MANAGEMENT OF SOIL AND PLANT HEALTH IN THE ERA OF CLIMATE CHANGE

EDITOR

Assoc. Prof. Dr. Ahmet ÇELİK

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Assoc. Prof. Dr. Ahmet ÇELİK

AUTHORS

Prof. Dr. Ali Fuat TARI
Prof. Dr. Korkmaz BELLİTÜRK
Prof. Dr. Osman SÖNMEZ
Assoc. Prof. Dr. Ahmet CELIK
Assoc. Prof. Dr. Çetin MUTLU
Assoc. Prof. Dr. Zubair ASLAM
Assist. Prof. Dr. Hülya SAYĞI
Assist. Prof. Dr. Somayyeh RAZZAGHI
Dr. Ali AHMAD
Res. Asst. Dr. Ferhat UĞURLAR
Res. Asst. Fatma Nur KILIÇ
PhD Candidate Sabeela YAQOOB
PhD Candidate Suat CUN
PhD Candidate Zemzem FIRAT
(the names are arranged in
alphabetical order)

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Publishing House

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TURKEY TR: +90 342 606 06 75
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PREFACE

Climate change has become a serious global problem for living things, with significant impacts on soil and plant health. In particular, the increasing temperatures, changing precipitation regimes, and changing weather events pose a significant threat to the sustainability of global food production, distribution, and consumption systems. These changes have a detrimental impact on the agricultural production process, which is a crucial element in ensuring the long-term viability of these systems.

As climatic changes increase, the health of soils and plants is increasingly at risk. Of these risks, key elements such as soil fertility, water resource availability and plant health are particularly vulnerable to degradation under the pressure of climate change. This can lead to reduced crop yields, increased pest infestations and greater agricultural production losses. For small-scale family farmers in developing and less developed countries, increased crop losses will significantly reduce their income per unit area.

One of the most crucial aspects of mitigating the aforementioned risks is to enhance the resilience of the agricultural sector. Specific measures, such as the augmentation of soil carbon, the prudent utilization of water, the cultivation of climate-resilient crop varieties, and the implementation of integrated pest management strategies, serve to safeguard agricultural productivity while also attenuating the consequences of climate change.

The successful continuation of soil and plant health management practices lays the foundation for a livable environment and agri-friendly production. Good quality, healthy soils act as carbon sequestrants, trapping carbon dioxide from the atmosphere and reducing greenhouse gas emissions. Sustainable farming practices such as cover cropping, crop rotation and reduced tillage help improve soil organic matter content, which in turn increases soil fertility and water holding capacity. These practices also promote biodiversity, which contributes to a more resilient ecosystem.

Plant health is equally important in the face of climate change. Healthy plants are better able to withstand stress from heat, drought and pests. By adopting integrated pest management strategies and using disease-resistant crop varieties, farmers can reduce their reliance on chemical pesticides and fertilizers that can harm the environment. In addition, precision agriculture techniques, such as using sensors and drones to monitor crop health, can help farmers optimize resource use and minimize environmental impact.

In conclusion, soil and plant health management practices are essential for reducing the impacts of climate change and ensuring sustainable food production. Developing sustainable and lasting solutions is vital not only to safeguard current food production systems but also to create a more livable world for future generations.

I would like to thank everyone who contributed and supported our book.

December, 2024
Assoc. Prof. Dr. Ahmet ÇELİK

CHAPTER 1

CROP RESIDUES MANAGEMENT STRATEGIES FOR A SUSTAINABLE AGRICULTURE SYSTEM

Assoc. Prof. Dr. Zubair ASLAM[1]
PhD Candidate Sabeela YAQOOB[2*]
Prof. Dr. Korkmaz BELLITÜRK[3]
Dr. Ali AHMAD[4]
Assoc. Prof. Dr. Ahmet CELIK[5]

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[1] Plant and Microbial Ecology Lab, Department of Agronomy, University of Agriculture, Faisalabad, Faisalabad-38040 Pakistan. OrcID: 0000-0002 3094-9175. E-mail: zauaf@hotmail.com

[2] Plant and Microbial Ecology Lab, Department of Agronomy, University of Agriculture, Faisalabad, Faisalabad-38040 Pakistan. OrcID: 0009-0007-3103-8211. E-mail: sabeelayaqoob68@gmail.com

[3] Department of Soil Science and Plant Nutrition, Tekirdag Namık Kemal University, Tekirdağ, Turkey. OrcID: 0000-0003-4944-3497. E-mail: kbelliturk@nku.edu.tr

[4] Pakistan Agriculture Research-PAR, Pvt. Ltd. Suite #37, Old Rally Building, I.I Chundrigarh Road, Karachi, Sindh, 74000 Pakistan. OrcID: 0000-0002-8319-1118. E-mail: aliahmadsial2643@gmail.com

[5] Department of Soil Science and Plant Nutrition, Faculty of Agriculture Adiyaman University, Adiyaman, Turkey.
https://orcid.org/0000-0001-8958-4978. ahmetcelik@adiyaman.edu.tr
*Corresponding Author: sabeelayaqoob68@gmail.com

1. Introduction

Crop residues are the plant biomass or remnants of the agricultural crops in the field, such as rice and wheat straw, sorghum, maize stalk, sugarcane trash etc. Crop residues can be classified as primary or secondary residues. Primary crop residues are plant parts remain on field after harvesting, such as stems, stalks, leaves, seed pods, and straw. Residues are produce during processing such as husks, seeds, roots, molasses, and bagasse is known as secondary crop residues (Sadh et al., 2018; Shinde et al., 2022). In the world, 2445.2 million tons of crop residues produce and 85 % residues contributed from rice, wheat, maize, barley, sugarcane and soybeans crops. In Pakistan, there exist about 181 million tons' annual crop residues (Warnatzsch and Reay, 2020). The total agricultural crop residues are approximately 181 MT, with cereal commodities (70%), rice (34%), and wheat (22%). Rice is the leading contributor to agricultural residue burning, accounting for 43% of the total, followed by wheat 21%, sugarcane 19%, and oilseed crops 5% (Bhuvaneshwari et al., 2019). This rise in residue production is closely related to increased cropping intensity and increase in area under sown to fulfil demand of food. Food demand is expected to increase 35-56% due to the growth of population in the world (van Dijk et al., 2021). This expansion increases crop residues every year (Scarlat et al., 2015; Warnatzsch and Reay, 2020). Grain-to-residue conversion factors Lal (2005) and FAO (2023), worldwide residue production has more than tripled, from 1,589 million tonnes in 1960-61 to 5,390 million tonnes in 2022-23, driven by increased agricultural productivity. Major issue is the excessiveness of crop residues which unintentionally add to management difficulties, if used properly are rich source of plant nutrients, and can be decomposed by microorganisms. The global production of crop residues over past seven decades show in the Fig:01

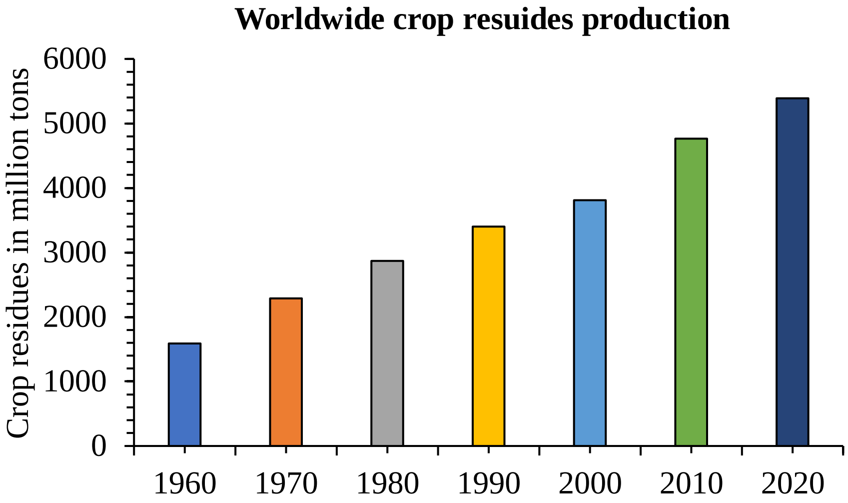

Fig. 1. The global production of crop residues over past seven decades.

1.2. Characteristics of crop residues

1.2.1. Composition

Crop residues are mostly composed of cellulose, hemicellulose, and lignin, with small quantities of pectin, nitrogen compounds, and mineral leftovers (Andlar et al., 2018). Lignin, a complex aromatic macromolecule that fills gaps between cellulose and hemicellulose, binds to and protects cellulose-hemicellulose core by generating a cross-linked encrusting network structure (Anwar et al., 2014; Wang et al., 2021).The crystallinity of cellulose, the hydrophobic character of lignin, and the protective covering of the lignin-hemicellulose matrix on the cellulose fibres all contribute to resistance of lignocellulosic biomass to breakdown by microbial enzymes (Abdel-Hamid et al., 2013; Isikgor and Becer, 2015; Zheng et al., 2014). According to various studies percentage of cellulose, hemicellulose and lignin in different crop residues show in table.1

Table 1. Chemical compositions of crop residues

Crop residues	**Cellulose**	**Hemicellulose**	**Lignin**	**References**
	Percentage			
Sugarcane bagasse	40-45	31-34	2029	Rai et al., 2014 & Jiang et al., 2012
Maize stalk	35-41	27-29	8.4	Zhang et al., 2014a, Jiang et al., 2012 & Li et al., 2009a
Wheat straw	34-39	26-32	16-19	Saratale et al., 2008 & Jiang et al., 2012
Rice straw	32-46	19-27	05-24	Saratale et al., 2008 & Jiang et al., 2012
Barley straw	35-44	27-34	14-18	Isikgor and Becer 2015 & Borrega et al., 2022
Rye straw	26-35	28-33	13-20	Sun et al., 2000 & Isikgor and Becer 2015
Oat straw	25-34	22-33	18-15	Zheng et al., 2021 & Rencoret et al., 2023

2.0. Methodology

Chapter is based on a narrative review. However, we followed a protocol to locate all relevant literature. We searched databases (Google Scholar, Research rabbit, Scopus and Web of Science) for existing literature using a combination of specific search terms (e.g., crop residue production, burning, field fire, residues composition, management options like as on-farm management (Residues use as feed, bedding material, surface retention, mechanization usage and bioenergy) and off-farm management (Residues valuable product like compost, use in mushroom cultivation and buildings etc.). It could also be that the assumption is that contribution of crop residue management, is a sustainable agriculturesSystem.

3.0. Crop residues management options

Crop residues have a wide range of agricultural and industrial uses, but their effective management is important, as no single method can be universally applied across all regions. The cropping systems variation, residue utilisation patterns, local resources, and farmers' socioeconomic conditions all influence the choice of management strategies. As a result, options for residue management:

3.1. In-situ management

Crop residue management on field is one of the most efficient ways to reduce transportation costs, recycle vital nutrients back into the soil, and save time. In such management practices, crop residue is either mixed with soil or left on the soil surface, and seed sow with the mechanization. Recycling crop residue into soil provides various ecosystem services that are necessary to enhancing soil health and supporting different plant components (Sarkar et al., 2020). Key options include surface retention (e.g., mulching and zero tillage) and in-situ incorporation (Bhattacharjya et al., 2019). Efficient on-farm operation of crop residues helps recycle nutrients while eliminating need for transportation, saving time and effort.

3.1.1. Crop residues burning

In many developing countries, manual harvesting methods are common due to the lack of mechanization. Mechanical harvesting, however, results in significant amounts of crop residues left in the fields. Due to labour shortages, poor suitability as fodder and the limited time available for sowing the next crop, a significant part of crop residues burned on the fields. This is not a new idea but started many generations ago with a routine practice can also help to reduce pests, insects, parasites, weeds and disease by burning leftover, producing harmful smoke (Kaur and Singh 2022). Burning crops residue releases significant greenhouse gases (GHGs) like carbon dioxide (CO_2), methane (CH_4), carbon monoxide (CO), and nitrous oxide (N_2O). For example, burning residues emits 12,204 kg CO_2/ha, which accounts for 37% of total GHG emissions from sugarcane production (Arsenio et al., 2016). A huge loss of nutrients, and these elements are burned, they are transformed into multiple environmental pollutants, which have a negative impact on air quality, human health, and contribute significantly to climate change (Kaur and Pandey 2021 and Jiang et al., 2024). Residue burning also imposes negative effects on soil biota (1 m^{-2} of organic temperate agricultural soil contain 1000 species of organism population density in order of $10^6/m^2$ for nematodes, $10^5/m^2$ for micro-arthropods and $10^4/m^2$ other for invertebrate group), (Gupta et al., 2004 and Bhuvaneshwari et al., 2019).

3.1.2. Crop residue as mulch

Retaining crops residue on the soil surface is an energy-efficient and environmentally friendly strategy to in-situ residue management. Modern machinery enables direct seeding in residue-covered soils by creating narrow slits for seeds and fertilizers while leaving the rest of the soil undisturbed. This practice reduces evaporation, irrigation demand, and soil erosion while enhancing soil carbon sequestration, fertility, and enzyme activity (Lohan et al., 2018; Stella et al., 2019 and Bimbraw, 2019). It also improves crop tolerance to terminal heat stress and suppresses weeds, favoring crop growth, particularly in spring (Boateng and Dennis, 2001; Sidhu et al., 2015). However, surface residue retention under zero-till systems can encourage weed seed accumulation in the upper soil layer and reduce pre-emergence herbicide efficacy due to residue interception (Buhler, 1995; Chauhan et al., 2006). Combining crop residue mulching with zero tillage naturally promotes moisture conservation and enhances soil productivity. This approach reduces input costs while slightly improving yields (Wu et al., 2021). Future research on improved weeds control, mechanical straw spreaders, and bio-decomposers for faster residue mineralization could enhance crop productivity and promote wider adoption of this practice.

3.1.3. In-situ incorporation

In situ incorporation of crop residues involves mixing straw, stubble, or crop leftovers into the topsoil during tillage to accelerate decomposition and minimize surface residue for easier intercultural operations. Uniform spreading, achieved with mechanized straw spreaders and combine harvesters, is crucial for effective incorporation (Lohan et al., 2018). Studies indicate that incorporating rice residues, weed biomass, and microbial inoculants like *Trichoderma viridi* improves soil porosity, water retention, organic matter, nutrient availability, and crop yields (Choudhary et al., 2020). Similarly, combining rice straw with fertilizers and *Trichoderma reesei* enhances soil pH, carbon content, microbial activity, and wheat yields (Gaind and Nain, 2007). Factors such as residue composition, soil type, climate, and microbial activity influence decomposition rates, which can be accelerated with irrigation, nitrogen fertilizers, and microbial inoculants. For instance, sugarcane trash decomposes in as little as 45 days (Jat, 2017). Fox et al. (1990) observed that finer residue particles decompose faster due to increased surface area, they may also release phenolic compounds that inhibit degradation. Research shows no consistent advantage of residue size or tillage method, though shallow incorporation of 20–25 cm residues is practical for subsequent cropping operations (Goswami et al., 2020; Zhang and Wu, 2021; Panagos et al., 2015). Crop residue recycling has been shown to improve soil health and yield by an average of 5% (Lu, 2020).

