso and macropores in clayey soils. Thus, by balancing aeration and water conductivity issues in these soils, it leads to an increase in agricultural production

SOM contributes significantly to the soil organic carbon (SOC). SOC is the main component of SOM and constitutes 55-65% of SOM. Since SOC supports critical soil functions such as stabilization of soil structure, nutrient availability, infiltration and storage of water in the soil, etc., it holds critical importance for soil health, productivity, and food production (Stockmann et al., 2015; ÇEM, 2018). Soils contain a carbon stock that is approximately twice that of the atmosphere and about three times that of vegetation (Smith et al., 2008). While there are 800 billion tons of carbon in the atmosphere and 560 million tons in plant and animal life, this number is estimated to be 2,500 billion tons in soil. SOC enters the soil through the decomposition of plant and animal residues, root exudates, living and dead microorganisms, and soil biota.

Except for situations where inorganic forms arise, most of the carbon is referred to as soil organic carbon (Stevenson, 2024). SOC constitutes a key element of the global carbon cycle among the atmosphere, vegetation, soil, rivers, and oceans. The amount of carbon (C) in soil organic matter and decomposing plant material is 2-3 times greater than in living biological mass (Blanco-Canqui et al., 2013; Smith et al., 2008; Stockmann et al., 2015). SOC is extremely crucial in plant production. According to a study, it has been shown that when the SOC amount drops below 1.1%, crop yield in tropical regions decreases by 20% (Aune and Lal, 1997).

Despite its importance in soils, the agricultural lands in our country organic matter content varies from region to region, but generally, it is low or very low in % 88,56% of cases (Sönmez et al., 2018). Due to long years of monoculture farming, climate conditions, soil cultivation, and erosion, the organic matter content of soils is also decreasing. The crop rotation systems implemented in agricultural areas, the duration of soil cultivation, soil tillage techniques, the state or degree of damage of the soil surface vegetation, the burning or burial of plant residues, the agricultural techniques used, and the type of fertilization are all controllable factors that influence organic matter levels in addition to climatic factors such as temperature and rainfall patterns. The burning or removal of plant residues, which are the main source of organic matter in agricultural areas due to agricultural activities, can also be added to these reasons (Koçyiğit, 2008; Sağlam et al., 1993). The decrease in SOM in agricultural soils has not been considered, and the use of chemical fertilizers for plant production has increased. The discovery of chemical fertilizers revitalized the productivity of agricultural areas that had weakened nutritionally. The increased use of these fertilizer materials is due to the possibility of storing dozens of plant nutrients in 1 ton of fertilizer and sending them cheaply over long distances. As a result, many parts of the Earth are being over-fertilized, leading to contamination of drinking water and a reduction in species diversity in terrestrial and marine ecosystems due to excessive use of nitrogen and phosphorus. While the overuse of fertilizers by farmers may contribute to short-term crop yield guarantees, a large portion of the fertilizers leaches into the groundwater or is washed away, disrupting ecosystems and polluting water bodies (Brown, 1998). Along with the gradual reduction of organic material in the field soils (approximately even lower than 1%), the soil improvement matter is gaining more importance and attention (Bellitürk, 2016). With the increasing awareness of the role of organic matter in agricultural production and the rising trend toward organic farming, farmers have started applying more organic materials to their soils. Today, the popularity of organic farming has led to an increase in the demand for organic fertilizers. The limited amount of organic matter that can be applied to soils has prompted researchers to seek new organic matter sources. One of the organic materials that can be used in soil is municipal solid waste compost (MSWC), which comes from municipal solid waste. This study evaluates the solid waste and recycling services of municipalities in Turkey, the agricultural importance of MSWC, its effects on soils, and provides a general assessment of MSWC.

2. DISPOSAL METHODS FOR SOLID WASTES

These wastes, referred to as garbage, increase in quantity in parallel with the growing population and are among the most significant problems for municipalities. A significant portion of municipal waste consists of organic materials. In developed countries, about 36% of waste is food or garden waste, while this ratio is around 50% in developing countries (Brown, 1998). The methods for disposing of these wastes are diverse. These can be categorized into three classes.

2.1. Landfilling

Open dumping, which is still widely used in less developed countries, is being replaced by regulated landfilling in many countries.

Open landfills or open dumping areas, which are common in developing countries, involve the indiscriminate dumping of waste into low-lying areas of open land. Municipal landfills produce leachate containing concentrated toxic chemicals (Narayana, 2009). The extent of damage caused by leachate is largely unknown. Given the complexity of leachate flow in landfills, the system of aquifers can be affected. Landfills and open dumping sites also emit methane gas, in addition to taking up space. It is noted that 10% of anthropogenic methane gas emissions originate from decomposing organic matter in landfills, and methane traps atmospheric heat at a rate twenty times faster than CO_2 (Brown, 1998). Despite these negative views, regulated landfills can also have some benefits. In particular, in long-term planning, regulated landfilling can convert the generated gas into a short-term gas source, provide long-term carbon storage, and together with the landscaping and environmental improvement that comes with regulated landfilling, can facilitate the redevelopment of degraded areas (Białowiec et al., 2011).

2.2. Incineration

One of the methods for disposing of municipal solid waste (MSW) is incineration. Incineration involves the controlled burning of waste in the presence of oxygen at temperatures of around 800 °C and above, resulting in the release of heat energy, gases, and inert ash (Patil et al., 2014). Incineration is more costly compared to composting (Ayari, 2010). According to a study conducted in America, the cost of composting was calculated to be $351 per ton, while the cost of incineration was $527 (USEPA, 1997). Additionally, various new forms, including air emissions, ash, and liquid discharges, emerge at the end of the process. These forms pose significant risks to the environment and human health (Thompson and Anthony, 2005). Air emissions from incineration furnaces have been found to be carcinogenic. The incineration of solid waste results in air emissions containing heavy metals, dioxins, and other volatile organic compounds. Furthermore, the incineration process results in the production of ash. Ash is a by-product of the incineration process. The disposal of the ash produced as a result of the incineration process is also problematic. Eventually, the toxins in the ash leach into the soil and water from ash deposits (Banerjee, 2018; Kumar, 2011). Some researchers indicate that municipal solid waste contains hidden energy due to its organic matter content, and this energy can be recovered with appropriate waste processing and treatment technologies. They also express that the amount of solid waste is reduced by 90% through incineration, depending on the composition of the waste and the appropriate technology, leading to a decrease in land demand for landfilling, reduced environmental pollution, and savings in transportation.

2.3. Composting

Municipal Solid Waste (MSW) is rich in organic matter, and composting is favoured as the most suitable method for disposing of this organic matter-rich waste. Composting is the controlled decomposition of organic matter through biological processes, resulting in the production of nutrient-rich humus (Kumar, 2011). The waste composition of developing countries clearly indicates that composting is the best option for dealing with MSW (Narayana, 2009). Composting provides a more environmentally friendly solution compared to other methods. Through composting, solid waste is not only disposed of, but a material with high organic matter that can be used as a soil conditioner and fertilizer is obtained. However, there are some concerning situations in the composting of MSW. MSWs may contain some waste substances, harmful elements, persistent organic compounds, and microorganisms that can be detrimental to plants. Therefore, the content of Municipal Solid Waste Compost (MSWC) may contain harmful heavy metals and microorganisms for soil and plants. With proper composting, microbiological components can be cleaned, but heavy metals remain a problem. The high heavy metal content in MSWs is due to the failure to separate solid waste at the source and mixed collection. There is a concern that the compost produced may have increased heavy metal content due to the presence of materials such as batteries, plastics, and rubber, which could create heavy metal issues (Ayari et al., 2010; Epstein, 1992).

3. WASTE AND COMPOST MANAGEMENT IN TURKEY

The increasing amount of waste paralleled by the growing population is a significant problem for municipalities. In Turkey, the amount of waste collected by municipalities increased from approximately 25 million tons in 2002 to about 30 million tons in 2022. The amount of waste collected by municipalities has increased by more than 20% over the past 20 years. The per capita waste amount collected was 1.34 kg per day in 2002, but it began to show a decreasing trend, reaching 1.03 kg per day in 2022. Until the 2000s, most of this waste collected by municipalities was dumped into municipal landfills. However, with the increase in the number of controlled landfills, the amount of waste sent to municipal landfills has significantly decreased in recent years. The number of regulated landfills increased from 12 in 2002 to 191 in 2022. Consequently, the annual amount of waste sent to municipal landfills, which was approximately 16 million tons/year in 2002, has decreased year by year to about 4 million tons/year in 2022. During this period, the amount of waste sent to waste processing facilities has also increased, rising from about 7 million tons/year to approximately 26 million tons. Although the increase in the number of composting facilities has varied from year to year, it has risen to 11 in recent years, the amount of waste brought to composting facilities has decreased year by year, from 268 thousand tons/year in 2006. In 2022, it decreased to 120 thousand tons. The amount of compost produced has remained almost the same over the last 20 years (Table 1). The number of compost facilities in Turkey continuously changes. In some years it decreases, while in others it increases (TUIK, 2024). Some reasons for the low number of compost facilities or their closure are as follows:

1. High initial setup costs and operating expenses,
2. Insufficient organic solid waste amounts that do not meet operational capacity,
3. Low sales due to farmers' lack of awareness or interest in MSWC. A large portion of the compost produced in Turkey is used by municipalities for fertilizing parks and gardens (ISTAÇ, 2024).

Table 1. Statistics on solid waste and recycling collected by municipalities over the years (TUIK, 2024)

Municipal waste services and management indicators, 2002-2022											
	2002	2004	2006	2008	2010	2012	2014	2016	2018	2020	2022
Amount of municipal waste collected (Thousand tonnes/year)	25.373	25.014	25.280	24.361	25.277	25.845	28.011	31.584	32.209	32.324	30.284
Average amount of municipal waste per capita (Kg/capita-day)	1.34	1.31	1.21	1.15	1.14	1.12	1.08	1.17	1.16	1.13	1.03
Waste treatment facilities	7.430	7.353	9.683	11.223	13.941	15.639	17.933	22.430	25.615	26.707	26.017
Municipality's dumping sites	16.310	16.416	14.941	12.678	11.001	9.772	9.935	9.095	6.521	5.493	4.093
Other disposal methods	1.634	1.246	656	460	334	437	141	58	74	124	174
Waste disposal and recovery facilities statistics of which are operated by municipalities, 2002-2022											
Controlled landfill sites number	12	16	22	37	52	80	113	134	159	174	191
Controlled landfill sites Capacity (Million tonnes)	277	278	376	390	423	-	620	-	799	1.208	1.408
Composting plants number	4	5	4	4	5	6	4	7	8	9	11
Composting plants Capacity (Thousand tonnes/year)	664	667	605	551	556	-	310	-	483	561	722
Amount of waste brought to the facility (Thousand tonnes)	-	-	268	276	216	159	94	140	138	127	120
Amount of waste composted (Thousand tonnes)	-	-	29	47	38	-	34	-	35	34	30

4. EFFECT OF MSWC ON SOIL PROPERTIES

Although MSWC is primarily regarded by researchers as a good soil conditioner, it is also considered a fertilizer material due to its high organic matter and nutrient element content (Atav and Yüksel, 2024; Hargreaves et al., 2008; Rawat et al., 2013; Singh and Chandel, 2023). MSWC is rich in organic carbon, which positively affects the physicochemical properties of soils. The effects of MSWC on soil properties vary depending on compost composition, application dosages, and the maturity level of the compost (Crecchio et al., 2001; Weber et al., 2014). Many studies have shown that MSWC positively impacts the physical, chemical, and biological properties of soils. The effects of MSWC on soil properties are summarized below.

4.1. Effect on Soil Physical Properties

Numerous studies conducted on MSWC have shown that it positively affects physical properties of soils such as aggregate stability, bulk density, water holding capacity, and hydraulic conductivity. This positive effect is primarily attributed to the ability of MSWC to regulate the soil structure. MSWC contains a high amount of organic matter, which enhances aggregate stability by improving soil structure (Annabi, 2007; Karami et al., 2012). The regulation of structure positively affects soil porosity, thereby improving aeration and water transmission (Eibish, 2015). The effect of MSWC on soil structure can generally be attributed to the humic substances it contains. In sandy soils with larger pores, MSWC increases aggregation, resulting in a higher number of meso and macro pores. In clayey soils with micro pores, aggregation also increases the number of meso and macro pores. Thus, while the hydraulic conductivity of sandy soils decreases, it increases in clayey soils (Arthur et al., 2012; Babalola et al., 2012; Yüksel and Kavdır, 2020).

MSWC significantly affects the bulk density of soils. Due to its organic matter content, MSWC regulates the structure of the soil, increases aggregation, and enhances porosity, thereby reducing bulk density (Eibisch et al., 2015; Tejada and Gonzalez, 2007; Diacono and Montemurro, 2010). Another reason for the decrease in bulk density is the reduction in the weight of the mixture due to the incorporation of lower density organic matter into the soil (Maylavarapu and Zinati, 2009).

MSWC also positively impacts the water retention capacities of soils for several reasons:

1. MSWC regulates the structure due to its high organic matter content. It increases the volume of meso and micro pores in sandy soils while increasing the volume of macro and meso pores in clayey soils. As a result, hydraulic conductivity decreases in sandy soils (Arthur et al., 2012) while it increases in clayey soils (Lal, 2020; Yüksel et al., 2004). This leads to an increase in the available water retention capacity of soils.

2. Organic matter retains a high amount of water because OM particles have a large surface area for exchange. These exchange surfaces attract water with adhesive force, binding it to the surface (Bhadha et al., 2017). Studies have shown strong positive correlations between organic matter content and water retention capacity (Franzluebbers, 2022). Factors such as the origin and degree of maturation of organic matter can alter water retention capacity. Research has presented varying values for the water retention capacity of organic matter. Some studies indicate that organic matter can retain water up to 20 times its own weight (Glenn, 2014) or 10 times its weight (Bhadha et al., 2017).

3. Along with soil compaction, water conductivity decreases and water retention increases. Organic matter physically enters the spaces between soil particles, thereby relatively preventing the compaction of soil particles. While compaction is beneficial in sandy soils for water retention, it can lead to excessive water retention in clayey soils.

4.2. Effect on Soil Chemical Properties

MSWC affects the chemical properties of soils. It increases the organic matter content of soils (Atav and Yüksel, 2019; Crecchio et al., 2001; Diacono and Montemurro, 2010; Yüksel and Kavdır, 2020). It influences a significant chemical property of soils, which is pH. By increasing the buffer capacity of soils, it protects the soil and plants against pH fluctuations. Specifically, it raises the pH in soils with low pH. In a study conducted on three soils with different pH levels (5.25, 6.70, and 7.62), it was reported that the application of 150 t ha^{-1} of MSWC raised the pH value from 5.34 to 6.67 in the low pH soil, while increases in the other soils were not statistically significant (Atav and Yüksel, 2019). Many studies have reported that MSWC raises the pH of soils with low pH (Mkhabela and Warman, 2005; Sayara et al., 2020; Zhang et al., 2006), while it does not have a statistically significant effect in soils with high pH (Carbonell et al., 2011).

MSWC has a positive effect on the cation exchange capacity (CEC) of soils. MSWC contains a high amount of organic matter and, therefore, primarily increases the organic matter content of soils and consequently their CEC (Gallardo-Lara and Nogales, 1987). This is because there is a close relationship between organic matter and CEC. As organic matter (OM) increases, CEC also increases (Loveland and Webb, 2003). When the organic matter content of soils increases, the quantity of colloids in the soils increases, the surface area expands, and the amount of exchangeable cations increases (Sağlam et al., 1994). However, this positive effect is more pronounced in soils with low CEC. A study conducted on three soils with different textures showed that CEC values increased in parallel with increasing doses of MSWC application. In the highest dose of 150 t/ha of MSWC, the CEC value in sandy clay loam textured soil increased from 11.77 cmol kg^{-1} to 15.10 cmol kg^{-1}. This increase was found to be statistically significant, while increases in the CEC values of clay loam (CL) and clay (C) textured soils were not statistically significant (Atav and Yüksel, 2019). Various studies have determined that the application of organic matter increases the CEC values of soils by between 20% and 70% (Nortcliff and Amlinger, 2008), while another study reported increases between 25% and 90% (Hemmat et al., 2010).

4.3. Effect on Nutrient Elements in Soils

Composts are generally rich in available nutrient elements for plants due to their high organic matter content. Organic materials are sources of nitrogen (N), carbon (C), phosphorus (P), and sulphur (S) for plants. Nitrogen is one of the most important elements for plant development. Under normal soil conditions, organic matter provides 95% of nitrogen and sulphur and 20% of phosphorus. Therefore, the addition of compost to the soil enriches it with important elements such as N, C, S, and P, which are crucial for plant growth and development (Sayara et al., 2020). Municipal solid waste compost (MSWC), due to its high organic matter content, supplies plants with available nutrients, especially N, P, and S. It is particularly thought to be rich in nitrogen; however, researchers have reported that during the initial periods of applying MSWC to soils, nitrogen contents show a sharp decline but do not change in later periods (Carbonell et al., 2011). Additionally, some studies have indicated that while MSWC increases the nitrogen content of soils, it is less effective in terms of available nitrogen content compared to mineral fertilizers in the first year of application (Hargreaves et al., 2008). In another study, it was estimated that the nitrogen availability in MSWC in the first year after application was around 10% (Giannakis et al., 2014). The low initial nitrogen content of MSWCs is suggested to be due to factors such as low pH and high fat content, leading to delayed microbial activity and slow decomposition (Atagana et al., 2003; Neves et al., 2009). As a result of this, MSWCs decompose more slowly than other organic fertilizers and have longer-lasting effects in the soil. Another viewpoint suggests that the low nitrogen availability in the initial periods is due to the consumption of nitrogen by microorganisms as a result of increased microbial activity in the soil (Giannakis et al., 2014).

4.4. Effect on Plant Growth and Yield

While MSWC is defined by many researchers as a soil conditioner, it is also classified as an organic fertilizer due to its plant nutrient content. Composts, seen as an alternative to synthetic commercial fertilizers because of their nutrient content, are widely used worldwide to enhance long-term soil fertility and productivity. Additionally, the use of organic fertilizers reduces the reliance on commercial fertilizers, leading to significant savings in fertilizer costs (Romero et al., 2013). MSWC has been utilized as an organic fertilizer in developed countries for many years due to its high organic matter and nutrient content. Numerous studies have reported that the application of MSWC to soils positively affects plant growth and crop yield.

In a two-year field trial, the application of MSWC at varying rates (0, 20, 40, 80, 100, 120, and 160 t/ha) in the first year was found to increase barley yield. In the first year of the study, the control treatment recorded a grain yield of 8.90 kg/plot, which increased to 14.30 kg/plot at the 120 and 160 t/ha doses. In the second year, the yield in the control treatment was 3.6 kg/plot, while it rose to 9.9 kg/plot at the 100 t/ha dose. These results indicate that the effect of MSWC continued into the second year, resulting in nearly a twofold increase in yield even in the second year (Yüksel et al., 2002).

In a study conducted under conditions in Çanakkale (Turkey), the effect of MSWC on sunflower yield characteristics was examined. In the field trial, increasing doses of MSWC (0, 40, 80, 120, 160, and 200 t/ha) were applied to plots, which positively influenced sunflower yield. In the first year, the yield in the control was 257.33 kg da^{-1}, whereas the highest yield was observed at 120 t/ha, reaching 334.77 kg da^{-1}. In the second year, the yield in the control was 258.34 kg da^{-1}, with the highest result (310.93 kg da^{-1}) occurring at 8 t/ha application. In both years, an increase in yield was observed compared to the control, with increases of approximately 30% in the first year and about 20% in the second year. It was found that the effect of MSWC largely continued into the second year even in the trial where only the first year of compost application occurred without any commercial fertilizers (Yüksel et al., 2011).

In a study conducted on three soils with different pH levels (5.25, 6.70, and 7.62), it was reported that the application of 150 t ha^{-1} of MSWC raised the pH value from 5.34 to 6.67 in the low pH soil, while the increases in the other soils were not statistically significant (Atav and Yüksel, 2019).

In a pot experiment investigating the effect of MSWC on the growth of barley plants in soils with different textures and pH levels (sandy clay loam (low pH), clay loam (neutral pH), and clay (high pH)), varying amounts of MSWC (0, 50, 100, and 150 t da^{-1}) were applied based on dry weight. According to the research results, the application of MSWC positively affected plant growth in barley. In sandy clay loam textured soil, the application of 150 t/da of compost increased the plant height to 28.94 cm compared to the control (24.82 cm). In clay loam textured soil, the height increased from 23.96 cm to 25.45 cm, while in clay textured soil, it increased from 24.26 cm to 25.41 cm (Figure 1). The most pronounced results were observed in soils with sandy clay loam texture (Atav, 2018).

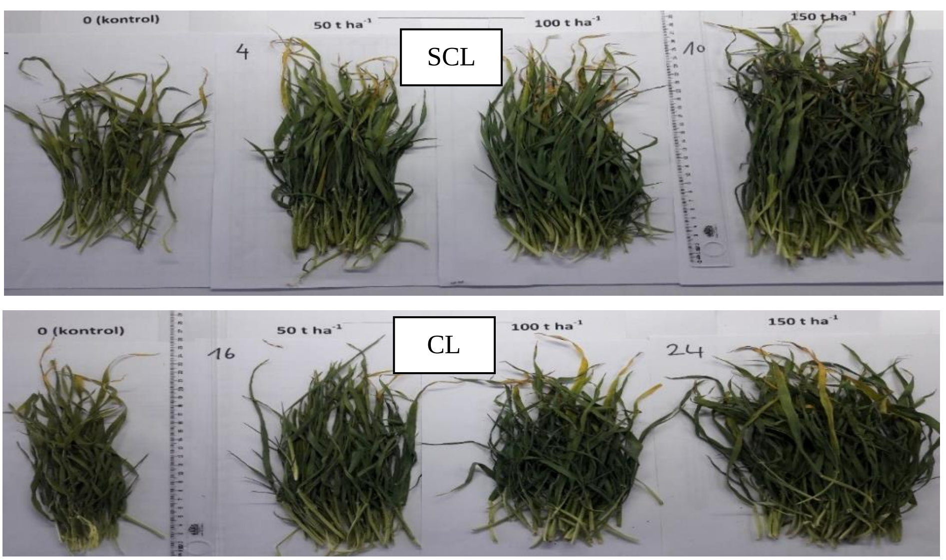

Figure 1. The Effect of MSWC Application on Barley Growth in Soils with Different Textures

The composting of municipal solid waste (MSW) has been a management system practiced in developed countries for a long time. Today, many countries prefer composting for waste management, and factors such as the origin of the compost, maturation stages, and methods of production affect the quality of MSWC. The quality of compost is a function of the characteristics of the waste and the decomposition obtained. The quality of the resulting compost varies based on the preparation of the waste, pretreatment processes, and suitable environmental conditions for optimal mineralization (Kumar, 2011).

4.5. Risks of Using MSWC for Agricultural Purposes

The presence of heavy metals in MSW compost primarily arises from unprocessed municipal solid waste. These solid wastes may contain materials such as batteries, metals, motor oils, paint waste, and plastics, which can contaminate the organic fraction of the solid waste, leading to heavy metal pollution (Khan et al., 2022; Hamdi et al., 2003). One way to overcome this issue is to separate solid waste at the source. By segregating recyclables from solid waste, relatively clean composts can be obtained, alleviating concerns about their use for agricultural purposes. In developed countries, household waste is collected separately and sent to relevant recycling facilities. Because compostable household waste is collected separately in these countries, there are no hazards in the compost produced. In Turkey, however, household waste is generally collected in a mixed manner. As a result, there are concerns regarding the compost produced. In some developed countries, relevant institutions classify composts based on quality and establish limit values for heavy metals. Although the number of compost facilities in Turkey varies by year, there are only 11 throughout the country. While regulations have been established in this regard, the existing classification only considers pH changes and provides limit values.

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CHAPTER 7

EVALUATION OF ANIMAL MANURE AS COMPOST

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1. Introduction

The number of environmental problems in the world increases with the increasing population, industrialization, technological change and increasing consumption. Like all economic activities, agriculture also creates pressure on the environment as it is based on the existing natural resources and their use. For this reason, the concept of sustainable agriculture has come to the fore in recent years. Sustainable agriculture refers to the management of natural resources in a way that they can be used in the future and also makes it mandatory. The existence of a balanced relationship between agriculture and the environment will ensure the future usability of agricultural lands and natural resources and the minimization of environmental problems (Dişbudak, 2008).

Animal production should be planned by taking into consideration climatic conditions, topographical features, the number of existing enterprises and animal capacities of these enterprises, farming types, demands and requirements of the sector and enterprise owners (Ünalan et al., 2015).

Today, the animal husbandry sector provides new business areas that enable the increase of the value of the products obtained by processing them and the reuse of wastes (Anonymous, 2020). Türkiye has a more suitable structure for agricultural production among the countries in the region in terms of its topography and climatic conditions (Anonymous, 2009; Çayır, 2010). At the same time, similar to the world in general, animal-based foods, which are rich in protein in Türkiye, have a share in raising future generations in a healthier way by providing a sufficient and stable nutrition for the country's population (Terin et al., 2017).

In today's agriculture, obtaining more and more qualified products from a unit area without creating pressure on the environment can be achieved by using high-yielding seeds, choosing the right soil tillage methods, carrying out agricultural control activities at the right time and effectively, choosing the right irrigation systems and methods, as well as effective and appropriate manure applications. In order to prevent the negative effects that arise as a result of the use of chemical fertilizers, the use of farm manure, which has been known to be useful since ancient times, has returned to the agenda of producers. Organic manure is effective in regaining the amount of organic matter that is decreasing day by day from the soil structure and in meeting the plant nutrient needs.

With the development of agriculture and the increase in the number of integrated animal farms shelter capacities, more animal manure is produced. When the general structure of the enterprises is examined, the biggest problem encountered is the management of the manure. Processes such as cleaning and disposal of manure in the shelter, processing with different systems and application on agricultural land are generally ignored (Şimşek et al., 2001). As a result, while the gases formed due to manure inside the shelter have negative effects on the air inside the shelter, manure and waste stored in unsuitable conditions around the shelter cause large-scale environmental problems by creating soil and

water pollution as well as odor and visual pollution (Sainsbury, 1981; Jacobson et al., 1999; Öztürk, 2017; Çayır, 2010; İnan, 2012). At the same time, uncontrolled collection of solid and liquid manure in the shelters or their disposal without evaluation causes a national wealth to be wasted (Şimşek et al., 2001).

Although ineffective manure management policies and lack of incentives for good manure management (Teenstra et al., 2014) and improper processing and use of manure in enterprises that do not have sufficient capital to invest in the necessary equipment (Ström at all., 2017) limit the success of manure management practices, successful results have been achieved in recent years in studies on the management and re-evaluation of manure in countries where animal husbandry is intensive, technologically advanced and with large capacity barns (Şimşek et al., 2001).

In this study, the composting technique, which has an important place among the methods used in the disposal of animal waste, and its positive effects on the soil will be evaluated in the light of literature information.

2. Evaluation of Animal Waste

Animal shelters are structures that are equipped with traditional or latest technologies and designed accordingly, where animals are housed and their vital activities are carried out. However, no matter which system is used in the shelters (whether traditional or latest technologies are used), some materials defined as waste will definitely emerge in the shelters (Atılgan et al., 2004). These materials formed in animal shelters and defined as waste can be listed as animal manure and urine, floor covering material laid under the animals, water used for cleaning purposes during milking, runoff water in the walking courtyard and silage water (Öztürk, 2017). These wastes are defined as “diffuse pollution” and can cause more pollution than the environmental problems caused by many industrial wastes (Özek, 1994; Ongley, 1996; Can, 2021).

Animal manure has an important place in the nutrient cycle in terms of supporting the soil with the nutrients it contains and meeting the nutritional needs of farm animals. The macro and micro nutrients it contains are recycled and play a role in improving soil fertility and health, and as a result, it helps to increase agricultural productivity by improving the biological diversity and structure of the soil (Teenstra et al., 2015). Animal manure is a very important supporter for soils deficient in organic matter and plant nutrients, as well as a material that improves the soil conditions. When animal manure is matured with the right method, it reduces operating costs, minimizes the risks on the environment, and the benefits provided are greater than those of mineral manures (Kacar and Katkat, 2009; Diacono and Montemurro, 2010). The composition of animal manure varies depending on the effects of various factors. Factors such as the type of animals, their age and nutritional status, the type of bedding material used, and the storage method of organic fertilizer play an important role in the composition of animal manure obtained from agricultural enterprises. The most important factor affecting the amount of manure is the breed of animal (Kızılgöz, 2012).

The benefits to be gained by evaluating animal waste can be listed as; processing the waste with appropriate technologies, helping sustainable agriculture and therefore the development of the country, providing a more livable environment in environmentally sensitive areas and popularizing the use of organic fertilizers (Manav et al., 2008).

When applied excessively to the land, manure not only causes water pollution but also adversely affects the physical conditions of the soil by reducing the pore space within the soil and causing soil crust formation (Olgun and Polat, 2005). In addition, as a result of incorrect or no manure management, manure used in agricultural lands may contain a wide range of zoonotic pathogens that can cause disease in humans (Pell, 1997; Carrique-Mas and Bryant, 2013; Yugo and Meng, 2013; Milinovich and Klieve, 2011), and may pose a public health hazard, as well as causing excessive greenhouse gas emissions and eutrophication (Gerba and Smith, 2005; Albihn and Vinnerås, 2007; Jongbloed and Lenis, 1998).

When unprocessed agricultural wastes (vegetable and animal) are used on agricultural lands for plant production purposes, substances that may be present in the wastes and may cause toxic effects cause environmental problems as well as having negative effects on the productivity of agricultural land over time. The problems that may be encountered due to poor management of wastes resulting from animal production can be listed as follows (Anonymous, 2013):

- It creates heavy metal pollution in soil, groundwater and plant content.
- It causes unpleasant odors in the environment.
- It causes adverse conditions that put human health at risk.

- Over time, it creates pressure on natural resources and causes them to become unusable.
- It carries organisms that have the risk of causing disease.

In Türkiye, animal wastes have been used as both manure and fuel for many years (Manav et al., 2008), but today, four different alternative disposal methods are widely used, where animal waste is evaluated without causing environmental problems and by taking into account its economic contributions. These methods are using in plant production with dewatering process, creating compost in oxygen environment, creating compost in oxygen-free environment (Biogas) and burning methods (Gül, 2006; Erdener, 2010).

2.1. Legal Regulations Regarding the Use of Animal Manure in Agricultural Areas in Türkiye

As in all sectors, the concept of sustainability is very important in the agricultural sector. While chemical fertilizers are used uncontrollably in Türkiye as well as all over the world, agricultural production continues intensively by ignoring the problems caused by the techniques used for processing the products and the technologies related to these techniques (Turhan, 2005). In recent years, in order for agricultural practices to be sustainable, the concept of 'Sustainable Agriculture', in which an agricultural system and practices are formed by using agricultural technologies that do not harm natural agricultural resources, as well as the production of sufficient and quality food at affordable costs and the protection of natural resources in the long term, has come to the fore (Turhan, 2005; Anonymous, 2023a). In this context, efforts have been made to take precautions against these threats arising from the agricultural sector in Türkiye as well as all over the world, and the necessary legal regulations have begun to be made.

In the "Solid Waste Control Regulation", which was first published in the Official Gazette dated 14.03.1991 and numbered 20814, and later updated by being published on different dates and finally in the Official

Gazette dated 05.04.2005 and numbered 25777, it was stated that in order for the compost material obtained by processing organic waste to have a healing effect on the soil structure; first of all, organic wastes that accelerate the composting process should be stored separately, they should be prepared in structures specially designed for the composting process, and home kitchen and garden wastes should also be used as compost raw materials.

In the “Soil and Water Pollution Regulation” published in the Official Gazette dated 31.05.2005 and numbered 25831, the estimated possible limit values for the use of compost in soil are given in the Annex IA table (Table 2.1) in the Soil Pollution Parameters Limit Values section, and the heavy metal content limit values are given in the Annex 1-C table (Table 2.2). In line with the relevant regulation, the compost must meet the following criteria;

a) If the C/N ratio in the reactor is higher than 35, nitrogen should be added to the compost material so that the product reaction can take place under the most suitable conditions.
b) The amount of organic matter in the compost should not be lower than 35% of the amount of dry matter that forms the compost.
c) The water content of the compost offered for sale should be at most 50%,
d) The weight of visible materials (leather pieces, plastic, metal, slag) in the compost offered for sale should be less than 2% of the total weight.

Some criteria have been determined for obtaining products containing animal wastes, their use in agricultural areas and their supply to the market in accordance with the “Regulation on the Production, Import and Marketing of Organic, Organomineral Fertilizers and Soil Conditioners and Microbial, Enzyme Containing and Other Products Used in Agriculture’ published in the Official Gazette dated 04.06.2010 and numbered 27601 (İnan, 2012). Later, with the ‘Regulation on

Organic, Mineral and Microbial Source Fertilizers Used in Agriculture' published in the Official Gazette dated 23.02.2018 and numbered 30341, while the limitations on the heavy metal content ratios of the fertilizer obtained in order to minimize the negative effects of domestic and plant welded compost on the environment and human health were maintained without any changes (Table 2.3.) some criteria were updated (Table 2.4.)

2.2. Compost

Increasing the amount of plant production from agricultural lands is directly related to increasing soil productivity. It is known that one of the most effective ways to increase soil productivity is to choose and use the right manure (Berkes, 1993). Chemical fertilizers produced today have positive effects on the quality and yield values of the product obtained through their various plant nutrients (Bellitürk et al., 2019). They also play an effective role in the improvement of exhausted soils.

The increase in agricultural production that occurred with the use of chemical fertilizers, pesticides and chemical additives in the 1950s and 1960s was called the "Green Revolution" as it was thought to bring a solution to the hunger problem in the world. However, over time, it was seen that these chemicals, which increased the production amounts, caused the death of microorganisms that showed beneficial activities in the soil and caused a decrease in soil fertility, plant nutrient quantity and quality (Sinha et al, 2009). Mineral fertilizers, one of the basic inputs of agricultural production, are also the second largest expense item for Türkiye after petroleum products in which foreign exchange expenditures are made (Eskicioğlu, 2013).

The wastes generated due to the increasing agricultural production due to the developing world and rapid population growth cause economic and environmental problems (Castaldi et al, 2005, Vieyra et al, 2009) and the emergence of the problem of disposal of these wastes (Kılbacak et al., 2021). In terms of sustainable agriculture and environment, the most emphasized issues are to work on technologies that are financially valuable and minimize the negative effects on the environment and to reuse organic wastes which are considered as valuable wastes (Raj and Antil, 2011; Kütük, 2013). The soils in Türkiye have a poor organic matter content due to the improper and misuse of agricultural lands, destroyed pasture and forest areas, intensive cultivation of soils, ignoring crop rotation practices and being constantly exposed to erosion (Erbayram, 2013). Only 30-35% of our soils contain sufficient organic matter (Demirtaş et al. 2005). For the sustainability of agriculture and agriculture-based businesses, it is very important to be careful in the use of existing resources and to process the wastes and make them reusable (Kütük, 2013).

In the simplest terms, compost is the process of decomposing organic matter (Smith, 2011). In a similar expression, the product that does not cause any health problems as a result of the exposure of organic wastes to microbial decomposition (decomposition) under conditions where contact with air is provided, has a rich plant nutrient and organic matter content, and has a soil appearance due to its dark color, is defined as compost (Erdim, 2003). In Article 3 of the "Solid Waste Control Regulation" dated 05.04.2005 and numbered 25777, compost is defined as the material obtained as a result of the separation of organic-based solid wastes into their components in an oxygenated environment and has positive effects on soils (Anonymous, 2005).

Table 2.1. Possible limit values estimated for the use of compost in soil (Official Gazette dated 31.05.2005 n. 25831)

Cadmium	Cd	3
Copper	Cu	450
Nickel	Ni	120
Lead	Pb	150
Zinc	Zn	1100
Mercury	Hg	5
Chromium	Cr	350
Tin*	Sn	10

Table 2.2. Heavy metal content limits allowed in the resulting compost (Official Gazette dated 31.05.2005, no. 25831)

Heavy Metal (Total)	pH 5-6 (mg kg^{-1}) Oven Dry Soil	pH>6 (mg kg^{-1}) Oven Dry Soil
Lead	50	300
Cadmium	1	3
Chromium	100	100
Copper	50	140
Nickel	30	75
Zinc	150	300
Mercury	1	1.50

Table 2.3. Permissible heavy metal contents in manure (ppm) (23.02.2018 t. 30341 p. Official Gazette)

Heavy Metal (Total)	Limit Load Value (gr/da/year, in dry matter)
Lead	1500
Cadmium	15
Chromium	1500
Copper	1200
Nickel	300
Zinc	3000
Mercury	10

Table 2.4. Animal manure production and marketing criterion (23.02.2018 t. 30341 p. Official Gazette)

Fertilizers	**Product Description**	**Raw material content, dosage, amount of plant nutrient material required to be in the content and other criteria.**	**Other information about the product such as EC, pH etc.**	**Mandatory content to be declared on the label**
Solid Farm Manure	The product obtained by the ripening (maturation/composting, removal/reduction of moisture) of animal feces on floors with or without litter.	Organic matter minimum: 30% Total nitrogen minimum: 1% Maximum humidity: 20% C/N=8-22	pH * ** EC (dS m^{-1})	-Organic matter -Total nitrogen -Maximum humidity -Water-soluble potassium oxide (K_2O) (if it exceeds 1%) - C/N -Total phosphorus pentoxide (P_2O_5) (if it exceeds 1%) - Total (Humic + Fulvic) acid (if it exceeds 1%)
Liquid Farm Manure	Liquid product obtained by suspending solid farm manure in water or naturally.	Organic matter minimum: 5% Total nitrogen minimum: 1%	pH * ** EC (dS m^{-1})	-Organic matter -Total nitrogen -Water-soluble potassium oxide (K_2O) (if it exceeds 0.5%) -Total phosphorus pentoxide (P_2O_5) (if it exceeds 0.5%) - Total (Humic + Fulvic) acid (if it exceeds 1%)
Poultry Solid Manure	Products obtained as a result of aerobic composting of poultry feces with or without litter and removal/reduction of moisture, or products obtained as a result of ripening (maturation) of other poultry feces in their natural environment or aerobic composting and removal/reduction of moisture.	Organic matter minimum: 30% Maximum humidity: 20% $CaCO_3$ (Lime) EC (dS m^{-1})	pH * ** EC (dS m^{-1}) (For those exceeding EC 10 dS/m, the statement "should not be used in salt-sensitive plants")	-Organic matter -Total nitrogen -Total phosphorus pentoxide (P_2O_5) (if it exceeds 1%) -Water-soluble potassium oxide (K_2O) (if it exceeds 1%) -Total (Humic + Fulvic) acid (if it exceeds 1%) -Maximum humidity - Lime ($CaCO_3$) -The raw material used will be specified in the type name.
Bat Guano	Products obtained as a result of aerobic composting of bat waste and removal and/or reduction of moisture or products obtained as a result of ripening (maturation) of other poultry feces in their natural environment or aerobic composting and removal/reduction of moisture.	Organic matter minimum: 30% Maximum humidity: 20%	pH * **	-Organic matter -Total nitrogen -Total phosphorus pentoxide (P_2O_5) (if it exceeds 1%) -Water-soluble potassium oxide (K_2O) (if it exceeds 1%) -Total (Humic + Fulvic) acid (if it exceeds 1%) -Maximum humidity

Organic Fertilizer Obtained as a Result of Fermentation	Product obtained as a result of anaerobic fermentation and aerobic hygienization of single or mixed domestic waste and/or animal feces.	Organic matter minimum: 15% The raw materials used in the product will be specified in the process.	- Organic matter -Total nitrogen -Organic nitrogen -Total (humic + fulvic) acid (if it exceeds 2%) -Free amino acids (if exceeds 2%) - Total nitrogen (if it exceeds 1%) - Water soluble potassium oxide(K_2O) - Total phosphorus pentoxide (P_2O_5) (if it exceeds 1%)

The raw material to be used in composting is placed in a pile or series (extended pile) and the decomposition process is started. The success of the decomposition process varies depending on the oxygen level in the environment, ambient temperature, moisture content, physical, chemical and biological factors as well as the compost technology used (EPA, 1994).

The composting process occurs rapidly when suitable growth conditions are created for microorganisms and these conditions can be kept under control during the process. The efficiency of the composting process depends on many factors such as the C/N ratio, the ventilation rate in the pile, the moisture content of the pile, particle size, pH value and pile temperature. The conditions that should be considered for the rapid composting process are shown in Table 2.5 (Anonymous, 1992).

Composting is a process in which the development of plants and the reuse of waste (green agriculture) can be utilized as plant nutrients and the decomposition process is carried out by keeping the conditions under control. This degradation occurs as a result of microbial activities and is decomposed by fungi, bacteria and other unicellular organisms in the mixture into darker, stable and usable substances with high organic matter content, darker in color, which can be used as a soil improver or fertilizer, consisting of animal and plant waste (Bernal et al, 2009; Pankhurst et al, 2011; Smith 2011; Chen et al, 2017; Shan et al, 2021).

Table 2.5. Conditions required for a rapid composting process

Condition	Accepted range [a]	Recommended range
C/N ratio	20:1-40:1	25:1-30:l
Moisture content	40-65% [b]	50-60%
Oxygen concentration	>%5	>>%5
Particle size (cm diameter)	0.32-1.27	Exchangeable [b]
pH	5.5-9.0	6.5-8.0
Heat	43-66	54-60

[a] These values are valid for rapid composting. Values outside these ranges can also be used.
[b] Varies depending on material used, pile size and/or weather conditions.

During the composting process, oxygen in the environment is consumed by the microorganisms in the mixture to decompose organic materials. During the active composting process, a large amount of water vapor (H_2O), carbon dioxide (CO_2) and heat are released in the environment. The amount of carbon dioxide (CO_2) and water vapor (H_2O) produced can be approximately 50% of the weight of the material used as raw material in the first stage. The order of events during this process is as follows; Firstly, the biochemical reaction is realized by microorganisms by using oxygen in the environment. Heat is released as a result of the biochemical reaction. The generated heat causes the water in the environment to evaporate and thus the compost material to dry slowly (Ekinci et al., 2004; Keener et al., 2000).

As with the different recovery methods used, composting reduces the amount of organic wastes sent to incineration or landfill, thereby reduces the costs required for the disposal of these wastes. In addition, compost is an important alternative product that can be preferred by producers, public and private sector organizations, as it has the feature of improving the structure of the soil and can be used as mulch material by covering the soil surface (EPA, 1994).

Compost production, although widely used in the world and not popular enough in Türkiye, is a cheap and simple method that can be used in the utilization of animal wastes, which is another important waste problem for Türkiye, as well as being a suitable disposal method for domestic wastes (TÜBİTAK-MAM, 2001).

Its qualities such as containing some macro (N, P, K) and micro (Cu, Fe, Zn) nutrients, providing a successful aeration by increasing the pore volume of the soil, better utilization of nutrients and facilitating the cultivation of the soil make the use of compost as a material that improves soil conditions widespread (Özbaş et al., 2002; Yıldız et al., 2010).

Compared to animal manure, compost can have equivalent or higher values than animal manure. Considering the average values of the substances it contains, approximately 10 tons/da of compost can be applied under field conditions, corresponding to 150-200 kg da^{-1} of commercial fertilizer. Compost, which is environmentally friendly, profitable due to reducing the use of commercial manure and provides more products, will become increasingly important in the coming years as a new option for many growing environments or a material that supports the environment (Yalçın et al., 2010).

A significant part of the waste in Türkiye is suitable for composting (especially plant wastes). The compost to be produced as a result of the application of this method is a qualified and high-yield product that can be applied in agricultural areas (Yıldız et al., 2010).

3. Result and Suggestions

Animal manure, which has a very rich content in terms of plant nutrients and has the ability to improve soil conditions, may cause various problems that may put pressure on the environment due to liquid and solid wastes resulting from manure if the storage conditions are not suitable. For this reason, it should be emphasized that manure storage conditions in animal shelters should be improved and storage structures in newly established animal shelters should be designed together during the construction of the shelter.

When the structure of agricultural enterprises in Türkiye is examined, it is seen that chemical fertilizers are widely used instead of utilizing animal manure, which is a very valuable resource, due to the effect of fertilizer firms that are dominant in the sector. The ease of application of chemical fertilizers and the high initial investment costs of facilities to be established to evaluate animal manure as energy and fertilizer (Biogas, compost, etc.) are also effective in this regard. Supporting the facilities related to the evaluation of animal manure and establishing central facilities by encouraging the owners of the enterprises to cooperate will reduce the cost problem relatively.

Composting is one of the most widely used methods for the evaluation of wastes from animal shelters. However, when literature studies are examined, it is seen that compost production and applications have not reached a sufficient level in Türkiye. One of the most important reasons why producers are not interested in compost product is that the quality classes related to compost have not been determined. This problem was solved with the "Compost Communiqué" published in the Official Gazette numbered 29286 in 2015. It will be possible to produce and use high quality compost by considering the limit values specified in the Communiqué.

Compost is a very valuable resource in terms of implementing a sustainable agricultural policy, eliminating the deficiencies of plant nutrients and organic matter in the soils in Türkiye, thus preventing the decrease in productivity in agricultural areas and eliminating the lack of alternatives in chemical fertilizers. At the same time, it will reduce the pressure on the environment and provide new employment opportunities for the local community through the facilities to be established.

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CHAPTER 8

THE IMPORTANCE of SOIL MICROORGANISMS in SUSTAINABLE AGRICULTURE

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1. Introduction

Soil, one of the basic production factors of agriculture, is a limited and non-producible resource. In this regard, it is of great importance to prefer practices that will increase the quality of agricultural lands and to use these practices in a sustainable manner in order to ensure people's access to adequate and reliable food, to support rural development and to create a livable environment (Okur, 2021). The biggest concern of the agricultural sector is soil fertility with soil health and quality problems. Long-term and continuous use of chemical fertilizers in agricultural lands causes negative effects that lead to decreased productivity in agricultural production (Prakash, 2022). In this respect, improper use of agricultural lands causes the natural balance of the soil to be disrupted, the plant nutrient content to change, and the physical, chemical and biological properties to be damaged, leading to problems such as erosion and desertification (Cüre, 2022).

With the increase in the world population, the demand for agricultural products is increasing day by day. This situation reveals the necessity of increasing the productivity of agricultural lands in order to prevent nutritional and environmental problems. Concerns about the potential health and environmental impacts of heavy use of mineral fertilizers and chemical pesticides have led to intense interest in alternative strategies for improving crop yield and quality, such as sustainable agriculture. Sustainable agriculture is the construction of an agricultural structure in which agricultural technologies that do not harm the environment are applied while ensuring the protection of natural resources in the long term. For this reason, in order to protect agricultural production, it has become of great importance to ensure product yield and sustainability in agricultural lands.

Worldwide agricultural production must double food production by 2050 to feed the growing population and at the same time reduce dependence on inorganic fertilizers and pesticides (Singh et. al., 2017). The soil in which interactions between the plant and the environment occur must be of sufficient quality to ensure good plant development and growth. There are many different types of soil on Earth, each with its own unique biodiversity. However, the common feature of all of them is that the relationship between organic matter, structure and dynamics is mostly due to microorganism activities that occur at a depth of approximately 20 centimeters from the soil surface. Plants and soil microorganisms regulate organic matter and nutrient cycles so that the soil can sustain life. Soil organic matter increases microorganism activities; microorganisms improve the physical and chemical structure of the soil, making agricultural soil more suitable for plants growing on it. For this purpose, the need to exploit beneficial interactions between plants and microorganisms is becoming increasingly important. Positive contributions of microorganisms to plant growth include nitrogen fixation, uptake of essential nutrients, promotion of shoot and root development, control and suppression of diseases and improved soil structure (Gupta, 2012). The soil microbial community often erodes minerals from rock surfaces and decomposes soil organic matter into plant-usable forms. Therefore, soil organic matter turnover is related to the activity and size of the microbial mass. Additionally, the role of soil organisms in oxidation and reduction reactions in the nitrogen cycle is critical for natural ecosystems (soil, water, air). Therefore, soil fertility can only be rised by increasing the amount of organic matter and microbial activity in the soils (Mutlu, 2018).

Soil is an ecosystem where millions of living species live and interact with each other. There are many beneficial microorganisms such as bacteria and fungi that live in the soil and provide suitable conditions for the development of plants (Ortiz and Sansinenea, 2021). One gram of soil contains approximately 9×10^7 bacterial cells, approximately 4×10^6 actinomycetes and 2×10^5 fungal cells, as well as various organisms such as algae, protozoa and nematodes (Karaoğlu et al., 2024). The beneficial interactions of these microorganisms with plants include providing nutrients to crops, stimulating plant growth, producing phytohormones, biocontrol of phytopathogens, improving soil structure, bioaccumulation of inorganic compounds, and bioremediation of metal-contaminated soils (Sansinenea, 2019). Therefore, soil microbiota is one of the fundamental elements of a sustainable system and plays a critical role in the sustainability of natural ecosystems. Plant growth promoting microorganisms is a concept that includes all microorganisms (nitrogen fixing and non-nitrogen fixing bacteria, actinomycetes, fungi and algae) that have direct or indirect beneficial effects on plant development. Plant growth-promoting microorganisms play an important role in supporting the development, productivity and sustainability of crops by increasing plant growth and soil fertility. Plant growth-promoting rhizobacteria, plant growth-enhancing microorganisms and mycorrhizal fungi promote plant growth by contributing to the uptake of nutrients from the soil, especially through mechanisms such as siderophores, antioxidants and stress resistance responses (Kumar and Verma, 2018). In addition, soil microorganisms play a role in the decomposition of organic matter, nutrient cycling and respond quickly to changes in the soil environment, so microbial activity in the soil is very important as a soil quality indicator (Okur, 2017). In this respect, the removal of plant nutrients from the environment by being washed away by excess irrigation water, the decrease or disappearance of the amount of organic matter in the soil due to wrong practices such as excessive soil tillage, etc., and the compaction of the soil due to intense agricultural machinery and equipment traffic negatively affect the microbial activities in the soil, thus negatively affecting soil fertility and therefore sustainability.

Soil microbial communities are a group of different microorganisms that can positively or negatively affect plant growth and productivity (van der Heijden et al., 2008; Chandra, 2019). This group constitutes a significant portion of global terrestrial biodiversity and drives a variety of processes that are critical to soil health and productivity in both natural ecosystems and agricultural systems. Many species of beneficial microorganisms found in the soil create suitable conditions for the development of plants (Ortiz and Sansinenea, 2021). Among these microorganisms, bacteria and fungi are the most important organisms (De la Fuente Cantó et al., 2020). This is because the energy flow and nutrient transfer in terrestrial ecosystems are largely provided by these groups of organisms. In fact, soil microorganisms directly affect plant growth by establishing mutualistic (symbiotic) or pathogenic relationships with roots or indirectly by altering the nutrient availability rate through free-living microorganisms (non-symbiotic) (van der Heijden et al., 2008). Among these root-associated microorganisms, arbuscular mycorrhizal fungi, which have the capacity to provide the host with limiting nutrients such as phosphorus (P) in the soil in exchange for carbon, are widely found (Georgiou, et al., 2017). Nitrogen-fixing bacteria provide the most soil nitrogen for plant community productivity in many ecosystems, especially in plant communities where legumes are dense (van der Heijden et al., 2008; Pajares and Bohannan, 2016). This nitrogen provides approximately 20% of the total annual nitrogen needs of plants (Cleveland, 1999; van der Heijden et al., 2006). There are also many important groups of microorganisms that fix nitrogen indirectly and are not in direct symbiotic relationships; examples of these are free-living nitrogen fixers, lichens and cyanobacteria (Cleveland, 1999).

The purpose of this article is to present the benefits of environmentally friendly microorganisms as an alternative to increased application of mineral fertilizers and chemical pesticides, and the importance of microbial interactions in the rhizosphere of crops with the natural biodiversity of soil microorganisms in sustainable agriculture.

2. Effects of soil microorganisms

2.1. Improving plant nutrition

- Microorganisms increase the nitrogen source in the soil or can give nitrogen directly to the plant because they have the ability to fix nitrogen from the atmosphere and make it available to the plant.
- Thanks to the microorganisms, the bioavailability of phosphorus in the soil increases. This is due to enzymatic activities and other components that convert insoluble phosphorus into plant-usable forms.
- The soil microorganisms make iron available to the plant through the production of binders such as siderophores. Thus, soil microorganisms convert the iron in the soil into absorbable iron for the plant.

2.2. Enzymes and phytohormone output

- The capacity of microorganisms to produce hormones such as gibberellin, indole-acetic acid and butyric acid promotes the elongation of the root parts of the plant.
- The microorganisms produce enzymes such as aminocyclopropane carboxylate deaminase (ACCD), which inhibits the synthesis of ethylene resulting from stress.

2.3. Biocontrol

- The microorganisms have the capacity to inhibit phytopathogens by producing antibiotics or other antagonistic methods.

Communities of organisms that spend all or part of their lives in the soil form the soil food web. The soil food web can be thought of as a soil biome. A healthy soil biome can provide plants with a constant flow of nutrients from soil organic matter and mineral content. Figure 1 shows the soil food web and some of the interactions within and between different trophic levels. The first level includes those that perform photosynthesis. Plants or their products, in this case root exudates, are consumed by second-level microorganisms. At the third level, primary carnivores; predators, decomposers and herbivores eat the second level microorganisms; at the fourth level, secondary predators prey on the primary carnivores.

The main groups of micro-organisms that constitute the soil food web are fungi, bacteria, protozoa, nematodes and micro-arthropods. These groups interact with each other and with plants, helping to create functional ecosystems. Some interact with living plants and animals (herbivores and predators), while others interact with dead plant wastes (detritivores), fungi or bacteria. Others survive without consuming (parasites) their hosts. Plants, mosses and some algae are autotrophs and produce organic compounds and living tissues using carbon (C) obtained from solar energy, water and atmospheric carbon dioxide (CO_2), thus assuming the role of primary producer. Fungi and bacteria found in soil release nutrients from sand, silt and clay particles, making them available to plants. This, ensures that plants can access the nutrients they need exactly when they need them. As a result, easy access to these nutrient sources helps plants protect themselves against pests and diseases and natural disasters such as drought and floods (Bragato Research Institute, 2020).

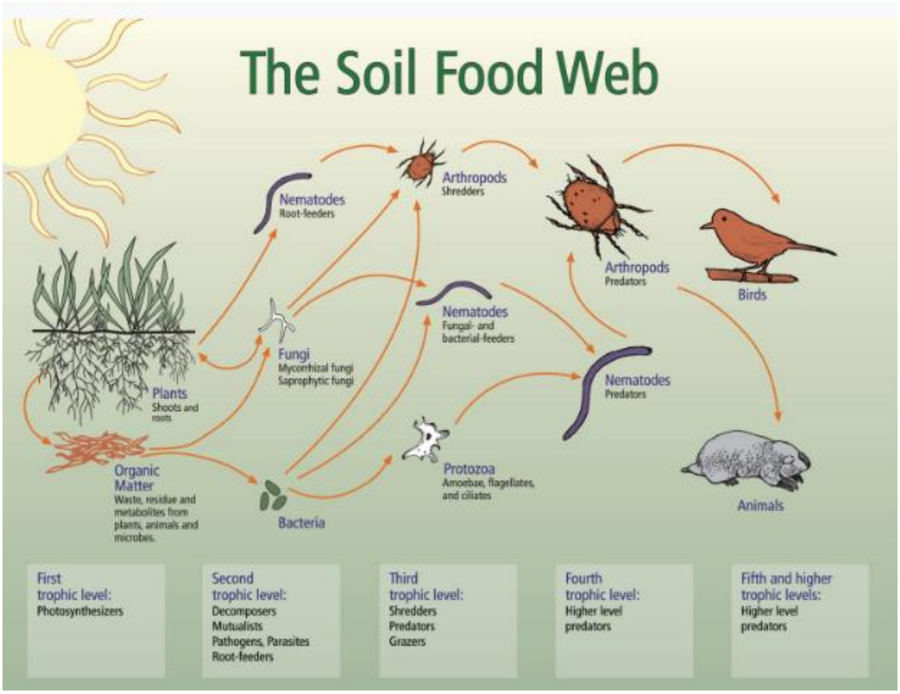

Figure 1: Relationships and Interactions in the Soil Food Web (Bragato Research Institute, 2020)

A healthy and balanced soil food web provides many benefits beyond providing nutrients to plants. These benefits include:

- Increased nutrient cycling,
- Increased carbon accumulation in the soil,
- Increased soil aggregation, which alleviates soil compaction and anaerobic conditions and increases water infiltration rates,
- Increased water retention capacity and drought resistance,
- Increased resistance to soil erosion.

Soil organisms can be classified in various ways based on their size, feeding habits, and the soil depths at which they live. Soil organisms are divided into three groups according to their size: microfauna, mesofauna and macrofauna (Coleman et al., 2004; Bardgett, 2005; Lavelle et al., 2006). Micro and mesofauna regulate the number and activities of microorganisms and microbial consumers that play an active role in the soil organic matter cycle. Thus, they ensure the breakdown of the dead cover and its integration into the mineral soil. They create microhabitats that have an effect on other soil organisms through their meso-macrofauna activities. This group generally consists of ants, termites and earthworms (Çakır and Makineci, 2011).

2.4. Microfauna

Microfauna, smaller than 100 μm, are the smallest living creatures of the soil fauna and can only be seen under a microscope (Fierer et al., 2007) The two most important soil organisms of the microfauna group are nematodes (roundworms) and protozoa (single-celled organisms). Roundworms, which need thin layers of water surrounding them in order to move, are especially common in sandy soils. Protozoas are single-celled and have small sizes and different shapes. These creatures obtain their energy from organic carbon sources and feed on small pieces of decayed organic matter, bacteria and other small organisms. Protozoa constitute an important group in the soil ecosystem. Herbivorous protozoas are decomposers and ensure the decomposition and cycling of organic matter (Hallett and Caird, 2017).

2.5. Mesofauna

Mesofauna includes all invertebrates that grow between 100 μm ile 2 mm in length and live in soil or organic wastes on the soil surface (Swift et al., 1979). This group includes some mites, arthropods and white worms. Mesofauna feed on many different species, including microorganisms, animal material, living or decaying plant material, fungi, algae and lichens. They play an important role in the transfer of nutrients as a result of microbial activities by providing an interaction between microfauna and macrofauna (Xin et al., 2012).

2.6. Macrofauna

Species classified as macrofauna are larger than 2 mm and can be seen with the naked eye (Swift et al., 1979). This group includes large animals such as rabbits and ground squirrels that spend part of their lives in the soil, as well as other creatures such as moles, snails, leeches, earthworms, ants and centipedes that spend their entire lives in the soil. Macrofauna play an important role in soil decomposition and dispersal by moving within the soil. This movement loosens the soil structure and improves soil aeration and drainage. They also contribute to the formation of soil organic matter by leaving nutritional residues in the soil. Earthworms, which are in the macrofauna group, are important organisms that contribute to soil fertility (Mısırlıoğlu, 2011). The fertilizer that worms create by consuming plant residues and organic matter in various stages of decomposition is quite rich in content (Ahmad et al., 2024). Thus, they contribute to the development of soil organic matter as they leave their nutritional residues in the soil (Bellitürk et al., 2023). They help to form a good soil structure as a result of the galleries and holes they create in the soil (Bellitürk et al., 2022). In addition, organic worm fertilizer called vermicompost is produced with many types of worms (Bellitürk et al., 2020).

Soils also contain three main types of microflora: bacteria, fungi and viruses. Bacteria are part of vital transformations that occur in the soil, such as the decomposition of rocks, minerals and organic matter, and nutrient cycling (Wang et al., 2024). A certain group of bacteria is of great importance in the nitrogen cycle. However, only some bacteria, blue-green algae and fungi can directly utilize this nitrogen from the atmosphere. Among these, *Rhizobium* spp. bacteria perform nitrogen fixation by forming nodules in the roots of plants in the *Leguminosae* (Legume) family. In this way, legumes both provide their own nitrogen needs and leave nitrogen-rich soil for subsequent plants. Free-living soil bacteria help promote plant growth by producing and secreting various regulatory chemicals around plant roots (Basu et al., 2021; Khoshru et al., 2020). In addition, some bacteria increase phosphorus solubility. Many studies have shown that the use of plant growth-supporting bacteria as biofertilizers helps increase plant production and soil fertility (Bhattacharyya and Jha, 2011; Garcia-Fraile et al., 2015; Vejan, 2016).

In a study examining the effects of phosphorus-solubilizing bacteria (*Bacillus* megaterium) on yield and phosphorus uptake in tomato plants, it was determined that bacteria with phosphorus-solubilizing ability increased the yield of the plant and positively affected the uptake of elements such as phosphorus, iron, zinc and copper (Turan et al., 2004).

In recent years, the use of bacterial biofertilizers containing one or more bacterial formulations that increase the development and productivity of plants has also become widespread. It has been determined that these bacteria increase the access of plants to nutrients by converting nutrients in the soil into a form that plants can use, thus affecting nutrient uptake. In addition, it has been described that these bacteria have various mechanisms to support plant development, such as phytohormone biosynthesis, reducing or preventing environmental stresses and preventing pathogen-induced plant diseases (Malusá and Vassilev, 2014). These processes are also effective in increasing the resistance of plants to diseases (Pal et al., 2000; Romeiro, 2000). Therefore, the integration of plant growth promoting bacteria into agricultural practices is of great importance for sustainable agriculture.

In well-aerated and cultivated soils, fungi constitute a major portion of the total microbial protoplasm. These organisms are particularly active in the organic layers of shrubland and forest areas and are among the dominant microorganisms in these regions. In acidic pH soils, fungi are the main elements of organic matter decomposition. The most important role of fungi is to ensure the decomposition of organic matter with their extracellular enzymes. Mycorrhizal fungi have a special place among soil fungi. Arbuscular mycorrhizal fungi (AMF) are beneficial fungi that establish a symbiotic relationship with plants and many agricultural crops through the roots of higher plants (Liu et al., 2021). The symbiosis established with arbuscular mycorrhizal fungi improves the rhizosphere microenvironment of the plant, increases the absorption of mineral elements by the plant, strengthens stress and disease resistance and promotes plant growth (Mitra et al., 2021). Other important roles are to bind and stabilize soil particles and to provide nutrients to soil fauna that feed on microorganisms (Ruiter and Moore, 2004). The main effect of mycorrhizal symbiosis is enhanced phosphorus (P) uptake through the extensive hyphal network. Arbuscular mycorrhizal fungi transfer water and nutrients from the soil to the plants through the roots, while the plants feed the fungi with organic compounds they produce through photosynthesis. This symbiotic relationship increases the resistance of plants to stress conditions, promotes root development and improves soil health. Thanks to this cooperation between plants and fungi, mycorrhizal fungi significantly support sustainable agriculture (Díaz-Urbano et al., 2023).

The proliferation of arbuscular mycorrhizal fungi plays an increasingly critical role in sustainable agricultural practices as they improve soil quality and structural stability. Harnessing the benefits of these mycorrhizal relationships can effectively increase agricultural productivity by reducing the use of chemical inputs such as pesticides and fertilizers (Janowski et al., 2022). This approach supports both environmental sustainability and improves soil health. Arbuscular mycorrhizal fungi not only increase nutrient and water uptake by plants, but also play an important role in improving soil structure and quality. These fungi increase the amount of organic matter in the soil, increasing its water-holding capacity and reducing soil erosion. In addition, mycorrhizal networks formed by these fungi promote soil health and plant growth by increasing interaction with soil microorganisms because external hyphal networks promote soil aggregation by creating a solid skeletal structure in the mycorrhizosphere. This structure creates bonds between soil particles, making the soil more stable and durable. Therefore, arbuscular mycorrhizal fungi play a critical role in agricultural productivity and ecosystem health.

Actinomycetes are also prokaryotic bacteria and are considered an intermediate form between bacteria and fungi and represent a large group of bacteria that form threadlike filaments in the soil. Soil actinomycetes are generally aerobic organisms and are more common in dry soils than in moist conditions. Actinomycetes are heterotrophic organisms that survive on organic matter in the soil. They use simple and high molecular weight organic acids, sugars, polysaccharides, lipids, proteins and aliphatic hydrocarbons as carbon sources. They are especially abundant in soils rich in organic matter and are not tolerant of low pH levels. Actinomycetes interact with some non-legume plants to fix nitrogen that is beneficial to both the host plant and other surrounding plants. Although actinomycetes are of less biochemical importance in soil than bacteria and fungi, they perform the following functions in the soil ecosystem:

- They provide the decomposition of some durable plant and animal tissues in the soil. Actinomycetes do not react immediately when natural carbonaceous substances are added to the soil. They compete very poorly against bacteria and fungi as long as simple carbohydrates are present in the environment. They usually become active as effective competitors when compounds that are difficult to decompose remain in the environment.
- Humus formation occurs by transforming plant tissues and leaf litter into different forms.
- Thermophilic actinomycetes are the dominant group in the maturation and transformation processes of green manure, compost and animal manure piles. Under these conditions, the surface of compost piles typically becomes white and gray due to the spread of these organisms. Spore-forming bacterial species such as *Thermoactinomyces* and some *Streptomycetes* are prominent as competitive species.

Viruses are the smallest, simplest organisms that live in the soil. All viruses are parasitic, meaning they live on other flora and fauna. Soil viruses are important because of their ability to influence the ecology of soil biological communities through their ability to transfer genes from host to host.

2.7. Effects of microorganisms on soil and plant health

Soil microorganisms have a major impact on plant productivity. Elements such as C, N, P, S, Fe and Mg that plants need are made usable for plants through various decomposition and synthesis processes by microorganisms. Microorganisms actually carry out these processes to provide their own nutritional and energy needs. Plants and soil microorganisms obtain their nutrients through organic matter decomposition and metabolic activities, respectively, and these processes can cause changes in soil properties. In this respect, soil microorganisms have various effects on plants, such as mineralization of organic matter and homogenization of irregular nutrients. Thus, plants and soil organisms facilitate the cycling of organic matter and nutrients, helping the soil to continue to support life. Plants interact with soil microorganisms through metabolites secreted by roots, particularly in the rhizosphere (Figure 2). Microorganisms create buffer substances that balance the concentrations of nutrient ions in the soil solution, increasing the water-holding capacity of the soil and helping to better aerate the roots. Soil microorganisms provide the decomposition of plant and animal residues, the formation and transformation of humus, while also producing the carbon dioxide necessary for plants to photosynthesize. In addition, microorganisms store water-soluble plant nutrients and also play an important role in the production of vitamins and hormones that support plant growth. Plant growth-promoting microorganisms not only promote growth but also have an important place in increasing the resistance of plants to various biotic and abiotic stresses (Arnold et al., 2003; Sun et al., 2010; Agler et al., 2016; Azad and Kaminskyj, 2016; Singh, 2016; Oleńska et al., 2020; Rai et al., 2020).

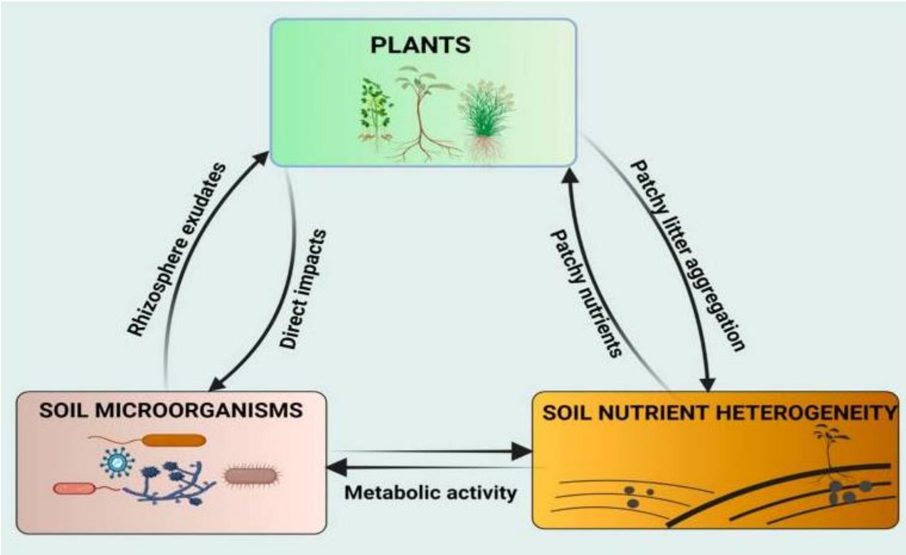

Figure 2. Schematic Representation of the Interactions Between the Plant, Soil Microorganisms, and Soil Nutrient Heterogeneity (Adomako et. al., 2022)

Various microorganisms in the soil cause the soil particles to coalesce into larger particles through their secretions and filaments. These particles are of great importance for soil life and vitality and affect many important soil processes, from preventing erosion to maintaining soil moisture, aeration and regulating soil reactions. Soil microorganisms and some macroscopic organisms increase the fertility of the soil and contribute to the development of vegetation, especially in natural ecosystems. It brings soil particles together and clusters them, allowing the soil to become tempered, thus allowing rainwater to infiltrate and store in the soil before it passes into the surface runoff. For this reason, soil health is the fundamental element of agricultural sustainability (Magdoff and Van Es, 2021).

2.8. Effects of microorganisms on agricultural production

Various soil management practices have been implemented to grow healthy plants, control pests and promote beneficial organisms in order to obtain high quality and high product yields. Agricultural practices can have both positive and negative effects on soil organisms.

Land management and agricultural methods alter the composition of soil biota communities at all levels and produce important results in terms of soil fertility and plant productivity. Various farming methods preferred by farmers have a significant impact on the structure, activities and diversity of soil biota. Since fertilisers and pesticides used to promote agricultural development increase both crop and soil fertility, these practices (fertilisation, pesticide use, etc.) are considered important elements in agriculture (Baweja et al., 2020). However, excessive use of chemical fertilizers and pesticides has negative effects on soil health, crop productivity, the environment and human health. Therefore, these practices lead to the formation of low-quality soils and the deterioration of food security systems, causing serious problems such as soil erosion, organic matter loss and nutrient imbalance (Montanarella et al., 2016; Kumar and Pawar, 2018). Therefore, agricultural practices such as the addition of lime, manure and animal manures, soil tillage methods or the use of pesticides change the physical and chemical environment, significantly altering the proportions and interactions of different organisms.

The effects of soil organisms on agricultural productivity include:

- Organic matter decomposition and soil aggregation,
- Degradation of toxic compounds, both metabolic by-products of organisms and agricultural chemicals,
- Inorganic transformations that make essential elements such as iron and manganese, as well as nitrates, sulfates and phosphates, available,
- Fixing nitrogen into forms that higher plants can use.

2.9. The Role of Soil Microorganisms in Ecosystem Functions

The majority of microorganisms in terrestrial ecosystems reside in soil, and the microbiology of these ecosystems is generally considered as soil microbiology. In many terrestrial ecosystems, microorganisms and soil animals play a major role in the cycling and exchange of chemical elements because they are highly metabolically active, even though they constitute only a small part of the total biomass. In natural ecosystems, plant and animal organic residues are decomposed and integrated into the soil by the joint activities of soil microorganisms. There are different microorganisms in the agricultural ecosystem that use various strategies such as fixing, solubilizing, mobilizing and recycling nutrients and increase plant growth and productivity (Bhowmik and Das, 2018). These microorganisms have the capacity to break down and detoxify harmful organic and inorganic compounds accumulated in the soil as a result of various activities. In this way, they perform the bioremediation effect that improves soil and plant health (Tarekegn et al., 2020). Therefore, the activities of soil microbial communities play a vital role in the productivity and sustainability of global ecosystems (Wagg et al., 2011; Bowles et al., 2014).

3. Conclusion

There are many different microorganisms in soils, from macroscopic construction to microscopic. The vitality and activity of these microorganisms vary depending on the structure of the soil. The microorganisms that interact with plants provide nutrients to crops, control phytopathogens and support plant growth. Beneficial microorganisms play an important role in sustainable agriculture thanks to their ability to promote plant growth and fight against pathogens in an environmentally friendly manner. Thus, the main goal of ecological soil management is to create a healthy underground living space with good soil structure, rich and diverse soil organisms and sufficient nutrients to achieve high yields.

One of the most important factors to ensure sustainability and productivity increase in agricultural production is the improvement of soil properties. Soil microorganisms are of critical importance in sustainable agriculture because of their ability to promote plant growth and fight against pathogens in environmentally friendly ways. Soil microorganisms are of critical importance in sustainable agriculture because of their ability to promote plant growth and fight pathogens in environmentally friendly ways. Therefore, in order to increase the productivity capacity of the soils, proper soil management must be implemented to improve the biochemical and physical soil properties.

In order to provide the food needs of the increasing world population, it is of great importance to implement agricultural production methods that aim to increase productivity, protect human health and the environment, and use agricultural lands in a sustainable manner. When using agricultural land, the aim should not only be to obtain the highest yield from the unit area; at the same time, the continuity of sustainable agriculture should be ensured by adopting a use that is compatible with nature and appropriate to the quality and capacity of the soil. In order for our people to have access to sufficient and safe food, to raise healthy generations, to support rural development, to develop the economy and to protect a livable environment, we should focus as much as possible on practices that will increase the quality of our agricultural lands and enable the sustainable use of these lands. In addition, agricultural management practices should be designed to minimize undesirable effects on the soil environment and to work in harmony with biological processes to support sustainable agricultural systems.

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CHAPTER 9

SUSTAINABLE AGRICULTURE AND PLANT BREEDING

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1. INTRODUCTION

Sustainable agriculture can be defined as agricultural practices that ensure the production of quality and sufficient food in harmony with nature and with sustainable criteria. In other words, sustainable agriculture is the production of plant and animal products with techniques that protect the environment, public health, society and animal welfare by ensuring food security. Sustainable agricultural practices are based on the efficient use of natural resources by protecting the yield and quality of the products obtained by producers, as well as ensuring profitability. Today, the negativities that arise due to the intensive use of agricultural inputs and the use of excessive agricultural techniques to meet the food needs of the increasing population have led to the search for and development of environmentally friendly production techniques that can be an alternative to agriculture where input use is intensive.

Obtaining more products from a unit area to meet the food needs of the increasing world population is the most important concentration of agricultural practices. For this reason, instead of considering many features that provide resistance to abiotic and biotic stress factors in improved varieties, the focus is on breeding high-yielding varieties that respond well to excessive input. Intensive agricultural practices focused on high yield and based on excessive input use accelerate the destruction of soil and water resources, and cause difficult-to-solve problems on soil and water resources and the environment.

Sustainable agriculture should not only target production but also the provision of the necessary food while protecting the environment. It represents a harmonious relationship between producers and modern scientific innovation for environmental, social and economic sustainability. In its simplest form, sustainable agriculture refers to a set of agricultural practices that aim to meet our current needs without compromising the ability of future generations to meet their needs.