3.1.4. Residue decomposition supported microbiome

Crop residues decomposition rate is influenced by their physico-chemical properties, application methods, soil characteristics (texture, moisture, pH), and environmental factors such as temperature and humidity. Lignin in residues acts as a barrier to breakdown of hemicellulose and cellulose during enzymatic hydrolysis, slowing decomposition, particularly with the onset of winter when temperatures drop. Studies highlight the use of microbial and fungal consortia such as *Phanerochaete chrysosporium*, *Candida tropicalis*, *Aspergillus spp.*, *Trichoderma viride*, and *Bacillus atropheus* to enhance lignocellulosic residue decomposition, improve carbon-to-nitrogen ratios, and boost crop yields (Tiwari et al., 1987; Gaind and Nain, 2007 and

Sharma et al., 2014). Microbial activity, including xylanase and endoglucanase enzymes, is more pronounced under thermophilic conditions (55°C) than mesophilic conditions (35°C) (Reddy et al., 2013).

The decomposition process also varies with microbial community composition. Gram-positive bacteria dominate in the initial stages of rice residue breakdown, while fungi and actinomycetes are crucial for decomposing recalcitrant compounds later (Guo et al., 2018). Zero-tillage combined with residue retention enhances fungal and bacterial diversity, whereas conventional tillage promotes actinobacteria (Wang et al., 2014). Aerobic decomposition accelerates in warm, moist conditions but increases CO_2 emissions, while anaerobic conditions favor CH_4 production, with the highest emissions observed at extreme soil temperatures (±5°C) and full soil saturation (Tang et al., 2016). The use of high C:N ratio residues like rice and sugarcane remains during winter wheat and subsequent rice puddling presents implications for greenhouse gas emissions and residue management. Future research should explore temporal and spatial nutrient dynamics, microbial decomposer interactions, and global warming potential under various agronomic practices to optimize residue recycling in diverse cropping systems.

3.1.5. Insect-pest and weed dynamics with crop residues

Residues presence on the soil surface provides a favourable environment for insect multiplication, as well as a habitat for rodents. Studies observed that residue retaining in wheat significantly increases the density of burrows and exacerbates rodent issues, leading to reduced crop yields (Sharma and Singh, 2018 & Singh et al., 2019). Moreover, pests such as the armyworm, pink stem borer, and Fusarium head blight have been more prevalent under residue-retained wheat cultivation (Kaur et al., 2021). A study by Kumar et al. (2022) also revealed a notable rise in armyworm and mealybug populations, alongside increased infestations of bandicoot rats in rice within a conservation agriculture-based wheat- rice-mungbean system. The retention of crop residues has been linked to a 12–43% increase in fusarium head blight comparing to straw incorporation (Dill-Macky & Jones, 2000). Additionally, the adoption of zero-tillage has been shown to affect pest populations, with the lowest root aphid incidence and maximum pink stem borer damage observed under zero-tillage systems. Residue retention promotes pest carryover from previous crops and provides a stable environment for larvae, leading to higher infestations in subsequent crops.

In terms of weed management, crop residues can either inhibit or encourage weed emergence through physical barriers or allopathic properties (Teasdale & Mohler, 2000). While residues generally stimulate weed growth under partially covered soil (Buhler et al., 1996), long-term zero-tillage can shift weed flora towards broadleaf species like *Rumex dentatus* and *Malva parviflora* (Chhokar et al., 2007), while reducing the proliferation of *Phalaris minor*. The incorporation of residues such as rice and sunflower straw into the soil has been found to reduce weed density in succeeding crops (Ullah et al., 2018). For rice, zero-till direct seeding led to significant reductions in weed emergence, including *Cyperus iria* and *Echinochloa colona* (Mishra et al., 2022). However, the efficacy of pre-emergence herbicides remains a challenge due to interception by straw and varying herbicide adsorption rates (Aslam et al., 2013). Increasing the carrier volume for herbicides has been shown to improve efficacy by enhancing coverage and penetration (Borger et al., 2013). Future focus on studying dynamics of insect-pest and weed populations, evaluating herbicide & insecticide efficacy, and optimizing application strategies under various residue management practices.

3.2. Machinery for handling crop residues

Most cultivable land is still managed using conventional tillage systems. In these systems, studies highlight innovative machinery for residue handling, helping to address the issue of residue burning in-situ management.

3.2.1. Seedbed preparation

3.2.1.1. Rotavator

An improved land preparation method can significantly save time and energy compared to traditional techniques. The rotavator are effective for incorporating crop residues during seedbed preparation. When used in heavier soils, a tractor-mounted rotavator saves 32-35% of both time and energy. Due to its versatility handling tasks like tillage, puddling, mulching, leveling, soil moisture conservation, and pulverization rotavator usage increased (Singh et al., 2016; Chaudhary et al., 2019 and Tian et al., 2024).

3.2.2. Incorporating crop residues

3.2.2.1. Reversible mould board plough

A mould board plough works by rotating the upper layer of soil, effectively mixing crop residues into the ground. This incorporation of straw enhances soil fertility and accelerates the decomposition process, providing additional benefits for soil health (Tian et al., 2024).

3.2.2.2. Rotary till-drill

The rotary till-drill efficiently incorporates rice residue before sowing next crop. Using rotavator blades, it cuts & mixes the residue into the soil, while also performing pulverization and seeding on single pass. This saving fuel and time compared to traditional methods. The machine features a fluted roller mechanism that distributes seeds into tubes, which are then incorporated into the soil. This process also absorbs crop residue and can be used for rice pudding production (Sharma et al., 2008; Humphreys and Roth, 2006). With an effective field capacity of 0.3–0.4 ha/h, it is operated by a 45 hp tractor (Parihar et al., 2023).

3.2.3. Seeding machineries

3.2.3.1. Rotary disc drill

The rotary disc drill is a conservation agriculture machine with a rotational mechanism and three discs, designed for seeding wheat and mixed crop residue. It operates as a single-pass seeder with minimal soil disturbance and can also be used to seed sugarcane ratoons. This machine works well in all residue moisture conditions and can seed crops sown at any time of day or night. It offers time and fuel savings when seeding wheat after basmati rice harvest (Sharma et al., 2008; Humphreys and Roth, 2006). However, its main limitation is seed covering issues in dry soil conditions (Kumar et al., 2023).

3.2.3.2. Zero seed drill

A zero-seed drill directly drills wheat seeds into standing paddy stubbles, particularly use in areas where basmati rice is manually harvested, leaving behind short, anchored stubbles (Mishra et al., 2021). This lightweight equipment can be easily pulled by tractors with lower horsepower (45 HP). The field capacity of the zero-seed drill ranges from 0.24 to 0.4 ha/h (Kumar et al., 2023).

3.2.3.3. Spatial No-till drill

A no-till drill with a three-member frame and increased vertical clearance allows wheat to be drilled under loose straw and anchored stubbles. The 60 cm spacing between the tynes helps prevent straw buildup behind the tynes. Operated by a 45 hp tractor, the machine has a field capacity of 0.24–0.4 ha/h and can handle up to 30% of previous crop residues for optimal performance (Parihar et al., 2023). However, straw accumulation in the furrow openers is a major limitation (Hegazy et al., 2011 & Sidhu et al., 2021).

3.2.3.4. Happy seeder

The Happy Seeder, enhanced with a press wheel assembly, allows for wheat planting in fields with cut and spread stubble from a straw cutter-cum-spreader. It helps spread and press chopped paddy straw as mulch, promoting better germination, emergence, and early establishment, resulting in increased wheat yields by about two quintals per acre. This machine also reduces fertilizer costs and saves time and money (Regatti Venkat, 2019; Kathpalia et al., 2021 and Parihar et al., 2023). Before its introduction, seeding in fields with retained rice residue was challenging, despite its benefits for soil quality and reducing environmental pollution from stubble burning. The Happy Seeder combines drilling and mulching in one pass, making it suitable for direct seeding in combine-harvested rice fields (7–9 t/ha straw) with a 45 hp tractor, operating at 0.6–0.75 acres per hour (Parihar et al., 2023). However, it struggles on uneven fields, in wet residue conditions, and has a lower field capacity than conventional seed drills (Kumar et al., 2023).

3.2.3.5. Super seeder

The super seeder is primarily used to incorporate rice chaff into the soil while simultaneously sowing wheat in multiple rows after rice is harvested with a combine harvester, its key components include a seed and fertilizer box, rotary unit, gearbox, furrow opener, and ground wheel. The rotary device chops and mixes stubble and straw, furrow opener creates rows for seeds and fertilizer, and the seed covering roller ensures proper residue incorporation and seed compression. Its field capacity is 0.35 ha/h, with a fuel consumption of 6.7 l/ha (Parihar et al., 2023; Sun et al., 2024).

3.2.3.6. Smart seeder

The device features 9 rows for seeds and fertilizers, utilizing a strip-till mechanism for wheat planting and a rotor for incorporating rice residue. Rotor blades handle narrow-strip tillage and incorporate stubbles and straw into furrows, while disc-type furrow openers release seeds and fertilizers through plastic tubes. Furrow-closing rollers enhance seed and fertilizer coverage, improving seed-soil contact for better germination. Strip tillage seeding is an effective straw management method, offering mulching and residue incorporation benefits. The device's field capacity is 0.4 ha/h, with a fuel consumption of 5.7 l/ha (Parihar et al., 2023; Li et al., 2024).

3.2.4. Straw cutters

3.2.4.1. Chopper-cum-Spreader

The machine gathers leftover stubbles, chops them into small pieces, and scatters them across the field, where they are incorporated into the soil with a disc harrow or rotavator and decompose post-irrigation. Operated by a 45 hp tractor, it features a rotary shaft with flail blades and a chopping unit to cut stubbles into 8–10 cm pieces. With a flail speed of 900 rpm and chopper speed of 1500 rpm, its field capacity is 0.33–0.46 ha/h, consuming 6–6.5 l/ha of fuel. A drawback is field skidding instead of proper penetration ((Pari et al., 2018; Unger and Glasner, 2019; Suardi et al., 2019; Mukesh and Rani 2017; Faisal et al., 2022; Parihar et al., 2023 & Tian et al., 2024).

3.2.4.2. Shredder (straw)

The straw shredder features swinging flail cutting blades, a gearbox for power transmission, telescoping shafts, a flexible side link for height adjustment, and a safety guard. Made of medium carbon alloy steel, the blades finely chop loose straw and anchored stubbles. Operated by a 25 hp tractor or higher, it is used for clearing shrubs, monsoon growth, and grasses in fields, helipads, and forest areas, as well as for ex-situ disposal of paddy residue (Nikam, 2021; Akhtar et al., 2023 and Parihar et al., 2023).

3.2.4.3. Super SMS

The super SMS, attached to the back of a combine harvester, cuts residues into fine pieces and distributes it uniformly across field. Using a 110 hp engine, it processes straw from the combine's walkers, releasing it through a spinning disc and deflectors for even spreading. This reduces straw buildup, simplifies sowing, and boosts wheat productivity by 2–4%. However, it is unsuitable for small holdings and increases fuel consumption to 2.5–3 l/h during operation (Singh et al., 2019; Kumar et al., 2023).

3.2.4.4. Mulcher

Rice or wheat straw is a popular mulching material for fruits and vegetables, enhancing soil fertility upon decomposition. A mulcher creates a uniform stubble mulch layer befor wheat sowing with a rotavator or happy seeder but struggles with wet straw due to blade slippage. Its field capacity is 0.32 ha/h with fuel consumption of 5.88 l/h, and it chops residue into pieces as small as 10 cm. However, it requires additional field operations (Verma et al., 2016; Kumar et al., 2023).

3.2.5. Straw collection and disposal

3.2.5.1. Baler

Straw balers produce rectangular or spherical paddy bales, with rectangular balers more common in Punjab. Operated by a 45-hp tractor, they create 15–35 kg bales, processing 6–7 acres daily. These bales are used in composting, packing, brick kilns, and energy industries. Baling instead of burning reduces emissions by 45 times and supports eco-friendly uses like biofuel, animal feed, and industrial applications such as boilers, cardboard, packaging, and biogas production (Pal et al., 2019; Mangaraj and Kulkarni, 2023).

3.2.5.2. Raker

A raker arranges harvested stubbles into windrows, enhancing straw baler efficiency by reducing passes needed for collection and increasing field capacity (Parihar et al., 2023).

4.0. In-vitro rsidues management

4.1. Crop residues use as animal feed

A significant portion of crops residue is utilized as food for domestic animals (Devi et al., 2017; Maw et al., 2019). Animals can digest cellulose due to enzymes produced by microorganisms in their rumen. However, digestibility of residues reduces due to lignin presence, and their low protein and mineral content further limits their effectiveness as fodder (Bath et al., 1980). Cereals residues, particularly rice straw, are among poorest in protein content & have a high crude fiber content (Goswami et al., 2020). In contrast, leguminous crop residues provide better crude protein and nutrient content than cereal leftover (Iqbal, 2015 and Win et al., 2021). Common practices include straw grazing, where livestock graze on land after harvesting, and value addition, involving chopping and storing residues. Enhancements such as adding nitrogen-rich compounds improve their palatability and nutritional value. The nutrient composition and lignocellulose content vary among crop residues, influencing their palatability. Crop residues like wheat straw are typically used as bedding material in developed countries. Conversely, in developing nations, carbohydrate-rich stubbles are vital resources for growers, serving as affordable animal feed during fodder shortages (Goswami et al., 2020).

4.2. Bedding material

Crop residues, particularly straws, are commonly used as bedding materials for animals due to their excellent H_2O absorption properties (Lips et al., 2009), which help maintain cleanliness and comfort (Werhahn et al., 2010). This practice also facilitates the collection of waste like dung and droppings. Depending on availability, materials such as rice hulls, straw, and peanut hulls are frequently used in poultry bedding help to maintain birds dry and healthy (Diarra et al., 2021). Using crop residues as bedding enhances their degradation into compost when placed in animal sheds (Eberl et al., 2024). After serving as bedding, these residues become nitrogen-enriched mixtures of litter, producing high-quality compost (Brown and Rosen, 1998; Duan et al., 2021). This approach not only benefits animal care but also promotes efficient crop residue utilization. Recent research by Duan et al. (2021) demonstrated that combining bedding material with cow manure significantly improves composting quality and speed. The optimal ratio of bedding material to manure was found to be

40:60, which accelerated organic matter breakdown and increased composting temperatures, yielding excellent results.

4.3. Bioenergy options with crop residues

Crop residues hold immense potential for bioenergy production through various methods, including the generation of biogas, bioethanol, biohydrogen, biomethanol, biobutanol, pyrolytic products, enzymes, bioactive compounds, mushrooms, single-cell proteins, and organic acids (Singh and Sidhu, 2014; Kamusoko et al., 2021; Wang et al., 2022). These residues can be transformed into liquid fuels like ethanol or used for electricity generation via combustion (Bijay-Singh et al., 2008). Ethanol production involves enzymatically breaking down cellulose in the residues into monosugars, which are then fermented to produce ethanol (Liska et al., 2014). For electricity, crop residues can be combusted alone or mixed with other fuels (Singh and Sidhu, 2014). Gasification is another viable method, where straw is heated with limited oxygen and carbon dioxide, producing a mixture of gases such as N_2, H_2, and CO, collectively known as producer or synthesis gas. Alternatively, pyrolysis heats crop residues without oxygen, yielding high-energy pyrolysis liquids. Both producer gas and paralyzed liquid can be stored and utilized for heat or electricity. Biogas production is another option, achieved through anaerobic decomposition of crop residues combined with manure. Biogas can serve as cooking fuel or generate electricity (Einarsson and Persson 2017). Additionally, residues mixed with manure can be compressed into briquettes for various fuel applications (Singh and Sidhu, 2014). Despite these possibilities, practical challenges hinder the widespread adoption of such methods, particularly for small-scale farmers. The limited time between crop harvest and the next sowing season makes residue disposal difficult. Collecting and transporting residues requires significant labor and machinery, often exceeding the value of the residues themselves. Furthermore, removing residues for convenience during intercultural operations results organic carbon loss and nutrients essential for soil fertility. Given these challenges, most eco-friendly approach is on-farm recycling of crop residues. Techniques such as retention, incorporation into the soil, or composting can ensure the return of valuable carbon and nutrients, improving soil fertility while addressing the disposal issue sustainably.

4.4. Composting

Composting is a traditional method for treating organic waste, effectively transforming crop residues into nutrient-rich bio-fertilizers. This process enhances soil organic matter (Sharma et al., 2019), supports microbial diversity (D'Hose et al., 2018), and having a neutral pH is best boosts crop productivity. Additionally, composting minimizes the environmental and health risks associated with organic waste, offering a safe, cost-effective, and sustainable fertilizer source for agriculture (Awasthi et al., 2022). Its simplicity, affordability, and efficiency make it a popular choice for the eco-friendly management and reuse of organic waste. But one to two months' time period require for traditional composting methods (Lin et al., 2018).

4.4.1. Methods of Composting

Traditionally, there are two methods of composting: Open air composting (hot composting) and Direct Composting (in-ground composting)

4.4.2. Open Air Composting

Open-air composting typically involves piling crop residues in a backyard or using a simple bay constructed from readily available, inexpensive materials. Alternatively, it may involve upturned bins like the commercially available Gedyebin or wire cages lined with piping to hold water and capture heat, which can be utilized in hot water systems for sustainability. This method is generally classified as hot composting, though smaller waste quantities may produce less heat and are sometimes referred to as cold composting.

4.4.3. Direct Compost

Direct composting involves digging a hole or trench to bury crop residues. As one of the oldest and most effective composting methods, it has limitations, particularly its slow decomposition process. However, it promotes abundant worm activity, enriching the soil and benefiting the garden. The methods of direct composting include:

- **Combined Composting**: A mix of different organic materials for balanced decomposition.
- **Commercial Composting**: Large-scale composting using specialized processes and equipment.

- **Mechanical Composting**: Utilizing machinery to accelerate the breakdown of organic matter.

Vermicomposting is a stabilization of organic carbon matter present in crop residues, this process of vermicompost acceleration through *Eisenia fetida* is known as epigeal species (Karmegam *et al*., 2019) and converts carbon matter into stabilized decomposed matter through decomposition occurred in their gut and passes through whole body called as "worm casting" (Yadava *et al*., 2023). Vermicompost contains soil microbiota, including N_2 fixing and P solubilizing organisms (Yatoo *et al*., 2020). To sustain crop production by combination of bioorganic fertilizers with reduced chemical fertilizer application can maintain nutrients requirement (Cai *et al*., 2017). Vermicompost really has the ability to physically, chemically and biologically improve soil fertility (Tammam *et al*., 2023). Vermicompost can improve soil aeration, porosity, bulk density, water holding capacity, pH, organic matter content and electrical conductivity (Das and Ghosh, 2022; Hu *et al*., 2022). Table 2: Nutrient composition of compost and vermicompost (Srinivasarao *et al*., 2014; Chahal *et al*., 2019).

Table 2. Nutrient composition of compost and vermicompost (Srinivasarao *et al*., 2014; Chahal *et al*., 2019).

Nutrients	**Content**	
Macronutrients	**Vermicompost**	**Compost**
N	1.69 %	0.80 %
P	1.07 %	0.43 %
K	1.20 %	0.51 %
S	0.58 %	0.4457%
Ca	64.20 %	12.01 %
Mg	19.87 %	0.49%
Micronutrients		
Zn	21.94 ppm	11670 ppm
Fe	76.02 ppm	11.9 ppm
Cu	4.07 ppm	17.1 ppm
Mn	121.13 ppm	412 ppm

4.5. Biochar from residues

Biochar is created through pyrolysis, a process in which crop residues is heated to temperatures between 300–600℃ in the absence or limited presence of oxygen (Singh and Sidhu, 2014). Due to its resistance to decomposition, biochar can persist in soil for centuries. Recently, it has gained popularity as a soil amendment. By trapping carbon from crop residues carbon that would otherwise be released into the atmosphere as CO_2 biochar helps reduce agricultural carbon footprint (Puget and Lal, 2005; Whitbread et al., 2003). Applying biochar to soil enhances soil fertility, increases organic carbon content, lowers greenhouse gas emissions, and boosts fertilizer efficiency by reducing nutrient leaching (Nematian et al., 2021). With large crop residues concentration globally, pyrolyzing them offers a dual benefit: producing bioenergy to decrease reliance on fossil fuels, and creating biochar as a carbon-sequestering soil amendment (Tagade et al., 2021). During pyrolysis, approximately half of the carbon in biomass is released, potentially usable as fuel to lessen petroleum dependency, leaving behind stable biochar residues (Khare et al., 2021; Lehmann et al., 2006). Due to its porous, neutral, and amorphous structure, biochar promotes healthy microbial growth (Hamer et al., 2004) and acts as a small reservoir for plant nutrients and water (Warnock et al., 2007). However, the biochar impact on soil health, nutrient efficiency, and microbial activity across changed cropping systems (Hiloidhari et al., 2014).

4.5. 1. Crop residues as a substrate for mushroom cultivation

Residues like as wheat and rice are ideal substrates for growing button mushrooms (Niazi et al., 2021) & straw mushrooms (Biswas and Layak, 2014). Other 2 mushrooms, Lentinus and Pleurotus, are grown on logs and stumps. Straw for growing button mushrooms is frequently mixed with manure and hay to optimise mushroom development on the substrate (Wuest et al., 1987). When paddy straw mix banana pseudo stems with ratio 50:50 has been shown to boost mushroom cultivation yield. (Biswas and Layak, 2014). Mushroom cultivation using crop residues as a substrate is a profitable aspect of diversified agriculture, allowing crop waste to be transformed into high-value, nutrient-dense food (Hu et al., 2021; Manzi et al., 1999).

4.6. Building materials

In many countries, cereals crop residues are commonly used for roofing houses and sheds. An ancient technique involves mixing straw with clay to create bricks and walls, with the straw providing added strength. In modern applications, straw combined with suitable binders is used to produce boards, bio-composite materials, and other products like interior partitioning, packing & similar other uses (Russ and Meyer-Pittroff 2004). There have also been successful efforts to create boards from straw without bonding agents (Zhao et al., 2014). The demand for eco-friendly composite boards is growing, particularly as substitutes for synthetic materials and solid wood in industries such as packaging, aerospace, furniture, and automotive (Aladejana et al., 2020). Abundant natural fibers from wheat, rice, and corn residues have significant potential for producing these innovative materials.

4.7. Crop residues based crop breeding

To meet future crop production challenges, agronomic practices must be combined with breeding strategies, considering the differing responses of cultivars under no-tillage and conventional conditions. Modern varieties need improvement, especially due to dwarfing genes reducing the length of coleoptile (Rajbir Yadav et al., 2014). Wheat breeding should focus on traits like rapid root growth, fast germination, & emergence under high residue conditions (Christian et al., 2022 and Joshi et al., 2007). Varieties with longer coleoptiles have faster emergence and leaf area improvement. Several wheat genotypes like as HD3117, HDCSW18 and PBW 343 etc. perform better under no-till conditions, making them ideal for conservation tillage systems (Sagar et al., 2016). Hybrid rice varieties such as PSD 3, Rajalaxmi, and others are suited for aerobic conditions (Verma et al., 2021). Varieties like PR126 and Pusa 1121 allow wheat sowing by late October, though higher temperatures can lead to moisture depletion show initial heading in wheat. Conservation agriculture can mitigate these issues by regulating soil temperature. The novel wheat variety HDCSW 18, is a step in this direction.

Conventional rice varieties also face iron, zinc, and phosphorus deficiencies, especially under direct-seeded conditions (Joshi et al., 2007). Tillage-specific genotypes can boost crop productivity by integrating practices like tillage type, residue management, and crop rotations, unlocking the potential of conservation agriculture.

5.0. Policy intervention

Technological advancements in crop residue management must be supported by robust policy measures to ensure better farmer adoption of sustainable practices. According to the National Policy for crop residue management is encourage sustainable residue use and curb residue burning. Subsequently, regional initiatives targeting biomass burning and the 2018 National Biofuel Policy, which emphasized converting crop residues into ethanol. States like Punjab and Haryana, where rice-wheat residue burning is prevalent, also implemented bioenergy policies to promote renewable energy from rice straw. Financial measures, such as subsidies for residue handling machinery, community based farms implement banks for custom hiring, and penalties for residue burning, have been introduced to promote alternatives. Despite these efforts, residue burning persists due to challenges like small landholdings, the high cost of machinery, socio-economic barriers, local resource diversity, supply chain inefficiencies, and inadequate infrastructure for industrial residue utilization.

To address these gaps, a stronger focus on in-situ residue management is essential, supported by incremental incentives for farmers engaging in residue recycling, particularly during the first 4-5 years. Providing financial aid for machinery and microbial inoculants can further ease adoption. For industrial uses, government support transfer of crop residues from fields to processing unit similar to municipal garbage collection is crucial. Additionally, district-level industrial infrastructure and small-scale residue pre-treatment plants at the block level are necessary to reduce transportation costs and strengthen supply chains. Policymakers must adopt a participatory approach, empowering farmers through training and discussions, making them key stakeholders in policy reforms. Integrated government interventions are vital to change farmers practice burning to sustainable alternatives, ensuring environmental preservation and resource sustainability.

6.0. Conclusion

Sustainable crop residue management is essential for balancing agricultural productivity with environmental conservation. Residues improve soil health and recycle nutrients, but improper practices like burning cause air pollution, nutrient loss, and soil degradation, worsened by climate change. Adopting in-situ strategies such as surface retention, incorporation, and composting enhances soil fertility and organic matter. Mechanized tools support residue incorporation, while industrial uses like bioenergy and biochar offer economic benefits. Transforming residues from waste into resources requires innovation, policy support, and farmer awareness. Sustainable residue management reduces environmental impact, promotes resource efficiency, and ensures resilient agriculture for food security and ecological health.

6.1. Implication/Recommendation/Suggestion

- Proper crop residue management can significantly reduce environmental hazards like air pollution, soil degradation, and climate change impacts.
- Incorporating residues into farming practices improves soil fertility, enhances carbon sequestration, and ensures sustainable agricultural productivity.
- Industrial applications of residues offer economic opportunities while reducing reliance on non-renewable resources.
- Promote in-situ residue management practices such as surface retention, incorporation, and composting to improve soil health.
- Develop and subsidize efficient farm machinery for residue handling to reduce costs and labor requirements.
- Encourage research and development of innovative uses for residues, including bioenergy and biochar production.
- Policymakers should incentivize farmers to adopt eco-friendly residue management practices through financial support and awareness campaigns.
- Strengthen farmer training programs to highlight the economic and environmental benefits of sustainable residue management.

- Foster public-private partnerships to explore industrial applications of residues and create market linkages for value-added products.

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CHAPTER 2

CAN SOIL HEALTH MANAGEMENT ENHANCE CARBON SEQUESTRATION AGAINST CLIMATE CHANGE?

Assist. Prof. Dr. Somayyeh RAZZAGHI [1*]

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[1] Department of soil Science and Plant Nutrition, Faculty of Agriculture, Erciyes University, Kayseri/Turkey, Address, OrcID: 0000-0002-8028-452X
E-mail: srazzaghi @erciyes.edu.tr
*Corresponding Author: srazzaghi@erciyes.edu.tr

1. Introduction

Soil serves not merely as a beneficial environment for plant growth. The soil is also a living storage that may function as a carbon (C) sink or source. Soil can sequestrate extra carbon dioxide (CO_2) from the atmosphere, that is making the planet warmer (Razzaghi, 2021). Taking excellent care of soil health can enhance C concentration that be could possibly be sequestrated (Razzaghi et al., 2022). Therefore, soil health management plays an essential function in addressing worldwide climatic mitigation (Meena et al., 2024).

When farmers want to enhance soil health, they use crop rotation, cover crop planting, and no-tillage, and enhance the quantity of soil organic carbon (SOC) (Razzaghi, 2021). These methods improve the soil's physical (Hubbard et al., 2013), biological (Mullen et al., 1998), and chemical (Sharma et al., 2018) properties that prepare suitable conditions where higher C content can be sequestrated in the soil. In addition, healthy soils can better combat soil erosion, which helps further increase their capacity to store C (Rojas et al., 2016).

Consequent to the above, the promotion of sustainable farming practices for increasing SOC sequestration has its most important consequence regarding climate change mitigation processes (Nazir et al., 2024). Healthy soils, with no application of chemical fertilizers in farming, link to better crop yields due to improved water usage(Lehmann et al., 2020). This aligns with Zhao et al. (2024), hence having a better effect in terms of causing more GHG reduction. In this vein, managing soil health can mitigate climate change and enhance crop yield and food security (M. Tahat et al., 2020; Timsina, 2018). This makes it a fundamental part of focusing on climate change for rural areas and farming communities (Sharma et al., 2016).