2. SUSTAINABLE AGRICULTURE

Sustainable agriculture consists of main components such as ecological, economic and social sustainability.

Ecological sustainability: There is no sustainable agriculture without ecological sustainability, which ultimately forms the basis of ecologically sustainable agriculture. The health of the ecological environment is as important as the production of healthy and reliable food. Sustainable agricultural practices should be practices that prioritize soil health, biodiversity and the protection of resources. For these practices to be carried out successfully, crop rotation, which is based on the production of different products in a certain order that protects and improves soil quality and prevents disease and pest cycles, minimum tillage or no-tillage agricultural practices that reduce soil erosion and protect soil structure, and practices that envisage integrating trees and other woody plants into farming systems to improve land use, protect biodiversity and provide additional sources of income can be counted. Ecological sustainability is agricultural techniques that aim to apply nature-friendly organic products instead of intensive synthetic pesticides and chemical fertilizers that can cause problems for both the environment and the health of consumers.

Economic sustainability: For the effective use of sustainable agriculture, producers should be an application that foresees that food production is the most important link and that the applications should ensure the economic sustainability of the producers. While producers implement applications that protect or even improve the environment, they should obtain appropriate economic returns from the fields as a result of the applications they implement to earn their living. Reducing input costs, market durability and providing support to small farmers are important in sustainable agriculture. Sustainable applications aim to protect the environment and increase the profits of producers by reducing excessively used inputs that increase the cost of agricultural production. The fact that producers produce different products and adopt environmentally friendly sustainable methods makes producers more resilient to market fluctuations. Supporting small-scale farmers and encouraging equal access to resources is essential for economic sustainability.

Social sustainability: Spreads the benefits of sustainable agriculture to all communities. Fair wages, community participation and food security are the most important links in social sustainability. For agricultural production to be sustainable, it is important to ensure the continuity of employees in this field and to provide suitable working conditions for effective agricultural production. Different segments of society need to participate in agricultural and food systems. Sustainable agriculture does not only aim to protect nature or the environment but also to guarantee access to safe and nutritious food. As a result, sustainable agriculture aims for a future where not only abundant food but also delicate balances are preserved in the world and production and distribution are carried out in a way that respects living things, with practices that protect the environment, promote economic viability and advance social equality.

The world faces increasing environmental challenges and a growing global population, and the importance of sustainable agriculture is increasing. Sustainable agriculture can be a safe solution for safe food. The importance of sustainable agriculture can be explained as follows.

Food Security: Effectively establishing sustainable agricultural practices will be the most important guarantee of global food security. The global population is expected to reach approximately 10 billion by 2050, and the increasing population will also increase the demand for food. Sustainable agricultural practices are critical to ensuring a consistent and safe food supply. Crop rotation practices, organic farming, supportive plant breeding studies and other sustainable methods can increase product yields. Sustainable agricultural practices form an important basis for the production of safe food in global climate change, the effects of which are becoming more apparent day by day.

Sustainable Environment: The environment is a structure directly related to the provision of food. Today, agricultural practices such as intensive use of pesticides and chemical fertilizers, monoculture farming, incorrect soil processing techniques and excessive irrigation in many areas cause soil degradation, water pollution and loss of biodiversity. Sustainable agricultural techniques are important in eliminating or alleviating these problems. With sustainable agricultural practices, soil health is preserved, the need for intensive chemical inputs is reduced and biodiversity is preserved. Sustainable agriculture is an effective protector of the environment thanks to practices such as agriculture according to the field structure and no-till agriculture.

The Impact of Climate Change: Climate change is becoming an increasingly important global problem, and if the necessary precautions are not taken, its negative effects on reducing the effects of sustainable agriculture will increase day by day. Improving soil structure and preventing heavy soil tillage through sustainable agricultural practices reduce greenhouse gas emissions by locking carbon in the soil. This supports the fight against climate change by locking carbon in the soil and reducing carbon concentration in the atmosphere. In particular, increasing agricultural forestry practices have made significant contributions to the fight against climate change. By integrating trees into farming systems, carbon is locked in woody biomass and soil, which provides strong support for reducing climate change. In a world where climate change threatens agriculture and the lives of societies, sustainable agriculture reduces the negative contribution of the agricultural sector, which makes an undesirable negative contribution to global warming, while also offering a way to adapt to new climate realities.

Efficient Use of Resources: Sustainable agriculture emphasizes the efficient use of resources such as water, energy, and arable land. Efficient irrigation techniques, where water is applied directly to the plant root zone, limit water waste and ensure efficient use of water. Sustainable agriculture generally encourages the use of renewable energy sources in agricultural practices and aims to minimize waste in agricultural practices. These practices not only reduce the negative impact on the environment, but also contribute to economic sustainability for producers and, ultimately, for everyone by reducing input costs.

Ecosystem Protection: There are various ecosystems necessary for life on Earth. Sustainable agriculture aims to work in harmony with ecosystems, taking into account the importance of these ecosystems. Integrated pest management and polyculture practices instead of monoculture reduce the need for intensive chemical applications and ensure the protection of ecosystems. Avoiding intensive pesticide use, avoiding excessive fertilizers and applying soil protection techniques promote biodiversity, protect pollinators and provide a healthy balance in the ecosystem. Sustainable agriculture should not be considered only as a source of income, sustainable agriculture ensures food security, protects the environment, mitigates climate change, promotes resource efficiency and protects the vitally important fragile ecosystem, in other words, it touches every aspect of life.

Sustainable agriculture ranges from improving crop yields to protecting the environment to promoting economic resilience. Sustainable agricultural practices provide many benefits.

Increasing Yield: Various studies have shown that sustainable agricultural practices increase yield. Techniques such as crop rotation, organic farming, soil management and agroforestry create healthy and more productive soil, which in turn leads to higher yields. The effect of sustainable agricultural practices may not be apparent in a short time like some other agricultural practices, but a continuous increase in yield can be achieved over time with the effect that occurs.

Healthy Soil: Soil is the most important resource of agriculture, and for sustainable practices to be successful, soil health must be protected or even improved. Crop rotation and minimum or zero tillage agriculture contribute to the formation of healthier soils. Appropriate crop rotation practices help break pest and disease cycles that cause intensive use of pesticides without implementing practices that harm nature, while organic agriculture supports biologically active and nutrient-rich soil. Minimum or zero tillage agriculture prevents soil erosion, protects soil structure and contributes to the preservation of soil structure by reducing soil compaction that prevents plant root growth.

Economic Resilience: In today's world of volatile markets and unpredictable climate conditions, economic resilience is one of the main advantages of sustainable agriculture. Sustainable agricultural practices save farmers money on chemical applications, which are significant costs for farmers. Polyculture farming also makes farmers more resilient to market fluctuations.

Reducing Environmental Impact: Sustainable agricultural practices have a significant impact on reducing the carbon footprint, which is a major problem in food production. Reducing the use of synthetic pesticides, chemical fertilizers, and other harmful inputs with sustainable agricultural practices minimizes the negative impacts of these practices on the environment. Minimizing the use of pesticides, chemical fertilizers, and other harmful inputs leads to less pollution, lower greenhouse gas emissions, and the preservation of biodiversity.

Increasing the Carbon Storage Capacity of Soils: Today, sustainable agriculture is emerging as a valuable tool in combating the negative effects of climate change. Agricultural practices such as agroforestry and zero tillage contribute to maintaining or even increasing the carbon storage capacity of soils. Since plants and soil act as sinks to capture and store carbon dioxide in the atmosphere, the concentration of carbon in the atmosphere decreases, which means they mitigate the effects of climate change.

Improvement of Water Management: Sustainable agriculture ensures responsible and efficient use of water through efficient irrigation methods. In this way, unnecessary and intensive use of water is prevented, water is saved and helps to protect water, which is very important for the natural balance.

Protection of Biodiversity: Biodiversity is one of the most important support chains of agricultural production. Integrated pest management and agroecological practices reduce the need for chemical applications and ensure the preservation and even development of biodiversity. This also secures pollinators and other vital components of ecosystems, which are important supporters of agricultural production.

Safe Food: In organic agriculture, which is also an important complement to sustainable agriculture, the health and safety of consumers are the most important goals. Organic agriculture, which is carried out without synthetic pesticides and chemical fertilizers, produces healthy foods with less harmful substance residue. This not only promotes healthier ecosystems and farmers but also consumers. Sustainable agriculture offers a path to a sustainable future, from increasing yields to protecting the environment and increasing economic resilience.

Sustainable agriculture encompasses a variety of approaches and practices that vary according to climates and agricultural needs.

Organic farming encourages crop rotation practices, cover crop cultivation and biodiversity conservation by avoiding pesticides and chemical fertilizers that are widely and intensively used in agricultural production and considering natural alternatives to control diseases and pests and to preserve and enrich soil fertility. It provides consumers with the opportunity to purchase healthy food by ensuring that products produced in organic farming meet certain standards.

Permaculture can also be defined as a practice that integrates soil, resources, people and the environment through mutually beneficial synergies. Permaculture, which also means permanent agriculture, actually takes as a model system that operate in a natural cycle. Focusing on the deteriorating human-nature relationship as natural resources are rapidly depleted, permaculture aims to create easy-to-maintain, stable and self-sufficient production areas by bringing plants, animals and people together in nature.

Agroforestry is the use of trees in agricultural lands and the creation of an ecosystem in these areas. In other words, it offers many benefits such as increasing soil fertility, improving water management and protecting biodiversity by integrating trees into agricultural systems. It is the harmonization and combination of human nutritional needs with the needs of nature. In this ecosystem, agricultural products, livestock, trees, and plants are all found in the same agricultural land. These trees and shrubs are an integral component of productive agriculture.

No-Tillage Agriculture is a practice that avoids ploughing the soil and leaves crop residues on the surface to protect the soil from erosion. By preserving organic matter and soil structure, no-till agriculture helps to preserve soil health, minimize damage to the ecosystem and reduce carbon emissions. In traditional tillage systems, no work is done to preserve soil, water and energy. In addition, tillage of the soil takes a long time and requires high amounts of inputs such as labour, fuel and machinery (Derpsch and Moriya, 2007). Soil conservation techniques have been developed to prevent soil losses and preserve soil moisture. In this context, conservation tillage is common in areas where rainfall causes erosion and in areas where soil moisture conservation is important due to low rainfall (Unger and Baumhardt, 2001). Zero tillage is one of the examples of sustainable agricultural practices and technologies and this system has provided better input use. Water conservation in the soil was achieved, the amount of organic matter was increased, erosion was reduced, water pollution was prevented and productivity was increased (Pretty, 2002).

Biodynamic Agriculture in addition to the increasing problems such as the damage to human and environmental health and the deterioration of the ecological balance due to the excessive use of pesticides and chemical fertilizers, the excessive demand of consumers in our age has led people to develop new agricultural systems. For this reason, concepts such as ecological agriculture, organic agriculture, and biodynamic agriculture have become issues that attract attention and are considered very important in the world. Organic agriculture, one of these agricultural practices, is applied in many parts of the world and yields positive results. Biodynamic agriculture is applied with different and stricter rules than organic agriculture. Increasing the energy density in the soil and plant and adding liveliness and dynamism, requires the use of some special preparations, unlike organic agriculture. The most important application difference between organic agriculture and biodynamic agriculture is the special preparations used and the obligation to comply with a certain application schedule (Babita and Thakur, 2015).

Conservation Agriculture is based on interrelated principles such as minimal mechanical soil disturbance, permanent soil cover with living or dead plant material, and crop diversification through crop rotation. It helps farmers maintain and increase yields, and increase profits while reversing land degradation, protecting the environment, and mitigating the increasing challenges of climate change.

Sustainable Agriculture Practices and Methods: Sustainable agriculture is an important agricultural practice that not only increases agricultural productivity but also promotes environmental stewardship and the social well-being of societies by protecting the environment and nature.

Crop Rotation: Agricultural crop cultivation is one of the most sensitive and vulnerable sectors in the context of climate change (Kurukulasuriya and Rosenthal, 2013). Global warming changes the climatic suitability of plant species. Extreme weather conditions, including high temperatures, sudden temperature changes, and heavy rains, cause a loss of crop yield (Stott, 2016). Moreover, it causes drier and hotter soil, harming the growth of beneficial soil microorganisms, thus affecting soil health and increasing the severity of plant diseases, pests, weeds and other problems, which greatly affects crop yield and quality (Zhang et al., 2007).

The sequential cultivation of two or more plant species in the same field at different periods can provide resistance to adverse climatic conditions, extreme weather events, and pest outbreaks (Fitt et al., 2016). Compared to monocropping, spring and winter crop rotations have provided higher yields under high temperatures and insufficient rainfall (Marini et al., 2020). Increasing crop rotation diversity can improve yield stability in maize (Bowles et al., 2020), winter wheat (Degani et al., 2019), and corn and soybean (Gaudin et al., 2015).

Crop rotation means sowing different crops on the same land (Arriaga, 2017). Many researchers have found that crop rotation can effectively improve the climate resilience of crops by improving water dynamics, soil health, and biological conditions in cropping systems. It has been stated that diversified crop rotation can effectively improve soil health, and break the cycle of weeds and pathogens, thereby increasing crop yields and providing high economic benefits (Bowles et al., 2020). Under drought conditions, diversified crop rotation can reduce the effects of increasing droughts and heat waves by ensuring that the yield of corn and other crops can withstand extreme weather conditions. It has been stated that diversified crop rotation can help improve the stability of the cropping system reduce the pressure on the ecosystem during extreme weather conditions and increase resistance to uncontrollable weather conditions and organisms (Li et al., 2019).

Integrated Pest Management: There are many diseases, weeds and pests that damage products at every stage of plant production, which is one of the main factors in agricultural production activities. One of the most important elements of increasing productivity in plant production is combating these harmful organisms. Combating methods vary depending on production conditions, technology and the possibilities of producers. Among these combat approaches, integrated pest management has emerged as one of the most important and preferred combat strategies in efforts to increase productivity. Integrated combat is one of the most effective tools of integrated product management and integrated production in agriculture due to its environmental friendliness, and economic and social responsibility. Integrated crop management is a system that strives to minimize damage to the agricultural ecosystem while growing healthy plants and encourages natural pest control mechanisms.

Cover Crop Sowing: Cover crops increase soil organic matter and improve soil fertility by capturing excess nutrients after the crop is harvested. They also increase the soil's moisture-holding capacity, help prevent soil erosion, limit nutrient runoff, reduce soil compaction, and can even help suppress some pests.

Conservation Tillage: Conventional tillage can leave soil vulnerable to wind and water erosion, high temperatures, and moisture loss. No-till farming can minimize wind and water erosion and protect soil from high temperatures and moisture loss. Additionally, organic matter from previous crops enriches no-till soil. No-till farming can also reduce annual farm fuel and labour costs.

Agroecology: "Agroecology" emphasizes the integration of various crops and animals by mimicking natural ecosystems. By promoting natural processes and biodiversity, agroecology improves crop yields and overall farm resilience while protecting the environment.

Polyculture: Polyculture describes a variety of methods used to grow multiple crops in the same agricultural area (Lutz, 2003). It often, but not always, involves the cultivation of species that benefit each other by growing them in the same area. This mutual benefit or synergy can result from pest removal and changes in the quality or abundance of available water. Polyculture mimics natural ecosystems and promotes biodiversity. It also minimizes crop risk from pests or diseases that target specific plant species. This practice improves soil health, reduces the need for chemical inputs, and increases crop resilience.

Water Efficiency: Water efficiency is one of the most fundamental elements of modern agriculture. Especially with the gradual decrease in water resources, the effective and efficient use of water in agricultural production is gaining importance. Because water is a basic requirement for the growth and development of plants, and if it is not managed correctly, both its productivity decreases and environmental problems arise. Water-efficient irrigation methods such as drip irrigation reduce water waste by applying water directly to the plant root zone. These practices help protect water resources and promote responsible water use.

Nutrient Management: Balanced nutrient management is important for both soil health and environmental protection. Sustainable agriculture can reduce nutrient runoff that can lead to pollution by judiciously using organic and synthetic fertilizers, adjusting the nutrient application needed according to crop needs and timing it correctly. Nutrient management is an important part of sustainable agriculture. Twenty nutrients are considered essential for good crop growth.

3. PLANT BREEDING

The continuing growth of the world's population means that one of the main challenges of the 21st century is to increase crop production. This increase can be achieved in two ways: by increasing the cultivated area or by increasing yield per unit area: However, arable land area is limited and increasing yields means using more inputs, which can potentially have negative environmental impacts. The agriculture of the future requires plant production systems that maintain high production levels without compromising quality, and that provide high efficiency in input use to minimize environmental impact. Agricultural research should be driven as a priority to provide appropriate technology to achieve these goals. Plant breeding is key to the vision of meeting the food production needs of the world's population. Increasing production sustainably on less land requires new genotypes developed through breeding as a priority. Breeders are using technologies and new approaches to accelerate the breeding of climate-smart, resource-friendly, nutritious and high-yielding varieties that are vital to feeding the global population and improving the livelihoods of producer communities. Modern agricultural practices have enabled food production to meet or even exceed the demands of growing populations. However, rapid production growth has often come at the expense of significant soil and water degradation, biodiversity losses, and increased greenhouse gas emissions. Therefore, there is a need to implement agricultural techniques that produce the food needed while protecting the environment. Increasing production per unit area sustainably requires breeding genetically appropriate varieties. Plant breeders are working hard to provide producers with climate-smart, resource-friendly, nutritious, and high-yielding varieties to feed the global population and improve the livelihoods of farming communities.

By 2050, 2.4 billion people will be added to the populations of developing countries. This could further worsen the already fragile agricultural productivity situation. Due to the increasing impact of global climate change, the risk of food security is also increasing. Therefore, plant breeding should have goals that take into account the feeding of growing populations and the increasingly risky environment. Plant breeding is an important sector that has contributed to increasing sustainable crop production in the past and will play an even greater role in the future. It was found that the yield increase of winter wheat varieties introduced in Germany from 1965 to 2013 was between 32 and 42 kg ha^{-1}. The study showed that the annual yield increases due to the improved varieties showed a steady upward trend throughout the entire period and that the varieties produced between 2000 and 2013 did not show any significant signs of decline in the subsequent period. This shows that even after more than 100 years of breeding, the genetic potential of wheat yield has not been exhausted and this is seen in both high-input and low-input agriculture (Voss-Fels et al., 2019). The contribution of breeding for sustainable crop production to crop improvement and crop sustainability is very important for developing countries as well as developed countries. Plant breeding includes different applications.

Pre-breeding: "Pre-breeding refers to all activities performed to identify desirable traits from non-adapted material that cannot be used directly in breeding populations and to transfer these traits to a set of intermediate material that breeders can use. Typically, pre-breeding involves crossing wild or non-adapted germplasm with adapted material, followed by transferring the trait of interest to the adapted parent by one or more backcrosses.

Traditional Breeding: Traditional breeding methods that allow the selection of genotypes with superior characteristics in terms of sustainability from populations created with different techniques are one of the most important breeding methods. Due to the increase in global climate change, there is an increase in high temperatures, drought, diseases and pests. New genotypes to be bred for sustainable agricultural practices should be bred for resistance to abiotic and biotic stress factors. Conducting plant breeding studies using local genotypes and wild species that are superior in terms of resistance to abiotic and biotic stresses as a source of variation will provide significant contributions.

New Breeding Techniques: With new breeding techniques, the breeding period is shortened and plants with the desired characteristics can be selected effectively. There are problems in hybridization between distantly related species with traditional breeding methods and useful hybridizations between somatic cells have been successfully obtained and new genotypes have been obtained. In the hybridization of species/breeds that do not reproduce sexually, interspecific and intergeneric hybrids have been produced using new breeding methods. Such hybrid combinations need to be increased for sustainable agriculture. For example, triticale obtained by wheat-rye hybridization and tritordeum obtained by wheat-barley hybridization are important successes. In triticale, which is a hybrid between wheat and rye, F_1 offspring were sterile due to unequal chromosome numbers, but cytokinesis was prevented by doubling the chromosomes (by colchicines) during cell division and fertile plants were obtained.

To obtain superior genotypes to be improved for sustainable agriculture; effective use of genetic markers, namely MAS selection, to accelerate and increase the efficiency of genetic processes, utilization of genomic data to predict and select desired traits, to improve sustainable crop varieties in a short time, i.e. to shorten the breeding period, and to ensure the level of interest and adoption of the subject by including farmers and communities in the breeding process is important. In recent years, a powerful set of techniques recently developed to modify the genome, known as genome editing or gene editing, CRISPR (or CRISPR-Cas), is the most widely used method for editing genomes due to its ease of use and relatively low cost. Unlike genetic engineering, genome editing targets specific locations in the genome and most cases does not result in foreign DNA in the final product. The majority of current applications of genome editing result in rendering a gene dysfunctional. However, it is also possible to adjust the DNA sequence of a gene to a more favourable form or to insert a gene. Although genome editing is easier than other methods, it requires detailed sequence information for the targeted gene. Some of the areas where genome editing is promising concerning climate change include drought tolerance (Shi et al., 2017), salinity tolerance (Zhang et al., 2019), disease resistance (Kumar et al., 2018), yield improvement under stress (Wang et al., 2018), improved nutrition (Kaur et al., 2020).

Plant breeding has been very successful in producing varieties in favourable environments that increase agricultural production several times over, along with excessive use of fertilizers and chemicals for the control of weeds, pests and diseases. The current high-input agricultural system has more negative environmental effects and causes increasing concerns about products. The contribution of plant breeding methods to sustainable agriculture are;

a) *Development of Climate-Appropriate Plants:* While agriculture and food production contribute up to 29% of total greenhouse gas emissions and land expansion is generally only possible in areas where biodiversity is dense, it is obvious that increasing the planted areas to meet the needs is not very possible. Therefore, new approaches are needed for the food needs of the increasing population. Varieties that can better adapt to changing climatic conditions to be developed through climate-appropriate plant breeding can help farmers increase their sustainability, reduce the stress factors imposed on plants by their environment, and contribute to and better food supply. For example, the International Wheat and Maize Improvement Center (CIMMYT) has developed varieties, including the Borlaug 100 wheat variety, which is not only drought and heat-resistant but also rich in the micronutrient zinc. This variety can help Nepal’s growing population meet the challenge of feeding in the face of increasing climate variability, while also addressing a specific nutrient deficiency problem. In Kenya, the International Potato Center has developed a potato variety called Unica, which is virus-resistant and can produce good yields in adverse climate conditions. Unica has been bred for flood-prone and heat-stressed agricultural areas, such as Meru in Kenya. By growing the Unica potato variety in areas such as Meru District, farming and consumer communities are less affected by the damaging effects of climate change on food security.

b) *Utilization of Genetic Diversity:* The “green revolution” and industrial agriculture have led to a decline in the total genetic diversity cultivated in farmers’ fields globally, even though many farmers have switched from traditional varieties or landraces to more uniform and productive modern varieties, and despite the obvious global production benefits of the switch. After all, disease susceptibility is a property of genetic diversity.

When genetic variation from breeding program resources becomes limited, it is necessary to contribute to the plant genetic resource pool from a wider variety. Targeted and strategic evaluation of landraces and wild-related germplasms provides the opportunity to ensure that suitable genetic diversity is not depleted in breeding to develop future varieties driven by demand. Plant breeding studies to be conducted based on the following objectives will contribute to sustainable agricultural production.

- Enrichment of source material with landraces by appropriate breeding methods for increased yields.
- Screening of varieties, breeding techniques and genotypic profiles.
- Selection in segregation generations should be based on individual plant evaluation and performance that can reduce genotype x environment (G x E) interactions.

c) *Availability of Plant Genetic Resources:* To be successful in plant breeding studies that contribute to sustainable agriculture, competence is required in some areas. Plant genetic resources continue to be a fundamental component of global food security. Plants are the most important source of human nutrition, used directly for human food and indirectly in processed products and as animal feed. Since ancient times, plants have changed different methods such as different selection and hybridization. Plant genetic resources have gone through various evolutionary processes such as protection, diversification, adaptation, improvement and then seed production systems. Plant genetic resources are unique materials in the development of plants resistant to abiotic and biotic stress factors in sustainable agriculture with their wide variation. Although many countries have a large genetic resource pool, genetic resources are not used effectively and sufficiently in the breeding of new genotypes.

Agricultural biodiversity is the backbone of food security worldwide. The existing biodiversity provides valuable functions for plant breeding and agricultural production. The protection and development of agricultural biodiversity and the effective use of their valuable traits are valuable for sustainable agriculture or food security. Today, there is a serious threat of loss of agricultural biodiversity due to intensive agricultural practices. To protect and even improve the existing biodiversity, the conservation of genetic resources, the development of an agro-ecosystem approach to pests and disease and soil management are very important for sustainable agriculture. Various genetic resources provide plant breeders with an abundant pool of useful traits for plant breeding to resist diseases, pests and environmental stresses (e.g. heat, drought, cold). Today, many countries have rich biodiversity in cereals, fruits, vegetables, industrial crops and forage crops. However, this rich biodiversity, which is very important for sustainable agriculture, is not used in plant breeding at a sufficient level, and even decreases in biodiversity occur for various reasons.

Only a very small portion of the total genetic diversity in the world's plant species is used as commercial varieties. The use of plant diversity can be used to achieve breeding goals in major crops, to obtain new products, to provide reliable food for the world's population, and to ensure the sustainability of crop production. Different breeding methods have the potential to quantitatively assess diversity, characterize desired genes, select desired recombinations by observing chromosomes, genes, or gene combinations through breeding programs, and generate new germplasm using different sources.

Agricultural sustainability depends on improving the environmental interaction with genotype through biological approaches, ecological, and agronomic management, manipulation and understanding of product redesign. Today, abiotic stress factors such as drought, high - low temperature and salinity cause widespread yield reductions in plants produced in large areas. It is very important to improve plants tolerant to abiotic stresses for meeting the food needs of the increasing world population and for sustainable agriculture. Drought is increasing due to high temperatures resulting from increasing global climate change. Breeding for drought, heat and salinity tolerance is a difficult and complex trait. If local or wild genetic resources rich in these traits are developed and used with different breeding methods, they should be used. Abiotic stress is predicted to increase in many crop growing regions around the world. Heat and drought stress are the most common abiotic stress factors, while flooding, salinity, and unseasonal temperature changes are also common abiotic stress factors.

Plant breeders are trying to increase stress tolerance by evaluating various germplasms in various ways. They determine their response to stress conditions by growing plants in multiple locations such as greenhouses or growth chambers where stress is likely to occur. Wild relatives of plants and landraces have often been evaluated as potential sources of stress tolerance. Plant breeders are sometimes hesitant to include unadapted germplasms in elite breeding populations due to some difficulties. Many traits have been investigated for their potential to identify germplasms resistant to abiotic stresses. Researchers are actively working on slow wilting and root architecture traits for drought tolerance from abiotic stresses.

Slow wilting is a phenotype observed in soybean (Glycine max) and other plants; mean wilting under drought stress may vary by cultivar. In soybean, the trait was first reported in a Japanese landrace, PI 416937; this landrace and a landrace from Nepal (PI 471938) have been used to develop drought-tolerant soybean cultivars (Kunert and Vorster, 2020). Although the mechanisms are not fully defined, slow wilting is thought to be largely due to reduced transpiration early in the growing season, which conserves moisture in the soil profile later in the season.

Although root architectural traits are difficult to assess, root systems are receiving increasing attention to enhance crop adaptation to abiotic stresses exacerbated by climate change (Lynch, 2022; Ober et al., 2021). Deep root systems may be valuable for accessing moisture stored deep in the profile during a dry year, but shallower roots may better utilize intermittent rainfall throughout the growing season (Ober et al., 2021). Despite the variability and uncertainty, breeders are beginning to make progress by focusing on the stress conditions prevailing in a particular target environment.

Wild relatives, often required to survive stressful environments, have provided genetic variation in root traits, resulting in improved crop performance (Leigh et al., 2022). For example, it has been reported that transferring a chromosome segment from wild emmer wheat (*Triticum durum* subsp. *dicoccoides*) to a durum wheat (*T. durum*) variety resulted in deeper roots and better yield under drought stress (Mercuk-Ovnat et al., 2016). A chromosome translocation from another wheat relative, *Agropyron elongatum*, to bread wheat also resulted in deeper rooting under drought conditions (Placido et al., 2020).

Numerous studies have been conducted by different researchers in terms of biotic stress resistance, especially resistance to diseases and pests. In recent years, it has been estimated that temperature increases due to global climate change will significantly increase crop yield losses by causing an increase in diseases and pests and the emergence of new disease strains (Irish and Volk, 2023). For example, in maize (*Zea mays*), an average increase of 31% in production losses due to insects has been predicted if global temperature increases by 2 °C (Deutsch et al., 2018). The fall armyworm, *Spodoptera frugiperda* (J.E. Smith), is native to the Americas, but its range has expanded since 2016, invading maize fields in 47 African and 23 Asian countries (Singh et al., 2021). Rising temperatures may accelerate the development of fall armyworm eggs, pupae and larvae, which could herald even greater damage in the future (Huang et al., 2021; Diaz-Alvarez et al., 2021). Tolerance to fall armyworm has been identified in several maize landraces and other germplasms, including their wild relatives (Singh et al., 2021). The International Maize and Wheat Improvement Center (CIMMYT) recently developed three fall armyworm-tolerant hybrid maize genotypes for eastern and southern Africa (Singh et al., 2021).

Puccinia graminis f. sp. *tritici* is among the most effective diseases of wheat, and outbreaks of the disease are predicted to become more frequent as a result of climate change (Prank et al., 2019). The emergence and spread of virulent strains of the pathogen have led researchers to find permanent sources of resistance. Recently, an effective black rust resistance gene has been cloned from *Aegilops sharonensis*, a diploid relative of wheat. The gene was introduced into a susceptible wheat variety through genetic engineering, and lines resistant to all known strains of the pathogen have been obtained.

4. CONCLUSION

Sustainable agriculture, which means agriculture carried out without harming nature to meet the nutritional needs of future generations, is important for reliable food production and access to safe food due to the increasing global climate change. Since changes in temperature and precipitation, prevalence of pathogens, insects and weeds, soil structure and nutritional changes interact with other factors, plant breeding becomes more difficult to keep up with climate changes. Breeders are forced to determine more than one breeding target and develop product resistance against the combination of many abiotic and biotic stresses occurring simultaneously. Today, the main goal of plant breeding is to shorten breeding periods with both traditional and modern breeding techniques for sustainable agricultural production and safe food and to develop new genotypes that are minimally affected by changing environmental conditions and maintain yield and quality.

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CHAPTER 10

FLAME APPLICATIONS IN WEED CONTROL IN AGRICULTURAL PRODUCTION

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INTRODUCTION

In agricultural activities, pest control is essential, and in managing agricultural pests, chemical control—namely pesticides—is often preferred due to its ease of application, rapid effectiveness, and typically lower cost compared to other methods.

Due to the rising cost of labor worldwide, herbicides have become the most widely used group of agricultural pesticides. However, as society becomes more aware of the negative impacts of pesticides on both the environment and human health, there has been an accelerated search for methods that are more environmentally friendly and pose minimal harm to human health, instead of relying on toxic chemicals. Various alternative methods have been developed for weed control, one of the most critical issues in plant production. In this context, flame weeding has emerged as a noteworthy method.

The history of flame application dates back quite far. However, commercial products for weed control using flame application are produced in only a few countries and have not been widely adopted as a common practice worldwide. In our country, especially in organic farming enterprises in the Aegean region, where the use of chemical pesticides is highly restricted, it is known that weeds in vineyards and orchards are neutralized using flame heads, known in the industry as "torches" or "blowtorches".

It has been observed that flame weeding is not practiced in field agriculture in our country, and there are no suitable commercial flame machines available. If the technical and economic feasibility of this method can be improved on both regional and national scales, the use of chemical pesticides can be reduced under certain conditions, and the share of the organic agriculture market can potentially be increased. From this perspective, developing alternative methods to chemical pesticides is both a necessity and a priority; moreover, it can be considered a crucial issue.

Until today, flame application has been tried and, to some extent, applied more frequently in vineyard and orchard agriculture compared to field agriculture. Commercial products developed for flame application are also available in some countries.

Figure 1. Tractor-trailed Flamethrower (Red Dragon, 2019)

Flame weeding is a method based on applying heat to the growth points of weeds, particularly those newly emerging on the soil surface. The primary principle here differs from burning, relying instead on a short-duration, high-temperature application that causes the cell sap in the weeds to expand, rupturing the cell walls and subsequently leading the plant to wilt and die. For this purpose, gases such as propane and similar flammable substances are commonly used.

When the temperature within plant tissue cells rises above 50 °C, cell proteins coagulate. If the exposure to heat causes the plant tissue to reach over 100 °C in as short a time as 0.1 seconds, the cell sap boils, bursting the cell membrane. Consequently, the weed cannot absorb nutrients, loses water, and dries out, ultimately dying.

There are specially developed tools for this purpose, which can be handheld or backpack-mounted, as well as tractor-integrated models suitable for large-scale applications. In fact, contrary to common belief, flame weeding is not a very recent method. The first flame weeding machine for agricultural use was patented in 1852 and was widely used until the discovery of herbicides. However, with the advent of herbicides in the 1940s, its importance and popularity declined. Today, with the emergence of the side effects of pesticides, flame weeding stands as a viable and increasingly favored alternative to herbicides. The production of flame weeding machines is prominent in countries such as Sweden, Denmark, the Netherlands, and the United States.

Figure 2. Flaming Application in Field Agriculture

Flame weeding is used in both agricultural and non-agricultural areas. In non-agricultural settings, it is primarily used to control weeds along roadsides, in parks and recreation areas, around courts, tracks, sidewalks, buildings, and similar structures.

In agricultural areas, flame weeding is applied in three stages: pre-sowing, pre-emergence, and post-emergence. In pre-sowing applications, weeds that emerge early in the prepared seedbed are eliminated before the crop seeds are sown. Sometimes, irrigation is even done to encourage weed emergence. In this way, weeds that would germinate just before or simultaneously with the crop seeds and cause early competition—crucial during the critical period—are eradicated.

In pre-emergence applications, weeds that have emerged before the crop seedlings reach the soil surface are controlled. This eliminates young and sensitive weeds at the seedling stage, preventing them from harming the newly emerging crop seedlings. This method is particularly effective in crops like carrots and similar crops that are grown from seeds and germinate slowly.

Studies conducted in Europe have shown that weeds in carrot fields can be reduced by up to 80% using flame weeding alone.

In post-emergence applications, weeds are controlled after the crop plants have emerged. Post-emergence flame weeding can be applied in two ways: cross-flame weeding and parallel flame weeding. In cross-flame weeding, flame torches are positioned at a specific angle on both sides of the crop row. This type of application is suitable for crop species that are tolerant to high temperatures due to their structural characteristics or when the plant stem is strong enough to withstand the heat.

The flame torch should be adjusted to target the crop's root collar area, and the torches on either side of the row should not be positioned facing each other. Otherwise, turbulence may form, and the rising heat could damage the crop plant. The flame from the torch should never come into direct contact with the crop.

Cross-flame weeding is effectively applied to monocot crops like corn, where the growth point is protected by a sheath, or to crop plants such as grapevines and fruit saplings that are slightly elevated from the ground and resistant to high temperatures. Parallel flame weeding, on the other hand, is a method primarily applied to crops that are sensitive to high temperatures or in the early stages of growth. In this method, the flame torches are positioned parallel to the crop row, effectively controlling weeds between the rows.

Both cross-flame and parallel flame weeding equipment can be integrated with row-crop tillage implements. Although there are crop plants in the area, this selective method can control weeds both between and within rows, making it an extremely valuable alternative to herbicides, especially for organic farmers. Flame weeding also reduces the frequency of tillage. As a result, crop roots are not damaged, and weed seeds brought to the surface by tillage do not pose a problem.

Weeds that have recently emerged, with a height of 3-5 cm or in the 2-4 leaf stage, are more susceptible to flame weeding. Broadleaf weeds are also more susceptible to flame weeding compared to narrow-leaf weeds. This is because the growth points of narrow-leaf weeds are well-protected, and in the early stages, many of their growth points are below ground. For this reason, a second application may be necessary to achieve successful results against these types of weeds, waiting until the growth points are exposed. Some weed species, particularly perennials, are resistant to flame weeding.

The responses of weeds to flame weeding also vary depending on their growth stages. For successful results in flame weeding, critical parameters include the weed's growth stage, application speed, and the pressure of the applied gas, or in other words, the temperature applied. The disadvantage of this method is that it can be somewhat more expensive than chemical control, and the high temperature near the soil surface may break seed dormancy (germination inhibition) in weed seeds.

Flame resistant weeds

Elymus repens	Echinochloa crus-galli	Poa annua
Seterla viridis	Circium arvense	Convolvulus arvensis
Rumex acetosalli	Urtica diocia	Stellaria media
Rorippa slyverstris(l.) besser		

plants such as.

Weeds that flameding provides successful results according to the development periods

Polygonum convolvulus	Matricaria inodora	Chenopodium albüm
Polygonum aviculare	Chrysanthmum coronarium	Stellaria media
Sinapis arvensis	Polygonum lapathifolium	Galium tricorne
Brassica napus	Spartium junceum	Urtica urens
Viola tricolor	Caspella bursa-pastoris	Fumaria officinalis
Lamium amplexicaule	Solanum nigrum	Geranium L.
Amaranthus retroflexus	Senecio vulgaris	Artemisia absintii

plants such as.

FLAME TECHNIQUES IN WEED CONTROL

The optimal time for flame application is when weeds are approximately 5 cm in length. As weeds grow taller, they advance to the next developmental stage, becoming more resistant to external factors, including thermal stress. Therefore, multiple applications may be necessary. Some researchers recommend performing flame weeding multiple times within a single growing season (Diver, 2002).