This chapter investigates various management practices in soil health that boost C sequestration in the direction of mitigating climate change. Improvement in methodology for crop rotation, cover cropping, reduced or no tillage, agroforestry, and Utilization of organic fertilizers improves soil organic matter (SOM) stock capacity, and its main fraction is named C. The chapter goes in-depth on the scientific strategies by which healthy soils act as C sinks, decreasing CO_2 concentration in the atmosphere. Furthermore, this chapter explored thoroughly other deeper ecological and agricultural benefits of these practices, which improved soil productivity, water retention, and biodiversity.

2. The Link Between Soil and Climate

2.1. Carbon Cycle and Soil

In contrast to popular belief, the majority of the C is stored in soils mainly in the manner of organic matter rather than in the atmosphere (Wu et al., 2024). In the worldwide C cycle, soil behaves as either a source or a sink. (Nazir et al., 2024). Plants absorb atmospheric CO_2 by photosynthesis, and upon dying and decomposing, a greater fraction of that C returns to the soil (Murphy, 2024). Nonetheless, human activities such as deforestation, intensive farming, and erosion-related and other types of soil degradation have accelerated C release from soils to the atmosphere and enhanced GHG emissions (Arif, 2024). The opposite happens in healthy soils when well-treated, by sequestering a high content of C and lowering the rate of atmospheric CO_2, hence mitigating climate change (Lal, 2021).

2.2. Carbon Sequestration and Soil Health

This therefore allows for higher SOC stock since healthy soils have better structure, biological activity, and organic matter (Rao, 2013). The main role of conservation agriculture through cover cropping, reduced or no-tillage, and organic fertilizers is to offer more C capture and storage in the soil (Krauss et al., 2022). It also means that food production would have to rely less on climate-sensitive areas. Sustainable soil management strategies can enhance the long-term storage of SOC and therefore, make SOC more stable through this elevated technique (Francaviglia et al., 2023). Healthy soils are also more resilient to erosion and degradation processes, as well as to their C-stock potential (Lal, 2004; Rinot et al., 2019). Improving soil health is thus crucial to reducing different aspects of climate change by improving the SOC sequestration rate.

2.3. The Soil Organic Carbon and Climate Change

Even so, healthy soils by enhancing water retention, assisting biodiversity, and improving nutrient cycling can mitigate climate change (Kundu & Kumar, 2024). Under dry climate conditions, a substantial concentration of SOM can store more water for crop needs, thus decreasing the requirement for irrigation (Lal, 2020). Such soils provide a home to micro- or macroorganisms, that play essential functions in nutrient cycling and the upkeep of ecosystem stability (Aqeel et al., 2023). Consequently, healthy soils enhance the soil's buffering capability under the effect of extreme climate change (Lal, 2011). Thus, soil health contributes not only to C sequestration but also to assisting the sustainability of agricultural systems in the context of a changing climate (Kumar et al., 2017).

2.4. Sustainable Soil Management and Climate Change

The soils will need to be managed more sustainably for the full utilization of their capacity to help promote the practices that mitigate climate change on concentrations that could possibly be sequestrated (Branca et al., 2013). These paractices include scientific research that supports policies, education of farmers (Romig et al., 1995), and ultimate adoption of regenerative practices that advocate soil health (Khangura et al., 2023). The C farming incentives (Toensmeier, 2016), enhancements in land-use policies (King et al., 2016), and international cooperation are vital for upscale efforts at the global level (Bausch & Mehling, 2011). Furthermore, soil health by a natural and economically efficient method can be integrated into the mitigation of climate change (Yang et al., 2024) which will prepare food security, water management, and biodiversity preservation. Therefore, the management of soil, especially organic C, should be the primary emphasis in the combat against climate change (Lal, 2013).

Fig. 1. "Soil and Climate: The Carbon Connection"

3. Soil Carbon Stock and Microorganisms

The microorganisms are involved in a close manner in the C cycle, since they decompose organic matter into more simple compounds, potentially affecting long-term C storage and atmospheric CO_2 emission (Mustafa et al., 2024). Moreover, microbial activity later generates stable organic molecules and governs their protection and stabilization (Paul, 2016). Soil microorganisms accomplish this by synthesizing enzymes that decompose organic substances into smaller, more stable molecules. These molecules, such as microbial necromass composed of deceased microbial cells, cannot undergo further decomposition and significantly contribute to the SOM (Sollins et al., 1996). Microbial-derived C creates enduring storage in soils and serves a crucial act in strengthening SOC sequestration (Zhou et al., 2024).

However, the diversity of soil microorganisms plays a significant role in the well's SOC sequestration (Bhattacharyya et al., 2022; Kabiri et al., 2016). By increasing the variety of microbes, techniques used in ecosystems to break down organic matter, like nutrient cycling and C stabilization, should work better and be stronger. This is because microbes have different metabolic abilities. Hence, microbial diversity is crucial in facilitating access to the full capacity of soils acting as C sinks (Dubey et al., 2019; Hu et al., 2024). In this respect, human actions that include overapplication of chemical fertilizers, intensive tillage, and monoculture help promote the deterioration of soil structure and reducing microbial diversity; hence, it is limited in storing SOC. Sustainable management practices involve the application of compost or biochar and the implementation of reduced or no-tillage practices that increase microbial activity and diversity, hence increasing C sequestration (Meng et al., 2024; Song et al., 2024). As mentioned above, only healthy soils promote a diverse microbial life that transforms organic compounds and plant residues into stable organic forms through humification. This procedure ultimately results in SOC sequestration over centuries (Walia & Kaur, 2024). Because of this, learning how SOC sequestration works and what role soil microorganisms play will make its effectiveness in mitigating climate change stand out more.

4. The Soil Health Practices for Soil Carbon Sequestration

Some of the soil health practices for soil C sequestration are outlined below (Fig. 2)

4.1. Crop Rotation

Fundamental to sustainable agriculture and ecosystem resilience is soil health improvement which assurances food security. (Lal, 2024). Healthy soils assist plant growth, improve water penetration, decrease different types of soil erosion (Turner et al., 2018), and support biodiversity (Adewara et al., 2024). The most crucial strategy for improving soil health contemplates crop rotation, where the farmers will have to plant different types of crops on the same piece of soil as their farming management practice (Aziz et al., 2011). This process reduces soil nutrient depletion (Keres et al., 2020), limits the potentiality of soil-borne diseases (Vargas Gil et al., 2008), and depending on the crop, decreases pest formation (Bullock, 1992). In addition, legumes or other nitrogen-fixing crops in rotations may replace some essential nutrients naturally, thus further reducing the necessity of utilizing synthetic fertilizers (Jensen et al., 2020).

4.2. Cover Crops

Another essential strategy adopted for soil health improvement is cover cropping. Cover crops may involve clover, rye, or legumes grown over the seasons when the major crops are not on the farm. Such crops aid in soil erosion control, restriction of weed growth, and improvement of SOM content (Razzaghi, 2021). When cover crops decompose, essential nutrients are returned to the soil, advocating the development of profitable microorganisms. Cover cropping also enhances the structure of the soil, such that the likelihood of compaction diminishes and its water retention capacity increases, which is important in drought prevention and flood management, respectively (Islam & Sherman, 2021).

4.3. Organic Fertilizers

Organic fertilizers like compost, legumes, manure, and biochar provide soil fertility. These fertilizers improve the soil structure, boost the availability of slow-releasing sources of nutrients, and improve microbial activities, which are vital for preserving fertile and healthy soils (Razzaghi, 2024). According to Yan and Gong (2010), the utilization of organic fertilizers can boost SOC and soil productivity. Furthermore, they reported that the changes in SOM and wheat yield have been significantly linearly related (Fig. 3). As mentioned above unlike chemical fertilizers, organic fertilizers can release their nutrients more slowly, providing plant's requirements while minimizing the risk of nutrients leaching into water systems (Shaji et al., 2021). Organic amendments enhance the SOC sequestration potential; therefore, climate change is mitigated since a higher content of C is stored while there is less emission of greenhouse gases (Razzaghi, 2022). Moreover, the application of soil health practices that decrease the application of synthetic fertilizers and favors using compost and natural inputs can decrease agriculture's C footprint. In addition, healthy soils require fewer chemical inputs, which will reduce energy use and the emissions associated with fertilizer manufacture and application (Razzaghi, 2024). Healthy soil management sequesters more C by combining organic matter and optimizing nutrient cycling (Waqas et al., 2020). This approach reduces GHG associated with farming activities (Powlson et al., 2011).

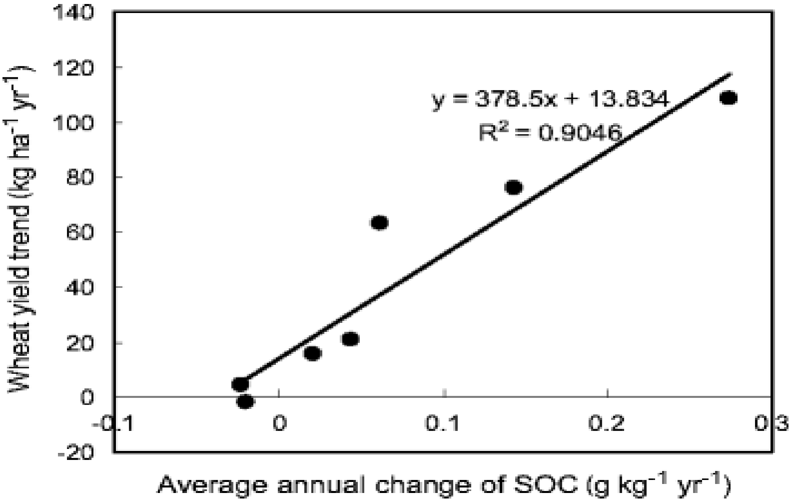

Fig. 3. The significantly linearly relation between SOC content and wheat yield (Yan & Gong, 2010)

4.4. Agroforestry

The most valuable soil health management practices are agroforestry and grazing control. Agroforestry is planting trees and shrubs among the farmland, which ensures their safety to combat erosion and boosts biodiversity and nutrient cycling via leaf litter and root interaction (Dollinger & Jose, 2018). In this method, to avoid overgrazing, farmers use rotational grazing of grasslands;

hence, the soil is not compacted to allow the growth of grass (Taylor, 2024). It is considered that these two practices, among others, are optimal management techniques for providing long-term soil health and, notably, developing agricultural resilience in response to climate change (Singh et al., 2024). According to Joshi et al. (2024), a poplar trees+wheat intercropping system could increase C sequestration compared to sole wheat or sole poplar planting in North India (Fig. 4). With such practices regarding soil health, farmers can construct more resilient ecosystems while keeping agricultural productivity at a higher rate.

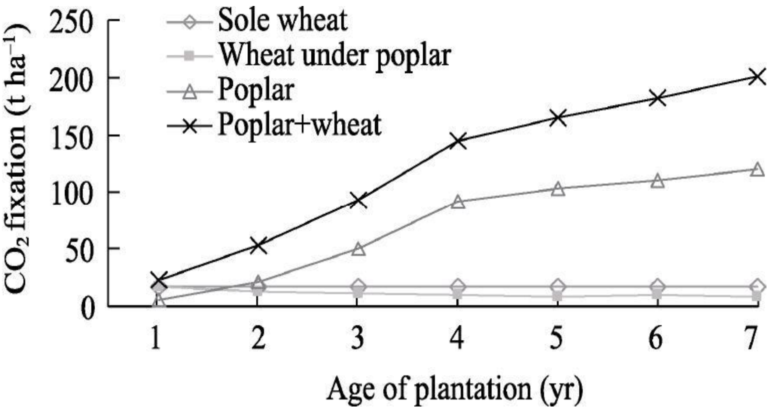

Fig. 4. The poplar-wheat intercropping system impact on Carbon sequestration (Joshi et al., 2024)

4.5. Conservation Tillage

Conservation tillage is one of those farming strategies regarding minimal soil disruption via reduced or no tillage; it also performs an outstanding function in C sequestration (Hussain et al., 2021). Keeping crop residues on the field and not conducting heavy tillage enables more organic matter to remain in the soil. That organic matter stores C, avoiding the spread of it into the atmosphere as CO_2 (Aziz et al., 2013). Further, this practice consolidates the soil structure and improves microbial activities, hence SOC sequestration becomes more sustainable for longer (Zhang et al., 2021). In this context, Ur Rehman et al. (2023) reported the highest SOC sequestration rate under fellow-wheat and mungbean-wheat cropping systems in combination with no tillage

(Fig. 5). Besides improving C storage, conservation tillage enhances general soil health: it reduces erosion, improves water retention, and increases biodiversity factors that in turn further help to stabilize and sequester C (Begum et al., 2022; Fiorini et al., 2022). Conservation tillage raises the level not only of soil sustainability but also enables farmers to offset climate change by making agricultural soils serve as effective C sinks.

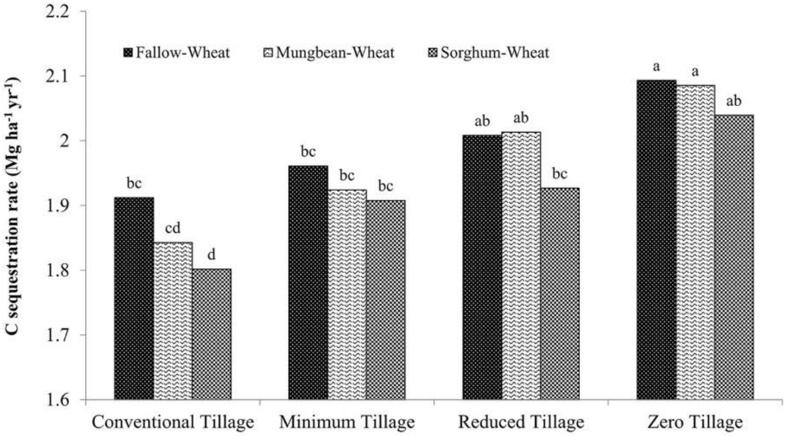

Fig. 5. SOC sequestration rate across various cropping and tillage systems (Ur Rehman et al., 2023)

4.6. Control of Soil Erosion

Management of soil health averts loss from stored C caused by the preservation of soil structure and reduction in erosion (Hussain et al., 2021). Control of soil erosion is essential in ensuring the promotion of soil health by boosting C sequestration. Wind and water erosion removes that portion of topsoil where organic matter and stored C are concentrated (Du et al., 2022). The lost topsoil releases C into the atmosphere as CO_2, subsequently contributing to increased climatic change (Yang et al., 2003). Consequently, the protection of soils from erosion will prevent this stored C from loss and guarantee its continued operation functioning as a C sink instead of a source of CO_2 emissions (Razzaghi et al., 2021). Contour farming (Farahani et al., 2016), vegetation buffers (Kavian et al., 2018), terracing, and cover cropping (Aziz et al., 2014) are some of the practices that decrease erosion and preserve the C stored in the soils. Healthy soils with strong structures can store this C over long periods; hence, they are beneficial C sinks (Saleem & Batool, 2024).