Figure 3. Flame application examples

Pre-Emergence Flame Technique

This application technique is primarily used in vegetable farming, where flame weeding is performed before the planted crop seeds germinate and emerge from the soil. Sometimes, flame application is also used on the seedbed before sowing to eliminate weeds, after which the crop is planted into a clean seedbed (Desvaux and Ott, 1986). Continuous monitoring of the development stages of both the crop and the weeds is necessary to determine the optimal timing for the application. Based on these observations, the most suitable time should be identified.

Post-Emergence Flame Technique

Post-emergence flame application is a controlled and selective burning technique applied after the crop has emerged and reached a stage where it can withstand exposure to flame. The application is conducted a certain period after emergence (Ulloa et al., 2011; Wszelaki et al., 2007). Flame weeding, whether pre-emergence or post-emergence, can be applied across the entire field surface, or specifically between crop rows or directly on rows for row crops. Flame application between rows is also referred to as band flaming. For this, the machine must be equipped with suitable attachments.

Cross Flame Technique

In this technique, flame-spraying nozzles are positioned to face the row in an offset arrangement, ensuring that no part of the row remains untouched by the flame. By angling the flame nozzles, the opposing flames create turbulence, preventing the heat waves from rising and damaging the main plant when they hit the ground. Thus, the cross-flame weeding technique is a row-directed flame application targeting the plant's root zone (Diver, 2002).

Figure 4. Flame Weed Control in Vineyard

Parallel Flame Technique

In contrast to the cross-flame technique, the flame nozzles are positioned parallel to the row. Parallel flame application was developed in the late 1950s as an alternative to cross-flame weeding. The potential for burn damage to plants and significant yield reductions with the existing cross-flame method accelerated research in parallel flame application (Trupper and Mathews, 1954). Another advantage of parallel flame application is the ability to use nozzles to improve propane efficiency and protect the crop from intense heat (Ascard, 1995; Bruening, 2009).

STUDIES ON FLAME CONTROL

Ascard and Mattsson (1989) successfully applied flame weeding on onion plants. They found that flame weeding was more expensive than chemical spraying. However, a key advantage of flame weeding was the potential for producing less contaminated agricultural products.

(Nemming, 1994) tested flame applications in the organic production of sugar beets and onions. He developed an economic model based on the relationship between flame application costs and the treated area, using field trials and the model to compare the costs of two different flame configurations. He concluded that flame weeding was more economical than manual mechanical hoeing in areas of 1-5 hectares. According to his findings, an area of 6-20 hectares was sufficient to reduce the per-hectare cost of flame weeding below 1000 Danish Kroner.

(Ascard, 1995) researched the response of plants and weeds to flame application, focusing on the effects of propane dosage and progression speed. By applying 10-20 kg ha-1 of propane to annual weed species in the 0-4 leaf stage, 95% control was achieved, and with a dosage of 20-50 kg ha-1, 100% of the weeds were eliminated. However, at later weed development stages, an increased propane dosage was required. Heat-tolerant weeds could not be fully controlled with a single application, regardless of dosage. Various types of flame machines were also tested, with enclosed flame applications found to be more effective on heat-tolerant weed species than open flame applications. Progression speed varied depending on the propane consumption of the flame machine; for example, a machine using 34 kg h-1 of propane had an effective progression speed of 8 km h-1 on small weeds, while a machine using 12 kg h-1 of propane had a speed of 2,6 km h-1.

In 1995, Ascard provided additional evaluations regarding the cost of flame machines. The total cost of flame applications was generally higher than chemical weed control, primarily due to the high cost of flame machines and their limited field capacity. Progression speed is a significant factor in weed control, impacting the total cost. In flame applications, the cost of propane is comparable to, though not higher than, chemical costs, with propane being a significant component of the total cost. During the 1940s to the 1960s, flame weeding was applied to crops such as corn, cotton, soybeans, potatoes, beans, grapes, and strawberries. The most extensive research focused on using flame weeding to eliminate small weeds within rows in heat-tolerant cotton.

In another study, (Ascard, 1995) examined the effect of flame angle at 10 cm above ground level on weed control and temperature distribution. He tested forward and backward angles at 45°, 67°, and 90°. The greatest reduction in weed quantity was observed at a backward flame angle of 67°, although it was noted that differences between flame angles were not significant. Certain weed species protected from flame heat due to their position exhibited heat tolerance, whereas weeds directly exposed or with sensitive growth organs unshielded had lower heat tolerance. The temperature generated by flame application was tested in laboratory conditions at field-tested angles 1 cm above the soil surface using a rail system. Temperature-time curves were obtained, maximum temperatures were recorded, and the duration of temperature effectiveness on the plant was determined.

Significant differences in temperatures were found among the various flame angles, yet no notable relationship was observed between the weed control levels achieved in the laboratory and field conditions. It became evident that evaluations of thermal weed control cannot rely solely on temperature, suggesting that research methodologies need further refinement. An important finding was that the flame angle found optimal in laboratory conditions was not optimal in the field, indicating that experiments in field conditions should identify the best flame angle, or that laboratory setups should better replicate field conditions.

(Rıfai et al., 1996) compared flame application to mechanical hoeing—a weed control method—in terms of effectiveness, labor savings, and efficiency in organic onion and carrot production. According to the researchers, weed control should be conducted early to avoid the competition period. When flame application was performed pre-emergence, weed numbers were controlled by 64-92%. The study concluded that flame weeding provided significant labor savings in organic farming; however, two rounds of flame application resulted in greater yield loss. In carrot production, manual mechanical weeding alone required twice the labor compared to one pre-emergence flame application combined with two rounds of manual mechanical hoeing. It was found that pre-emergence flame application in vegetable production significantly influenced subsequent weed control efforts and overall costs.

Furthermore, the study concluded that timing is crucial; a single, early flame application led to a reduction in yield.

(Seifert and Snipes, 1998) investigated the effects of flame application on cotton plants using liquid LPG gas at pressures of 100-175 kPa. They conducted flame applications during two different growth stages, at plant heights of 20-25 cm and 40-45 cm, and tested two methods: with and without a water shield. Over three years, minimal plant damage was observed in one year, but there was no change in total seed count or fiber quality. In 1994, without the water shield and at 175 kPa pressure, significant plant damage was observed regardless of growth stage. However, in the subsequent two years, no plant damage was reported. The water shield on the flame machine helped reduce plant damage. Flame application, whether or not the water shield was used, did not negatively affect growth or reproduction in the plants.

(Kang, 2001) tested temperature distribution across different flame machines, developed a flame machine, and examined its effects on weed control. He identified pressure, progression speed, and the corresponding application dose (kg ha-1) as key parameters. A gas dose of 40 kg ha-1 controlled 80% of weeds, while 60 kg ha-1 achieved 90% control. In trials conducted in the second year, a single dose (57.4 kg ha-1) combined with a tractor speed of 1 km h-1 provided 99% weed control with repeated applications.

(Lague et al., 2001) developed an experimental setup to study weed and plant disease control. Their system included a computer-controlled unit with a mobile carrier, an LPG tank, a gas emission monitor, and various flame units. Experiments conducted with three different flamers at pressures of 135–485 kPa gathered data on flame temperature, LPG consumption of each flamer, and the necessary thermal energy.

Studies have been conducted using flame machines in organic orchards and vineyards to eliminate weeds without herbicides. Considering environmental factors, it was noted that this method could provide substantial economic benefits to conventional agriculture (Bittner and Merwin, 2003).

(Ebell and Cuthbert, 2006) reported that flame machines and equipment are manufactured in Sweden, Germany, the Netherlands, Denmark, and the United States. They noted that various approaches exist for flame application in weed control, but open flame application was found to be the least effective. However, since flame weeding delivers the highest heat energy among thermal methods, it significantly increases the speed of weed control efforts.

Various weed control methods for railways—such as enclosed flame weeding, herbicides, radiation, wet infrared, high-temperature steam, and string mowing—have had their costs reported in Canadian dollars. These researchers determined that flame application and steam application were the thermal methods most suitable for agriculture. Comparing the costs of these thermal methods with herbicide use for a single application, they found that flame application costs $17,500, steam application $10,360, and herbicide application $45,000. The equipment costs were reported as $35,000 for a flame machine and $1.2 million for a hot steam unit. Herbicide use involved a service contract for the railways, so equipment costs were not reported.

(Sivesind et al., 2009) created dose-response curves for weeds encountered in horticulture in a specific region of Canada, concluding that flame application was more effective on broadleaf weeds than on grasses. Even at high LPG doses, at least half of the grasses could not be controlled. Redroot pigweed (Xanthium strumarium) was controlled at 95% with 1.19-2,72 kg km-1 LPG up to the 4-leaf stage, and common sorrel (Rumex crispus L.) was controlled at 95% with 0.83-2,85 kg km-1 propane up to the 6-leaf stage. Onions and broccoli tolerated a single flame application, but applying flame weeding up to 20 days post-transplant reduced yield.

In spinach and tuber crops, flame applications at the 4-6 leaf stage resulted in yield losses, while pre-emergence applications showed no yield loss. These findings suggest that flame weeding should be performed during the early growth stages of weeds. Similar to pre-emergence herbicide application, pre-emergence flame weeding proved to be more effective and did not cause yield loss, indicating its potential as a labor-efficient alternative in weed control.

(Knezevic et al., 2014) reported that commercial flame machines for weed control range in cost from $6,000 to $15,000, depending on size and technical features. They noted that these machines are unsuitable for small research plots and advocated for the development of machines specifically for research purposes.

In our country, no commercially manufactured flame machines are available. In flame machines made for research, however, commercial gas nozzles do not provide sufficient flame spread in weed control flame heads, limiting working width. This study designed and custommanufactured various types of gas nozzles for weed control. Using a plunge erosion method, five conical and three slotted-fan gas nozzles were designed, totaling eight types. Among these, three types of round-nozzle tips were found to be usable. Tips 3 and 5 were less suitable for tractor-based work than Tip 1, as they did not maintain work efficiency. Tips 3 and 5 or similar types could be adapted for low-speed, hand-pulled, or backpack flame machines (Turaloğlu, 2019).

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CHAPTER 11

WASTE MANAGEMENT IN AGRICULTURE WITH A ZERO-WASTE GOAL AND A CIRCULAR ECONOMY APPROACH

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1. Introduction

The agricultural sector is one of the most fundamental areas of activity, meeting human needs and contributing to economic development. Agriculture, which is of strategic importance for food security, rural income generation, and economic growth, also presents challenges for environmental sustainability due to its intensive use of natural resources (Tilman et al., 2002). Agricultural lands occupy 37% of the earth's land surface, representing a substantial portion of global ecosystems. Furthermore, agriculture accounts for 52% and 84% of anthropogenic methane and nitrous oxide emissions, respectively, which are significant drivers of climate change. Agricultural soils may act as either a sink or a source for CO2, though the net flux is relatively small (Smith et al., 2008). These environmental challenges emphasize the urgency for sustainable solutions in agriculture.

According to FAO (2021), the agricultural sector significantly contributes to greenhouse gas emissions, excessive consumption of soil and water resources, loss of biodiversity, and various forms of waste generation worldwide (FAO, 2018). Agricultural waste from plant and animal sources, if managed traditionally, can impose a serious environmental burden. Therefore, new strategies are needed to ensure environmental sustainability and minimize the sector’s impact on nature (Godfray and Garnett, 2014). As shown in Figure 1, agricultural waste can be transformed into valuable resources such as organic fertilizers and renewable energy. For example, crop waste (e.g., straw and husks) is collected for composting, while animal waste (e.g., manure) undergoes anaerobic digestion. Through these processes, agricultural waste is repurposed, reducing environmental impacts and creating economic value. Composting converts plant waste into organic fertilizer, enhancing soil fertility, while anaerobic digestion produces biogas as a renewable energy source and digestate as a nutrient-rich soil conditioner. These outputs are applied to soil, boosting crop growth, which supports livestock feed production and completes the agricultural cycle. This cycle, as visualized in Figure 1, highlights the potential of sustainable agricultural waste management to reduce environmental burdens and improve resource efficiency.

One such strategy is the zero-waste approach, which seeks to repurpose agricultural waste and incorporate it into recycling processes in line with circular economy principles to minimize environmental harm (Ghisellini et al., 2016). The zero-waste approach aims to protect natural resources by minimizing waste production. Instead of discarding products as waste at the end of their lifecycle, this approach envisions repurposing or using them as raw materials in other processes at every stage of the lifecycle (Lazdani and Lakzian, 2023). This not only reduces the environmental burden from agricultural activities but also supports economic sustainability by enabling more efficient use of natural resources (MacArthur, 2013; Kirchherr et al., 2017).

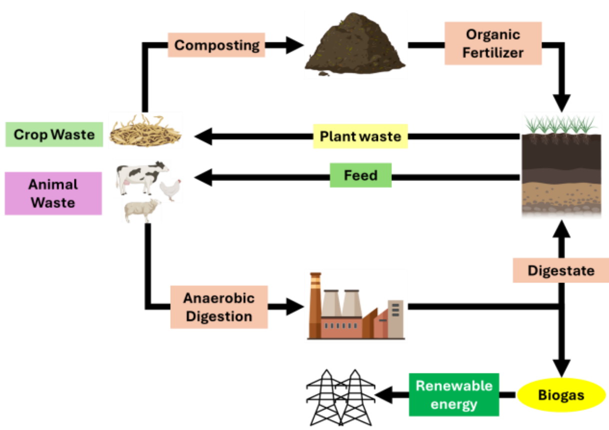

Figure 1. This figure illustrates the circular process of transforming agricultural waste into valuable resources, contributing to environmental and economic sustainability. Crop waste (e.g., straw and husks) is collected for composting, while animal waste (e.g., manure) undergoes anaerobic digestion. Through composting, crop waste is converted into organic fertilizer, which enhances soil fertility. Anaerobic digestion of animal waste produces biogas, a renewable energy source, and digestate, a nutrient-rich byproduct used as a soil conditioner. These outputs are applied to soil, boosting crop growth, which supports livestock feed production, completing the cycle. This process demonstrates sustainable agricultural waste management, reducing environmental impact and promoting resource efficiency.

The circular economy complements the zero-waste approach by replacing the linear model of production with a system that reuses agricultural waste as resources for new processes (Geissdoerfer et al., 2017). In this model, agricultural plant and animal waste can be repurposed as bioenergy, organic fertilizers, compost, or biomaterials. For example, the production of biogas from animal waste or turning plant waste into compost for organic fertilizers are examples of circular economy processes that allow agricultural waste to be repurposed without harming the environment (Hass et al., 2015) This minimizes the potential damage to soil, water, and the atmosphere from waste while creating value-added products.

When taken together, the circular economy and zero-waste approaches clearly offer a more sustainable and resource-friendly model for the agricultural sector. This model does not aim to eliminate agricultural waste entirely but instead focuses on transforming and reusing it as much as possible (Smol et al., 2015). Agricultural plant waste includes components such as straw, husks, and shells, while animal waste comprises manure, excrement, and various organic residues. Repurposing these wastes in agricultural production significantly contributes to a sustainable circular economy. For instance, through composting, agricultural plant waste can be recycled as natural fertilizer, which, in turn, enhances soil fertility and supports healthier agricultural production. Similarly, using animal waste for biogas production reduces dependency on external energy sources and offers farmers additional income opportunities (Paolini et al., 2018; Velasco-Muñoz et al., 2021).

The widespread application of zero-waste and circular economy approaches in agriculture not only contributes to environmental sustainability but also increases economic efficiency within the sector. Along with benefits such as preserving natural resources, saving energy, and reducing environmental pollution, the circular economy also enables agricultural waste to be reprocessed, generating economic value. Thus, promoting the zero-waste approach and circular economy practices in agriculture creates a more efficient, economically sustainable, and environmentally conscious agricultural sector (Kibler et al., 2018; MacArthur et al., 2015).

In this regard, to ensure the wide applicability of zero-waste and circular economy approaches in agriculture, policymakers, local authorities, civil society organizations, and agricultural enterprises must work collaboratively. Especially in developing countries, incentives, educational programs, and infrastructure investments are critical to enhancing the applicability of such sustainable waste management strategies. Taking concrete steps to implement circular economy and zero-waste practices in agriculture offers an important opportunity not only to protect the environment but also to support rural development and generate economic benefits.

2. Agricultural Waste and Circular Economy Solutions

2.1. Types of agricultural waste and their environmental impacts

Waste generated in agriculture can generally be classified into plant-based, animal-based, and chemical waste, each with distinct characteristics and environmental impacts. Plant-based waste, such as straw, stubble, harvest residues, husks, and pulp, is often left on fields after harvest or burned, contributing to air pollution and soil nutrient depletion (Srinivasan and Abirami, 2020; Phiri et al., 2023). With proper management, however, these materials can be repurposed into valuable resources like compost or bioenergy. Animal-based waste, including manure, excrement, and carcass remains, is rich in organic matter but poses significant environmental risks if improperly handled, such as methane emissions and water pollution from nutrient runoff. Composting and anaerobic digestion can mitigate these risks by producing renewable energy and nutrient-rich soil amendments. Chemical waste, which arises from excessive pesticide, herbicide, and fertilizer use, often persists in ecosystems, contaminating water and reducing soil fertility (Weldeslassie et al., 2018; Hossain et al., 2022). Strategies like precision agriculture and integrated pest management can help minimize these impacts.

By aligning with circular economy principles, agricultural waste can be repurposed to reduce environmental harm while conserving natural resources and creating value-added products, contributing to more sustainable agricultural practices (Kumar and Sharma 2014; Bernstad and la Cour Jansen 2012).

2.2. Circular economy solutions: converting waste into resources

The circular economy aims to create a regenerative system where waste is transformed into valuable resources, reducing environmental impact and maximizing resource efficiency. In agriculture, this approach addresses pressing challenges such as waste management, greenhouse gas emissions, and resource depletion, while also offering economic benefits. As illustrated in Figure 1, integrating processes like composting and biogas production into the agricultural cycle demonstrates how waste can be effectively repurposed into renewable energy and organic fertilizers.

One of the most widely adopted solutions in agriculture is composting, which transforms plant and animal waste into organic fertilizer. Composting not only increases the organic matter content of the soil but also reduces dependency on chemical fertilizers, improving soil health and productivity (Singh et al., 2020; Bellitürk et al., 2022; Rastogi et al., 2023). This process involves the controlled decomposition of agricultural biological waste, allowing it to reintegrate into the agricultural cycle (Manea et al., 2024). For example, composting initiatives in small farming communities have shown significant success in improving soil fertility while minimizing waste disposal issues (De Corato, 2020). Moreover, studies have demonstrated that vermicompost applications, particularly when combined with biogas liquid fertilizers, significantly enhance nutrient content such as nitrogen, phosphorus, and calcium in various crops (Koç et al., 2022).

Another critical solution is biogas production, achieved through the anaerobic digestion of animal waste. This process converts organic material into biogas, a renewable energy source, and digestate, a nutrient-rich byproduct used as a soil conditioner (Lee et al., 2021). Biogas production reduces methane emissions from decomposing waste and provides a sustainable energy source for rural farming communities (Bakkaloglu et al., 2022; Kabeyi et al., 2022). In some countries, biogas plants have become central to rural energy systems, enabling farmers to offset their energy costs while contributing to local energy grids (Rafiee et al., 2021; Robinson et al., 2023). Moreover, the liquid byproduct of biogas production, often referred to as biogas slurry or liquid fertilizer, has demonstrated significant benefits when applied to crops. Studies indicate that biogas slurry can enhance soil fertility and improve plant nutrient uptake, particularly when used in conjunction with other organic amendments such as vermicompost (Koc et al., 2022).

Biomass energy and heat production further expand the application of circular economy principles by utilizing plant residues, such as husks, stubble, and other agricultural byproducts, to generate sustainable energy (Kumar Sarangi et al., 2023). Biomass energy projects not only reduce dependency on fossil fuels but also provide a renewable energy source that supports energy needs in rural agricultural areas (Saleem, 2022). This method is particularly effective in regions with high agricultural production, where large volumes of plant residues are readily available (Awasthi et al., 2020).

Animal feed and feed additive production provides a sustainable method for repurposing plant-based agricultural waste. Residues like pulp, husks, and stalks can be processed into animal feed, reducing waste while supporting the livestock sector. This approach not only minimizes dependency on external feed sources but also enhances agricultural efficiency. In practice, farmers in resource-limited regions have successfully utilized agricultural residues as affordable feed alternatives, addressing feed shortages and reducing waste simultaneously.

Lastly, bioplastic and biomaterial production showcases how agricultural waste can be utilized to address broader sustainability challenges

(Rame et al., 2023). Bioplastics derived from agricultural residues, such as corn starch, sugarcane fibers, and other organic materials, offer an eco-friendly alternative to petroleum-based plastics (Muthusamy and Pramasivam, 2019; Ali et al., 2023). These materials are biodegradable and help reduce plastic pollution, making them an essential component of sustainable development strategies. For instance, companies are now producing biodegradable packaging from agricultural byproducts, replacing single-use plastics in consumer markets.

By adopting these circular economy solutions, the agricultural sector has the potential to transform waste into valuable resources, conserve natural assets, and support sustainable development. These practices provide practical frameworks to reduce environmental harm, increase resource efficiency, and enhance economic resilience, ensuring that agriculture can meet future challenges while protecting the planet.

2.3. Examples of circular economy practices in agriculture

Circular economy practices in agriculture have been successfully implemented across various regions, showcasing their potential to enhance sustainability and economic value. The European Union has been at the forefront of promoting these practices, encouraging initiatives such as composting and biogas production. These efforts transform agricultural waste into valuable resources, reducing dependency on non-renewable energy sources and minimizing environmental harm (Sertgümec et al., 2021).

Germany stands out as a leader in biogas technology, converting agricultural and animal waste into energy. Biogas plants in rural areas provide not only sustainable energy but also income diversification for farmers. These plants often integrate anaerobic digestion processes, yielding biogas and nutrient-rich digestate, which is applied as organic fertilizer to enhance soil health (Song et al., 2014).

In Turkey, advancements in circular economy practices are evident, particularly through initiatives like regional composting facilities and biomass energy projects. Turkey's considerable potential for utilizing agricultural residues in biogas production has been highlighted, with regional inventories identifying large quantities of organic waste as feedstock for renewable energy generation and soil enrichment (Sertgümec et al., 2021; Velasco-Muñoz et al., 2022).

In Iran, circular economy practices are being realized through the use of crop residues and animal waste for biogas production. With a significant proportion of the country's agricultural waste comprising organic materials, biogas plants are being integrated to address rural energy needs and reduce greenhouse gas emissions. Scaling up these initiatives could further support sustainable agricultural development (Ardebili, 2020).

In Africa, innovative approaches to circular economy practices are gaining traction in regions with abundant but underutilized agricultural waste. For example, Kenya and South Africa are exploring the use of agro-waste for bioenergy production and organic fertilizers. Kenyan smallholder farmers repurpose maize husks and sugarcane residues to produce energy and compost, while South African biomass energy projects convert forestry and agricultural residues into renewable energy, reducing dependence on fossil fuels (Tagne et al., 2021).

China provides additional insights into the scalability of circular economy practices. Household and medium-to-large-scale biogas plants showcase diverse applications of anaerobic digestion, addressing localized waste management and community-scale energy needs. These systems contribute to energy efficiency and create economic benefits by reducing waste and producing renewable energy (Song et al., 2014; Tagne et al., 2021).

These examples demonstrate the versatility and relevance of circular economy practices in achieving zero-waste goals in agriculture. By integrating biogas production, composting, and biomass energy systems, countries can significantly reduce agricultural waste while conserving resources and supporting rural economies. Moving forward, investments in digital technologies, such as big data analytics and IoT-based monitoring, could further optimize these processes, ensuring greater alignment with zero-waste and circular economy principles (Perçin, 2022).

2.4. Economic gains and sustainability through circular economy

Circular economy practices in agriculture address environmental challenges while creating significant economic opportunities. By converting agricultural waste into biogas, compost, and biomaterials, farmers can diversify their income and reduce dependency on costly external inputs. In Germany, for example, biogas systems supply renewable energy to local grids and produce digestate, an organic fertilizer that reduces reliance on synthetic alternatives (Sobczak et al., 2022). Similarly, in Turkey, composting facilities have supported rural economies by generating local employment and improving soil health through organic fertilizers (Velasco-Muñoz et al., 2022).

These practices also contribute to environmental sustainability by reducing waste and greenhouse gas emissions. Composting plant residues, for instance, eliminates the need for open-field burning, a major source of air pollution. Additionally, the application of organic fertilizers derived from waste enhances soil fertility and water retention, reducing long-term costs and supporting food security (MacArthur et al., 2015).

By aligning environmental sustainability with economic goals, circular economy principles create resilient agricultural systems that are better equipped to handle resource shortages and economic shocks. These practices establish a model for resource-efficient and competitive agriculture, paving the way for a sustainable future.

2.5. Challenges and solutions for transitioning to a circular economy

While circular economy principles hold great promise for agriculture, transitioning to this model is not without challenges. Key barriers include inadequate infrastructure for waste management and resource recycling, limited access to financing for implementing advanced technologies, and a lack of awareness among farmers about the benefits of circular practices. Additionally, the technical expertise required for operating systems like biogas plants or composting facilities often poses a significant hurdle, particularly in rural areas.

Addressing these challenges requires coordinated efforts from both public and private sectors. Governments and institutions can play a pivotal role by developing educational programs to raise awareness about the environmental and economic benefits of circular practices. Financial incentives, such as subsidies, low-interest loans, or tax breaks, can encourage farmers to adopt sustainable technologies. Furthermore, investments in infrastructure, such as regional composting plants and biogas facilities, are critical for scaling up circular economy solutions. Partnerships with private sector entities can also drive innovation and provide the technical expertise needed to support farmers (Lieder and Rashid, 2016).

By tackling these challenges through collaboration and targeted interventions, the agricultural sector can transition more effectively to a circular economy, unlocking its full potential for sustainability and economic growth.

3. Policy and Regulatory Framework

3.1. Global development of the zero-waste and circular economy approach

Increasing environmental issues and resource scarcity have led many countries to adopt zero-waste and circular economy goals. The European Union, in particular, is one of the first regions to prioritize the circular economy as a policy objective. The European Commission's Circular Economy Action Plan, implemented in 2020, aims to minimize waste production, increase resource efficiency, and extend product lifespans. This plan provides incentives for transforming agricultural waste into products like bioenergy, bioplastics, and compost, and seeks to raise recycling rates (Plan 2020; García-Navarro and Poltronieri 2024).

International organizations such as the United Nations Environment Programme (UNEP) and the Food and Agriculture Organization (FAO) are also developing policies for sustainable agriculture and waste management. Under FAO's "Zero Hunger and Zero Waste" goal, strategies to reduce waste management in agriculture and food waste are highlighted. These policies support not only sustainable agriculture but also resource efficiency and rural development.

3.2. Zero-waste and circular economy policies in turkey

Turkey has developed various regulations and policies in recent years to ensure environmental sustainability in the areas of zero-waste and circular economy. Initiated in 2017 by the Ministry of Environment, Urbanization, and Climate Change, the Zero-Waste Project aims to manage waste effectively for both local governments and the agricultural sector. This project marks an important step in reducing agricultural waste and repurposing it through recycling processes to minimize environmental impact (Basak 2019).

The Ministry of Agriculture and Forestry in Turkey has developed projects that encourage the use of agricultural waste as biogas and biomass energy. This includes supporting the establishment of facilities needed for biogas production and providing training for farmers. Additionally, organic farming subsidies and local composting projects are promoted within waste management efforts. These policies accelerate the agricultural sector's transition to a circular economy, contributing to sustainability goals.

3.3. The role of local governments

Local governments play a key role in implementing agricultural waste management. Adopting zero-waste policies at the local level not only facilitates farmers' compliance with these policies but also enables waste to be processed in local facilities for reuse. For example, some municipalities establish composting facilities to convert agricultural and organic waste and organize educational programs to inform farmers throughout this process.

Additionally, local government support for investments in biomass and biogas facilities helps convert waste into environmentally friendly energy.

3.4. Incentives and financial support

Various incentives and financial support mechanisms have been established to promote circular economy and zero-waste goals within the agricultural sector. European Union countries, for instance, offer eco-friendly grants and low-interest loans to finance circular economy projects. Projects for recycling agricultural waste are supported through programs like Horizon 2020 (European Commission, 2020). In Turkey, the Ministry of Agriculture and Forestry and the Ministry of Industry and Technology provide incentives for circular economy applications, such as biogas facilities and compost projects. These supports help reduce the transition costs for farmers and agricultural businesses, encouraging them to adopt sustainable practices.

3.5. Legislation and regulatory framework

Various legal regulations governing waste management in agriculture ensure the effective implementation of circular economy and zero-waste policies. In the European Union, regulations like the Waste Framework Directive require member states to manage agricultural waste sustainably. This directive encourages the recycling of agricultural waste rather than disposal and aims to reduce the environmental impact of chemicals used in agricultural production. In Turkey, the Environmental Law and the Waste Management Regulation provide a legal framework for the disposal and recycling of agricultural waste. These regulations serve as essential guidelines for farmers to comply with zero-waste practices and minimize environmental harm (Directive 2008; Wilts et al., 2018).

3.6. Recommendations for developing circular economy and zero-waste policies

To promote zero-waste and circular economy practices in the agricultural sector, collaboration among policymakers is essential (MacArthur 2013; Freitas 2021). Below are some policy and regulatory recommendations in this context:

a) Education and awareness: Raising awareness among farmers about waste management and the circular economy increases the applicability of these policies. Therefore, public institutions, local governments, and NGOs can organize educational programs targeted at farmers.

b) R&D investments: Increasing R&D investments is crucial for developing technologies aimed at circular economy practices in agriculture. Infrastructure such as biogas facilities and composting technologies play a vital role in processing agricultural waste.

c) Financing and incentive mechanisms: To support circular economy projects, low-interest loans, grant programs, and tax reductions can be offered to farmers. Such incentives will facilitate farmers' transition to the circular economy.

d) International collaborations: Strengthening international collaborations in agricultural waste management and disseminating best practices is important. Collaborations with the European Union, in particular, are valuable for sharing experiences and technology transfer in circular economy practices.

4. Conclusion

The agricultural sector is fundamentally important for food security, rural development, and economic growth. However, agricultural activities that directly impact the environment through high consumption of water, soil, and energy resources also generate substantial waste. The traditional linear economy model mainly focuses on disposing of this waste, which increases the environmental burden and moves us further from a sustainable future vision. Combined with global challenges like rapid depletion of natural resources, loss of biodiversity, and the intensifying effects of climate change, this situation calls for a new perspective in agricultural production. At this point, the circular economy and zero-waste approach offer significant solutions for creating a sustainable model in the agricultural sector.

The circular economy is an innovative approach that involves re-evaluating waste and reintegrating it into the cycle as a resource rather than discarding it. Transforming agricultural waste into environmentally friendly products, such as compost, biomass energy, and biogas, reintroduces this waste into the agricultural production chain, creating value both environmentally and economically. For instance, plant waste can be used as compost, enhancing soil organic matter, improving productivity, and reducing the need for chemical fertilizers. Biogas derived from animal waste, on the other hand, plays a crucial role as a renewable energy source that reduces dependence on fossil fuels. Such applications, aligned with the core principles of the circular economy, turn waste from an environmental problem into an economic opportunity.

In the future, the large-scale application of circular economy and zero-waste goals in agriculture could yield significant sustainability benefits. Addressing climate change and conserving natural resources are primary focuses of these goals. The spread of circular economy and zero-waste practices will play a critical role in reducing the agricultural sector’s carbon footprint and lowering energy costs. The environmental benefits, particularly in reducing carbon emissions, conserving water, enhancing soil fertility, and preserving biodiversity, demonstrate that circular economy practices can contribute substantially to agricultural production processes in the long term.

However, this transformation process faces certain challenges. Fully integrating circular economy and zero-waste practices into agricultural production requires new infrastructures, technological investments, and training for farmers. The widespread adoption of circular economy practices in agriculture may be constrained by initial costs, logistical issues, and lack of knowledge. Overcoming these challenges requires collaboration among government bodies, the private sector, and non-governmental organizations. Financial incentives such as low-interest loans, tax reductions, and grant programs should be provided to support farmers' transition to circular economy practices, while education and awareness programs should be used to improve farmers' knowledge levels. Additionally, promoting investments in biogas plants, composting systems, and biomass energy infrastructure will support the efficient conversion of agricultural waste.

The application of circular economy and zero-waste goals in agriculture can also contribute to the development of rural economies. Repurposing agricultural waste can create employment opportunities in rural areas, increase farmers' income, and strengthen local economies. In developing countries especially, these practices provide a model of sustainable rural development. At the same time, circular economy practices can increase environmental awareness in local communities, create societal awareness, and promote more conscious consumption of natural resources.

In conclusion, the widespread adoption of circular economy and zero-waste goals in agriculture offers a model that supports not only environmental sustainability but also economic development and social welfare. Sustainability in agriculture should be viewed not only as reducing or recycling waste but also as a strategic necessity to protect natural resources, use them efficiently, and leave a healthy environment for future generations. Circular economy and zero-waste practices contribute to transforming the agricultural sector into a more efficient, environmentally friendly, and resource-sustainable structure, offering an important solution for combating climate change.

In this context, it is essential that all stakeholders contribute to this transformation; public institutions, the private sector, local governments, and non-governmental organizations must work collaboratively. Adopting innovative strategies to drive transformation in the agricultural sector towards zero-waste and circular economy goals will help ensure that agriculture remains a successful sector in terms of both environmental and economic sustainability. Circular economy and zero-waste approaches are essential elements for the agricultural sector to achieve a nature-compatible and sustainable structure; embracing these approaches is the key to an environmentally friendly future in agriculture.

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CHAPTER 12

PREDICTION OF THE INTERNAL TEMPERATURES OF THE YARN BOBBIN DURING DRYING

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1. INTRODUCTION

Woolen yarns, one of the most unique materials nature offers for a healthy and comfortable life, can be utilized in various technical applications such as knitting, sewing, weaving, and embroidery. Woolen yarns are produced by twisting protein-based wool fibers obtained from animals such as sheep, goats, camels, llamas, and alpacas. Due to their natural and organic composition, yarns containing wool are highly preferred. Wool is renowned for its warmth, durability, and elasticity (www.etrofil.com.tr).

The type of wool used determines the variety of woolen yarns and their applications. For instance, sheep, the most commonly used animal in wool production, come in various breeds such as Merino, Rambouillet, and Corriedale. These breeds provide high-quality wool, each suited to specific uses (https://wellalux.com).

Wool is an animal fiber obtained by shearing the fleece of sheep, which is produced nearly everywhere in the world. Sheep are typically shorn once or twice a year, and the raw wool collected is referred to as fleece. An efficient shearer can remove the wool from a sheep in about two minutes. Wool can also be obtained from the pelts of slaughtered sheep through chemical processes or bacterial activity without damaging the hide.

Raw wool is often dirty, containing natural oils, grease, and sweat residues. These impurities are removed during wool cleaning and carbonization processes to produce cleaned wool. The quality of wool is significantly influenced by the breed of the sheep and environmental conditions. Additionally, wool differs in fineness, length, and purity depending on the body part from which it is sourced. Generally, wool is classified into fine wool, medium wool, long wool, and carpet wool (Malik, 2016).

Yarn production forms the foundation of all activities in the textile industry, making it a priority area for innovation efforts. Yarns are materials of specific length, twist count, fineness, and dyeability. The fibers that make up yarns are referred to as fiber. In the yarn industry, numerous processes and stages are involved in production. Before reaching the final product, yarn undergoes processes such as dyeing, printing, coloring, and drying (Koç et al., 2022).

Textile fabrics, whether knitted or woven, must be cleaned, prepared, dyed, or printed and subsequently undergo finishing processes following these wet processes. Drying, which lies between wet processing and dry finishing, is a critical step aimed at removing moisture and water from the material (Hamdaoui et al., 2013). The final drying stage is an energy-intensive and costly process. During this process, mechanical methods are first applied to remove moisture from the yarn. However, as mechanical methods alone are insufficient, secondary methods are applied to achieve complete drying (Koç et al., 2022).

Drying is a costly and time-consuming process, thus it is essential to remove as much water as possible from the yarn mechanically. Generally, textile products that have undergone preliminary drying through mechanical methods are then subjected to final drying to achieve the desired moisture content while retaining hygroscopic moisture (Üçgül et al., 2014). Furthermore, determining the moisture content in yarn is a key parameter affecting the efficiency of the drying method applied (Akyol, 2007; Akyol, 2011). Yarn drying is a method of removing water from the yarn through heat transfer, making it the most critical stage of yarn production in terms of cost, quality, and efficiency. Various drying methods and machines are used in the textile industry to perform this process (Jhanji et al., 2015; Gallopi et al., 2017).

One of the fields where drying techniques are applied is the textile industry. The most important aspect of the drying process is achieving the desired material characteristics with minimal energy consumption and maximum drying speed (Kodaloğlu and Kodaloğlu, 2023). Current drying methods used in textiles include Infrared Radiation (Broadbent et al., 1994), Microwave drying (Cochran, 2002), Radio Frequency and

Infrared Drying (Ruddick, 1990), hot air drying (Kodaloğlu and Kodaloğlu, 2023; Akyol et al., 2015), vacuum drying (Parish and Thorp, 1965), and heat pump drying (Durmuş et al., 2012).

The drying duration depends on parameters such as air temperature and speed, material type, and air humidity. Mathematical modeling of the drying process, which includes multiple parameters, is essential as it helps achieve optimal conditions, thereby reducing drying costs and time (Karakoca, 2017). Mathematical modeling, often composed of equations that describe the behavior of a process or system, provides a degree of convenience. To further reduce drying costs and time, Artificial Neural Networks (ANN) and Adaptive Neuro-Fuzzy Inference Systems (ANFIS) are prominent among today's AI-based prediction models (Buluş et al., 2024; Moralar, 2024).

Artificial intelligence methods are successfully applied across many fields. In most studies, AI methods are utilized for parameter estimation, data evaluation, monitoring specific conditions, diagnostics, classification, grading, detection, control, selection, optimization, and more. Since all AI methods are data-driven, they generate results within the range of data on which they were developed and aim to predict outcomes based on known variable parameters (Kodaloğlu and Kodaloğlu, 2023).

Artificial Neural Networks (ANNs) are designed based on the functioning of the human brain, aiming to address complex problems, make predictions, and perform image processing through mathematical functions of artificial neurons. Generally, ANNs are systems developed to model the human brain by mimicking the functions of the biological nervous system. In this way, they facilitate processes such as learning, association, classification, generalization, feature extraction, prediction, and optimization (Buluş et al., 2024).

LSTM (Long Short-Term Memory) is derived from an architecture within the family of Recurrent Neural Networks (RNN), which form a significant subclass of artificial neural networks. The LSTM architecture was developed to address the challenges RNNs face in learning long-term dependencies, a notable weakness of traditional RNNs (Hochreiter and Schmidhuber, 1997).

Standard RNNs (Recurrent Neural Networks) process sequential data by considering the effects of previous steps on subsequent ones. However, in cases involving long-term dependencies, RNNs often fall short in preserving and processing information effectively. The LSTM (Long Short-Term Memory) architecture addresses this issue through specialized components known as "memory cells" (Gers et al., 1999). LSTM, a member of the RNN family, is specifically designed to learn long-term dependencies. While traditional RNNs tend to lose the influence of previous states over time, LSTM cells overcome this limitation through their memory cell and gating mechanisms.

Support Vector Regression (SVR) is a regression technique derived from Support Vector Machines (SVM) and is primarily designed to address a function estimation problem. The mathematical foundation of SVR is based on the principle of risk minimization and the formulation of a general hypothesis using limited information.

The primary objective of this study is to produce bobbin yarn from cotton cultivated in agriculture and to dry it. The secondary goal is to make predictions using machine learning methods (ANN, LSTM and SVR) to reduce the time and energy required for laboratory experiments. To achieve this, estimated temperature values at specific regions of the drying system were determined.

2. MATERIALS AND METHODS

2.1 System description

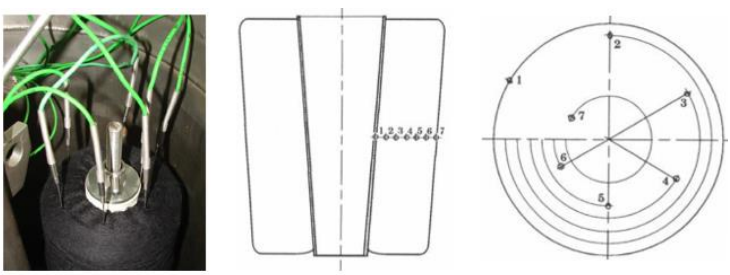
In this study, wool yarns of different sizes, commonly used in textile production in Turkey, were utilized. The yarn bobbins used in the experiments consist of 65% wool and 35% orlon. The drying process for the wool yarn bobbins was conducted using hot air in an experimental setup established at Tekirdağ Namık Kemal University. The hot air flowed exclusively through the interior of the yarn bobbins, achieving drying from the inside out due to the pressure difference. During the experiment, a hot air flow rate of 450 m³/h was applied. The temperature and pressure of the hot air were set to 80°C and 2 bar (effective), respectively.

Before the drying process, the bobbins were subjected to a water bath for 12 hours. Following the water bath, the bobbins were placed on a grid for 30 minutes to allow the excess water to drain and to ensure the water penetrated the yarn fibers. After draining on the grid, the bobbins underwent a pre-drying process with cold air (without heaters being activated) for approximately 10 minutes to remove a portion of the excess water. Subsequently, the drying process was carried out under the conditions set in the system.

Figure 1. General view of the bobbin drying experimental setup

In this study, the experiments were conducted on a yarn bobbin drying experimental setup, which serves as a prototype of a bobbin drying machine used in the textile industry and operates with pressurized hot air (Figure 1). In the experimental setup, the drying air taken from the environment is directed to an electric heating exchanger with a heating capacity of 25 kW using a fan with a power of 15 kW. The fan flow rate can be adjusted with a special frequency-controlled driver, while the airflow rate is measured using a flowmeter, and the pressure is determined with a pressure sensor.

The heaters are controlled by a PID algorithm, enabling precise regulation of the drying air temperature through proportional control. The heated air is directed to a compartment where the bobbins are placed. The temperature changes within the bobbins are measured using seven thermocouples, which are directly connected to a PLC and radially positioned at equal intervals inside the yarn bobbins (Figure 2). The measurement results are transferred to a computer for analysis.



(a) (b)

Figure 2. Thermocouples placed inside the yarn bobbins (a), Schematic representation of the yarn bobbin used in the experiments (b).

2.2 Data Prediction Method

During the drying experiments, the temperature changes over time for the yarn bobbins exposed to hot air for 101 minutes, as measured by seven thermocouples, are shown in Figure 3. As observed in Figure 3, drying occurs rapidly after the temperature reaches 45°C.

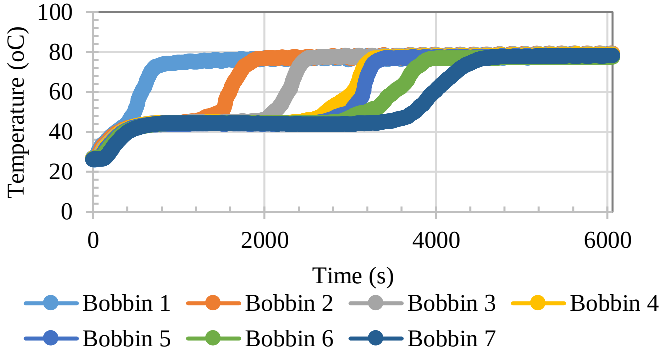


Figure 3. Temperature values measured by 7 thermocouples

2.3 Artifical Neural Network

Artificial neural networks are inspired by the nervous system of living organisms. The primary aim of artificial neural networks is to mimic the human brain. These networks have the ability to learn, remember, and generalize, much like humans. Due to their ability to solve complex and difficult problems quickly, artificial neural networks are widely used today in various fields, ranging from engineering to medical sciences (Öztemel 2003).

The basic elements of ANN are inspired by the functioning of biological neurons. The connections formed between these artificial neurons are grouped into layers, which together constitute the artificial neural network. Figure 4 shows the mathematical modeling of a nerve cell in the brain.

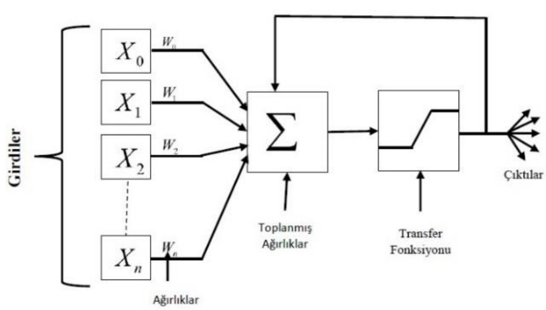


Figure 4. Mathematical representation of a biological neuron (Sidal, 2023)

Inputs

Each neuron in a network is as shown in Figure 5. The multiple input signals coming from the external environment are represented by the set {a_1, a_2, a_3, …, a_n}, similar to the dendrites in a biological neural network. The input signals (a_1, a_2, a_3, …, a_n) are signals or examples coming from the external environment, which are considered as inputs for a specific application.

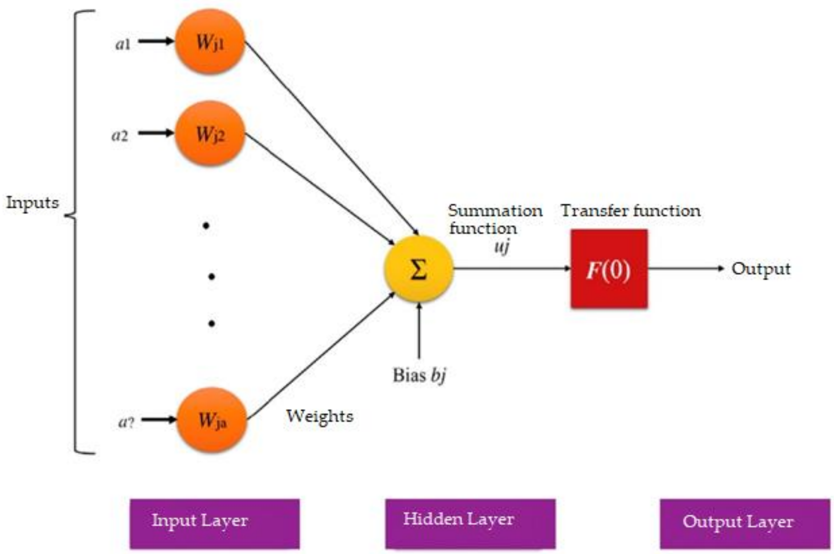


Figure 5. The model of an artificial neuron (Oğuz Erenler, 2023)

Weights

Synaptic weights (W_1, W_2, W_3, ..., W_n) represent the importance and influence of the inputs received by the neuron. This influence can be either positive or negative (Sidal, 2023). The weights of the inputs presented to the network are not fixed or uniform. As the neural network is exposed to new examples, it adjusts the weight values until the most optimal result is achieved, ultimately converging on the weight values that produce the best output. At the beginning of the training process, the weights are initialized randomly. If the output reaches an acceptable error level, the training process is considered complete. Otherwise, the process is reset, and the weights are adjusted again. The network is considered correctly trained when the error between the actual values and the predicted output values is minimized (Sönmez Çakır, 2020).

Summation function

The summation function is used to calculate the result of multiplying the inputs by their respective weights. Several methods can be used to compute this value.

$$\mathbf{s} = \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{x_i} * \mathbf{w} \qquad (1)$$

As shown in Equation 1, Xi represents the input value, and Wi represents the weight value. Each input, from the first to the last, is multiplied by its randomly assigned weight, and the results are summed to calculate the value of s.

Activation function

After calculating the summation function, the resulting value s is provided as input to the activation function. The results of the summation function are then transformed into the output through the activation function. The activation function computes the net input to the neuron and determines the corresponding output value for this input. If an artificial neural network lacks an activation function, the network would resemble a simple linear regression model. Depending on the problem type and network structure, various activation functions can be used.

Outputs

The outputs (Output) can either be the final value produced by the neuron when the input set is provided, or it can serve as an input value for other connected neurons (Oğuz Erenler, 2023).

After the activation function is applied, the resulting value becomes the output of the neuron. This value may serve as input to another neuron or be used directly as information.

To complete the process, the information flows to other process components in the same manner. When the process is finished, the neural network has completed its task and generated the required output (Sönmez Çakır, 2020).

2.4 Long Short-Term Memory (LSTM)

LSTM is derived from the family of Recurrent Neural Networks (RNN), which constitutes an important subclass of artificial neural networks. The LSTM architecture was developed to address the challenges RNNs face in learning long-term dependencies, which are a weak point of traditional RNN models. (Hochreiter and Schmidhuber, 1997).

The structure and functioning of LSTM cells are illustrated in the Figure 6.

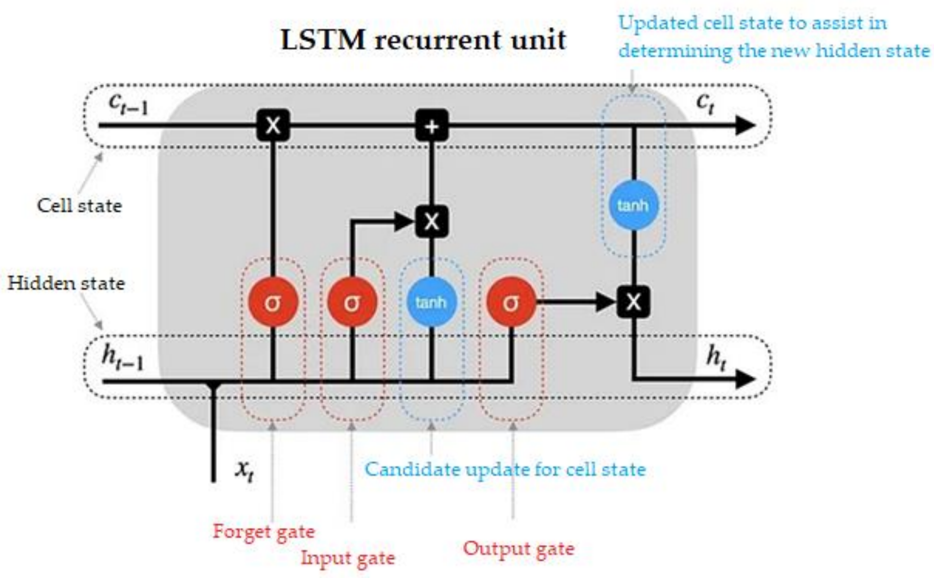


Figure 6. The basic structure of an LSTM

This visual is a diagram that illustrates the basic structure of an LSTM (Long Short-Term Memory) neural network. The main components in the visual can be explained as follows:

Cell State:

The horizontal line at the top of the diagram (from ct-1 to ct) represents the long-term memory of the LSTM. Information is stored, updated, or erased along this line.

Hidden State:

The horizontal line at the bottom (from ht-1 to ht) represents the short-term memory, which is updated at each time step.

Gates:

The visual shows three key gates:

Forget Gate: The first gate represented by the σ (sigma) function.

Input Gate: The second σ function.

Output Gate: The final σ function.

Activation Functions:

σ (sigma): Represented by red circles, these are sigmoid functions.

tanh: Represented by blue circles, this is the hyperbolic tangent function.

Operations:

x: Multiplication operation.

+: Addition operation.

Input Data:

Represented by xt, it is the new data that enters the network at each time step.

Thanks to this structure, the LSTM can decide which information to forget, which new information to add, and which information to use as output. This capability allows LSTMs to learn and remember long-term dependencies.

LSTM cells have three fundamental gates: input, output, and forget gates. These gates control the flow of information inside the cell, making decisions about how much information from previous steps should be retained, updated, or ignored. This enables LSTM cells to more effectively learn long-term dependencies (Graves et al., 2013).

The LSTM architecture has achieved successful results in many fields, such as time series analysis, natural language processing, machine translation, and speech recognition. In particular, its ability to capture long-term dependencies, compared to traditional RNNs, is one of the main reasons for the preference of LSTM (Lipton et al., 2015).

In recent years, various improvements have been made to the basic LSTM architecture, leading to the development of different derivatives. Among these are variants such as Bidirectional LSTM, Hierarchical LSTM, and Core LSTM (Bai et al., 2018). These variants aim to further enhance the performance of LSTM by better adapting to specific problems.

2.5 Support Vector Regression (SVR)

SVR (Support Vector Regression) is a regression technique derived from support vector machines (SVM). The goal of SVR is to learn the function f(x) from a given dataset and model the relationship between inputs x and outputs y. In this context, SVR focuses on the following minimization problem:

$$\min_{w,b} \frac{1}{2} \|w\|^2 + C \sum_{i=1}^{n} (\xi_i + \xi_i^*) \quad (2)$$

where:

- ‖w‖² represents the complexity of the model.
- C provides a balance between the error margin and regularization.
- ξ_i + ξi* represents the positive and negative deviations (slack variables).
- n is the number of data samples.

The goal is to model nonlinear relationships by satisfying the condition $|y_i - (w^T \phi(x_i) + b)| \leq \varepsilon$ within the ε-tube. Here, $\phi(x_i)$maps the data space to a higher-dimensional space using a kernel function $K(x, x')$ (Vapnik, 1995).

Typical kernel functions are:

1. Lineer: $K(x, x') = x^T x'$
2. RBF (Gaussian): $K(x, x') = exp(-\|x - x'\|^2 / 2\sigma^2)$
3. Polinomsal: $K(x, x') = (x^T x' + c)^d$

This mechanism allows the data to be linearly separable in a nonlinear feature space (Chang and Lin, 2011).

In SVR, the model is expressed by a decision function $f(x) = \sum_{i=1}^{n}(\alpha_i - \alpha_i^*) K(x_i, x) + b$

Here, α_i and α_i^* are dual variables, and they are only non-zero for support vectors. This makes SVR computationally efficient.

The learning process of an SVR model involves the following steps:

1. Model Training: The optimization problem mentioned above is solved on a given dataset to determine the support vectors.
2. Prediction: For a new data point **x**, the prediction is made using the kernel functions and the model parameters.

The advantage of SVR is its ability to work with high-dimensional data and its strong generalization performance.

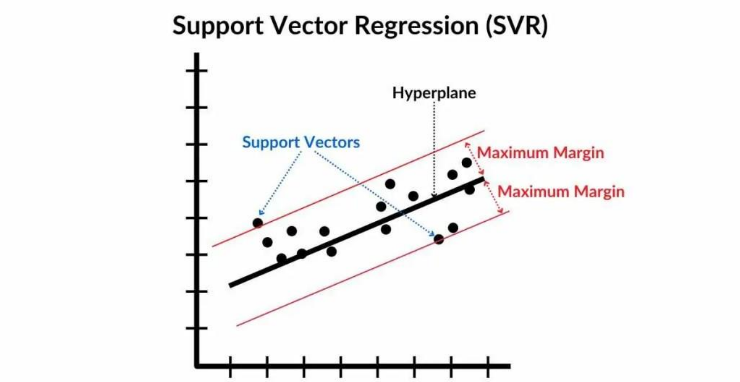


Figure 7. SVR graphic (https://spotintelligence.com/2024/05/08/support-vector-regression-svr/)

In Figure 7, the fundamental components of SVR are shown. Support Vectors are the data points that define the boundaries of the regression model. The hyperplane is the regression line or function that best represents the data. Maximum Margin refers to the distance between the support vectors and the hyperplane. The goal of SVR is to maximize this margin to achieve the best fit. Maximum Margin is the highest possible margin value.

2.6 Statistical analysis

The system has been modeled using various artificial intelligence techniques. The accuracy of the model was ultimately evaluated by selecting the output with the smallest estimation error, measured using the coefficient of determination (R^2), Mean Absolute Percentage Error (MAPE), Root Mean Square Error (RMSE), and Mean Absolute Error (MAE) (Eqs. 3-6) (Buluş et al., 2023).

$$RMSE = \sqrt{\frac{1}{n}\sum_{t=1}^{n}(Yt - Ft)^2} \tag{3}$$

$$R^2 = 1 - \frac{\sum_{t=1}^{n}(Yt - Ft)^2}{\sum_{t=1}^{n}(Yt - Fort)^2} \tag{4}$$

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{Yt - Ft}{Yt}\right| * \tag{5}$$

$$MAE = \frac{\sum_{t=1}^{n}|Ft - Yt|}{n} \tag{6}$$

ANN creates a model that must be tested to confirm it meets the desired criteria. This validation process assesses how effectively ANN has modeled the system by comparing outputs from the training data with those from a separate, non-training data set. The discrepancy between these outputs is quantified by the RMSE, which indicates the model's performance. A lower RMSE value reflects a more accurate model (Solichin et al., 2021).

3. MODEL ANALYSIS

3.1 ANN model analysis

The development, training, and testing of the ANN model were conducted using the MATLAB software package. MATLAB offers a robust simulation and testing platform for this purpose, enabling easy manipulation of the model's variables and parameters. As a result, it provides a comprehensive graphical representation of parameters and performance. Figure 8 illustrates the structure of ANN.

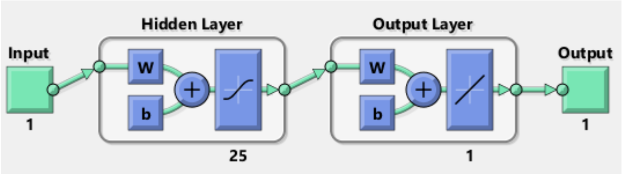


Figure 8. The structure of ANN

- Input: Time (T), Output: Bobbin Temperature (BT).

The ANN model created to predict the coil temperature has a single input and a single output. Time is used as the input, and the measured temperature from the coils is the output. The ANN model has a single hidden layer with 25 neurons. The suitability of this model was determined by conducting trials with different numbers of neurons. The transfer function used in the ANN model is the Tanh Sigmoid function, while the output function is selected as the Linear function. The training function used is Levenberg-Marquardt. The number of training epochs is set to 1000, and the error value defined at the 23rd epoch was achieved. Looking at the validation performance graph in Figure 9, the best validation value was determined at the 17th epoch.

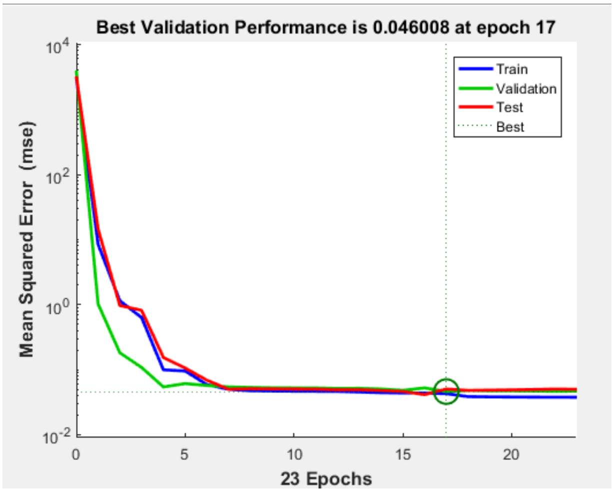


Figure 9. Validation performance of ANN

For modeling the time-dependent coil temperature processes using an Artificial Neural Network (ANN), 80% of the available 607 data points (485 data points) were allocated for training the ANN model, while 20% (122 data points) were used for testing the trained model. These 485 data points were divided into three subsets—training, testing, and validation—during the training phase. The regression graphs for the training processes are provided in Figure 10.

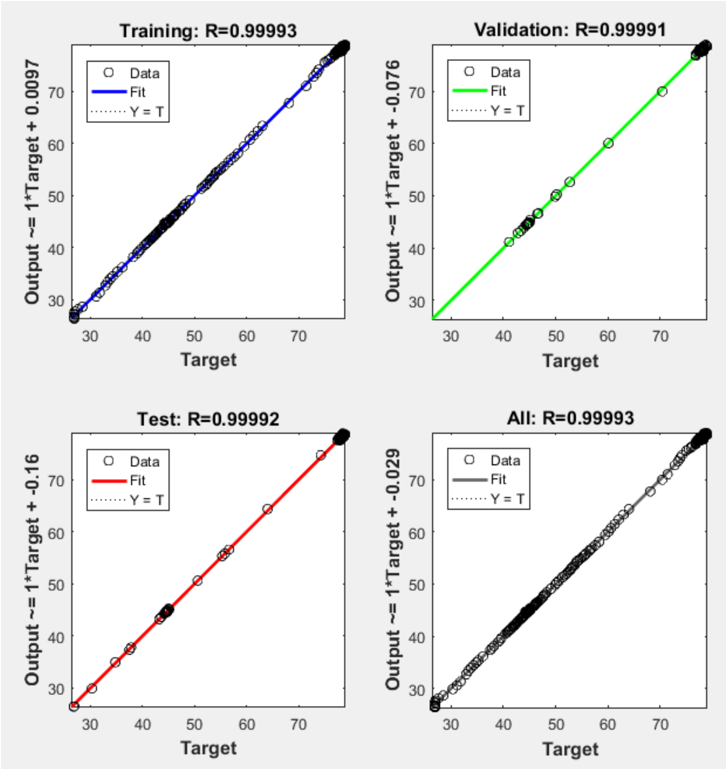


Figure 10. The regression graphs of the training process

3.2 LSTM Model Analysis

The development, training, and testing of the LSTM model were carried out using Python in the Google Colab environment. The Python platform provided a robust simulation and testing environment, enabling easy manipulation of the model's variables and parameters. As a result, it offers a comprehensive graphical representation of the parameters and performance.

The model was designed to make predictions based on the previous 60 samples in the time series. Since a sample is taken every 10 seconds, a 10-minute window is considered. The test environment contains a total of 607 records. Of these, 80% were selected as training data, and 20% as test data. Since the data is a time series, the test data was separated from the end.

The LSTM model developed to predict coil temperature has 60 inputs and a single output. The inputs consist of the current value and the previous 60 values. The input data for the LSTM model is reshaped accordingly. The LSTM model expects three-dimensional input data (number of samples, time steps, number of features). The output is the temperature measured from the coils.

The LSTM model consists of an input layer, an LSTM layer, and a dense layer. The 'adam' optimization algorithm and 'MSE' (mean squared error) loss function were used during the compilation of the model. The model was trained using the training data, and the 'epochs' parameter defines the number of training iterations. 'Epochs' was set to 100. The 'batch_size' parameter, which defines the number of data points used per iteration, was set to 32. After training, the graphs for training, testing, and all data are shown in Figure 11.

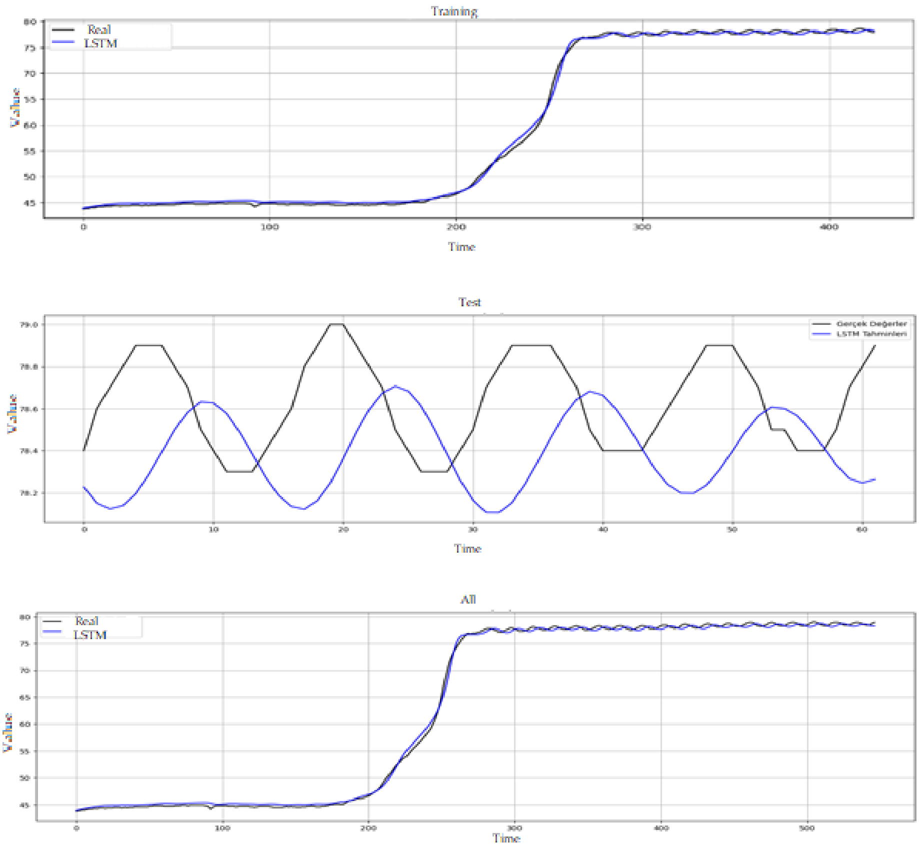


Figure 11. LSTM Model Training-Test-All Data Graphs

Additionally, the LSTM model regression graphs are shown in Figure 12.

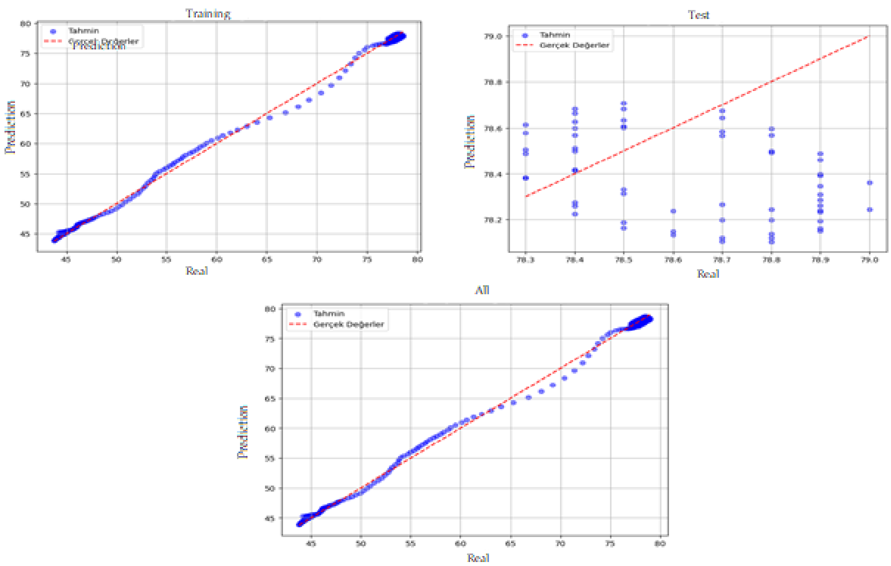


Figure 12. Regression graph of LSTM model

3.3 SVR Model Analysis

The training and test sets created for the LSTM model were also used in the SVR model. When creating the SVR model, the Radial Basis Function (RBF) kernel was used. The regularization parameter, C, was set to 100. C controls the balance between the complexity of the model and its fit to the training data. The error tolerance epsilon was set to 0.1. Epsilon determines the model's tolerance for error, and errors smaller than this value are ignored. After training, the model is able to learn the patterns from the training data and make predictions for future data.

After the model training, the training, test, and all data graphs are shown in Figure 13.

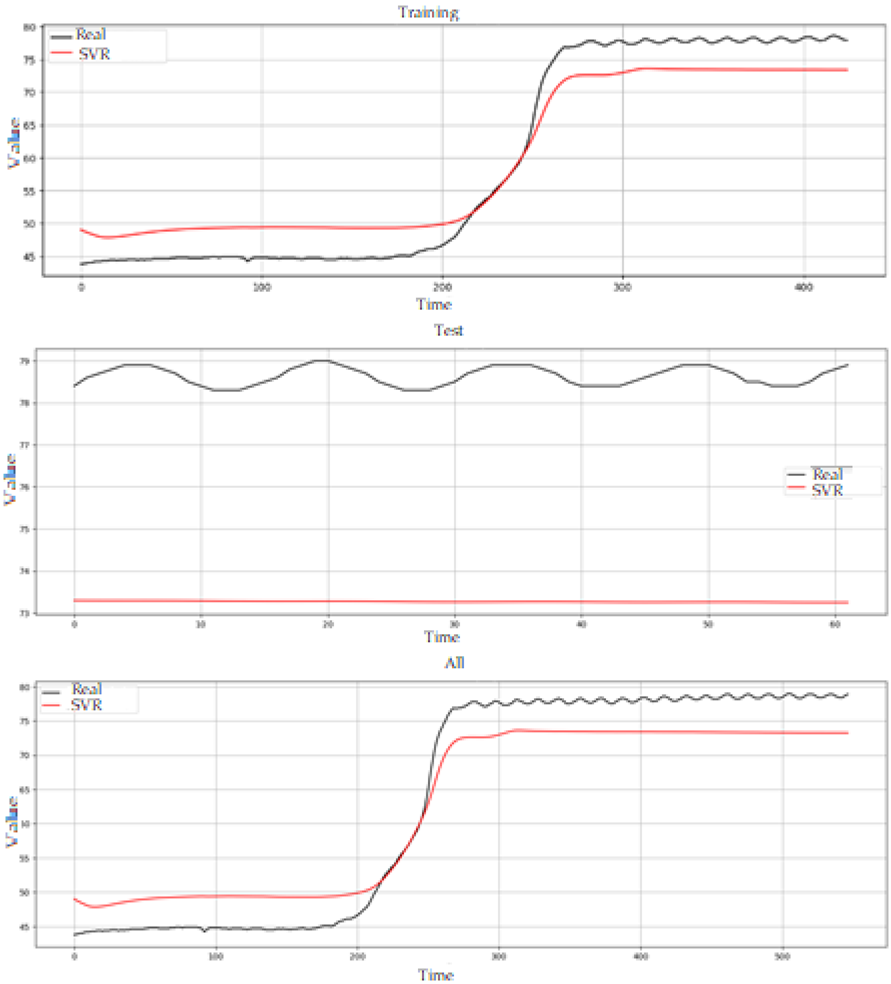


Figure 13. SVR Model Training-Test-All Data Graphs

Additionally, the regression graphs for the SVR model are shown in Figure 14.

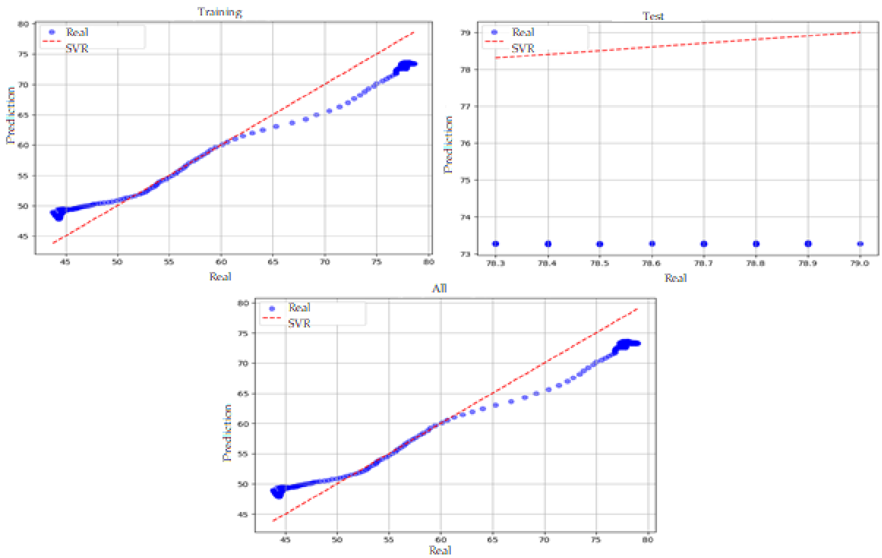


Figure 14. Regression graph of SVR model

The RMSE, MAPE, R^2, and MAE values for the predictions made using the three techniques employed in the model construction and their corresponding training sets are provided in Table 1.

Table 1. Correlation values of training and test dataset

		ANN	LSTM	SVR
Training	RMSE	0,052989	0.422702	4.232786
	MAPE	0,460792	0.004737	0.072274
	R^2	0,999932	0.999257	0.925544
	MAE	-0,000557	0.293403	4.033117
Test	**RMSE**	0,048380	0.565537	5.370496
	MAPE	0,468077	0.006154	0.068233
	$\mathbf{R^2}$	0,999943	-5.694808	-602.732991
	MAE	0,000369	0.484568	5.366080
All	RMSE	0,052100	0.454659	4.477199
	MAPE	0,462249	0.004997	0.071013
	R^2	0,999934	0.999179	0.920371
	MAE	-0,000372	0.331504	4.300744

The goal is to achieve an R^2 value as close to 1 as possible, alongside RMSE, MAE, and MAPE values approaching zero. For R^2, the values ranging from 0.999932 to 0.999943 for the ANN model indicate a very high degree of correlation. A MAPE value of less than 0.10 denotes highly accurate predictions, between 0.10 and 0.20 reflects good predictions, between 0.20 and 0.50 suggests reasonable predictions, and a MAPE value greater than 0.50 indicates low accuracy (Kacar and Korkmaz, 2022; Buluş, 2024). As shown in Table 1, the MAPE values reflect both good and reasonable levels of prediction. Additionally, the RMSE values, which range between 0.048380 and 0.052989, are close to zero, further validating the accuracy of the models. In an ideal situation, MAE should also be close to zero. This indicates that there is no systematic bias in the model's predictions, and that the predictions are generally linear.

4. CONCLUSIONS

In this study, we predicted specific temperatures within the system during the drying process at 3 bar pressure and temperatures of 80°C using ANN, SVR, and LSTM models. The ANN model, consisting of one hidden layer, provided accurate results using 607 data points, with 80% (485 data points) allocated for training and 20% (122 data points) for testing. The statistical results for RMSE, MAPE, R^2, and MAE were 0.0048380, 0.468077, 0.999943, and 0.000369, respectively for ANN; 0.565537, 0.006154, -5.694808, and 0.484568, respectively for LSTM; and 5.370496, 0.068233, -602.732991, and 5.366080, respectively for SVR, indicating the accuracy of the test. The primary goal of these predictive models is to reduce the number of tests required in future drying processes. Additionally, they will facilitate the prediction of various other parameters within the drying system.

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CHAPTER 13

THE FUTURE OF SUSTAINABLE VITICULTURE

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1.1.Introduction

Grape growing, one of humanity's oldest agricultural practices, stands at a pivotal crossroads in the 21st century. With global production reaching 77.8 million tons annually, the viticulture industry faces unprecedented challenges that demand innovative, sustainable solutions (Anonymous, 2023).

The viticulture industry is under increasing pressure from climate change, environmental degradation, and evolving consumer preferences, necessitating a fundamental shift toward more sustainable practices (van Leeuwen et al., 2019). While traditional viticultural methods have been historically effective, they are increasingly challenged by rapid environmental changes and economic pressures, requiring innovative solutions (Santos et al., 2020).