4.7. Nutrient Cycling

Nutrient cycling is fundamental to soil health management practices and hence continuous supplementation of nutrients due to various natural phenomena of decompositions, mineralization, and microbial activities come back to the soil for growing better plants with structural improvement and water retention capacity (Iamjud, 2021; Singh et al.; Yousuf et al., 2022). Nutrient cycling in this respect includes the organic material from plant residues and animal manure that provide nutrient storage, decomposing through soil organisms, and providing it available to plants (Schröder et al., 2016). Besides soil fertility, nutrient cycling supports C sequestration as a very crucial strategy in the mitigation of climate change (Kirkby et al., 2013). Organic matter and plant residues broken down through nutrient cycling can keep C within the soil as stable organic materials (Razzaghi et al., 2021). Once this C gets sequestered, the atmospheric CO2 concentration will reduce, hence helping offset GHG (Razzaghi et al., 2022). Where nutrient cycling is active, healthy soils are more effective at capturing and storing C, hence acting as better C sinks (Chowdhury et al., 2021).

4.8. Organic Farming

Organic farming, as noted in organic fertilizers, has great potential to improve SOC sequestration through the improvement of soil health (Gamage et al., 2023) and the reduction of GHG emissions due to its valuable practices (Squalli & Adamkiewicz, 2023). Composting, crop rotation, manuring, and cover cropping provide a high content of SOM because of lack of synthetic fertilizers, herbicides, and pesticides (Goldan et al., 2023; Shakywal et al., 2023). Due to this high level of organic matter, the soil's capability to capture and store C increased, hence considering it a natural C sink (Mosa et al., 2023). As mentioned above, other organic farming practices, such as crop rotation, reduced tillage, and agroforestry, enhance further the soil structure, prevent erosion, and give a helping hand to biodiversity toward the sequestering of more C within plant biomass and soil. As repeatedly described in past sections, organic farming reduces climate change by decreasing GHG emissions

(Aguilera et al., 2015; Pegu et al., 2024). In addition, contrary to organic farming, conventional farming often depends on very energy-intensive input materials, such as chemical fertilizers and fossil fuels, leading to a high rate of emissions (Rosati et al., 2021; Tittonell, 2014). Organic farming also contributes to biodiversity and produces food sustainably (Underwood et al., 2011). Additionally, it makes the soil resilient to store more C for a longer period (Rohit Yadav et al., 2024). It therefore promotes food security and environmental health but also mitigates more considering climate change by C sequestration (Banerjee & Sarkar).

4.9. Precision Agriculture

The innovative tools of precision agriculture include GPS, drones, sensors, and data analytics; these enable the farmer to apply all inputs-that is, worthwhile compounds like water, fertilizers, herbicides, and pesticides-in precisely correct content to the right place; hence, diminishing waste of these costly and vital inputs (Razzaghi & Kılıç, 2024). Precision agriculture can also help C sequestration by adopting improved farming practices that drop emissions and improve the capture of more C within the soils by biomass (Balafoutis et al., 2017). Besides useful use of inputs, this type of agriculture also promotes zero tillage farming, cover cropping, and optimized crop rotations to help accumulate the SOM and develop C sequestration (Cillis et al., 2018; Handayani & Folz, 2021). As a result, this method of agriculture by appropriate soil management will increase soil fertility and soil health, SOC sequestration, and mitigation of climate change (Balasundram et al., 2023; Nath, 2024; Roy & George K, 2020; Shaheb et al., 2022).

4.10. Regenerative Agriculture

Some of the main techniques in this soil health management practice include agroforestry, holistic grazing (Cusworth et al., 2022), reduced or no-till methods of farming (Pontius & McIntosh, 2024), and cover cropping (Jordon et al., 2022) were used. These procedures can help farmers produce organic matter in soils and enhance the long-term C sequestration, decrease atmospheric emissions, and, on the other hand, improve biodiversity and enhance soil health (Sahu & Das, 2020). As previously described, C-rich Soils not only reduce atmospheric CO_2 but also enhance soil fertility and productivity in plants by enhancing water retention and increasing resilience against climate change conditions (Victoria et al., 2012).

Sequestration as a repeated continuous word in regenerative agriculture is a natural phenomenon that, through photosynthesis, include the uptake of CO_2 by plant and the transference of C into the soil via roots and fixed in aggregates of the soil after organic matter decomposition (Ravina Yadav et al., 2024). This balances out the emissions and, therefore, creates one of the potential solutions for mitigating climate change while restoring ecosystems (Ravina Yadav et al., 2024). Such methods in regenerative agriculture can turn the soil into a C sink to contribute to more sustainable agricultural systems in all aspects, from C sequestration to climate-friendly agriculture.

4.11. Biodiversity’s Role

In the preceding sections, it was discussed widely that biodiversity in plants and micro and macroorganisms can improve soil health, which is an important part of C sequestration. As known ecosystems that will be more diverse, such as forests, grasslands, and wetlands. This diversity caused them to capture different amounts of C due to their differences in photosynthesis (Daba & Dejene, 2018). In polyculture systems, plant species with different rooting systems are more varied and are in higher depth than those in monoculture species (Lei et al., 2012). Thus, the rooting architecture strengthens soil stability and favors the transfer of C to a deeper layer of the soil (Freschet et al., 2021; Hodge et al., 2009). Ecosystems foster healthy soil microbiomes for better soil C stock through nutrient cycling. It follows that the higher the biodiversity, the more resistant the ecosystems are to disturbances, like pests and diseases, and climate changes; therefore, they are in a position to maintain C sequestration for a long period (Hartmann & Six, 2023; Prasad et al., 2021; Yadav et al., 2021). By applying soil management like crop rotation, cover cropping, polycultures, and agroforestry, we can improve biodiversity and, consequently, C sequestration due to enhancements in SOM content (Jhariya et al., 2023; Weißhuhn et al., 2017).

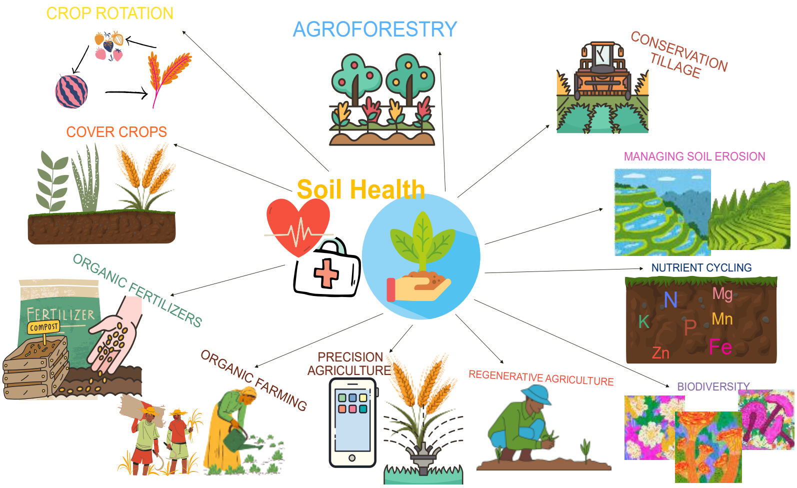

Fig. 2. The Soil Health Practices for Soil Carbon Sequestration

5. Some of the Successful Soil Health management paractices for Carbon Sequestration

Soil health management practices are essential in enhancing C sequestration for climate change mitigation. Some of the described practices that work in the recent and previous studies for improving C sequestration and climate change mitigation are listed in the table below (Table 1). The combined practice has greatly contributed to increased soil C stocks, improved soil health, and a more robust agriculture system in response to climate change.

Table 1. Some of the successful soil health management practices affect on soil C sequestration and climate change

Soil Health Management Practice	Effect on Soil C Sequestration and Climate Change	References
Cover Cropping	↓Erosion, fix atmospheric N_2, ↓N leaching, and ↑soil health.	(Kaye & Quemada, 2017)
	↑SOC most in ↓-C soils (<1% C) and after 5 yr (when cover crops created >2 Mg biomass ha^{-1})	(Blanco-Canqui, 2022)
	Potential global SOC sequestration of 0.12 ± 0.03 Pg C yr^{-1} by cover cropping	(Poeplau & Don, 2015)

No-till or Reduced Tillage	No-till↑ ~38% SOC concent (0–5 cm depth), SOC stock ↑ by 14% or 5.4 Mg C ha^{-1} over 0–30 cm depth. SOC content was predicted to range from 1.4 - 1.7 Mg ha^{-1} (by yr 2054), and 2.3 - 3.1 Mg ha^{-1} (by yr 2100). Crop yield↓ of wheat (7.7%) and maize (2.3%), SOC sequestration↑ by 9.9%, No-till + crop residue + crop rotation ↓the negative impact of No-till on crop yield (5% to 2.44%), and ↑SOC sequestration > 12.77%.	(Mondal et al., 2023) (Sorenson et al., 2024) (Cui et al., 2024)
Organic Amendments (Compost, Manure)	Restores SOC and ↓atmospheric greenhouse gases (GHG). ↑SOC sequestration and pool and ↑soil quality ↓atmospheric GHG.	(Owusu et al., 2024; Shivangi et al., 2024) (Alvarenga et al., 2020)
Biochar Application	Globally, ↓emission reductions of 3.4–6.3 PgCO2e, with half of this amount dedicated to CO_2 removal. ↓Climate change by ↑SOC sequestration and ↓soil GHG emissions	(Lehmann et al., 2021) (Franco et al., 2024)
Agroforestry and Perennial Crops	↑ SOC sequestration rates by 5–10 times, and ↑ SOC stocks by a factor of 3–10. Agroforestry ↓the emissions of CO_2 by sequestering C from the atmosphere Agroforestry systems sequester ↑C in subsurface layers of soil near the tree	(Toensmeier, 2017) (Tefera et al., 2019) (Sow et al., 2024)
Crop Rotation and Diversification	Modifications in Finnish agricultural crop rotations, in mineral soils↓ the reduction of SOC content by 1336 Mg C $year^{-1}$, in organic soils↓ CO_2 emissions of by 10,475 Mg C $year^{-1}$.	(Kostensalo et al., 2024) (Yang et al., 2024)

	The diversified rotations » wheat–maize + sweet potato +peanut and soybean » ↑yield > 38%, ↓N_2O emissions by 39%, and ↑ the system's GHG balance by 88%. Legumes in crop rotations » ↑soil microbial activities » ↑SOC stocks by 8%, and » ↑soil health Index by 45%.	

↑= high or increased, ↓=low or less, decreased

5.5. Conclusion

Overall, from this point of view, throughout the fight against climate change, managing soil health is one of the promising techniques for C sequestration, which has huge beneficial implications both for the surrounding environment and farming. Practices in soil health enhance SOM, offer a healthy microbial ecosystem, and encourage soils to capture more C and store it longer, hence offsetting some of the GHG emissions responsible for global warming. A positive correlation exists between soil health and climate mitigation. It was demonstrated that promoting soil fertility and sustainability can reduce atmospheric CO_2 rates. Cover cropping, crop rotations, reduced tillage, and organic fertilization as accomplished practices in improving soil health present the potential of such strategies to create considerable results in enhancing C sequestration. Enhancing soil health will also minimize soil erosion, thereby enhancing soil C stock and its stability. Innovation techniques like precision agriculture and agroforestry enhance the sustainability of different soils in a wide range of agricultural ecosystems. Any accurate vision of sustainability for the future should make soil health management integral to any set of policies regarding climate change. It is, therefore, important that governments, agriculture sectors, and regional communities around the world focus their efforts on those practices that help in SOC sequestration and balance productivity with sustainability and ecological health. Enhancing operational methodologies in soil health with investment in research and training will provide a functional pathway toward mitigating climate change and protecting soil resources for future generations.

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CHAPTER 3

DRAINAGE-SALINITY PROBLEMS AND SOLUTIONS IN TÜRKİYE

Prof. Dr. Ali Fuat TARI[1*]

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[1] * Harran University, Faculty of Agriculture, Department of Agricultural Structures and Irrigation, Şanlıurfa, Türkiye. aftari@harran.edu.tr, ORCID: 0000-0001-9157-1682
*Corresponding Author: aftari@harran.edu.tr

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1. Introduction

Drainage is defined as the removal of excess water from the surface and subsurface layers of the soil and is a necessary approach to developing the ideal balance of water and air in the cultivated field soils. This approach is mostly related to forming appropriate conditions of soil to allow roots to grow well. Thus, soil gets completely saturated, causing the soil oxygen level to decrease and leading to root rot if excess water is not removed (Ekmekçi et al., 2005; Eğilmez, 2018).

On the other hand, soil salinity refers to the presence of soluble salts like sodium, magnesium, and calcium in the soil, which is harmful to plants and reduces the fertility of the soil (Hailu & Mehari, 2021). This condition is usually assessed by the value of the electrical conductivity of the soil, whose salinity levels higher than a specified value are considered injurious to agricultural production (Temel & Şimşek, 2011; Çullu et al., 2015).

In the light of that fact, this potential, being very important, will belong to Türkiye because Türkiye is a country containing vast areas of agricultural usage (Yavuz, 2005). Some of the crucial causes hampering agricultural productivity in a vital farming country are inadequate salination due to the deficiency of appropriate integrations of drainage into the projects of irrigation. Moreover, all these issues constitute crises and are highly emergent in arid or semiarid regions due to high irrigation rates there. Besides yielding losses, this low drainage and salinity have some potential long-term after-effects related to soil health and environmental sustainability (Singh, 2021).

In this part, the chapter discusses the causes of Türkiye's drainage and salinity problems, the influence both factors have on agricultural yield, and possible remedies based on both factors.

2.Overview of Drainage and Salinity Issues in Türkiye

The cultivation difficulties faced in agricultural production in Türkiye emerged from geographical and climatic diversity, the mistakes made in the planning and implementation of irrigation projects, and the deficiencies in land management, which caused drainage and salinity problems (Temel & Şimşek, 2011; Eğilmez, 2018). These issues are increasingly significant, especially in irrigation-dominant areas (Çullu et al., 2015). Causes of drainage and salinity problems below, their effects on agricultural production, and regional differences in Türkiye are discussed in detail.

2.1. Geographical and Climatic Factors

Climatic characteristics of Türkiye are one of the main factors affecting the regional distribution of drainage and salinity problems (Çakmak and Gökalp, 2011). Especially in arid and semi-arid regions, the prevalence and severity of these problems are more evident:

- **Arid and Semi-Arid Regions (Southeastern Anatolia, Central Anatolia)**: As it is well known, rainfall being small in arid and semi-arid areas, irrigation projects lacking sufficient draining cause salinization in the soil at an almost incredible rate (Akış et al., 2005). Additionally, this high evaporation rate has augmented the upward salt transport towards the surface of the soil further contributing to an increase in salt accumulation.
- **Humid and Semi-Humid Regions (Aegean, Mediterranean)**: In regions with higher rainfall, insufficient drainage systems lead to waterlogging in soils, further exacerbating drainage-related issues.

2.2. Agricultural Irrigation and Water Management Practices

Irrigation projects in Türkiye are a key factor contributing to the development of drainage and salinity issues.

- **GAP Region:** The Southeastern Anatolia Project (GAP), one of Türkiye's largest irrigation initiatives, has greatly expanded irrigation activities in the region (Üzen et al., 2013). However, insufficient drainage following irrigation has resulted in significant salt accumulation. For instance, in the Harran Plain, the failure to remove excess water has caused fertile agricultural lands to become saline (Figure 2.1).

Figure 2.1. Agricultural land with salinity problem

- **Konya Plain**: The uncontrolled use of groundwater and the lack of adequate drainage systems following irrigation have resulted in both a decline in water levels and an increase in salinity in this region (Ökten, 2012). Surface salinity problems are frequently observed around Salt Lake (Demir, 2006).
- **Aegean and Mediterranean Regions**: Salinity from seawater intrusion and uncontrolled use of irrigation water have increased the risk of salinity in these regions.

2.3. Soil Characteristics and Salinity

Salinity formation and spreading depend basically on the characteristics of the soil (Tang et al., 2020). Variability in the structure of soils in different parts of Türkiye greatly affects the distribution of salinity problems. The physical, chemical, and biological properties of the soil have a direct impact on the rate and effects of salt accumulation; therefore, they play a critical role in this process.

2.4. Effects of Soil Types on Salinity

Salinity is closely linked with the type of soil, which is the prime factor for the determination of water flow and thereby the deposition of salt. Major soil types prevailing in Türkiye are:

- **Clay Soils**: Having high water retention capacity with low permeability, this type of soil is most susceptible to salt deposition (Li et al., 2014). If the drainage is not proper after irrigation, saline water starts accumulating on the surface, accelerating the problem of salinity.
- **Loamy Soils**: These soils possess moderate characteristics for water retention and drainage (Mallants et al., 1998). Salt accumulation is lower than in clay soils and takes more time.
- **Sandy Soils**: These are highly permeable soils that have a low possibility for salt accumulation (Huang & Hartemink, 2020). However, this same characteristic promotes other drawbacks: rapid nutrient and water leaching.
- **Organic Soils**: These are relatively resistant to salt accumulation on account of the organic content's capacity to bind high amounts of water and salts.

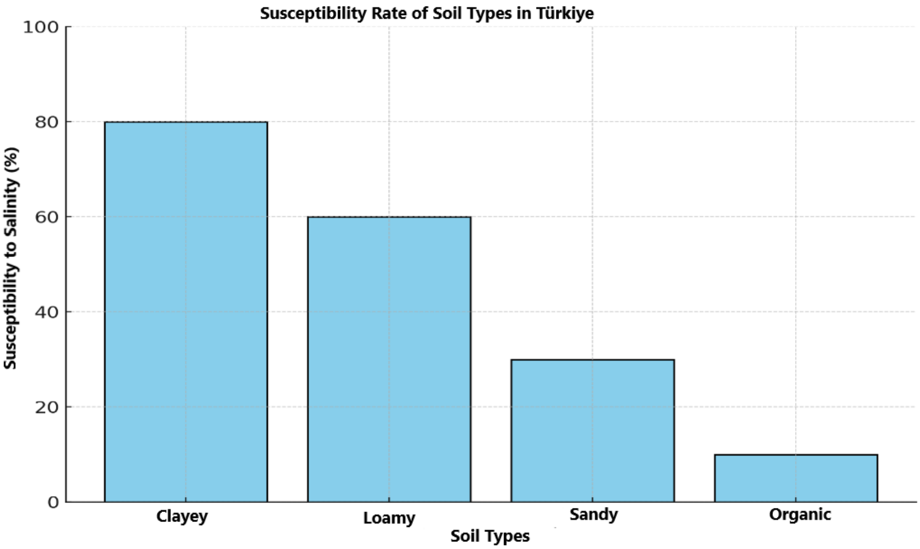

Figure 2.2. Salinity tendencies of soil types

The graph above illustrates the susceptibility rates of these soil types to salinity. While clay soils pose a high risk at 80%, organic soils exhibit a significantly lower susceptibility of 10% (Figure 2.2.).

2.4.1. Salinity and Soil Chemistry

All these factors influencing soil chemistry have a significant impact on both plant nutrition and soil fertility (Jones, 2012). A detailed examination of chemical properties is crucial for effectively managing salinity problems and ensuring agricultural sustainability. The role of soil chemical properties in salinity formation is discussed in detail below:

- **Cation Exchange Capacity (CEC)**: Determines the soil's capacity to bind salts (Zaman et al., 2018). Soils with high CEC values may mitigate the effects of salinity.
- **pH Levels**: Soil pH directly influences the impact of salinity (Lin & Banuelos, 2015). High pH levels (alkaline conditions) may increase salt solubility, leading to higher salt accumulation.
- **Sodium Adsorption Ratio (SAR)**: Indicates the sodium content in the soil, particularly the ratio of sodium to other cations, and is a critical indicator in salinity issues (Gharaibeh et al., 2021). Soils with high SAR values lose permeability, resulting in compaction and hardening problems.

2.4.2. Regional Distribution of Soil Salinity

Saline soils in Türkiye are predominantly concentrated in arid and semi-arid regions:

- **Konya Plain**: Salinity poses a significant challenge due to rising groundwater levels and high surface evaporation rates.
- **Harran Plain**: Salt accumulation is commonly observed due to drainage deficiencies in the irrigation projects of the Southeastern Anatolia Project (GAP).
- **Salt Lake Region**: In addition to natural salt accumulation, agricultural activities have further exacerbated salinity in this area.

3. Drainage Issues

Drainage is a crucial method for maintaining the optimal water balance in agricultural lands by removing excess water (Figure 3.1).

Figure 3.1. Underground drainage system

However, the lack of adequate drainage stands out as one of the weakest aspects of irrigation projects in Türkiye. The main reasons for this issue include:

- **Insufficient Infrastructure**: Drainage systems are often neglected or given low priority in irrigation projects.
- **Deficiencies in Soil and Water Management**: Insufficient planning is conducted for the removal of excess water after irrigation.
- **Economic Factors**: The construction and maintenance of drainage systems are not adequately supported due to high costs.

The consequences of inadequate drainage are severe and widespread:

- **Flooding**: The inability to remove excess water deprives plant roots of oxygen, leading to root rot.
- **Degradation of Soil Structure**: Persistent waterlogging causes soil compaction and a loss of permeability.
- **Increased Salinity**: Evaporation of surface water accelerates the accumulation of salts.

The lack of drainage is a particularly critical issue in regions with intensive irrigation projects:

- **Southeastern Anatolia**: The Southeastern Anatolia Project (GAP), Türkiye’s largest irrigation initiative, aims to enhance the region’s agricultural production capacity. However, the failure to implement irrigation systems as planned and the inadequacy of drainage infrastructure have led to serious problems, resulting in significant water losses from over-irrigation (Figure 3.2).

Figure 3.2. Harran Plain Arıcan Main Drainage Canal

Suruç Plain is a clear example of these challenges. Before the region was opened to irrigation, irrigation methods were planned based on pressurized irrigation systems, leading to the assumption that a drainage system would not be necessary. However, most farmers chose surface irrigation methods instead of pressurized systems. Since water application in surface irrigation is often uncontrolled, over-irrigation occurred, which subsequently resulted in significant drainage issues.

- **Aegean and Marmara Regions**: In these areas, the lack of surface drainage systems has led to waterlogging and soil compaction.
- **Black Sea Region**: In this high-rainfall region, the absence of underground drainage systems has exacerbated soil erosion and increased the occurrence of floods.

4. Salinity Issues

Soil salinity is a significant problem that directly impacts agricultural production. The primary causes of salinity include:

- **Improper Irrigation Practices**: Excessive application of water during irrigation and the absence of adequate drainage systems lead to the accumulation of salts in the soil.
- **Quality of Irrigation Water**: The use of water with high salt content for irrigation gradually increases soil salinity over time.
- **Rising Groundwater Levels**: Insufficient drainage causes groundwater levels to rise, bringing salt to the soil surface.

Salinity problems are particularly prevalent in arid and semi-arid regions. This condition limits the ability of plant roots to absorb water and nutrients effectively, resulting in stunted growth, yield losses, and reduced crop quality. In Türkiye, regions such as the **Konya Plain**, **Harran Plain**, and **Salt Lake** are particularly affected by these issues.

5. The Coexistence of Salinity and Drainage Problems

Salinity and poor drainage are two critical problems that most often threaten agricultural production and soil health, according to Mukhopadhyay et al. (2021) and Kahlown & Azam (2003), respectively; these problems nearly occur together. These problems usually accelerate each other, making the situation more complex and challenging to manage. Poor drainage systems lead to water retention in the soil after irrigation, and as this water evaporates, the rate of salt deposition on the surface increases. This is particularly problematic in semi-arid and arid regions such as Türkiye and causes significant losses economically and environmentally.

5.1. Impact of Drainage Deficiency on Salinity

The poor drainage systems allow water left behind in the soil after irrigation to evaporate with the salts that have dissolved from water. Particular contributing factors:

- **Rising Groundwater Levels**: Poor drainage brings irrigation water to lift up the groundwater table. Since the groundwater is often full of salts, when it rises to the top and evaporates, its salinity deposits at the top layer of the land are observed.

- **Quality of Irrigation Water**: Using low-quality, saline irrigation water without adequate drainage accelerates the development of salinity problems.
- **Soil Water Saturation**: In water-saturated soils resulting from poor drainage, leaching of salts to the lower depths is reduced and hence concentration on the surface takes place.

5.2. Impact of Salinity on Drainage Systems

Salinity not only affects plant growth and soil fertility but also negatively impacts the functionality of drainage systems:

- **Clogging of Drainage Channels**: Salt accumulation may lead to sedimentation and blockages in drainage channels, reducing their efficiency (Wang, 2024).
- **Chemical Damage to Drainage Pipes**: High salt concentrations may cause chemical corrosion in drainage pipes made of metal or plastic materials.
- **Reduced Drainage Efficiency**: Soil compaction caused by salinity hinders the drainage system's ability to efficiently remove excess water.

5.3. Regions Where Salinity and Drainage Issues Coexist

In Türkiye, the regions generally associated with salinity and also drainage problems include:

- **Harran Plain (GAP Region)**: Because of the inadequacy of the drainage infrastructure, water that gathers on the surface after irrigation rapidly evaporates and re-deposits salts. Consequently, it reduced soil fertility and landfilled some areas unsuitable for agriculture.
- **Konya Plain**: Increasing groundwater levels and salt accumulation, coupled with deficiencies in drainage, have brought about huge losses in agriculture. The problem has also been further exacerbated with the extensive use of surface irrigation methods.
- **Salt Lake Region**: This area already has naturally high salinity levels. Insufficient drainage infrastructure and irrigation activities have worsened the situation.

5.4. Effects of Salinity and Drainage Issues on Agricultural Production

Combined salinity and drainage problems significantly reduce agricultural productivity:

- **Stunted Plant Growth**: The salt accumulation creates osmotic stress for plant roots to absorb available water. Besides, the deficiency in drainage restricts the oxygen supply to the roots, which further slows down plant growth.
- **Yield Losses**: Inability to absorb nutrients because of salinity, along with water stress arising out of poor drainage, leads to severe reductions in crop yields, hence causing economic losses.
- **Soil Degradation**: Salt accumulation and waterlogging lead to compaction, disruption of aggregate structure, and reduced permeability of the soil, which, over time, can render the soil completely unproductive (Hagage et al., 2024).

5.5. Management of Salinity and Drainage Issues

Management of salinity and drainage problems: an integrated approach

- **Improvement of Drainage Systems**: Constructing or upgrading surface and subsurface drainage systems may facilitate the rapid removal of excess water, preventing salt accumulation.
- **Reclamation of Saline Soils**: In areas with high salt accumulation, soil amendments such as gypsum may be used to facilitate the leaching of salts.
- **Proper Irrigation Technique:** There are methods, like pressurized irrigation, that allow for controlled use of water to avoid over-application and reduce the risk of salinity.
- **Regional Planning and Education**: Educating farmers on irrigation and drainage management is a critical step in preventing these issues.

6. Technological and Managerial Approaches to Problem Solving

These will, therefore, require both technological and managerial approaches in the control of drainage and salinity:

- **Modern Drainage Systems**: Surface and subsurface drainage systems suitable for agricultural lands should be designed. For example, horizontal drainage pipes and open drainage channels can facilitate the removal of excess water

- **Salt-Tolerant Plant Species**: Choosing plant species tolerant of saline soil reduces losses in production.
- **Irrigation Management**: Application of irrigation water in adequate quantity, besides proper timing, prevents the accumulation of salt.
- **Chemical Applications**: Gypsum and other soil amendments may be applied in saline soils to allow leaching of salts into lower layers.

7. Successful Solutions Implemented in Türkiye

Several successful projects in Türkiye have addressed drainage and salinity problems:

- **GAP Project**: The installation of modern drainage systems in the Harran Plain has significantly mitigated salinity issues.
- **Konya Plain Project**: Reducing the use of groundwater and implementing controlled irrigation practices have alleviated salinity problems.
- **Examples from the Aegean Region**: The cultivation of salt-tolerant plant species and improvements in drainage infrastructure have reduced yield losses.

8. Legislation and Policies

There are gaps in legislation addressing drainage and salinity in Türkiye. To resolve these issues:

- **Drainage and Irrigation Regulations**: The enforceability of existing regulations should be enhanced.
- **Support Programs**: Farmers should be incentivized for the installation and maintenance of drainage systems.
- **International Collaboration**: Türkiye should benefit from successful international projects in combating salinity.

9. Conclusions and Recommendations

Drainage and salinity problems are among the most significant challenges threatening Türkiye's agricultural production potential (Özdemir, 1995). These issues not only negatively impact agricultural productivity but also jeopardize soil health and environmental sustainability in the long term. In countries like Türkiye, where irrigation projects are rapidly expanding and effective natural resource management is critical, finding solutions to these problems is of vital importance.

9.1. The Severity of Drainage and Salinity Problems

Salinity and drainage problems are interconnected; one problem aggravates the other, thus affecting agricultural production in a negative way (Umali, 1993). These have also caused production losses and economic damage in different parts of the world, such as Southeastern Anatolia (Tekinel, 2002), the Konya Plain (Bozyiğit & Güngör, 2011), and surroundings of Salt Lake (Kavurmacı et al., 2010). These problems, which have been exacerbated by inappropriate irrigation practices, inadequate infrastructure, and natural conditions, negatively affect rural economic development and farmers' incomes.