Climate change represents the most significant threat to traditional viticulture. Projections suggest that 25–73% of current wine grape-growing regions may become unsuitable for cultivation by 2050 under a high-emission scenario (Morales-Castilla et al., 2020).

Rising temperatures, changing precipitation patterns, and the increased frequency of extreme weather events are altering the suitability of traditional grape-growing regions (Jones, 2014). Warmer temperatures are also causing earlier budbreak, which heightens the risk of frost damage and reduces grape quality. To mitigate these impacts, grape growers are adopting climate-smart practices such as using drought-tolerant rootstocks, implementing precision irrigation systems, and planting grape cultivars better suited to warmer conditions.

Water scarcity is another critical challenge for the grape-growing industry. As a water-intensive activity, viticulture is under pressure to reduce its water footprint. Sustainable grape growers are adopting water-saving technologies, such as drip irrigation and mulching, to minimize water waste and optimize water use (Pereira et al., 2012).

Environmental degradation also poses significant challenges. The use of chemical pesticides, fungicides, and fertilizers harms biodiversity, contaminates waterways, and contributes to soil degradation (Gomez et al., 2018).

Despite these challenges, opportunities exist for sustainable grape growers to thrive. Consumers are increasingly demanding sustainable and environmentally friendly products, driving market growth for sustainable wines. Additionally, governments and regulatory bodies are implementing policies and incentives to encourage sustainable practices (European Commission, 2020).

In order to take advantage of these opportunities, sustainable grape growers are adopting various strategies. One approach is certification programs, such as Organic, Biodynamic and Fairtrade, which provide frameworks for sustainable practices and offer marketing advantages (Reganold et al., 2010). Another strategy involves investing in precision agriculture technologies, such as drones, sensors, and satellite imaging, to optimize crop management, reduce waste, and improve yields (Kobayashi et al., 2019).

Numerous studies have focused on sustainability in viticulture, and some noteworthy research includes:

Borghi et al. (2024**)** highlighted the importance of selecting soil microbes to promote resilient and sustainable grape growing. The use of endophytes for stress management is seen as a nature-compliant strategy to enhance crops' ability to cope with drought and plant diseases.

Advances in soil health have become increasingly important in vineyard management. Research emphasizes four principal development areas: understanding soil biology, integrating soil data interpretation, improving in-field measurements and modeling the soil–grapevine–water–atmosphere system (Karlen et al., 2019; Visconti et al., 2024).

Climate change significantly affects grapevines, with warmer temperatures shifting the entire wine grapevine growth cycle earlier in the season. Fonseca et al. (2024) demonstrated that vineyard microclimatic zoning could enhance sustainable grape growing under changing climate conditions.

Advanced satellite technologies, including Sentinel-2 and Landsat-8, provide high-resolution imagery that enables territorial-scale monitoring of vineyards. These technologies offer valuable insights into the spatio-temporal variability of grapevines and soils, including topsoil moisture, water status, and the performance of various training systems (Mucalo et al., 2024).

This review aims to deal with the fundamental aspects and future of sustainable viticulture.

1.2. Sustainable Viticulture

The concept of sustainability in viticulture has evolved significantly over the past few decades. Sustainable viticulture refers to the integration of practices that balance environmental health, economic profitability, and social responsibility. Key principles include reducing chemical inputs, efficiently managing natural resources, and enhancing vineyard biodiversity (Altieri et al., 2021).

The fundamental components of sustainable viticulture are as follows:

1.2.1. Environmental sustainability

The environmental aspect focuses on minimizing the ecological footprint of viticulture through:

1.2.1.1. Reducing chemical inputs

Sustainable practices promote the use of organic fertilizers, biopesticides, and natural pest control methods to protect soil and water quality.

1.2.1.2. Climate-resilient practices

Techniques such as cover cropping, efficient water management, and selection of drought-resistant grape varieties help mitigate the impacts of climate change on vineyard systems.

1.2.1.3. Biodiversity preservation

Maintaining vineyard ecosystems by fostering habitats for beneficial organisms and conserving natural landscapes surrounding vineyards enhances ecological balance.

1.2.2. Social sustainability

Social sustainability in viticulture emphasizes fair labor practices, community engagement and education:

1.2.2.1. Fair labor and worker safety

Ensuring safe working conditions and equitable wages for vineyard workers is fundamental to social responsibility.

1.2.2.2. Community engagement

Sustainable vineyards often support local communities through educational programs, eco-tourism, and collaboration with local farmers.

1.2.3. Economic sustainability

Economic sustainability focuses on the financial viability of sustainable practices:

1.2.3.1. Cost-effectiveness

While the initial investments in sustainable technologies may be high, long-term savings from reduced input costs and premium pricing for eco-certified wines significantly enhance profitability.

1.2.3.2. Market differentiation

Sustainability certifications, such as organic and biodynamic, provide access to niche markets and boost brand value, offering strong economic incentives for producers.

1.2.4. Evolution of the sustainability concept

Originally focused on minimizing environmental harm, the concept of sustainability in viticulture has evolved into a holistic framework that integrates environmental, social, and economic dimensions:

1.2.4.1. From organic to regenerative agriculture

Early approaches to sustainable viticulture focused primarily on organic farming. However, recent trends emphasize regenerative practices that aim to restore soil health, increase biodiversity, and sequester carbon.

1.2.4.2. Integration of technology

Emerging technologies, such as precision viticulture and AI-based decision-making tools, are redefining sustainable vineyard management by enhancing resource efficiency and optimizing production (Garcia et al., 2023).

1.3. The Future of Sustainable Viticulture

Sustainable viticulture is crucial in addressing the pressing challenges of climate change, resource scarcity, and environmental degradation. The future of this discipline depends on integrating innovative practices and technologies with traditional knowledge systems to achieve economic viability, environmental protection, and social equity.

One significant trend shaping sustainable viticulture is the adoption of precision viticulture. Advanced technologies, including drones, remote sensing, and artificial intelligence, enable real-time monitoring of vineyard conditions. These tools facilitate targeted interventions that optimize water use, minimize pesticide applications, and enhance overall resource efficiency (Bramley et al., 2011). Furthermore, the increasing adoption of renewable energy sources and energy-efficient equipment is reducing the carbon footprint of grape production, making sustainability a core aspect of modern viticulture.

Agroecological practices form a crucial pillar for the future of sustainable viticulture. Techniques such as cover cropping, intercropping, and organic farming not only enhance soil health but also promote biodiversity, fostering a resilient vineyard ecosystem (Altieri, 1999). These methods align with the increasing consumer demand for eco-friendly and ethically produced wines, boosting market competitiveness.

Adapting to climate change will be essential. With shifting temperature and precipitation patterns, vineyard management must prioritize drought-resistant grape varieties, advanced irrigation systems, and effective canopy management techniques to maintain grape quality and yield under unpredictable conditions (Mozell and Thach, 2014). Additionally, exploring novel terroirs, such as higher altitude or latitude regions, offers opportunities to expand the geographical boundaries of viticulture and sustain production in the face of environmental change.

Collaborative efforts across the industry will be crucial to advancing sustainability. Certification programs, such as the Sustainable Wine Growing alliance, provide frameworks for implementing and verifying sustainable practices, thereby encouraging widespread adoption. Additionally, policies that promote research, education, and financial incentives will support grape growers in transitioning to more sustainable systems (Jones, 2004).

1.4. Conclusion

In conclusion, the future of sustainable viticulture will depend on the dynamic interplay of technological innovation, agroecological resilience, and collective commitment. By embracing these approaches, the viticulture industry can navigate emerging challenges and contribute to a more sustainable and equitable agricultural future.

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CHAPTER 14

CALCULATION OF COOLING LOAD OF EVAPORATIVE COOLING SYSTEM

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1.Introduction

The comfort, convenience and advantages created by the cooling technique of our age have entered many places and left their mark on many things. Now, many stages of our personal and social life have come under the domination of the cooling technique (Erol, 1993).

Cooling is the process of removing heat to reduce the temperature of a substance or environment below the temperature of the surrounding volume and maintain it there. The simplest and oldest form of cooling is to preserve ice formed by nature in cold regions and place them in hot or desired places to remove heat (Özkol, 1999).

Fruits and vegetables contain approximately 75-95% water and lose water during the storage phase depending on their respiration rate. Products that lose water become shriveled, wrinkled and lose quality as a result. As a general principle, fruits lose approximately 4-6% of water and vegetables lose 3-5%, causing them to wrinkle and lose their commercial value. In cold stores where design errors are made, low-surface coolers also cause excessive water loss from the fruits. In the cold stores where the fruit is stored, humidity should be between 90% and 95% with humidifiers, and in the cold stores, humidity should be increased either with humidifiers or by watering the wall surfaces and floor. The front of the coolers should always be left open and the return air should be circulated freely. Most of the food items to be stored in cold rooms are pre-cooled after being taken from their natural sources, cooled rapidly and then placed in long-term storage rooms, which extends the storage period of these items in the cold room (Özkol, 1999).

No matter how well the optimum storage conditions are provided, each fruit and vegetable can only last for a certain period of time. This period varies from a few days to 5-6 months. At the end of these storage periods specific to each product, the stored product rapidly loses its quality and eventually spoils completely. The most important factor in cold storage is the storage temperature. As a general principle, the temperature in storage is 1-2^{0}C above the freezing point of the stored fruit or vegetable (Cemeroğlu & Acar, 1986). Deep learning techniques were used to determine maturity of fruits (such as persimonn) (Kahya et al., 2023) and vegetables (such as pepper). before cold storage (Kahya et al., 2024).

Cold storage is the process of storing food at low temperatures between -5^{0}C and 0^{0}C. The mentioned low temperatures are achieved with cooling systems. It is a healthier storage method than freezing. Food cannot be stored for a long time in this way (Altınkurt et al., 1990).

Özkol (1999) states that heat exchange occurs in many parts of the cooling system during the cooling process and that heat transfer is the most important factor in the cooling area. He also explained that heat transfer occurs in almost every element of the cooling system, from the heat insulation of cold rooms to the evaporator and condenser design, from various types of materials stored in the cold room to the heat flows in the compressor body. First, he stated that the cooled environment itself is subject to heat transfer and that the reason for this is that the cooled environment is colder than the surrounding volumes and that the heat flows from the surrounding volumes to the cooled environment. He reported that the heat entering the cooled volume combines and multiplies with the heat present or occurring in the cold room itself and the heat from the external air circulation occurring when the door is opened. He also defines this total heat taken by the evaporator/cooler and transferred to the refrigerant as the "Cooling Load".

According to Erol (1993), it may not always be possible to determine all inputs of the cooling load of a system, therefore, some deviation in the magnitude of the cooling load can be expected and the point to be emphasized is to minimize the deviation.

It is explained as being able to choose the cooling system elements (compressor, condenser, evaporator, thermostatic expansion valve, refrigerant pipes and other cooling components) correctly and economically. It was also stated that with the correct choosing of cooling elements, the system will be able to operate efficiently, in a manner that meets expectations and without any problems for many years (Özkol, 1999).

Taner (1987) and Aybers (1992) explained that a good cooling load calculation is necessary for the ideal selection of the cooling system, emphasized that in a good cooling load calculation for a cold storage, full importance should be given to the cooling load sources suggested in nine items below.

The main and obvious sources of cooling load are listed as follows;

a- heat emitted from cooling materials,

b- heat transmitted through windows by radiation and conduction,

c- heat transmitted through walls, ceilings, floors, doors and pipe circuits,

d- open heat emitted from people,

e- heat emitted from electrical devices and machines,

f- heat generated by air leaking through doorways and wall cracks,

g- heat generated by fresh air brought in from outside,

h- latent heat,

i- heat emitted from other sources

Anonymus (1994) explained that when calculating the cooling load, the ambient temperature of the environment to be cooled, the condition in which the stored product will be taken to the cold storage, the daily working time (16-20 hours) and the product to be stored were important. It was reported that the type of system can be determined according to the working conditions of the cooling facility, the type of refrigerant to be used, the compressor capacity, the condenser and evaporator type.

Anonymus (1994-a) explained that the compressor, which will ensure the operation of the cooling system, is the heart of the system and performs the compression of the cooling gas. Among the compressor types, reciprocating compressors have a wide range of use in many different types of cooling facilities. These compressors are divided into two groups as hermetic and semi-hermetic. In hermetic type compressors, the compressor and the motor are located in a single sealed structure. This structural form allows the formation of a completely closed refrigerant system and is generally used in small cooling systems. In semi-hermetic type compressors, the motor is separate from the compressor and is driven by a belt-pulley or clutch. These types are used for larger cooling loads. Rotary compressors are used as first stage auxiliary compressors in large industrial facilities. Screw compressors are replacing rotary and reciprocating compressors in large, modern industrial facilities. These types of compressors are very suitable for automatic control and are a reliable compressor type with very little maintenance requirements. Centrifugal compressors are used in large industrial plants with refrigerants (such as R11) that require the passage of gas at low pressures and in large volumes through the compressor. These compressors are also used in plants with R12 and R717 (ammonia). These types work on the same principle as centrifugal pumps. As the fans rotate, the advancing gas is compressed.

Dağsöz (1981) stated that when R12 is used as a refrigerant in fully hermetic compressors, 0.52 to 6.3 m^3/h fluid circulates and 100...10000 frig/h cooling is achieved in operating conditions of -15^{o}C to -40^{o}C. It was stated that fully hermetic compressors are resistant to external stresses, have low refrigerant losses, operate without noise and are easy to replace in case of failure.

Vassogne (1986) stated that the gas compressed by the compressor in the system comes to the condenser and the condenser is where the refrigerant gas is liquefied. Since air or water is used to absorb the heat released as a result of the cooling and saturation of the superheated vapor coming out of the compressor and its subsequent condensation, condensers are divided into two main groups as air or water cooled. In addition, it is explained that condensers are also used in which the condensation heat is removed by means of another fluid that evaporates at a lower temperature than the condensation temperature of the refrigerant or by spraying water into the air.

Savaş (1987) stated that the compressor capacity should be at a value that can absorb the vapor movement volume of the refrigerant circuit and pump it to the condenser. Since the vapor movement volume is directly formed according to the system cooling capacity, the compressor capacity for any cooling circuit should be equal to the cooling capacity of the system. If the compressor capacity is smaller than the cooling capacity of the system, the evaporation temperature and therefore the evaporation pressure increase. As a result, sufficient cooling cannot be done and the compressor experiences compression and excessive strain. If the compressor capacity is larger than the cooling capacity of the system, the evaporation temperature and therefore the evaporation pressure decrease. Even the low-pressure side of the system may go into vacuum. If the vacuum of the low-pressure side goes down, the compressor's throat bellows and valve system packings may be overstressed by the effect of atmospheric air and atmospheric air may leak into the system. In this case, after a certain period of time, the refrigerant circulates in the air together with the refrigerant in the cooling circuit, which reduces the cooling effect and increases the condensation pressure. As a result, the system cannot cool at sufficient capacity and the compressor work increases, and at very low temperatures, evaporation in the cooling unit causes excessive frosting, which can damage food items stored in the volume being cooled. In a cooling circuit, the sum of the cooling capacity of the system and the compressor compression heat is equal to the condenser condensation heat.

Anonymus (1994) reported that the condensed gas leaving the condenser comes to the expansion valve and this valve allows the refrigerant gas to slowly escape to the low-pressure side of the system. Thermostatic expansion valve detects the level of superheat in the gas vapor leaving the evaporator. It is widely used in commercial type refrigerators. The automatic expansion valve is used to maintain a constant pressure in the evaporator. It is mostly produced for home refrigerators, water cooling systems and small air conditioning systems. In addition to these, capillary tubes are used to provide the desired pressure drop. It is explained that it is used in refrigerators, freezers, and even residential and small commercial air conditioning systems where the cooling load is constant. The refrigerant (liquid gas) whose pressure is reduced in the expansion valve comes to the evaporator. The function of the evaporator is to allow the liquid refrigerant to take heat from the cooling substance and thus to allow the refrigerant to evaporate and turn into gas. Therefore, the main task in the system is the evaporator.

Evaporators has three types as plate (sheet), bare tube and finned tube. The refrigerant is circulated in channels between two plates to provide a large cooling surface. It is widely used in home refrigerators. The bare tube type is sometimes used in cold rooms with natural air circulation on the tubes. The most commonly used evaporator type is the finned tube type. It has been reported that it is usually found in systems where air circulation is provided by a fan (Anonymus, 1994).

Bulgurcu et al. (1992) state that in the cooling system, the hot gaseous fluid is pressed into the condenser by the compressor in the discharge line. A pressure difference is created in the entire circuit and the fluid is allowed to circulate. In large systems, the oil is prevented from passing into the condenser by an oil separator connected to this line. Noise and vibrations are prevented by a silencer and vibration absorber. Liquid fluid entering the compressor from the condenser is prevented by a check valve.

Lovatt et al. (1998) used a model to simulate the performance of two large industrial refrigeration systems used for meat. A recently developed model for estimating the heat released during refrigeration and freezing provides a more accurate estimate of the performance of the freezers than older models.

Fikiin et al. (1999) used experimental engineering data and estimated equations for equivalent thermophysical properties (thermal conductivity, heat diffusivity, specific heat capacity and density) and surface heat transfer coefficient of fruits in cases.

Tashtoush (2000-a) investigated the natural losses in fruits and vegetables stored under cold conditions. A mathematical model was defined that took into account heat and mass transfer during storage and the equations obtained using the results were solved using the MathCad 7 program.

Tashtoush (2000-b) investigated heat and mass transfer processes during cold storage of vegetables and fruits. A mathematical model representing these processes was defined and the equations obtained from the results were solved for different storage conditions. The relative humidity and temperature of the air blown into the environment and the temperature of the stored product volume were found for different air speeds and air humidities.

Meunier et al. (1998) explained that temperature-entropy diagrams are commonly used to describe heat-driven engines, such as vapor-compression refrigerators, but have not yet been used in sorption refrigeration systems. The Carnot cycle is presented here to describe the three sorption refrigeration technologies (liquid absorption, solid absorption, chemical reaction).

Al-Nimr et al. (1999) gave a description of a mathematical model for the modified Australian cooling system. The modified Australian cooling system is a night cold storage developed from a radiative cooling system. An analytical, closed-form solution is presented to estimate the temperature of the modified system. It was found that the theoretical results are in very good agreement with the experimental results.

Bakker-Arkema et al. (1999) discussed absorption cooling, secondary coolers, cooling load calculations, alternative cooling sources, small-sized cooling tanks, controlled atmosphere storage, measurement systems, safety and cooling equipment.

2. Design of Cold Stores with Evaporative Cooling System

The circuit diagram of the evaporative cooling system is given in Figure 1 below.

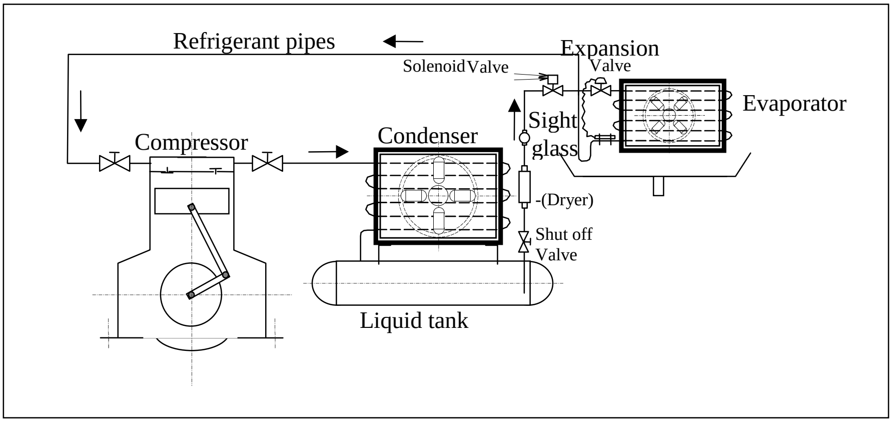

Figure 1. Cooling cycle components

In the cooling cycle; the compressor compresses the refrigerant gas in vapor form and increases its enthalpy. The compressor does work on the system. The compressed refrigerant vapor comes to the condenser and the heat of the refrigerant is taken from the atmospheric air. Thus, the refrigerant is condensed. The refrigerant that has become liquid is stored in the liquid tank. The liquid tank stores the excess fluid that can be used. The dryer located in the condensation line helps to retain foreign substances and sediments in the refrigerant and absorbs moisture. The liquid sight glass in the condensation line allows the amount of refrigerant to be easily controlled (The refrigerant charge is checked by looking at the sight glass. Bubbles in the refrigerant indicate that the gas is insufficient). The liquid refrigerant gas comes to the expansion valve. The expansion valve comes before the evaporator in the high-pressure region. The place that allows the restricted fluid to evaporate freely is the evaporator. The necessary heat is taken from the environment to be cooled in this element. The place where the refrigerant gas reaches the expansion valve is in the high-pressure region and this region forms the discharge line. After the expansion valve, the place where the refrigerant reaches the compressor is in the low-pressure region and this region forms the suction line (Erol, 1993).

2.1. Calculation of cooling load (Heat balance)

In cold storage, the monthly average air temperatures of the hottest month are taken into account when determining the outside temperature. In order to calculate the cooling load, the heat emitted by the heat sources in the storage are determined and added together. The total heat amount in the cold storage consists of the transmission heat (q1), infiltration heat (q2), product heat (q3), heat from other heat sources (q4) and unknown and unexpected heat gains (q5) (Özkol, 1999).

The basic parameters used in the calculation of the cooling load, such as the number of cases that can be placed in the cold store and how the product quantity is calculated, are given in the formulas below (Güzel et al., 1996).

$$K_s = \frac{0.8.a.b}{k_e.k_b} \cdot \frac{\left(h-\left(l_{tv}+l_{tb}\right)\right)}{k_y} \qquad (1)$$

K_s = Total number of cases to be placed in the cold store (pieces)

a = Cold store width (m)

b = Cold store length (m)

k_e = Case width (m)

k_b = Case length (m)

l_{tv}=Space to be left between the cold store ceiling and the top case (m)

l_{tb}= Space between the cold store floor and the case bottom (m)

h= Total cold store height (m)

k_y= Case height (m)

The amount of product to be placed in the cold store;

$$M = Ks * Mk \qquad (2)$$

M = Amount of product to be placed in the cold store (kg)
M_k = Product that a case can hold (kg/case)

2.1.1. Transmission heat-q1)

In order to calculate the transmission heat, the thickness and type of the insulation material, the building construction, the physical dimensions and temperature of the volume to be cooled, the temperatures of the external volumes and the effect of sunlight must be known. The amount of heat generated by transmission from walls and floors and the temperature difference are calculated with the following formulas (Güzel et al., 1996).

$$q_1 = \sum_{i=1}^{n} k_i . A_i . \Delta t_i \qquad (3)$$

$$\Delta t_i = t_{o_i} - t_{d_i} \qquad (4)$$

q_1=Heat generated by conduction through walls, ceiling and floors (kJ/h)
k_i = Total heat transfer coefficient (kJ/m^{2}h^{o}C)
A_i = Total surface area for each section of the cold store (ceiling, walls, floor) (m^2)
Δt_i = Temperature difference (^{0}C)
t_o = Outdoor temperature (^{0}C)
t_i = Indoor temperature (^{0}C)

Since the cold store surfaces are multilayer surfaces with thermal insulation material, the heat transfer coefficient is found from the following equation valid for multilayer flat surfaces (Güzel et al., 1996).

$$\frac{1}{k_i} = \frac{1}{\alpha_{o_i}} + \frac{L_{1i}}{\lambda_{1_i}} + \frac{L_{2i}}{\lambda_{2_i}} + \frac{L_{3i}}{\lambda_{3_i}} + \ldots + \frac{L_{ni}}{\lambda_{n_i}} + \frac{1}{\alpha_{i_i}} \qquad (5)$$

k_i= Heat transfer coefficient (kJ/m^{2}h ^{o}C)
$L_{1i}, L_{2i}, \ldots, L_{ni}$ = Material thickness (m)
α_o= External surface heat convection coefficient (kJ/m^{2}h ^{o}C)
α_i= Internal surface heat convection coefficient (kJ/m^{2}h ^{o}C)

λ_{1i}, λ_{2i},..., λ_{ni}= Material heat transfer coefficient (kJ/m h °C)

Calculations for a sample cold store were given in this research. The wall dimensions used in the calculations are given in Table 1, the type, thickness and heat conduction coefficients of the materials forming the side walls of the cold store are given in Table 2, the type, thickness and heat conduction coefficients of the materials forming the floor are given in Table 3, the type, thickness and heat conduction coefficients of the materials forming the ceiling are given in Table 3, heat conduction coefficients are given in Table 4, heat convection coefficients of the storage surfaces are given in Tables 5 and 6, values of the solar radiation effect as temperature differences for light colored wall facades and surface colors are given in Table 7, and neighboring volume temperature differences are given in Table 8.

Table 1. Values used in the calculation of the amount of heat generated by conduction through walls, ceilings and floors

Surface Type	Width (m)	Length (m)	Surface area (m^2)	k (kJ/m^2h^oC)	$\Delta t(^oC)$ (apple)
North outer wall(1)	1.90	2.22	4.218	1.071	30
South inner wall(2)	1.90	2,22	4.218	1.047	35
West inner wall (3)	2.22	4.52	10.034	1.047	30
East outer wall (4)	2.22	4.52	10.034	1.071	33
Base (5)	1.90	4.52	8.588	3.125	12
Ceiling (6)	1.90	4.52	8.588	2.983	30

Table 2. Type, thickness, heat conduction coefficients of the materials forming the side walls of the cold store (Özkol, 1999, Erol, 1993)

Surface Type	Material thickness (L) (m)	Heat conduction coefficients (λ)(kJ/m^{2}h^{o}C)
Lime plaster	0.03	3.138
Reinforced Concrete	0.10	5.021
Screed concrete	0.03	5.021
Perforated brick	0.12	1.883
Screed concrete	0.03	5.021
Bitumen	0.005	0.627
Foamglass	0.12	0.159
Screed concrete	0.06	5.021
Tiles	0.03	3.765
Total	0.525	-

Table 3. Type, thickness, heat conduction coefficients of the materials forming the base (Özkol, 1999, Erol, 1993)

Surface Type	L(m)	λ(kJ/m^{2}h^{o}C)	L/λ
Tile mosaic	0.030	3.765	0.079
Screed concrete	0.030	5.021	0.005
Foamglass	0,120	1.883	0.063
Bitumen	0,005	0.627	0.007
Gro concrete	0,100	4.602	0.021
Blockage	0,150	6.276	0.023
Total	0,435		0.198

Table 4. Type, thickness, heat conduction coefficients of the materials forming the ceiling (Özkol, 1999)

Surface Type	L(m)	$\lambda(kJ/m^2h^oC)$	l/λ
Screed concrete	0.03	3.765	0.079
Foamglass	0.12	1.883	0.063
Gro concrete	0.10	4.602	0.021
Lime (mortar)	0.03	3.135	0.009
Total	0.28		0.102

Table 5. Heat convection coefficients for non-reflecting, opaque surfaces (Özkol, 1999)

Non-reflective, opaque surfaces	Heat convection coefficients
Building interior surfaces (Walls, interior and exterior windows)	29.28
Building exterior surfaces (surfaces exposed to outside air)	83.68 (12 km/h wind velocity)
Floor and ceiling (if heat passes from top to bottom)	20.92

Table 6. Heat convection coefficients of Cold store surfaces (Savaş, 1987)

Heat convection coefficients $(kcal/m^2h^oC)$	North inner wall (1)	South inner wall (2)	West inner wall (3)	East outer wall (4)	Base (5)	Ceiling (6)
α_i	29.28	29.28	29.28	29.28	20.92	29.28
α_o	83.68	29.28	29.28	83.68	∞	29.28

Table 7. Values of the solar radiation effect as temperature differences (Δt) for light-colored wall facades and surface colors (Erol, 1993)

East	South	Roof
3°C	2°C	9°C

In the calculations, the internal temperature of the cold store was taken as +3°C for apples (Cemeroğlu and Acar, 1986, Anonymus, 1981, Özer, 1995, Ekinci, 2001). In addition, the external dry bulb temperature for Tekirdağ was taken as 33°C and the wet bulb temperature was taken as 25°C (Erol, 1993, Özkol, 1999). The temperatures of the neighboring volumes or the difference with the local outdoor air temperature and the floor temperatures of the volumes sitting on the earth floor are as follows (Özkol, 1999).

Table 8. Temperatures of the neighboring volumes or the difference with the local outdoor air temperature and the floor temperatures of the volumes sitting on the earth floor (Özkol, 1999)

	Temperature (°C)
For cold stores, workshops, etc. that are not forcibly ventilated	0
For compressor engine room (air condenser)	5
Soil-laying for hot-cold climates	15

The insulation thickness was taken as 120 mm to use foamglass in the range of (-4,+4) as cork equivalent, considering Tekirdağ as a cool region and for future research (www.foaminsulation.com).

Depending on the location of the walls (inside/outside the building), the neighboring volume temperature values given above were added to the internal and external temperature differences (Table 9).

Table 9. Temperature differences for the cold store surfaces

Temperature (°C)	Cold store surfaces					
	North outer wall (1)	South inner wall (2)	West inner wall (3)	East outer wall (4)	Base (5)	Ceiling (6)
Cold store temperature (t_i)	3	3	3	3	3	3
Outdoor temperature (t_o)	33	33	33	15	15	33
Neighboring volume temperature (t_{kom})	-	5	0	3	-	-
Temperature difference (Δt)	(33-3) 30	(33-3+5) 35	(33-3) 30	(33-3+3) 33	(15-3) 12	(33-3) 30

2.1.2. Infiltration heat (q_2)

In many cases, cracks or similar defects may occur in units such as doors, windows or walls of the places where cooling or air conditioning conditions are provided. The air mass that has managed to infiltrate into the refrigeration or air conditioning spaces in such ways causes a certain heat load. In addition to this, the opening and closing of the doors of the refrigeration rooms causes the air inside to go outside and the air outside to come in. The removal of the incoming air mass to room conditions causes a certain heat load. This heat load is calculated by the following formula (Erol, 1993).

$$q_2 = c.z.\ V.\ \gamma.(t_o - t_i) \qquad (6)$$

q_2= Heat generated by leakage and exchange air (kJ/h)
c= Specific heat of humid air (1.025kJ / kg ^{0}C) (Erol, 1993)
z= Number of air changes per day (20 is taken) (Erol, 1993)
γ= Specific gravity of leakage air (kg/m^3) (for 35 ^{0}C) (Savaş, 1987)
V= Room volume (m^3)
t_o= Temperature of outside air entering from adjacent volume (^{0}C)
t_i= Cold storage temperature (^{0}C)

Values used in calculating heat generated by leakage and exchange air are given in Table 10.

Table 10. Values used in calculating heat generated by leakage and exchange air

V	*c*	*γ*	*z*	t_d	t_i
m^3	kJ/ kg^{0}C	kg/m^3		^{0}C	^{0}C
19.06	1.025	1.121	20	35	3

2.1.3. Heat load caused by products placed in the refrigerated volume (q3)

The cooling load created by goods placed in cold storage is calculated in two stages.

1- Cooling of fruits at temperatures above freezing point ($q3_1$)

2- Heat generated during storage, ripening heat ($q3_2$)

The cooling load created by goods placed in cold storage (q3) can be calculated with the formula below.

$$q3 = q3_1 + q3_2 \qquad (7)$$

$q3_1$= Fruits cooling at temperatures above freezing point
$q3_2$= Heat generated during storage, ripening temperature
The amount of heat required to cool the daily loaded product to the storage temperature and the heat released by reducing the temperature of the product to be stored from t_o to t_i,

$$q_{31} = (G_k c_k + G_{ü} c_{ü}).(t_o - t_i) \qquad (8)$$

$q3_1$ = Heat Radiated from Materials to be Cooled (kJ/day)
$G_ü$ = Daily incoming product amount (kg)
$c_ü$ = Specific heat of product (kJ/kg^{0}C)
Gk = Daily incoming cases weight (kg)
c_k = Specific heat of case material (kJ/kg^{0}C)
t_o = Outdoor temperature (^{0}C)
t_i = Indoor temperature (^{0}C)

The specific heat of the product ($C_{ü}$) is given in table 11.

Table 11. Specific heat (Heating heat) for various products (Cü.) (Cemeroğlu and Acar, 1986, Özkol, 1999)

	Apple
Specific heat (kJ/kg^{0}C)	3.68

The temperature values given in Table 12 were used for the temperatures used in the calculations.

Table 12. Temperature values of the stored product (Erol, 1993)

	Apple
Storage temperature (t_i) (^{o}C)	3
Inlet temperature to the cold store (t_o)(^{o}C)	15

The total daily incoming case weight (Gk) is calculated using the following method;

$$Gk= ks*ka \qquad (9)$$

ks = Total number of cases that can be placed in the cold store

ka = Weight of a case (kg)

In case specific heat (Ck) calculations, 2.51 kJ/kg^{o}C can be taken for a wooden case (Cemeroğlu and Acar, 1986).

The heat generated during storage is defined as ripening heat and is calculated from the formula below.

$$q3_2 = Gü.\, c_s \qquad (10)$$

$q3_2$= Maturation temperature (kJ/24h)

c_s= Respiration temperature of the product during storage (kJ/t-24h)

The respiratory heat value (c_s) for the products used in the research is given in Table 13.

Table 13. Respiratory heat (c_s)(kJ/t-24h) (Özkol, 1999)

	Storage temperatures(°C)			
	0^0C	5^0C	3^0C	1^0C
Apple	794.9-941.4 (Mean 868.1)	1171.5-1652.6 (Mean 1412.1)	1194.5	-

All values used in the calculations are given in Table 14.

Table 14. Values used in calculating the heat emitted from the products to be cooled

	Gü (kg)	Cü (kJ/kg°C)	Gk (kg)	c_k (kJ/kg°C)	c_s (kJ/t-24-h)	t_o (°C)	t_i (°C)	Δt (°C)
Apple	2256	3.68	288	2.51	1194.5	15	3	12

2.1.4. Heat from heat sources inside the cooled volume (people, lighting, engine, etc. -q_4)

The equivalent heat energy (q4) of people working in the cold store, lighting, electric defrosting and ventilation systems is calculated as follows (Cemeroğlu and Acar, 1986, Özkol, 1999, Erol, 1993).

$$q4=q4_1+q4_2+q4_3+q4_4 \quad (11)$$

$$q4_1= n.c_i.t_1 \quad (12)$$

$q4_1$= Heat load emitted from people working in the cold store (kJ/day)
n= Number of people (It was assumed as 1)
c_i= Cold room heat load from people (kJ/h-person) (Özkol, 1999).
t_1= Daily average working time of people in the cold store, (1 h/day)

The heat emitted from humans is given in Table 15.

Table 15. Heat emitted from adult humans (Ci)(kJ/h-person)

			Interpolation	
	0(°C)	5(°C)	3(°C)	1(°C)
c_i (kJ/h-kişi)	983.2	878.6	1046.0	1004.1

$$q_{42}=3600*N_{ay}(kW)*t_2 \text{ (h/gün)} \quad (13)$$

$q4_2$= Heat generated in the cold store due to lighting (kJ/day)
3600=Heat equivalent conversion factor of work (kJ/kWh)
N_{ay}= Installed power of lighting facility (kW) (0.020kW)
t_2= Daily working time of lighting facility (h/day) (2h/day)

$$q4_3=3600*N_v*t_3 \quad (14)$$

$q4_3$= Heat load from ventilation (kJ/day)
N_v= Installed power of ventilation facility (kW) (0.185kW)
t_3= Daily operating time of ventilation facility (20 h/day)

$$q4_4= 3600*n*W*t_4*F \quad (15)$$

$q4_4$ = Heat given during electrical defrost (kJ/day)
n = Number of electrical defrost heaters (number) (2 units)
W = Electrical heater power (kW) (0.001kW)
t_4 = Daily defrost duration (h/day)
F = Defrost factor (Part of electrical energy entering the cold store as heat load (0.5 is taken)

2. 1.5. Effect of unknown and unexpected heat gains (q_5)

In the determinations related to the environment, after the heat gains that constitute the heat load were calculated, a 10% safety margin was added to include the effect of unknown and unexpected heat gains and a 24/20-time factor is added to the heat load, taking into account that the system will operate for 20 hours per day (Cemeroğlu and Acar, 1986, Özkol, 1999, Erol, 1993).

$$q_5 = 0.1.(q_1 + q_2 + q_3 + q_4) \quad (16)$$

q_5 = Unknown and unexpected heat load (kJ/day)
Q_K =(24/20)*(q1+q2+q3+q4+q5 (17)
Q_K = Total heat load to be removed (kJ/day)
24/20 = Time factor

2.2. Compressor, condenser and evaporator selection

In order to provide cold storage regime with a single stage cooling circuit, condensation temperature is generally taken as +30°C and evaporation temperature as –10°C in temperate climate regions. The theoretical refrigeration cycle pressure-enthalpy diagram is given in Figure 2. There is a pressure-enthalpy diagram for each refrigerant gas. Considering the diagram related to R404A gas used in the experiment, specific heat load of the evaporator, evaporation capacity of the evaporator, amount of refrigerant circulating in the system, specific heat load of the condenser, evaporation capacity of the condenser, compression heat of the compressor, practical power and theoretical power, operating coefficient (ε) were calculated (Dağsöz, 1981, Savaş, S., 1987).