9.2. Proposed Solutions

Both the short-term and long-term approaches are required to solve these problems. The following strategies have been worked out for the protection of agricultural land and reduction of its production loss:

9.2.1. Use of Modern Technologies

- **Pressurized Irrigation Systems**: Wider application of techniques such as drip and sprinkler irrigation may reduce water consumption and salt deposition.
- **Smart Farming Technologies**: Soil moisture and salinity may be periodically monitored using sensors and remote-sensing systems for the establishment of smart farming technologies.

9.2.2. Strengthening Drainage Infrastructure

- **New Drainage Systems**: Integrating surface and subsurface drainage systems into irrigation projects may accelerate the removal of excess water, preventing salinity problems.

- **Improvement of Existing Systems**: In regions such as GAP and the Konya Plain, existing drainage infrastructure should be upgraded to enhance its effectiveness.

9.2.3. Raising Farmer Awareness

- **Training Programs**: Farmers should be trained in irrigation techniques, water management, and how to reclaim the soil. In areas like Harran Plain where over-irrigation is practiced, there should be intensive training and seminars emphasizing that more water does not necessarily translate to a better yield. Training programs must be region-specific and concentrate on practical and easily adaptable techniques by farmers
- **Guides and Manuals**: Practical guidelines on the management of salinity and drainage should be prepared and made available to the farmers at the field level.

9.2.4. Ensuring Sustainable Soil and Water Management

- **Reclamation Projects**: The use of different soil amendments, such as gypsum in saline-affected agriculture, needs to be promoted.
- **Planned Use of Water Resources**: Water resources must be planned sustainably for their fruition either surface or groundwater while water-saving practices should be incentivized.

9.2.5. Considering Regional Differences

The solution methods to be applied should be shaped according to geographical, climatic, and socio-economic characteristics of the region. For example, in the case of the Suruç Plain, transition to pressurized irrigation methods should be promoted.

9.2.6. Future Directions

- **Research and Development (R&D)**: R&D studies regarding salinity and drainage problems of Türkiye should be supported, and solution methods should be developed. For instance, remote sensing for soil salinity and rapid intervention strategies may be effective.

- **Policies and Incentives**: Development of policies and incentives for farmers in order to encourage them toward the latest agricultural techniques. Expansion of state-supported projects on the reclamation of saline soils should also be considered.
- **International Collaboration**: The adaptation of models from successful international projects that have solved salinity and drainage problems could provide appropriate solutions to meet the needs in Türkiye.

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CHAPTER 4

EFFECTS OF CLIMATE CHANGE ON SOIL DWELLING PESTS AND NEW APPROACHES IN PEST MANAGEMENT

Assoc. Prof. Dr. Çetin MUTLU[1*]

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[1] Department of Plant Protection, Faculty of Agriculture, Harran University, Şanlıurfa, Türkiye
cetinmutlu21@hotmail.com, ORCID ID 0000-0003-4962-5506
*Corresponding Author: cetinmutlu21@hotmail.com

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INTRODUCTION

Global climate change refers to long-term climatic variations resulting from the accumulation of greenhouse gases in the atmosphere caused by human activities (IPCC, 2021). Since the Industrial Revolution, increasing levels of carbon dioxide (CO_2), methane (CH_4), and other greenhouse gases have raised the Earth's average temperatures. According to reports by the Intergovernmental Panel on Climate Change (IPCC), global temperatures are projected to rise by 1.5-2°C by the end of the century compared to pre-industrial levels. This scenario has the potential to create significant and lasting effects on natural ecosystems and biological cycles (IPCC, 2021).

Global climate change not only affects atmospheric processes but also impacts soil and plant health, leading to major changes in agricultural ecosystems. Rising temperatures, irregular precipitation, and extreme weather events cause significant disruptions to the balance of agricultural systems, making the management of pest organisms increasingly challenging. Moreover, changes in soil structure and disruptions in water-nutrient cycles reduce the resilience of plants to environmental stresses, creating more favorable conditions for the proliferation of pest organisms (Lal, 1993).

Climate change poses a significant threat to agricultural production worldwide (Wheeler and von Braun, 2013). In particular, temperature increases, changes in rainfall patterns, and extreme weather events have been reported to negatively impact soil structure, plant health, and pest management (Lesk et al., 2013). Therefore, climate change directly affects the behavior, population densities, and life cycles of pest insects (Yaşar et al., 2021). Rising temperatures allow pests to complete their life cycles in shorter periods, thereby increasing their reproduction rates (Gutierrez et al., 2009; Sharma, 2014; Mutlu and Sertkaya, 2016). Additionally, the expansion of pest species' distribution ranges threatens agricultural regions that were previously unaffected. These impacts have highlighted the increasing importance of soil pest insects, which are often overlooked, and underscored the need to reassess current pest control methods (Chatterjee and Lal, 2009).

These multifaceted impacts necessitate revising pest management strategies to adapt to new climatic conditions in order to maintain the sustainability of agricultural ecosystems (Parsa et al., 2014; Stenberg, 2017). In particular, the effective implementation of Integrated Pest Management (IPM) and biological control techniques is essential for addressing the challenges posed by climate change (Dara, 2019). Adaptable strategies developed at both global and local levels play a critical role in ensuring the continuity of agricultural production and food security (Lefebvre et al., 2015).

Climate change has become one of the most critical global challenges affecting agricultural systems worldwide (Wheeler and von Braun, 2013; Lal, 2020). Insects, representing a significant portion of Earth's biodiversity, are among the groups predicted to be most affected by global climate change (Yaşar et al., 2021). Rising temperatures, shifting rainfall patterns, and an increase in extreme weather events are altering not only ecosystems but also agricultural production. In particular, these changes are influencing the behavior of soil pest insects, which overwinter in the soil and spend much of their life cycle underground. Among the significant pest orders (e.g., Coleoptera, Diptera, Hemiptera, and Hymenoptera), soil-overwintering pests are particularly noteworthy. These include cereal pests such as the cereal ground beetle (*Zabrus spp*.), wheat stem sawflies (*Cephus pygmeus*, *Trachelus tabidus*), black cutworm (*Agrotis ipsilon*), and wireworms (*Agriotes* spp.). Additionally, pests like the beet webworm (*Loxostege sticticalis*), the vegetable pest tomato leafminer (*Tuta absoluta*), and important fruit pests such as the cherry fruit fly (Rhagoletis cerasi) and the olive fruit fly (*Bactrocera oleae*) target plant leaves, shoots, fruits, stems, roots, and underground organs, causing significant crop losses (Oerke, 2006; ZMMT, 2008; Birişik et al., 2015).Therefore, understanding the dynamics of these pest species in the context of global climate change is crucial for sustainable pest management.

Soil dwelling insect pest are particularly sensitive to climate-driven changes in soil temperature, moisture, and microbial composition (ZMMT, 2008). Warmer environmental conditions can accelerate pest development rates, leading to additional generations per year and the expansion of their geographic distributions (Rosenberg and Verhoef, 2015). Furthermore, shifting rainfall patterns can alter soil moisture, impacting pest survival rates and activity (Sharma, 2014).

A study by Bale et al. (2002) demonstrated that the overwintering success of many soil pests is directly influenced by temperature fluctuations, potentially resulting in population increases in regions previously unsuitable for these species. In Türkiye, *Zabrus* spp. (cereal ground beetle), known as one of the most harmful pests affecting wheat and barley, damages roots and underground plant organs, causing significant economic losses and posing threats to food security (Boron, 2003; Duman, 2019). Recent research has shown that the phenology and population dynamics of *Zabrus* spp. are changing due to climate change, highlighting the need for new management approaches for this pest (Duman, 2019).

Traditional pest management strategies, particularly chemical control, face various challenges under changing climatic conditions. Increasing pest resistance to pesticides and environmental concerns have driven researchers to explore alternative and sustainable methods. Integrated Pest Management (IPM) strategies, incorporating biological control, habitat manipulation, and the use of resistant plant varieties, offer promising solutions (Hoffmann et al., 2023). Additionally, advancements in remote sensing and predictive modeling provide opportunities for the early detection and monitoring of soil pest insects in the context of climate change (Porter et al., 2014).

This chapter aims to examine the direct and indirect effects of climate change on soil pest insects and discuss innovative management strategies to mitigate these impacts. However, in order for these strategies to be effectively implemented in response to climate change, it is essential to first understand the concepts of Integrated Pest Management (IPM) in agricultural pest control and reconsider these strategies accordingly.

1. Integrated Pest Management

Integrated Pest Management (IPM) stands out as a sustainable and environmentally sensitive approach in the control against pest organisms in agricultural production (Ehler, 2006; ZMMT, 2008; Pedigo, 2014). Rather than aiming to completely eradicate pest populations, IPM focuses on keeping them below the economic damage threshold (Pedigo, 2014). The fundamental feature of IPM is to provide solutions that minimize chemical use while being environmentally conscious. Its goal is to achieve the highest economic gain by ensuring the production of healthy and high-quality crops, minimizing losses caused by agricultural pests, and keeping pest populations below the level that causes economic damage. Furthermore, IPM aims to meet farmers' other objectives while minimizing the risks of pesticides to humans, animals, and the environment through the coordinated use of diverse tactics (ZMMT, 2008).

Integrated Pest Management (IPM) includes six fundamental methods (Cultural, Biological, Mechanical, Physical, Biotechnical, and Chemical control), which are used either together or separately depending on the pest species (ZMMT, 2008). Among these methods, cultural control stands out as the most environmentally friendly and easily applicable by producers within the framework of agricultural practices (Birişik et al., 2015).

Cultural Control: This involves the use of the most appropriate agricultural practices to prevent or reduce pest populations. It is the least costly and environmentally non-harmful method of pest control. Several cultural practices have been reported to be highly effective against pest organisms, including those listed below (Birişik et al., 2015). Crop rotation reduces pest population density by preventing the sequential planting of crops susceptible to the same pests. Post-harvest and pre-planting soil tillage practices help destroy larvae or pupae present in the soil. Moreover, using certified, disease-free seeds or plant materials prevents the movement of pests to new areas and minimizes the risk of infestation. On the other hand, excessive seed usage, overcrowding, or improper irrigation can create suitable microclimate conditions for pest proliferation, potentially leading to crop losses. Thus, plant density and irrigation management play a critical role in pest control.

Biological Control: Biological control involves managing pest populations through the use of natural enemies (predators, parasitoids, and pathogens) (Rat and Mamay, 2024). There are three main components of biological control: 1) the mass rearing of beneficial insects in insectarium and their release into the field, 2) the reduction of pesticide use to encourage the conservation of naturally occurring natural enemies in nature environment, and 3) the promotion of habitat conditions that support natural enemies in the environment.

Mechanical Control: This method involves the collection, removal, or destruction of pests using physical barriers, traps, or mechanical devices. Some traps used in mechanical control include pheromone traps, light traps, and sticky traps, which help capture pests. Direct collection of pests or physical removal methods, such as hand-picking, are also common in this type of control.

Physical Control: Physical control is a method that involves altering the physical environment of pests. This includes treatments such as hot water or steam applications and modified atmosphere techniques, typically used in small areas like greenhouses or product storage facilities (Cameron and Costello, 2020).

Biotechnical Control: Biotechnical control is an important component of Integrated Pest Management (IPM) strategies and plays a significant role in environmental sustainability. This method involves manipulating the behavior, biology, and physiology of pest insects using environmentally friendly techniques for pest control in agriculture. Methods used in biotechnical control include pheromone traps, light traps, colored sticky traps, the sterile insect technique, and food attractants (Mamay and Mutlu, 2019).

Chemical Control: Chemical control involves the use of pesticides to manage pest populations in agriculture. This method is applied when pest populations exceed the economic damage threshold and is typically used when other methods have not been sufficient to control the pest population. Chemical control should be considered the last resort within integrated pest management strategies.

2. Soil Structure and the Effects of Tillage on Pests

Within Integrated Pest Management (IPM), cultural control methods offer an environmentally friendly and sustainable approach to pest management (Birişik et al., 2015). In this context, maintaining soil structure and properly managing tillage practices are critical not only for pest control but also for the sustainability of agricultural production. The physical, chemical, and biological properties of soil play a decisive role in pest control strategies by directly influencing pest life cycles, population dynamics, and effectiveness (Kladivko, 2001).

2.1. Soil Structure and Pests

Soil structure is a key factor influencing the habitat, reproduction, and mobility of pest insects. Loosely structured soils allow pests to move more easily, while soils with a heavy texture, compact structure, and good drainage characteristics may create an unfavorable environment for pests (Stinner and House, 1990). Soil- dwelling pests such as the wheat root borer, *Zabrus* spp., prefer specific soil conditions to lay their eggs and develop their larvae, particularly in the fall. Soil organic matter content, water retention capacity, and pH levels can directly affect the populations of these pests. This is also true for other soil-dwelling pests, such as wireworms (*Agriotes* spp.), mole crickets (*Gryllotalpa gryllotalpa*), and cockchafer grubs (*Anisoplia* spp.). These pests, which prefer sandy and loose soils, can move more easily underground, causing significant damage to tuberous-rooted plants. Furthermore, changes in soil structure can affect microbial activity, potentially enhancing the effectiveness of beneficial microorganisms that could exert pressure on pests (Altieri and Nicholls, 2003).

2.2. Soil Tillage and Its Effects on Pest Management

Soil tillage is considered one of the fundamental practices in agricultural pest management. In field crop production, deep tillage can disrupt the overwintering habitats of pests or bring them to the surface, thereby reducing their populations. For example, the ground beetle (*Zabrus* spp.), a significant soil dwelling pest in cereal production, along with other soil-dwelling pests, require suitable areas to overwinter during their larval and pupal stages. By conducting tillage practices after harvest or before planting, overwintering sites can be disturbed, interrupting the pests' life cycles and reducing pest density (Lal, 1993). However, the timing and method of these practices are critical for effective pest control. To achieve this, it is essential to have a thorough understanding of the biology and bioecology of the pests being targeted.

Nevertheless, intensive soil tillage methods can have various negative impacts on beneficial organisms. During tillage, the habitats of natural enemies such as predator insects and entomopathogenic fungi may be destroyed, weakening the biological control potential. Furthermore, intensive tillage reduces soil organic matter, negatively affects microbial diversity, and jeopardizes long-term soil fertility (Six et al., 2000; Holland and Reynolds, 2003). Such degradation of soil health not only affects pest management but also harms plant growth and agricultural sustainability.