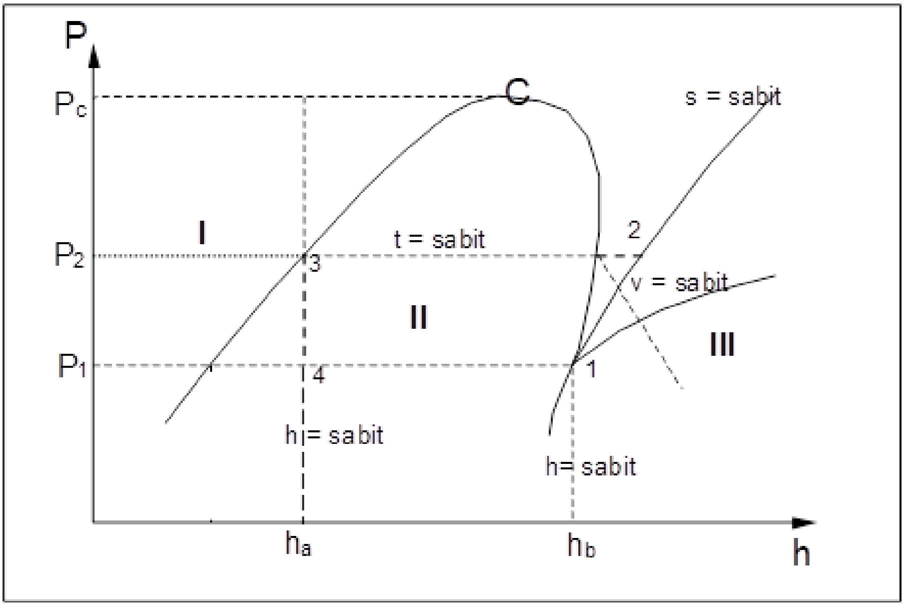

Figure 2. Pressure-enthalpy diagram of the refrigeration cycle (Dağsöz, 1981)

2.2.1. Compressor capacity calculation

Compressor capacity is equivalent to the amount of heat to be drawn from the cold storage unit in a unit time. If a compressor is to be used in a cooling facility, the compressor capacity is determined according to the daily operating time (tç) depending on the repair, maintenance and rest allowance. The total daily operating time is understood as the operating time of the cooling compressor. This period depends on the room temperature and evaporator temperatures and the defrosting period planned to be done per day. The total daily operating time of the compressors can be taken as 14 to 20, sometimes 22 hours. Since the products placed in the cold storage will be stored at 10C to 30C and automatic defrosting will be used, 20 hours was selected as the operating time of the compressor (Özkol, 1999).

Compressor capacity is taken as equal to the total heat load to be removed. The work done on the system in the compressor is calculated with the following formula.

$$L = (h_2 - h_1) \tag{18}$$

L = Work done on the system in the compressor (kJ/h)

h_1 = Enthalpy value of point 1 (kJ/kg)

h_2 = Enthalpy value of point 2 (kJ/kg)

$$q_k = G.L \tag{19}$$

q_k =Theoretical heat of compression (kJ/h)

G = Amount of refrigerant (kg/h)

$$Wt = \frac{q_k}{860} \tag{20}$$

860 = İşin ısısal eşdeğeri

W_t = Compressor theoretical power (kW)

860 = Thermal equivalent of work

After the theoretical power calculation is made, the practical power of the compressor can also be calculated.

Practical power or consumption power

$$W_p = W_t . \frac{1}{\eta_i} . \frac{1}{\eta_m} \tag{21}$$

W_p = Practical Power (kW)

η_i = Indicated efficiency (85%)

η_m = Mechanical efficiency (85%)

Power of the compressor drive motor depending on practical power

The drive motor power for starting with a triangle switch is calculated by formula 22.

$$W_m = 1{,}35.\ W_p \qquad (22)$$

Wm = Power of the drive motor (kW)

2.2.2. Calculation of refrigerant amount

The amount of refrigerant is calculated by the following formula.

$$G = \frac{QK}{h_1 - h_3} \qquad (23)$$

G = Refrigerant amount (kg/h)

QK = Cooling load of the system (kJ/h)

h_1 = Enthalpy value of point 1 (kJ/kg)

h_3 = Enthalpy value of point 3 (kJ/kg)

2.2.3. Determination of specific heat load and capacity of the evaporator

According to the accepted evaporation and condensation temperatures, the enthalpy values for R404A are found from the Mollier diagram and the specific heat load of the evaporator is calculated with the formula below (Ersoydan, 1967, Dağsöz, 1981).

$$q_b = h_1 - h_3 \qquad (24)$$

q_b = Specific heat load of evaporator (kJ/kg)

Since $i_1 > i_3$, the q_b value is positive. In other words, it shows that the system is receiving heat.

The evaporator capacity is equal to the total heat load to be removed. This cooling load is taken by the evaporator, transferred to the refrigerant and compressed by the compressor. The evaporation temperature should be at most 10^0C to 15^0C below the cold storage regime temperature. Therefore, since the internal storage temperature is 3^0C and the cold storage is in a temperate climate region, an evaporation temperature of -10^0C can be accepted.

$$Q_b = QK = G.\, q_b \qquad (25)$$

Q_b=Evaporator capacity (kJ/h)

6.1.2.4. Determination of specific heat load and capacity of the condenser

The specific heat load of the condenser was calculated according to the enthalpy values found from the Mollier diagrams for R404A according to evaporation and condensation temperatures.

$$q_y = h_3 - h_2 \qquad (26)$$

q_y= Specific heat load of the condenser (kJ/kg)

The q_y value is negative because $i_2 > i_3$. It shows that the system loses heat along the 2-3 line.

$$Q_y = G.q_y \qquad (27)$$

Q_y=Condenser capacity (kJ/h)

G= Refrigerant amount (kg/h)

In practice, the condenser capacity was taken as equal to 15% more than the hourly heat loss (cooling load).

$$Q_y = 1.15.QK \qquad (28)$$

2.2.5. Cooling effect

The main purpose of cooling systems is to extract as much heat as possible from the cold source and expel it. In vapor compression cycles, consuming the least amount of work in return for this heat to be expelled depends on the high operating coefficient. The cooling effect is calculated as (%) with the formula below.

$$\varepsilon = \frac{h_1 - h_3}{h_2 - h_1} \qquad (29)$$

ε: Cooling effect

h_1, …, h_4: Enthalpy values of points 1, 2, 3 and 4

The expected cooling load from the cooling system can be determined by calculating the cooling load from the given tables and formulaes, accurately. In addition, the cooling load calculation plays an important role in the choosing of cooling system elements in terms of costs.

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CHAPTER 15

THE CONTRIBUTION OF SMART TECHNOLOGIES TO SUSTAINABLE PRODUCTION IN DIGITALIZED AGRICULTURE

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1. Introduction

Digitalization leads to a groundbreaking transformation in the modern agricultural sector, providing an opportunity to move beyond traditional production methods. Integrating digitalization and smart technologies into agriculture not only increases production efficiency but also generates innovative solutions that support environmental sustainability, economic profitability, and rural development goals (Ciruela-Lorenzo et al., 2020; Mondejar et al., 2021). With the rapid growth of the world population and the increasing impacts of climate change, the development of more efficient, environmentally friendly, and sustainable methods in agricultural production has become essential. In this context, digitalized agriculture stands out as a critical tool for achieving sustainability goals (MacPherson et al., 2022).

Digitalization in agriculture encompasses collection, analysis, and decision-making based on data using smart technologies. Smart technologies integrate advanced tools such as the Internet of Things (IoT), big data, artificial intelligence, machine learning, drones, satellite imaging, and sensor systems into the agricultural sector, enhancing productivity while reducing environmental impacts (Nimbalkar et al., 2020). For example, with smart sensors, factors like soil moisture, air temperature, and plant health can be monitored in real time, enabling irrigation or fertilization only as needed (Paul et al., 2022). Such applications contribute directly to environmental sustainability by conserving water and energy, thereby reducing the environmental burden of agricultural production (Kamilaris et al., 2017; Wolfert et al., 2017; Liakos et al., 2018).

Digital agriculture applications supported by smart technologies offer significant contributions across the three main dimensions of sustainability: environmental, economic, and social sustainability (Hrustek, 2020). In terms of environmental sustainability, digital agriculture minimizes natural resource consumption and reduces greenhouse gas emissions (Balafoutis et al. 2017). From an economic sustainability perspective, smart technologies enable farmers to reduce production costs, optimize resource use, and achieve higher efficiency. In terms of social sustainability, digitalized agriculture supports rural development, provides higher-quality employment opportunities in the agricultural sector, and increases the income of farmers living in rural areas (Metta et al. 2022).

Moreover, the importance of smart farming applications in combating climate change is increasing. AI-supported analyses and satellite imaging systems enable the optimization of agricultural processes based on climatic conditions (Sishodia et al. 2020). These technologies facilitate early action by predicting climate risks, thereby enhancing the adaptive capacity of agricultural production to climate change. In this way, digitalization not only boosts efficiency but also contributes to making agricultural production more resilient in the face of climate change (Klerkx et al. 2019).

In this study, the contributions of smart technologies used in digitalized agriculture to sustainable production will be examined in detail. The advantages provided in environmental, economic, and social dimensions will be evaluated, and how digitalization supports agricultural sustainability will be analyzed. Modern agriculture, shaped by digitalization and smart technologies, has the potential to offer a sustainable food production model for both present and future generations.

2. The Need for Digitalization and Sustainability in Agriculture

The rapid growth of the world population, the depletion of natural resources, and the increasingly evident impacts of climate change on agriculture have made the need for sustainable production more urgent than ever (Foley et al. 2011). Although the agricultural sector is crucial for global food security, it also has negative effects on environmental sustainability due to high consumption of natural resources like water, energy, and soil and the use of chemical inputs in production processes. Meeting the rising food demands through agricultural production in a sustainable manner requires going beyond traditional methods and using more intelligent, efficient technologies (Godfray et al. 2010).

At this point, digitalization emerges as a key solution for achieving sustainability in the agricultural sector. Digital technologies provide the capacity to collect, analyze, and process data that is difficult to obtain through traditional agricultural methods, enabling smarter and more environmentally friendly production processes (Wolfert et al. 2017). Digitalization allows farmers to manage their production processes with much greater precision, optimizing the use of water, fertilizers, and energy, thereby reducing environmental impact. In this way, digitalization not only increases agricultural productivity but also supports sustainable production by reducing the environmental footprint of the agricultural sector (Balafoutis et al. 2017).

One of the most significant advantages of using digital technologies in agriculture is their ability to promote more efficient use of natural resources. For instance, with smart sensors, factors such as soil moisture, temperature, and nutrient levels can be monitored in real time, allowing for irrigation or fertilization only as needed (Jayaraman et al. 2016). These practices reduce water consumption, protect soil health, and contribute to long-term productivity. Additionally, drones and satellite imaging technologies enable easy monitoring of large agricultural areas, allowing for continuous assessment of plant health and timely intervention when necessary. Digitalization transforms the production process into a traceable and sustainable structure, making a significant contribution to environmental sustainability (Tzounis et al. 2017).

The role of digitalization in sustainable agriculture is not limited to environmental impacts; it also has a broad scope in terms of economic and social sustainability. Innovations brought by digitalization in the agricultural sector enable the reduction of production costs and an increase in efficiency. For example, data-based analyses such as soil analysis data or weather forecasts allow farmers to make more efficient production planning and optimize their costs. Additionally, digital agriculture applications increase farmers' access to information in rural areas, providing them with essential support in decision-making processes. This enables farmers to make more informed production decisions while also supporting rural development (Bronson and Knezevic 2016).

Moreover, data-based analyses facilitated by digitalization offer a significant advantage in helping agricultural production adapt to climate change. Climate change frequently poses threats in the agricultural sector, such as extreme weather events, droughts, or sudden temperature changes (Jayaraman et al. 2016). Digital agricultural technologies have the capacity to forecast these changes in advance through weather predictions, soil temperature, and moisture-based analyses, aiding farmers in developing production strategies suited to climate conditions. Thus, digitalization not only provides an environmentally friendly production model but also enhances the resilience of agricultural production against the adverse effects of climate change (Liakos et al. 2018).

Digitalization presents modern and innovative solutions to ensure sustainability in the agricultural sector. Smart technologies used in agriculture help protect natural resources, reduce environmental impacts, and improve agricultural efficiency, while also strengthening farmers economically and contributing to rural development. Sustainable agriculture supported by digitalization has the potential not only to meet current food demands but also to create a healthy, efficient, and environmentally friendly agricultural production model for future generations (Tilman et al. 2011).

2.1. Use of Smart Technologies in Agricultural Production

In the digitalization process, the agricultural sector has begun to use many smart technologies to enhance efficiency and sustainability (Jayaraman et al. 2016). Smart farming technologies provide the opportunity to manage agricultural production more precisely and effectively through data collection, analysis, and data-driven decision-making processes. These technologies have a wide range of impacts, from improving soil health and conserving water to optimizing energy use and reducing environmental impact. Below are some of the key smart technologies frequently used in agricultural production and their functions (Sishodia et al. 2020).

2.1.1. Internet of Things (IoT) and Sensor Technologies

The Internet of Things (IoT) is a technology that enables devices to communicate with each other via the internet. In the agricultural sector, IoT sensors measure parameters such as soil moisture, temperature, weather conditions, and water quality, providing real-time data. These sensors monitor factors like soil moisture or nutrient levels, indicating the optimal times for irrigation and fertilization to farmers (Balafoutis et al. 2017). This ensures the use of only the required amount of resources, conserving water and fertilizers. This data-driven approach not only reduces costs but also supports environmental sustainability. It offers advantages such as optimized water consumption, continuous monitoring of plant health, and increased efficiency in agricultural activities.

2.1.2. Drones and Satellite Imaging Technologies

Drones and satellite imaging technologies are among the most transformative tools in modern agriculture, each serving unique purposes. Drones are particularly effective for field-level monitoring. They capture high-resolution images, collect data on crop health, detect irrigation needs, and identify localized issues such as pest infestations. Equipped with advanced sensors, drones scan fields and provide precise data on soil conditions and plant health, enabling timely and targeted interventions (Zhang and Kovacs 2012).

Satellite imaging, in contrast, offers a broader view, enabling the monitoring of larger agricultural areas over time. Satellites provide consistent and repeatable data on vegetation health, water resource distribution, and overall field conditions. This macro-level perspective is invaluable for long-term agricultural planning and resource management (Zhang and Kovacs

2012). Satellite data is often complemented by the detailed, real-time insights provided by drones.

As shown in Figure 1, drones and satellites play distinct but complementary roles in agricultural monitoring. Drones excel at collecting detailed, localized data, while satellites provide large-scale, long-term observations. This combination supports precision agriculture by enhancing resource efficiency, improving decision-making processes, and enabling timely interventions to address risks and challenges.

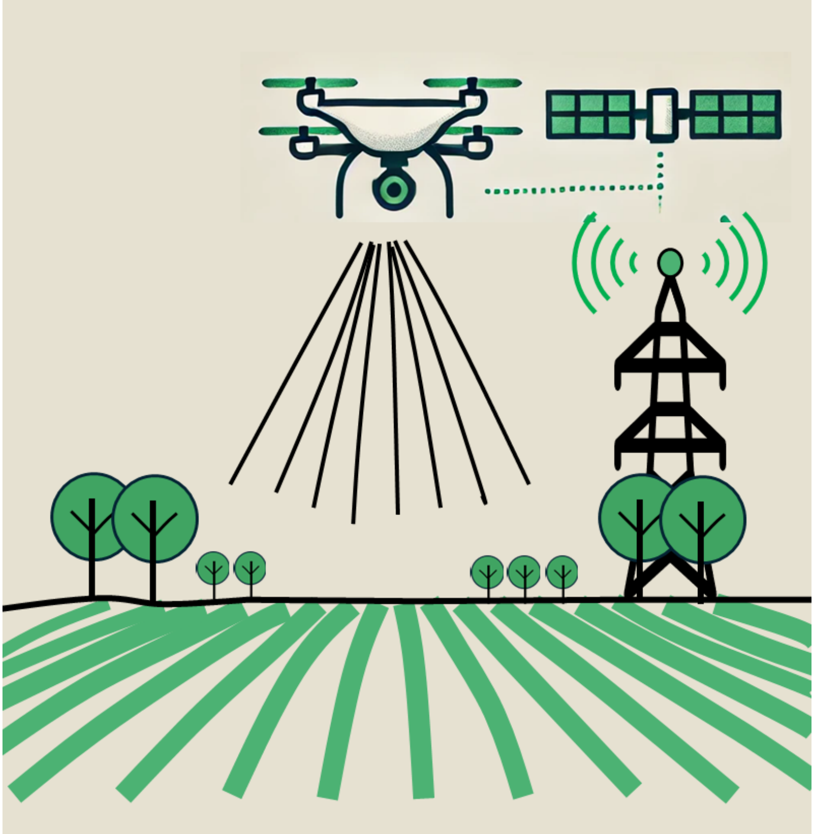

Figure 1. Drones and satellites support agricultural monitoring by providing complementary data. Drones focus on field-level details, while satellites offer a macro perspective for large-scale analysis.

2.1.3. Artificial Intelligence (AI) and Machine Learning

Artificial intelligence (AI) and machine learning are transformative technologies that significantly enhance decision-making processes in agriculture. Originally emerging as a scientific discipline in the mid-20th century, AI began to gain prominence with Alan Turing’s seminal work, including the "Turing Test" in the 1950s (Turing, 2009). Initially focused on mathematical models and computation, AI has evolved to integrate advanced techniques such as machine learning and data mining, making it an integral part of industries like agriculture.

The integration of AI into agriculture gained momentum in the 2000s, driven by advancements in data processing algorithms and the growing availability of big data. AI systems now work alongside sensor technologies, remote sensing tools, and the Internet of Things (IoT) to optimize agricultural processes, improve efficiency, and enable better decision-making.

AI applications analyze factors such as weather forecasts, soil conditions, plant growth patterns, and disease risks, offering farmers actionable insights. For example, machine learning algorithms can process data from soil moisture sensors to predict optimal irrigation schedules and water quantities (Togneri et al., 2022). By dynamically adjusting irrigation strategies to current conditions, AI contributes to water conservation and increased crop productivity. Additionally, AI systems are capable of analyzing thermal camera data and sensor inputs to detect plant diseases, pests, or physiological stress early, allowing timely interventions and minimizing potential losses (Orchi et al., 2021).

As illustrated in Figure 2, AI-driven systems process data from various sensors—such as humidity, temperature, and soil moisture—to create predictive models for plant growth and disease risks. These insights enable farmers to adapt their practices proactively, mitigate the effects of climate change, and enhance resource efficiency (Liakos et al., 2018). Moreover, AI-based decision support systems not only optimize irrigation and fertilization strategies but also contribute to sustainable water use and cost reductions in agriculture.

In conclusion, AI-powered technologies are revolutionizing agricultural production by making processes more predictable, efficient, and sustainable. They minimize resource waste, enhance productivity, and provide farmers with tools to make informed, data-driven decisions (Wolfert et al., 2017). By integrating AI with emerging technologies like IoT and remote sensing, agriculture is moving towards a more resilient and sustainable future.

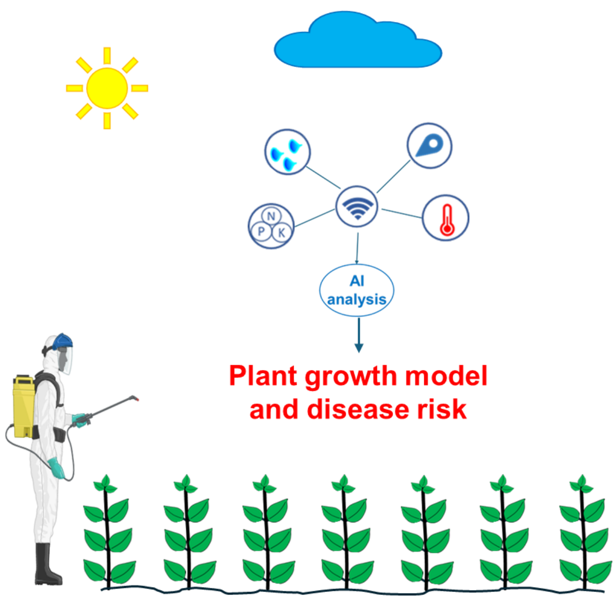

Figure 2. AI-based systems process data from sensors to predict plant growth and disease risks, enabling precise and proactive interventions.

2.1.4. Robotic Systems and Automation

Robotic systems are devices capable of automatically performing agricultural activities such as planting, irrigation, pesticide application, and harvesting. Automation technologies allow these activities to be conducted without the need for human intervention. Robotic systems are especially used in large agricultural enterprises throughout the processes from planting to harvest (Duckett et al. 2018). For example, planting machines can precisely place seeds, while robotic harvesting machines can pick fruits and vegetables without causing damage. This automation reduces the need for labor, ensures the efficient use of workforce, and minimizes harvest losses. It reduces labor costs, increases efficiency, and minimizes human errors (Shamshiri et al. 2018).

2.1.5. Smart Irrigation Systems

Smart irrigation systems are systems that automatically irrigate based on soil and weather conditions, optimizing water consumption. These systems generally work in integration with sensors and use only the necessary amount of water. By irrigating only when needed, smart irrigation ensures the most efficient use of water, providing cost savings and reducing negative environmental impacts. However, studies have shown that increased irrigation rates can significantly raise CO2 emissions due to the higher energy demands for water extraction and transportation (Ramazanoglu et al., 2024). Therefore, there is a critical need for optimized irrigation strategies to minimize emissions while maintaining agricultural productivity.

Figure 3 illustrates the working mechanism of a smart irrigation system integrated with IoT sensors. The sensors placed in the soil monitor moisture levels and communicate the data to a central control system. Based on this data, the water pump is activated, ensuring optimal irrigation without human intervention.

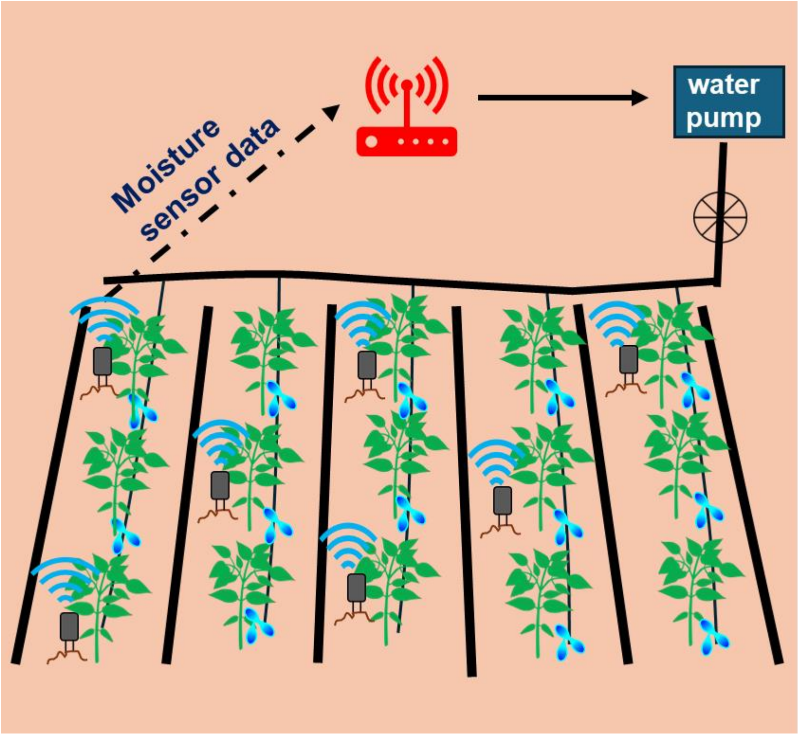

Figure 3. IoT-based smart irrigation systems monitor soil moisture and automatically control water distribution to optimize resource use.

2.2. Contributions to Sustainable Production

Smart technologies used in digitalized agriculture contribute to sustainable production in many ways. The use of smart technologies in agricultural production processes offers multifaceted benefits, such as reducing production costs, using natural resources more efficiently, minimizing environmental damage, and supporting rural development. These contributions can be examined within the framework of three main dimensions aligned with sustainability principles: environmental, economic, and social sustainability (Bongiovanni and Lowenberg-DeBoer 2004).

2.2.1. Contributions to Environmental Sustainability

Smart technologies play a key role in ensuring environmental sustainability in the agricultural sector. In traditional farming methods, the excessive use of water, energy, and chemicals increases environmental degradation. However, through digitalization and smart agricultural technologies, these resources are used more consciously and efficiently, reducing harm to the environment (Balafoutis et al. 2017; Zhang and Kovacs 2012; Kamilaris et al. 2017).

Efficient Use of Natural Resources: Smart irrigation systems, integrated with sensors, irrigate only the required amount based on soil and weather conditions, optimizing water consumption and helping to conserve water resources.

Reduction of Chemical Use: Precision farming applications and sensor technologies accurately calculate the amount of fertilizers and pesticides that plants need, ensuring that only the necessary amount is applied. This reduces chemical pollution and helps protect soil and water ecosystems.

Reduction of Carbon Emissions: Smart agricultural technologies increase energy efficiency, reducing fossil fuel use. For instance, drones powered by biofuels and electric agricultural machinery decrease the carbon footprint of agricultural activities. Additionally, precision planting and harvesting based on soil analysis and weather forecasts save energy and reduce emissions.

Protection of Soil and Biodiversity: Smart farming ensures that soil is protected from unnecessary chemicals, while precision irrigation and fertilization enhance soil fertility. This supports the preservation of plant and animal diversity, helping to maintain a healthy ecosystem.

2.2.2. Contributions to Economic Sustainability

The economic benefits of smart technologies in digitalized agriculture are directly related to reducing production costs and increasing crop productivity. For farmers, economic sustainability means increasing income and lowering costs, and smart technologies offer significant advantages to achieve this goal (Bongiovanni and Lowenberg-DeBoer 2004; Liakos et al. 2018).

Reduction of Production Costs: Sensor-based data analyses enable farmers to optimize the use of fertilizers, water, and pesticides, which lowers input costs and provides cost savings. Through systems like smart irrigation and fertilization, farmers can save by using only the resources they need.

Increased Efficiency: AI-powered analyses and satellite imaging technologies enhance crop productivity and prevent yield losses. Planting and harvesting plans based on climate conditions make it possible to manage crop growth processes more efficiently, maximizing productivity.

Access to Market Information and Pricing Advantages: Big data analytics provide farmers with information about market prices and demand trends. This allows them to determine the best time to sell their products at the highest price, maximizing profit.

Risk Reduction: Smart farming applications help mitigate climate-related risks through weather forecasts and soil analyses. Risks related to climate change, such as drought and extreme weather events, become predictable with these technologies, minimizing losses for farmers.

2.2.3. Contributions to Social Sustainability

Smart technologies play a significant role in enhancing rural development and improving the quality of the agricultural workforce. With digitalization, healthier working conditions and access to information in agriculture are provided, supporting social sustainability (Rijswijk et al. 2019; Rotz et al. 2019).

Supporting Rural Development: Digital agriculture applications increase farmers' access to information and modern agricultural techniques in rural areas. This accelerates rural development and helps farmers increase their income. Additionally, by creating non-agricultural job opportunities in rural areas, it contributes to the growth of the local economy.

Farmer Education and Access to Information: Digital farming technologies provide farmers with easier access to information through online platforms. Training programs and data-based analyses enable farmers to make informed decisions and adopt more efficient practices in agricultural production. This enhances the quality of the workforce and positively impacts agricultural productivity.

Improvement of Working Conditions: Smart farming reduces labor-intensive manual tasks, alleviating farmers' workloads. Robotic systems and automation technologies, in particular, allow tasks like planting, harvesting, and spraying to be done automatically. This enables farmers to work in less strenuous and healthier conditions.

Food Safety and Community Health: Smart farming technologies support food safety by reducing the amount of chemicals used in agriculture. Additionally, minimizing pesticide use reduces the negative impact on the environment and public health. Through smart production, society gains access to healthier food options.

2.3. Future Perspectives: How Digital Agriculture Will Support Sustainability

Digital agriculture is playing an increasingly critical role in achieving sustainability goals within the agricultural sector. Global issues such as climate change, population growth, and food security have necessitated the development of new solutions in agriculture (Poppe et al. 2015). Digitalization not only increases the efficiency of agricultural production but also provides lasting solutions for environmental, economic, and social sustainability. In the future, digital agriculture will continue to contribute to sustainability through advancing technologies and digital agriculture policies. Below, the future contributions of these technologies to sustainable agriculture are discussed (Rose et al. 2016).

2.3.1. Emerging Technologies and Smart Farming Solutions

In the future, the acceleration of digitalization in agriculture will increase the use of new smart technologies, making agricultural processes more efficient and precise (Liakos et al. 2018). For example, as artificial intelligence and machine learning algorithms provide more advanced analyses, agricultural productivity will further improve (Jayaraman et al. 2016). Real-time data on soil, air, water, and plant health will be collected through big data and IoT-based applications, enabling immediate data-driven production decisions (Kamilaris et al. 2017).

Robotic Agricultural Machinery: With more intelligent robotic systems in agriculture, tasks such as planting, fertilizing, spraying, and harvesting will be carried out without human intervention. These robots will monitor crop growth cycles and perform necessary actions at the right time, thereby enhancing labor efficiency while minimizing environmental impact.

Blockchain and Smart Contracts: Integrating blockchain technology into the agricultural sector will enhance traceability throughout the supply chain. This technology allows for transparent and reliable tracking of products from production to consumer. Additionally, with smart contracts, farmers can trade under fairer conditions when selling their products and encourage the preference for sustainable products.

Genomic and Biotechnology Innovations: With advancements in biotechnology, the development of crop varieties resistant to environmental conditions will support sustainable agriculture. Genome editing technologies will be used to increase crop productivity and produce varieties more resilient to the adverse effects of climate change.

3. Conclusion

Digitalization and smart technologies have become essential components of a sustainable transformation in the agricultural sector. The growing global population, the rapid rise in food demand, and the impact of climate change on agricultural production underscore the necessity of an efficient and environmentally friendly production model. In this context, digital agriculture applications serve as critical tools for achieving sustainability goals by conserving natural resources, reducing production costs, and enhancing agricultural productivity.

Smart farming technologies such as the Internet of Things (IoT), artificial intelligence (AI), big data analytics, and robotics enable farmers to use resources like soil, water, and energy more efficiently. These technologies contribute to environmental sustainability by optimizing water and fertilizer use while also preserving plant health and soil fertility. Technologies like sensors, drones, and satellite imaging allow for precise management of agricultural activities, minimizing resource waste. This reduces agriculture's environmental impact, decreases the carbon footprint, and helps protect natural ecosystems.

From an economic sustainability perspective, digitalized agricultural applications reduce farmers' costs, increase crop productivity, and create a more profitable production model. With digital technologies, farmers can reduce input costs, achieve higher yields and better-quality products, and access market information more quickly to sell their products at the best price. As digitalization becomes more widespread, it is anticipated that economic resilience in agriculture will strengthen, and farmers' income sources will diversify.

Digital agriculture also contributes to social sustainability by supporting rural development, improving workforce quality, and providing communities with access to healthier food. Social benefits such as improved working conditions for agricultural workers, increased employment in rural areas, and easier access to information are among the positive impacts of digitalization on the agricultural sector. Through education and digital agriculture applications, farmers can make informed decisions, creating more effective and sustainable production processes.

In conclusion, digital agriculture presents a significant opportunity to address the needs of today's agricultural production. The wider adoption of digital technologies in agriculture offers long-term solutions, providing both environmental and economic benefits in the pursuit of sustainability goals. Digital agriculture, supported by smart technologies, not only meets current demands but also addresses future food needs, conserves natural resources, and helps combat climate change. In this regard, digital agriculture is an integral part of an environmentally friendly and innovative future vision that supports sustainable production models.

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CHAPTER 16

DETERMINATION OF DIFFERENT MATURITY LEVELS OF TOMATO FRUITS (*SOLANUM LYCOPERSICUM*) BY DEEP LEARNING METHOD

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1.Introduction

Deep learning is one of the subfields of artificial intelligence and machine learning. It is a modeling that can automatically learn over data sets and creates complex models using multi-layered artificial neural networks. Its working basis is machine learning consisting of artificial neural networks. In this method, network training is done using a data set. As a result of training, it can correctly classify or predict new data.

With the development of technology, deep learning, which is used in many fields, has also been applied in agricultural applications. It is used in many areas such as deep learning in agriculture, plant breeding, soil analysis, forecasting, disease diagnosis, irrigation management, weed control storge and harvest efficiency. Akdemir and Bal (2016) investigated the validity of CFD models using the differences between model predictions and measurements as a basis for deep learning. Akdemir and Bartzanas (2015) used numerical and experimental methods together for temperature and relative humidity distribution in a cold storage to contribute to deep learning. An example is the use of deep learning to detect plant diseases and automatically detect disease symptoms in plants using image processing techniques. Thus, farmers can detect diseases and interfere more quickly. Also, by using deep learning for irrigation management and combining data such as soil moisture measurements and weather forecasts, it can be more accurately determined the irrigation requirements of plants. Using this method, water usage is decreased, costs are reduced and environmental impacts are decreased. Deep learning can also increase harvest efficiency. Uses in agricultural applications are developing day by day. Using drone or satellite images of fields plant growth and harvest time can be estimated. In this way, farmers can go to their fields at the best time to harvest and increase productivity. Weather forecasts can help farmers plan their production and increase their productivity. Weather conditions can be predicted by analyzing factors such as humidity, temperature, precipitation, wind, and sun rays in agricultural lands. All these examples are just a few examples of the use of deep learning in the agriculture industry. Deep learning decreases costs and increases productivity by providing more effective production management in the agricultural sector. With this feature, the use of deep learning in agriculture enables more efficient, sustainable, and environmentally friendly agricultural production.

The use of deep learning methods in tomato harvesting has become a widespread practice in the agricultural industry. Deep learning algorithms have been very effective in image processing and classification technologies used in plant harvesting. Deep learning algorithms used in tomato harvesting are primarily used to determine the growth stage and maturity level of tomato plants. Image processing techniques have been used to detect the color, size, and quality of tomatoes with deep learning. These processes allow tomatoes to be done automatically, rather than manually being selected and classified. Deep learning algorithms are also used to reduce waste that occurs during tomato harvest. Image processing technologies are used to detect un-harvested or rotten tomatoes. Thus, it is provided to reduce the waste and increase harvest efficiency. Deep learning techniques can be used to identify characteristics of tomatoes such as size, shape, color, and ripening. This data can be used to determine in which markets or enterprises tomatoes can be better sold. Using image processing techniques, it may be possible to detect and differentiate diseased tomatoes from other tomatoes. This can prevent diseased tomatoes from infecting other tomatoes and provide a healthier harvest. Deep learning techniques can be used in many areas such as the development of robotic systems used in tomato harvest and automating the harvesting process. The use of these technologies can help enterprises become more efficient and use human resources more efficiently. In a study carried out by Zhao et al. (2020) on quality determination for tomatoes with deep learning, the ripening degree for tomato harvesting was determined.

The YOLOv5 algorithm was used for deep learning. YOLOv5 (You Only Look Once version 5) is an object detection algorithm. This algorithm comes to the forefront as a deep learning model that can detect objects in real time. YOLOv5 is a faster and more sensitive algorithm than YOLOv4. YOLOv5 was developed using the PyTorch library and consists of two main components: a learning network and an inference network. The learning network is used to learn object characteristics from training data. The inference network performs real-time object detection using the information it learns from the training data.

YOLOv5 can detect objects of different sizes and determine the positions of detected objects using bounding boxes. There is also a post-processing stage to improve the estimated bounding boxes and class labels during object detection. In harvesting applications, the YoloV5 model can be used in many areas, such as the detection of plants in agricultural fields, pre- and post-harvest control, crop productivity analysis, and plant disease detection. In these applications, it is possible to use a pre-trained model or train a model using your data. When training your data, you can identify different characteristics of plant species and plant diseases and let the model detect these characteristics. The YOLOv5 algorithm can be taught according to data sets to be used in agricultural fields. These data sets can be obtained from farmers' knowledge, field data, sensor data, drone images, and other sources. These datasets can be used to train the YOLOv5 algorithm to achieve higher accuracy and efficiency in agricultural applications. When the literature was reviewed, it was seen that there are many studies. In their deep learning-based tomato harvesting robot study, Zhang et al. (2018) achieved an average accuracy rate of 91.9% with a prediction time of less than 0.01 seconds in experimental results. In their study of tomato fruit size classification with deep learning, De Luna et al. (2019) found low performances with 82.31%-78.21%-55.97% training validation-test accuracy for VGG16 and 48.17%-41.44%-37.64% for VGG16 with deep learning approach, independently from the algorithm. Mu et al. (2020) detected the presence of tomatoes on seedlings and their ripening degree in their deep learning study. (Afonso et al.,2020) used deep learning in a tomato fruit detection system for a greenhouse and determined that the method was successful. (Lawal ,2021) used deep learning algorithms YOLOv3 and YOLOv4 for tomato detection and found that the models apply to real-time robotic harvesting. In their studies of real-time monitoring of tomato growth with image segmentation based on deep learning, Widiyanto et al. (2021) explained that learning with the coefficients found could be used. Magalhães et al. (2021) developed an algorithm for a robotic tomato harvesting system using deep learning methods for robotic systems. In their study, Seo et al. (2021) achieved 88.6% detection accuracy in the classification system for tomato greenhouse when completely hidden fruits were not captured. When hidden fruits were excluded, the accuracy rate of the system was 90.2%. Chen et al. (2022) compared R-CNN, SSD, YOLOv3, YOLOv4, and Detectron2 methods in their study. They found that YOLOv4 was the best method, with an average accuracy of 96.15% and an image retrieval time of 0.06 seconds. Mutha et al. (2021) found the accuracy value for ripening to be 99.2%, 94.34% for un-ripening, and 90.23% for damaged products in their study. In their study, Kim et al. (2022) achieved 84.5% success in the classification process in the tomato classification system with deep learning. Moreira et al. (2022) used the YOLOv4 algorithm for the tomato detection system in the greenhouse. They found the F1-Score as 85.81%, the YOLOv4 Macro F1-Score as 74.16%, and the Balanced Accuracy value as 68.10% for the classification task. Zheng et al. (2023) compared the YOLOX and DenseNet algorithms for the cherry tomato detection system. They found that the YoloX-L method gave the best results. Wang et al. (2022) achieved 99.3% success with the online tomato prediction system using the YOLOv3 algorithm for tomatoes. Jun et al. (2021) performed positioning systems for robotic tomato harvesting with deep learning.

The tomato plant is a plant species belonging to the Solanaceae family and its scientific name is *Solanum lycopersicum*. It is also widely grown in Turkey. It is usually grown as an annual plant, but there are also varieties grown mainly as ornamental plants in some climates. An annual tomato plant generally grows to a height of 1-3 meters. The leaves of the plant are usually green and hairy. Plant maintenance processes such as irrigation, fertilization, and spraying should be done regularly. Tomato is a widely consumed vegetable around the world and is rich in vitamins and minerals such as vitamin C, potassium, and lycopene. Tomatoes are widely used in salads, sandwiches, sauces, soups, and meals. It is also used in many food products such as preserves, tomato juice, and ketchup. The tomato harvest is determined by several factors. These are:

- Climatic conditions: The tomato plant grows and bears fruit best in a warm and humid climate. In cold climates, the harvest may be less.
- Soil quality: Tomato plants grow better in nutrient-rich and well-drained soils. If there are not enough nutrients and water in the soil, the plant cannot grow and bear fruit.
- Plant maintenance: The tomato plant should be regularly irrigated, fertilized, and protected from diseases. If the plant is not well maintained, the harvest amount may decrease.
- Cultivated variety: Different tomato varieties may have different harvest amounts. Some varieties are more productive, while others bear less fruit.
- Harvest time: Appropriate timing for harvesting tomatoes can affect the amount of fruit. Enough time should be given for the tomatoes to ripen. However over-ripened tomatoes may be less productive when harvested.

All of the factors given above can determine when the tomato harvest will occur. On the other hand, tomatoes are generally harvested in summer and the harvest time and amount may vary depending on the growing conditions of the plants. The harvest quality of tomatoes is significantly affected by the processes applied during the harvest. Especially table tomato harvest is mostly done by hand today. However, plum tomato harvest is done by mechanization. The sensitivity during the tomato harvest determines the quality and value of the product to be exported and increases its value. Various studies are carried out in our country and the world for robotic harvesting applications. It was seen that there were studies on robotic harvesting in the literature. These studies were mostly in the form of prototype studies. The most important reason for making it as a prototype work is the high costs. Due to the human power deficiency, robotic systems remain as prototypes. One of the earliest studies on this subject was conducted by Kondo et al. (1996) .In their study, they developed a vision algorithm to detect the position of the tomato fruit. With the method developed with this algorithm, they provided the images to guide robotic harvesting. They determined the location of the fruit by performing spectrum analysis using a high-contrast imaging technique. As a result of the harvest method, they achieved a success rate of 70%. In another study, Qingchun et al. (2018) designed a structured light vision system for robotic tomato harvesting. In this study, they designed a vision system for determining the position of ripe tomatoes. They used an active sensing method based on light stereo vision. They calculated the fruit area using the pixel size and the bound on the circularity of the tomato. They found the 3D position of the fruit with a linear laser plane. They measured the measurement error as less than 5 mm, the center distance error between fruit and camera as less than 7 mm, and the single axis coordinate error as less than 5.6 mm. With the study, they effectively identified and found the ripe fruit. Taqi et al. (2017) developed a cherry tomato harvesting robot in their research. They determined the location of the cherry tomato with a real-time visualization method. Harvesting was achieved by separating ripe tomatoes. Feng et al. (2014) performed a robotic harvesting design for cherry tomatoes in their research. They conducted field testing of the newly developed robot and analyzed the results. They determined the successful harvest rate of the robot as 83%. They calculated the harvest time cost as 8 seconds. Ling et al. (2019) performed robotic tomato harvesting with binocular vision in their study. They found the success rate of the system with real-time image processing as 96% and the positioning error of the robotic arm as 10 mm. With the vacuum cup of the system, gripping, and wide-range cutting, the success rate in robotic harvesting was less than 87.5% and the harvesting time was less than 30 seconds. Benavides et al. (2020) developed a computer vision system for robotic tomato harvesting in their research. They performed a computer vision system to automate the detection and localization of the fruit in the system. With the system: (1) the detection of ripe tomatoes, (2) the location image of ripe tomatoes in XY coordinates, and (3) the location images of the stems of ripe tomatoes in XY coordinates were made. The detection time of the system was less than 30 ms. Fujinaga and Yasukawa (2021) conducted a study on the feasibility of tomato harvesting for robotic tomato harvesting and determined the location of the tomato on the branch. They used RGB images and image depth in their study.

The common features of the systems are image processing and deep learning. The primary input element of the robotic harvesting systems used is the detection of the products to be harvested with image processing and deep learning. Image processing and deep learning are used in the process of determining the location of the product to be harvested according to the definitions determined in robotic harvesting. Robotic systems, image processing, and deep learning methods, which are used in many fields from industry to medicine, have found a wide range of applications in agricultural applications. In this study, the YOLOv5 model, one of the deep learning approaches widely used in precision agriculture, was used to determine the harvesting criteria for tomatoes. The aim is to determine the harvest criteria via two classes formed according to the maturity of the fruit on the seedling. Determining the product to be harvested on the seedling is the most important criterion for robotic harvesting systems. The robotic systems recognize the farmer's harvest by eye and collect it manually in less time. Products separated according to ripeness ensure the formation of a harvest standard. If the farmer harvests according to the same standards, his economic yield also increases. The need for automated harvesting of tomato plants is the driving force behind this study. The evaluation of the tomato harvest, including yield and harvest quality, leads to an accurate harvest. As a result of tests with 4 different models of the YoloV5 architecture, the most successful model is recommended. Accurate classification in tomato harvesting is crucial for improving crop quality. By increasing classification reliability, the time required for training and testing is reduced. In this paper, an architecture based on four different deep-learning models of YOLOv5 (YOLOv5n, YOLOv5s, YOLOv5m, and YOLOv5l) for seedling tomato recognition and classification is presented.

In order, to accurately predict the ripeness of the tomato on the seedling, this study aims to recognize and classify the tomato to create a reliable framework by scanning photos according to the color of the tomato.

2. Material and Methods

2.1. Data Acquisition

In this study, red and green tomato varieties were selected according to the values of two parameters used in the harvesting phase of the most consumed tomato in our country. An important factor that influences the post-harvest quality of the fruit is the correct time of harvest. The best time to harvest tomatoes should be determined by physiological and anatomical data. It is a special method to determine the volume of tomatoes by photographic changes in the garden. One of the most important criteria for the visual quality of tomatoes is color.

Based on the American standard classification of tomatoes, a color image analysis was developed for the classification of fresh tomatoes in 6 degrees of ripeness. The tomatoes are classified according to the color ripening stages specified in the USDA color catalog: green ripening stage (the skin is completely green but physiologically ripe), color break stage (the skin is predominantly green but pinkish and reddish spots have started), color transformation stage (the skin is partially yellowish and pinkish but predominantly green), The color is classified according to the stages of pink maturity (the green color has completely disappeared and a light pink or reddish color predominates), light red maturity (the pink colors disappeared but the dark red colors not been reached), red maturity (completely red) (USDA, (1976); Batu et al.,(1997)).

If tomatoes are to be transported over long distances, they are usually harvested during the color range phase. If the tomatoes are to be transported over short distances, they are harvested in the pink or light red stage. The images of the test series used in the experiments were taken in the greenhouse of Namik Kemal University of Technical Sciences. The pictures were taken with a Nikon D3100 camera. The camera has a resolution of 1920 x 1080 and the images are in jpeg format. The pictures were taken between June 2024 and July 2024 at a distance of 0.5 cm from the tomato fruits. The greenhouse image is shown in Figure 1.

Figure 1. Greenhouse Images (Original)

The images used in the test phase were taken from different angles to increase variability. Since the most commonly consumed ripening stages of tomatoes in our country are green and red, the color of the ripening stage in the test set was defined as red and green. In the green ripening stage, the fruits are light green, plump, and round in shape. In the red ripening stage, 90% of the fruits are red. Figure 2 shows the images of these stages.

Figure 2. Maturity Degree Images (Original)

2.2. Dataset Construction

In order to effectively train an object recognition model using a data set, it is essential that the objects to be recognized within the data set are precisely labeled. Consequently, in the 3,200-image dataset, the regions containing tomato images must be delineated using bounding boxes and classified as either "red tomato" or "green tomato"," corresponding to the respective object categories. The data set was then divided into a training group and a test group in a ratio of 80:20. In addition, 150 images from the greenhouse of Tekirdağ Namık Kemal College Vocational School of Technical Sciences were used as a validation set. Numerous programs, websites and tools for image annotation are available in the open-source communities. Among these tools, Roboflow stands out as a widely used platform for object recognition projects. Roboflow offers a comprehensive suite of tools that facilitate the conversion of raw images into a specialized computer vision model and enable their use in various applications. The platform enables efficient selection, tagging and class assignment of images via its user-friendly graphical interface. The flow diagram of the study is shown in Figure 3.

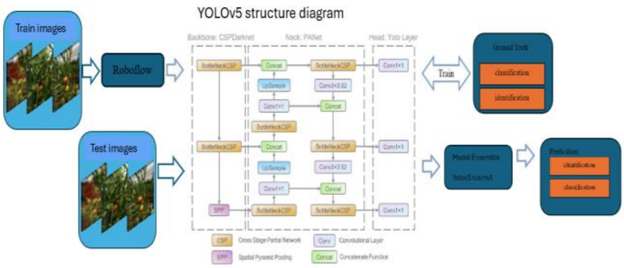


Figure 3. System Flow Diagram

2.3. Subsubsection

In order, for the YOLOv5 model to complete the aim of the project and to conduct the training, the following requirements were provided:

During the project development, Python 3.11.1, the latest version of Python, was installed in order, to run the tools, programs, and codes of the YOLOv5 model developed with Python.

PyTorch, an open-source machine learning library based on the Torch library, developed by Facebook AI Research Laboratory, was installed, to train the model, run the project using the trained model, and run the codes that will enable real-time tomato detection.

Jupyter Notebook, a server-client application developed within the Project Jupyter project, serving as an interactive notebook for the Python programming language and some other programming languages, enabling the written codes to be stored, presented, and run step by step, was installed. In order, for the YOLOv5 model and other programming components to work, the Pip (PIP Install Packages) tool, which enables the packages they are connected to be downloaded to the computer and managed after down-loading, was installed. The GitHub repo of the YOLOv5 model was transferred to the computer where the project was run, and the installation of the packages in the "requirements" text document in the repo, containing the tools necessary for the model to work properly, was done via Pip.

The “yolov5n.pt” file, which includes the trained weight coefficients of the YOLOv5n model to be used within the scope of this project and is available in the “releases” section of the YOLOv5 model repo, was downloaded and transferred to the YOLOv5 folder transferred to the computer. The “yolov5n.pt” file, which includes the trained weight coefficients of the YOLOv5n model to be used within the scope of this project and is available in the “releases” section of the YOLOv5 model repo, was downloaded and transferred to the YOLOv5 folder transferred to the computer.

2.4. Training Model Selection

In the project carried out, the YOLOv5 family, an open-source extension of the YOLO model series developed on the basis of the Convolutional Neural Network (CNN) methodology, was selected for implementation. The YOLOv5 model was chosen because it offers significant advantages in terms of accuracy and speed compared to models that use two-stage networks such as RCNN. This preference is based on its superior performance metrics compared to previous versions of the YOLO family. As described in the previous sections, the YOLOv5 framework includes various models within its architecture. In particular, the YOLOv5s (small), YOLOv5n (nano), YOLOv5m (medium) and YOLOv5l (large) models were selected for deep learning training as they provide an effective balance between fast execution and achieving accurate results.

2.6. Initiation of Training

To start training the model intended for tomato detection, the directory with the YOLOv5 model was opened on the local computer and an executable Python editor was started. The program train.py, located in the main directory and responsible for facilitating the YOLOv5 training, was checked for execution. This Python program allows customization through various parameters to optimize the training process.

After successfully executing the appropriate lines of code, the training process for the model was initiated. The program first performs a check of the YOLOv5 files and checks whether there are any updates. The training is then carried out over a specified number of cycles (epochs). During this training phase, the YOLOv5n, YOLOv5s, YOLOv5m and YOLOv5l models were used. Once training was complete, the model was saved and the test set was used for validation. The default hyperparameter settings of the platform used for training and the test set are listed in Table 1.

Table 1. Hyperparameter Values

Hyperparameter	Value	Hyperparamete	Valu	Hyperparamete	Value
lr0	0.01	cls	0.5	hsv_s	0.7
lrf	0.01	cls_pw	1.0	hsv_v	0.4
momentum	0.937	obj	1.0	translate	0.1
weight_decay	0.000	obj_pw	1.0	scale	0.5
warmup_epoch	3.0	iou_t	0.20	fliplr	0.5
warmup_momentu	0.8	anchor_t	4.0	mosaic	1.0
warmup_bias_lr	0.1	anchor	3	epochs	120
box	0.05	hsv_h	0.015	batch_size	20

2.7. Initiation of Training

Accuracy is the rate of correct classifications/predictions to the total amount of data. Although the problem with the accuracy metric approaching 1 can be stated as successful, it is not sufficient to comment only on this metric.

Accuracy=(TN+TP)/((TP+FP+TN+FN)) (1)

Error Rate is the rate of frequency of incorrect classifications/predictions in the problem.

Error Rate=(FN+FP)/((TP+FP+TN+FN)) or (1-Accuracy) (2)

Precision is the rate of the positive predictions made in the problem to the actual positive ones, in other words, correct ones.

$$Precision=TP/((FP+TP)) \quad (3)$$

Recall indicates how many of the observations that should have been correctly predicted were correctly predicted.

$$Recall=TP/((TP+FN)) \quad (4)$$

F1-Score: It is a metric that can be used instead of accuracy and is very important in terms of interpreting and observing the problem. It is the harmonic average of the Precision and Sensitivity metric values.

$$F\ Score=(2*Precision)/((Precision+Recall)) \quad (5)$$

True Positive (TP): Calling a real fact true by making a positive prediction

False Positive (FP): Calling a real fact false by making a negative prediction.

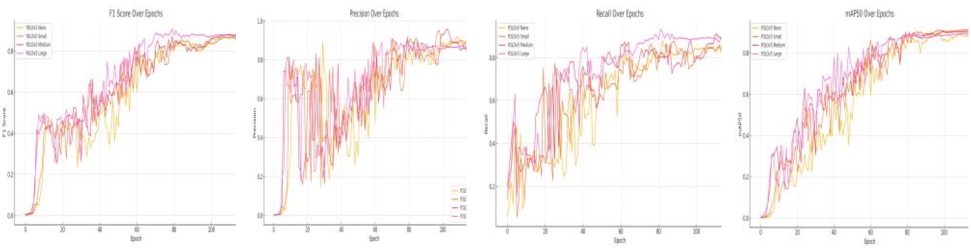
True Negative (TN): Calling a real error false by making a negative prediction.

False Negative (FN): Calling a real error true by making a positive prediction.

Within the project, the parameters and regulations in the code written below were preferred for squash fruit.

3.Results

Training results are as given in Figures 4 and 5.



(a) (b) (c) (d)

Figure 4. Training Results

The results of the Nano, Small, Medium, and Large models, which are different variations of the YOLOv5 model, were analyzed graphically. By analyzing the differences in the learning results of each model, the most successful and least successful models were identified. A comparison was performed on the metrics to support these results and the results analysis according to F1 scores are as follows. In general, all models showed a decrease in loss values and improvement in metrics during the training process. However, performance increased as the model size increased. The YOLOv5 Large model came to the forefront as the most successful model. This model was better at detecting more complex objects because it had a larger structure and achieved a higher mAP value. Other models may have difficulty accurately detecting some objects due to their smaller size. When analyzed according to F1 scores, it was seen that the YOLOv5 Large model had the highest F1 score. It showed that this value had both high precision and high recall values in the YOLOv5 Large model. The YOLOv5 Small, Medium, and Nano models also had lower F1 scores, respectively. As a result, it was seen that the YOLOv5 Large model was the most successful. This model showed better object detection performance due to its larger size and more complex structure. Other models, on the other hand, may have difficulty detecting certain objects accurately due to their smaller size. The F1 scores also showed that the YOLOv5 Large model had the highest performance (Figure 4a).

The analysis plots of the precision values obtained in the object recognition of the YOLOv5 models are shown in Figure 4b. The precision value is the ratio of the true-positive detections to the sum of the true-positive detections and the false-positive detections. The precision value is used to measure the accuracy performance of the deep learning model. When looking at the metric "Metric/Precision", it can be seen that the YOLOv5 Nano, YOLOv5 Small, and YOLOv5 Medium models have a low precision value at the beginning, which increases as the process progresses. It can be observed that the YOLOv5 Large model has a higher precision value at the beginning and continues to increase throughout the training process. This shows that the YOLOv5 Large model makes more precise predictions and therefore achieves a higher precision value (Figure 4b). The value of the recall metric is used to measure the ratio of true-positive detections to the sum of true-positive detections and false-positive detections as well as the accuracy performance of the model. A comparison of the metric "Metric/Recall" shows that the YOLOv5 Nano, YOLOv5 Small, and YOLOv5 Medium models have a low recall value at the beginning and increase in the course of the process. It can be observed that the YOLOv5 Large model has a higher recall value at the beginning and increases even further throughout the training process. This shows that the YOLOv5 Large model memorizes more objects correctly and therefore achieves a higher recall value (Figure 4c). When analyzing the metric "metrics/mAP_0.5", the values of YOLOv5n, Yolov5 s, and YOLOv5m remained low during the first 5 epochs. In the last 5 epochs, all metrics of the model improved. The metrics/mAP_0.5 values increase. During the first 5 epochs of the YOLOv5 Large model, the training loss of the model decreased and the precision and recall values increased. However, the mAP value is still low. During the last 5 epochs, an improvement can be observed in all metrics. The loss values decrease, the precision and recall values increase and the mAP value also increases. The YOLOv5 Large model is the model with the highest performance. It can be observed that the YOLOv5 Large model starts with a higher average precision value at the beginning and fluctuates throughout training. This indicates that the YOLOv5 Large model can classify more accurately and therefore achieves a higher average precision value. In general, all models show a decrease in loss values and an improvement in metrics during the training process. On the other hand, it can be seen that the performance increases with increasing model size (Figure 4d). When comparing the four models, the YOLOv5 Large model stands out as the most successful model. As this model has a larger structure, it was able to recognize more complex objects better and achieved a higher mAP value. The other models were found to have difficulty recognizing some objects accurately due to their smaller size.

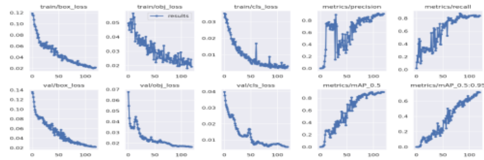
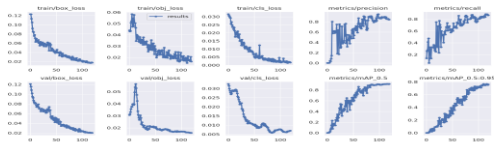
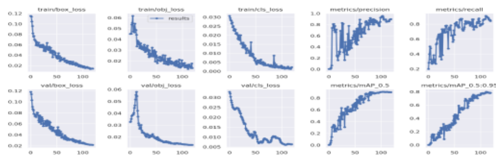
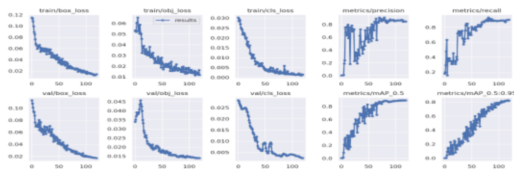
Size: 640x640, Batch: 20, Epoch: 120, Algorithm: YOLOv5n	
Size: 640x640, Batch: 20, Epoch: 120, Algorithm: YOLOv5s	
Size: 640x640, Batch: 20, Epoch: 120, Algorithm: YOLOv5m	
Size: 640x640, Batch: 20, Epoch: 120, Algorithm: YOLOv5l	

Figure 5. Yolov5 Algorithms According to Error Matrix Metrics and Loss Function Scores

According to the results obtained in the graphical comparison of the YOLOv5 models;

- Loss Values: In general, it was seen that each model obtained lower loss values in the last epoch (epoch 120). It was understood that the model learned from the dataset during the training. The YOLOv5 Nano model had higher values than the others in terms of box loss, object loss (obj loss), and class loss (cls loss), indicating that the model learned relatively more difficult.
- Precision and Recall: Sensitivity is the value that shows how many of the correctly detected objects in the model are correct. Recall measures how accurately the model has detected all the objects it should detect. It was seen that the YOLOv5 Large model presented the highest performance in terms of these two metrics.

- mAP (mean Average Precision): mAP is a measure of the model's performance on the verge of all classes and different IoU (Intersection over Union) thresholds. In general, a higher mAP means a better model. Here, the YOLOv5 Large model gave the best results at mAP_0.5 and mAP_0.5:0.95.
- When the "train/obj_loss" metric was examined, it was seen that the object loss in the YOLOv5 Large model was lower than the initial values in the other models and decreased throughout the training process. It was seen that the YOLOv5 Large model detected objects better and therefore achieved a lower object loss.
- In the comparison on the "train/cls_loss" metric, it was seen that the YOLOv5 Large model predicted classes more accurately and therefore achieved a lower-class loss.
- When the "metrics/precision" metric was examined, it was seen that the YOLOv5 Large model made more precise predictions and therefore obtained a higher precision value.
- In the comparison of the "metrics/recall" metric, it was seen that the YOLOv5 Large model correctly recalled more objects and therefore achieved a higher recall value.
- When the "metrics/mAP_0.5" metric was examined, it was seen that the YOLOv5 Large model was able to classify more accurately and therefore achieved a higher average sensitivity value.
- In the comparison of the metrics "metrics/mAP_0.5:0.95", it was seen that the YOLOv5 Large model achieved more accurate and consistent results and therefore a higher average sensitivity value.
- When the "val/box_loss", "val/obj_loss" and "val/cls_loss" metrics were examined, it was seen that the YOLOv5 Large model made more accurate predictions and had a lower error rate.

According to the measurement of these values, it was seen that the YOLOv5 Large model gave the best performance. However, this model required more computing power and recall than other models. Therefore, in the choice of model, there must be a balance between the available resources and the requirements of the application.

3.1. Initiation of Training

"Validation Batch" prediction markings of the models (YOLOv5n, YOLOv5s, YOLOv5m, YOLOv5l) are given in Figures 6 and 7 respectively.

Figure 6. "Validation Batch" Prediction Markings Resulting from the Training of the Models (Anonymous 1, 2, 3)

Figure 7. "Validation Batch" Prediction Markings Resulting from the Training of the Models (original)

3.2. Comparison of Model Algorithms

In the four trained models; the YOLOv5n algorithm, YOLOv5s algorithm, YOLOv5m, and YOLOv5l algorithm are used. The comparison of these algorithms is indicated in Table 2.

Table 2. Comparison of Algorithm Values

Models	Class	epoch	Completed(hours)	layers	parameters	GFLOPs	image	instances	Precision	Recall	mAP50	MAP50:95
YOLOv5N	all	120	0.047	157	1761871	4.1	12	48	0.873	0.851	0.871	0.707
	Green Tomato							22	0.780	0.818	0.769	0.561
	Red_ Tomato							26	0.965	0.885	0.974	0.853
YOLOv5S	all	120	0.058	157	7015519	15.8	12	48	0.928	0.867	0.936	0.785
	Green_ tomato							22	0.893	0.773	0.883	0.713
	Red_ tomato							26	0.962	0.962	0.989	0.857
YOLOv5M	all	120	0.108	157	20856975	47.9	12	48	0.879	0.799	0.878	0.77
	Green_ tomato							22	0.848	0.636	0.773	0.647
	Red_ tomato							26	0.911	0.962	0.982	0.892
YOLOv5L	all	120	0.306	157	46113663	107.7	12	48	0.907	0.877	0.899	0.831
	Green_ tomato							22	0.853	0.795	0.810	0.715
	Red_ tomato							26	0.961	0.960	0.989	0.947

The metric data of Model “4” and the difference of other models to these data are as given in Table 3.

Table 3. Comparison of The Models According to The Metric Data

Model	metrics/precision	Difference (Model 1)	Model	metrics/recall	Difference (Model 1)
Model 1	0.91194		Model 1	0.84129	
Model 2	0.84362	0.006832	Model 2	0.86713	-0.02584
Model 3	0.89773	0.01421	Model 3	0.84101	0.00028
Model 4	0.84758	0.06436	Model 4	0.90136	-0.06007
Model	**metrics/mAP_0.5**	**Difference (Model 1)**	**Model**	**metrics/mAP_0.5:0.95**	**Difference (Model 1)**
Model 1	0.89821		Model 1	0.71343	
Model 2	0.9127	-0.01449	Model 2	0.75849	-0.04506
Model 3	0.89765	0.00056	Model 3	0.7851	-0.07167
Model 4	0.89298	0.89298	Model 4	0.81806	-0.10463

Although the correct prediction successes and averages of the models in object detection play an important role in measuring the success of the models, it is not enough by itself. Missing values of models in both training and validation datasets are also important parameters that play a role in the examination of the model's success. The train/cls_loss and val/cls_loss parameters, which express classification losses in training and validation data, play an important role in models that require the detection of a large number of object classes. When the results were compared, it was seen that the YOLOv5 Small model showed the best performance in terms of the metrics. This model had high mAP and precision values and minimized the val/box_loss, val/obj_loss, and val/cls_loss values. On the other hand, the YOLOv5 Large model was the most suitable model for performing more complex and detailed object detection tasks on high-resolution images. It was understood that the performance of this model would increase significantly if it was used in high-resolution images

Table 4. Comparison of the Models According to The Training Data

Model	**train/box_loss**	**Difference (Model 1)**	**Model**	**train/obj_loss**	**Difference (Model 1)**
Model 1	0.021630		Model 1	0.019222	-
Model 2	0.017647	0.003983	Model 2	0.016422	0.0028
Model 3	0.014216	0.007414	Model 3	0.013348	0.005874
Model 4	0.014073	0.007557	Model 4	0.011812	0.00741
Model	**val/box_plots**	**Difference (Model 1)**	**Model**	**val/obj_loss**	**Difference (Model 1)**
Model 1	0.02193		Model 1	0.016523	-
Model 2	0.020347	0.001583	Model 2	0.015932	0.000591
Model 3	0.021519	0.000411	Model 3	0.013456	0.003067
Model 4	0.016974	0.016974	Model 4	0.013929	0.002594

One of the other models, the YOLOv5 Nano model required less computing power and recall than other models, it could be used in scenarios such as edge computing where resources were limited (Table 4).

The YOLOv5 Large model, which had the highest number of parameters among the four models, showed the best performance. It started with higher accuracy, recall, and mAP values than other models and improved them further during training. As the losses decrease, the model will converge rapidly. The larger capacity of the YOLOv5 Large model allowed it to capture more complex patterns and detect objects more accurately. In the Yolov5 Large model, higher accuracy, recall, and mAP scores were achieved throughout the training process. The superior performance of this model can be attributed to its larger capacity and more parameters. This feature of YOLOv5Large enabled it to capture complex object features and provide better object detection results. The choice of the most successful model depended on the specific requirements of the application. If a smaller model size that performed relatively well is preferred, the YOLOv5 Medium or YOLOv5 Small models may be appropriate options. However, for applications with higher accuracy priority and computational resources that can process to a larger model, the YOLOv5 Large model offers the best results.

4.Discussion

Yolov5 is one of the popular deep-learning models. It has the potential to be used as an important tool in image analysis and data processing in the agricultural sector. It is a model that can make important contributions to the sustainability and efficiency of agriculture in areas such as disease diagnosis, yield prediction, pesticide use, and harvest time determination. In this study, they determined that faster harvesting can be done with less loss. Park et al. (2023) harvested a total of 160 clusters of tomato seedlings in their study. The total success rate was 80.6% and the total harvesting time was 75.0%, 71.9%, 93.8%, 81.2%, and 81.2% for each input angle and the harvesting times were 20.2, 16.0, 13.5, 13.7 and 14.1 s, respectively. In another study, Gholipoor and Fathollah (2019) made a prediction study by planting the seeds of 692 domestic genotypes. In the study, they used 1243 images for training, 533 images for validation, and 592 images for testing. Ropelewska et al. (2022) used machine learning and image features to detect the changes in bell peppers as a result of lacto-fermentation in their study. The highest average classification accuracy for the models they developed reached 99%. Mustafa et al. (2023) detected and classified bell pepper leaf diseases using artificial neural networks. Experimental results show that the optimized CNN model of the proposed method can predict whether the leaf of a pepper plant is healthy or bacterial with 99.99% accuracy. However, the use of the model in practice brings challenges such as precise data collection and localization of the model. Therefore, the use of deep learning models such as YOLOv5 in agriculture requires careful planning and implementation. Using deep learning models, it is possible to determine the location of harvesting of fruits and vegetables. With the help of these studies, a more efficient harvesting process can be provided to farmers and will enable the digitalization of the agricultural sector. Deep learning algorithms have demonstrated considerable efficacy across diverse domains, encompassing picture categorization, object recognition, and plant disease diagnosis. By conducting training sessions on extensive datasets, deep learning models can acquire intricate patterns and generate precise predictions. Deep learning models have the potential to be taught in tomato classification, enabling them to distinguish various tomato varieties by analyzing their visual characteristics. Moreover, the application of deep learning models has demonstrated potential in the field of tomato disease detection, offering promising prospects for the timely identification and efficient control of plant diseases. The application of deep learning has demonstrated encouraging outcomes in the domain of plant disease diagnosis. In their study, Ecemis and İlhan (2022) undertook an investigation wherein they compared the efficacy of a lightweight convolutional neural network (CNN) with pre-existing networks in the context of detecting diseases in tomato leaves. The study demonstrated that the suggested lightweight convolutional neural network (CNN) attained performance levels similar to those of pre-trained networks. This finding underscores the potential of deep learning techniques in the field of plant disease diagnostics. Deep learning algorithms can be employed in tomato detection systems to effectively and precisely identify and locate ripe tomatoes for harvesting. The experiment done by Lee et al. (2022) focused on the implementation of an Internet of Things (IoT) camera-based system for the automated monitoring of tomato flowers and fruits, as well as the prediction of optimal harvest times. Deep learning-based detection was employed in the study to identify tomato fruits. The authors highlighted the prospective utilization of deep learning algorithms within the context of robotic harvesting systems designed for tomatoes. The tomato harvesting robot system, including an arm and a tomato detection system, was designed by Yeshmukhametov et al. (2022). Bargoti and Underwood (2017) conducted a study whereby they implemented accurate fruit localization techniques to automate robotic harvesting systems in agricultural settings. In their study using deep learning algorithms, they determined the F1 score for apples and mangoes to be greater than 0.9. To harvest tomatoes effectively, it is crucial to identify and position tomatoes correctly. Song et al. (2023) proposed a lightweight real-time tomato detection and collection point localization model called TDPPL-Net. This model used deep learning techniques for tomato detection and localization, which can be applied to robotic harvesting systems. Su et al. (2023), used the Yolo model in their deep learning-based cucumber recognition system. In the study, they compared the YoloV5s-Super, Yolov7-tiny, and Yolov8s models. They found that the YOLOv5s-Super model reached 87.5% mAP, 4.2% higher than the YOLOv7-tiny model and 1.9% higher than the YOLOv8s model. In 2023, Deng and Yu (2014) examined various deep learning models in rice disease and insect pest detection studies with deep learning for use on mobile phones. As a result of the study, they found that YOLOv5s achieved the highest F1-Score of 0.931, average sensitivity (mAP:0.5) of 0.961, and mAP (0.5:0.9) of 0.648. According to this result, they emphasized that Yolov5s is the best model. In their study, Wang et al. (2022) conducted a quality review of a rice planting machine with the Yolov5 deep learning model. In another study, Zheng et al. (2022) determined the recognition and location of tomatoes with the help of the Yolov5 deep learning model. Wang et al. (2022) conducted a study on a cucumber root-knot nematode detection model based on the modified YOLOv5s model to support the breeding of resistant cucumber varieties. Deep learning algorithms of robotic harvesting systems are used in the agricultural field, including recognition and localization, tracking and prediction, detection and manipulation, and arm and gripper development. By integrating deep learning algorithms into these systems, it is possible to increase the efficiency and accuracy of harvesting processes. Zhou et al. (2023) created a greenhouse climate tomato model by integrating the GreenLight and TOMSIM modules. As a result of the study, they emphasized the importance of integrating data-driven and knowledge-based methods in the simulation of greenhouse climate and crop production systems. He et al. (2024) proposed an improved T-Net for tomato image recognition. The result of the study was that the average errors of the center coordinates and diameter of the tomato were 8.5 mm and 2.5 mm, respectively. They emphasized that the model is an effective method for detecting and positioning tomatoes in real-time. The pose estimation of tomato was realized by using the sepal information of tomato. They stated that the proposed method can be used for tomato harvesting robots in practice (Jang et al.,2024). Islam and Hatou (2024) developed an artificial intelligence-assisted system for real-time monitoring of tomato plants. In particular, they proposed DeepD381v4plus, a deep learning-based network, and the DeepDet381v4 - YOLOv4M model for object recognition to perform tasks such as disease identification and classification in tomato leaves at early stages, pollination verification, and ripe fruit detection. Li et al. (2024) created a model called AHPPEBot equipped with a multitasking model YOLOv5 that performs detection, classification, and ripening prediction of tomato bunches and individual fruits. Beisekenov and Hasegawa (2024) developed a hybrid model using convolutional neural networks (CNN) and partially connected fields (PAF). This model uses data augmentation and transfer learning methods to ensure accurate identification of the center of mass of the tomato. In tests with 2260 different images, the model achieved recognition accuracy of 96.4%, significantly outperforming existing algorithms. Zhang et al. (2024) developed a YOLOv8n-DDA-SAM model for cherry tomato stem recognition and mask extraction. The model achieved a success rate of 85.90% and 86.13% according to mAP@0.5 and F1 score, respectively. They recognized cherry tomatoes with high precision. Liu et al. (2024) created a model to determine the most suitable greenhouse environmental conditions to achieve tomato maturity. The model is used to provide recommendations for studying the tomato growth cycle. Techniques for standardized cultivation in solar greenhouses are also proposed. Umar et al. (2024) proposed an improved target detection model based on YOLOv7 to accurately detect and categorize tomato leaves in the field. To improve the feature extraction capabilities of the model, they first integrated SimAM and DAiAM recognition mechanisms into the basic YOLOv7 network framework. In this study, tomato ripeness recognition was performed using two classes created for tomatoes using the YOLOv5 deep learning model according to ripeness. In the testing phase, four sub-models of YOLOv5 were used and important metric values of each sub-model were analyzed. The analyzed values were used to determine which model provided the best result. The results obtained are consistent with the results of the above-mentioned studies. The tomatoes have a color image analysis in 6 degrees of ripeness according to the American standard classification for fresh tomatoes. In Turkey, the country where this study was conducted, pickled tomatoes are produced from green tomatoes. Red tomatoes are consumed as tomato paste and table tomatoes. Therefore, this study provides a solution to the problem of selecting pickled tomatoes and tomatoes for table and tomato paste. In fact, this study not only contributes to solving the tomato identification problem but also to solving several problems, such as ripeness. Future studies will be conducted with more data and a data set labeled with 6 maturity levels. To increase the usability of the developed model in the real environment, it is considered to take control of the mobile application. This and similar applications will contribute to the development of precision agriculture. It is also expected that the evaluation of such studies will be of great importance for the development and optimization of robotic harvesting systems.

5.Conclusion

Example made with the data set prepared using YOLOv5 models object detection accuracies in training and validation images were analyzed. When the metric data and accuracy prediction rates indicating the object detection success of the model were examined, it was confirmed that the result of the model was successful. When the metric data and accuracy prediction rates indicating the object detection success of the models were examined, when the difference rates between the training and validation data were considered when examining the loss data, when the loss values on the validation data were considered to express a more general result, and when the optimization and learning speed values were examined, the model was confirmed to "YOLOv5large" with the following parametric characteristics.

"python train.py --img 640 --batch 20 --epochs 120 --data dataset.yaml --weights yolov5l.pt" was found to be correct.

It was understood that the YOLOv5 Large model had a better object detection ability and made more accurate predictions than other models. This success was due to the fact that the model had a larger structure and more parameters. The higher performance of the YOLOv5 Large model showed that it is capable of performing more complex object detection tasks based on more data. It should be considered that these results may change when working on datasets of different sizes and diversity when changes are made to the hyperparameters and general operating parameters related to the training algorithms, or when a success rating based on speed performance rather than object detection success is made. In this study, the maturity classification of tomato seedlings was carried out. Four different models belonging to the YoloV5 architecture were used, with YOLOv5l being the most successful. It is expected that improvements will be made to the Yolov5 backbone and accuracy can be further increased. This study is considered to have room for improvement and will be implemented in future studies.

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