In this context, conservation agriculture practices, such as minimum tillage or no-till farming, offer an environmentally friendly alternative for pest management. These practices indirectly manage pest populations while preserving beneficial organisms and improving soil health. By increasing soil organic matter content and supporting biodiversity, these approaches enhance soil's water retention capacity, preventing plant stress and indirectly building resistance against pests (Altieri and Nicholls, 2003). Such protective approaches are particularly important tools in addressing environmental challenges, such as climate change.

As a result, to enhance the effectiveness of soil cultivation strategies, the timing and methods of application must be optimized specifically for the target pest. For example, pre-winter cultivation disrupts the overwintering sites of pests, while interventions applied during critical stages of the pest's life cycle can increase pressure on the population. These approaches play an important role not only in pest management but also in enhancing the overall resilience of agricultural systems (Stinner and House, 1990). Well-planned soil cultivation practices can contribute to the long-term control of pests as well as the sustainability of agricultural ecosystems.

Soil cultivation can negatively affect the living conditions of pests by altering the soil's temperature and moisture levels. For instance, drier soil conditions can make it more difficult for pest species that require high moisture to survive (Kladivko, 2001). Additionally, during soil cultivation, burying plant residues can eliminate the feeding and sheltering areas of pests. This is particularly important for the population control of cereal pests (Holland and Reynolds, 2003).

2.3. Organic Agriculture Practices and Pests

Increasing the organic matter content of the soil provides a sustainable approach to pest management and offers significant benefits that support the ecosystem. The application of compost and organic fertilizers not only improves the physical and chemical properties of the soil but also creates a natural control mechanism against pests by enhancing biodiversity. These organic materials increase the populations of soil microorganisms and nematodes, thereby limiting the habitats and food sources available to pests. For example, beneficial microorganisms suppress the pathogens of pests or directly compete with them, reducing pest density (Altieri and Nicholls, 2003; Mäder et al., 2002).

Organic practices also contribute to the improvement of soil structure and an increase in water retention capacity. Increased organic matter content enables the soil to retain water for a longer period, making plants more resistant to drought stress. When plants are not under stress, their capacity to recover from damage caused by pests and resist pest attacks is also enhanced (Lal, 2004). In particular, soil-dwelling such as *Zabrus* spp., which damage the root zone, have been shown to encounter more resistant plants when these plants are healthy and well-nourished. In addition, organic agriculture practices support the diversity and abundance of beneficial organisms that can indirectly affect pests. The population of entomopathogenic nematodes living in soils enriched with organic fertilizers increases. These organisms target pests and disrupt their life cycles. Furthermore, some natural compounds released from organic matter have been reported to have repellent or lethal effects on pests (Larkin et al., 2010).

It is clear that organic agriculture practices not only support the ecosystem in pest management but also enhance environmental sustainability by reducing pesticide use. However, for these practices to be effective, it is important to plan them according to regional conditions and integrate them with other pest management methods.

2.4. The Role of Tillage in Integrated Pest Management Strategies

Within Integrated Pest Management (IPM) programs, the timing and method of tillage must be optimized based on the region and the target pest. Timing of tillage is crucial at this stage and should be applied during the periods when soil-dwelling pests are most vulnerable in their life cycle (e.g., during the egg or pupa stages). Additionally, to prevent further degradation of the soil structure, minimal tillage can be applied only in areas where pests are present. This approach not only reduces environmental impacts but also contributes to the preservation of beneficial organisms (Ratnadass et al., 2012).

As a result, IPM practices that incorporate methods that preserve soil structure and appropriate tillage techniques can improve pest management in agricultural systems while promoting sustainable agriculture. These approaches play a critical role in building a more resilient agricultural ecosystem in the face of environmental challenges such as climate change.

2.5 Tillage Strategies and Practices for Soil-Dwelling Pests

Due to global climate change, which has resulted in rising temperatures and disrupted rainfall patterns, it has become essential to manage tillage strategies for soil-dwelling pests in accordance with these changing conditions. In some cases, these methods may lead to an increase in pest populations because they reduce the impact of disrupting the pests' habitats. However, considering the positive effects of this approach, such as the preservation of beneficial microorganisms and organic matter accumulation, it is recommended to integrate these strategies with other IPM methods in pest control (Lal, 1993). The effective use of soil structure and tillage methods in pest management can enhance the success of IPM strategies. However, these practices should not only control pest populations but also be designed to preserve soil health and ecosystem balance. The selection of the most appropriate tillage method should be based on the biology of the target pest, regional climate conditions, and soil characteristics (Stinner and House, 1990; Holland and Reynolds, 2003).

The application of these methods in conjunction with other IPM components (such as biological control, mechanical control, etc.) can help achieve more sustainable results in pest suppression. Therefore, there is a need to develop innovative solutions that promote sustainable agriculture, preserve soil health, and maintain ecological balance in pest management within the context of climate change.

3. The Effects of Climate Change on Soil Structure, Plant Health, and Pests

3.1. Changes in Soil Structure and Plant Health

Soil provides not only a habitat for plants but also a significant habitat for pests (Klapwijk et al., 2012; Lal, 2020). Pests and other organisms are significantly affected by changes occurring in the soil (Gutierrez et al., 2009). Climate change and structural changes in the soil directly impact the growth, behavior, and distribution of pest populations (Frontiers, 2023).

Climate change, with its associated temperature increase and changing rainfall patterns, leads to significant alterations in soil structure (Lal, 2020). The rise in temperature can affect soil moisture, leading to soil compaction. Soil compaction restricts root development, making it more difficult for plants to absorb nutrients and water, which in turn makes them more vulnerable to pest attacks (Lal, 1993; Kladivko, 2001). Additionally, higher temperatures may cause organic matter in the soil to decompose rapidly, resulting in nutrient imbalances. The lack of organic matter weakens plant nutrient uptake and defense mechanisms (Campos and Calatayud, 2017).

Changes in rainfall patterns can lead to soil erosion. Increased rainfall can cause the upper layers of soil to shift, weakening plant root structures. Erosion also limits plant access to water, increasing stress levels during drought periods (Oerke, 2006). Moreover, changes in moisture levels can affect the activity of soil microorganisms. Excess moisture can lead to rapid proliferation of pathogenic microorganisms, while a lack of moisture may reduce the effectiveness of beneficial organisms (Holland and Reynolds, 2003).

3.2. Increase and Distribution of Pest Populations

Climate change has significant effects on pests and their biological control agents. The increase in temperature and irregular rainfall patterns directly impact pest populations. For instance, higher temperatures can create more suitable habitats for pests, potentially accelerating their spread (Chatterjee and Lal, 2009). Additionally, rising temperatures can shorten the overwintering period for pests, allowing them to produce more generations (Kumar and Goh, 2000). With the effects of global warming, it is predicted that rainfall will increase in some regions, while drought severity will intensify in others (Yaşar et al., 2021). These changes in rainfall patterns can lead to the death of some insect species or force them to move away from their host plants. For example, increased rainfall during the summer has been reported to cause a rapid increase in the population of soil-dwelling pests like wireworms (*Agriotes lineatus* (L.) (Coleoptera: Elateridae) (Staley et al., 2007).

Another example can be seen with wheat pests, such as the wheat stem sawflies (*C. pygmeus* and *T. tabidus*). These pests overwinter as mature larvae in the root zone of wheat. If the spring period is dry and there is insufficient moisture in the soil, they may not transition to the pupa stage, preventing them from maturing into adults and emerging into the environment (Wilcocks, 1925; Altınayar, 1975). Moreover, some pest species that were not previously a threat to plants in colder climates may begin to spread to new areas due to climate change. In temperate regions, previously unseen pests may emerge, and existing pest populations may increase (Borrelli et al., 2020). Climate change accelerates the life cycles of pests, leading to higher population densities throughout the year (Stinner and House, 1990).

3.3. Biological Control of Pests and the Effects of Soil Changes

Biological control strategies in pest management can also be influenced by climate change (Klapwijk et al., 2012; Sharma, 2014). Beneficial organisms living in the soil play a crucial role in the biological control of pests (Klapwijk et al., 2012; Frontiers, 2023). However, rising temperatures and changing humidity conditions can negatively affect the effectiveness of these organisms (Lal, 1993). The success of biological control agents is often dependent on soil conditions, and climate change can restrict the populations and activities of these agents. In this context, Altınayar (1975) reported that in wheat stubble, the larvae of the wheat stem sawfly (*C. pygmeus*), which undergo diapause in the soil, remain in diapause for two years when soil moisture is insufficient. However, when sufficient moisture reaches the roots, the larvae can later transition to the adult stage. A similar situation applies to other beneficial insects that overwinter in the soil.

Biological control agents play an important role in the control of soil-dwelling pests. These organisms naturally control pests and can be influenced by changes in soil structure. For example, soil tillage and rising temperatures can alter the activity of beneficial microorganisms living in the soil. Extreme temperatures and changes in humidity can limit the effectiveness of natural enemies, potentially increasing pest populations (Lal, 1993). The effectiveness of soil microorganisms varies according to soil structure and climate conditions. With climate change, the diversity of beneficial organisms in the soil may decrease, which could lead to an increase in pest populations. Therefore, a more sustainable approach to pest control should be adopted by preserving soil health and strengthening biological control strategies.

Climate change and changes in soil structure can directly impact the development of soil-dwelling pests. Factors such as temperature, humidity, and soil tillage can accelerate or slow down pest populations. Particularly, changes in soil moisture can affect the spread of nematodes and other soil-dwelling pests. Soil tillage and biological control strategies are important tools for effective pest management. However, considering climate change and soil health, sustainable pest management strategies should be developed. These strategies should aim to prevent the spread of pests and protect plant health.

In conclusion, climate change significantly impacts soil structure, plant health, and the effectiveness of pest management. Rising temperatures and irregular rainfall can weaken plant defense mechanisms and increase pest populations. To minimize these effects, Integrated Pest Management (IPM) strategies and sustainable agricultural practices are of great importance. Additionally, developing new approaches to biological control and soil health management can enhance the effectiveness of pest control.

3.4. Effects of Soil Changes Due to Climate Change on Soil Dwelling Pests and Their Interactions

Soil dwelling pests are organisms that develop directly in the soil environment and cause damage to plants. These pests can be significantly affected by soil degradation and climate change. In particular, increases in temperature, soil moisture, and soil management practices can influence interactions with these pests.

Soil dwelling pests, such as *Zabrus* spp., are directly influenced by changes in the soil surface (Duman, 2019). These pests thrive in moist soils but may experience population declines in excessively dry or warm environments. Changes in soil management and moisture levels can affect the reproductive cycles and movements of such species (Özpınar and Çay, 2013). With climate change, increased or decreased moisture can accelerate the spread of these pests. Another example is dung beetles (Coleoptera: Tenebrionidae). These beetles, like other soil dwelling pests, can be influenced by changes in soil structure. Soil management can alter their habitats, which may result in an increase in pest population density (Menéndez, 2007).

Nematodes are one of the major soil dwelling pests responsible for significant economic losses in crop plants. Soil nematodes (Nematoda) are another important group of pests that complete their life cycle in the soil. Changes in soil moisture can significantly affect the distribution of nematodes. Excessive moisture, particularly, can increase the population density of root-knot nematodes (Meloidogyne spp.), negatively affecting plant health. On the other hand, a significant decrease in soil moisture can make survival conditions difficult for these pests (Toba et al., 2021).

4. Soil Health-Oriented Management Approaches

4.1. Increasing Soil Microbial Diversity

Soil microbial activity plays a significant role in suppressing soil dwelling pests. Microbial biofertilizers or mycorrhizal fungi (Sing et al., 2011) can enhance plant growth, thereby increasing their resistance to pests. Organic matter applications, such as compost and biochar, improve soil structure, promote the growth of beneficial organisms, and make the living conditions of pests more challenging (Altieri & Nicholls, 2003; Holland & Reynolds, 2003). These organic amendments not only enhance soil fertility but also contribute to pest management by fostering a healthier soil ecosystem.

4.2. Use of Smart Farming Technologies

With the use of soil moisture and temperature sensors, soil conditions can be continuously monitored, pest emergence periods can be predicted, and preventive measures can be taken. For example, the wintering or reproductive periods of soil dwelling pests like *Zabrus* spp. can be detected early, enabling targeted control measures. Furthermore, drones and AI-powered imaging systems can be used to track pest populations and movements through digital imaging. This allows for faster and more precise pest control.

4.3 Redesigning Soil Tillage Strategies

Developing soil tillage methods tailored to local conditions is essential. Minimum tillage or targeted deep tillage methods should be integrated based on the region's climate and soil characteristics. The timing of tillage should align with the life cycle of pests (Lal, 2003). In this context, innovative tillage tools can be developed that specifically target the overwintering areas of pests, allowing for precision soil tillage aimed at minimizing pest populations while preserving soil health.

4.4. Climate-Focused Education and Collaboration

Farmer education programs should be implemented to provide written and visual training on the effects of climate change on pests, soil health, and Integrated Pest Management (IPM). These programs can help farmers adopt innovative methods tailored to local conditions. Additionally, fostering collaboration between researchers and farmers can enhance knowledge sharing and lead to the development of region-specific strategies. By bridging the gap between scientific research and practical farming, these collaborations can ensure that effective and sustainable pest management approaches are adopted at the local level.

4.5 Modeling Integrated Management Strategies

To enhance the effectiveness of Integrated Pest Management (IPM) strategies against soil-dwelling pests, it is crucial to develop appropriate predictive models. These models should predict pest populations, soil conditions, and climate changes, enabling optimization of IPM practices. Detailed scenario analyses should be conducted to predict the long-term effects of climate change, allowing for proactive measures to be taken under different scenarios. Such model-based analyses are beneficial not only for controlling pest populations but also for addressing broader issues such as soil health, water management, and overall agricultural productivity. Developing dynamic models is essential, as each region has unique climatic conditions and agricultural practices (Stenberg, 2017; Lefebvre et al., 2015). The integration of these models can better guide sustainable agricultural practices and support strategic decision-making.

Conclusion

Climate change is significantly altering the structure and functioning of agricultural ecosystems, leading to important shifts in the population dynamics of soil-dwelling pests, a trend that is expected to continue. Rising temperatures and irregular rainfall patterns are accelerating pest life cycles, facilitating their spread to larger geographic areas, and complicating control efforts. Particularly, significant soil-dwelling pests like *Zabrus* spp. are thriving under more favorable conditions due to climate change, resulting in increased crop losses. This situation necessitates a reevaluation of existing pest management strategies to adapt them to the changing climate.

Strengthening biological and cultural control methods within Integrated Pest Management (IPM) offers an environmentally friendly and sustainable approach. Optimizing practices like soil tillage and organic matter applications can enhance pest control effectiveness while simultaneously contributing to soil health preservation. Moreover, integrating digital agriculture technologies and predictive models into pest management provides new opportunities for early detection and targeted interventions. Innovative and sustainable strategies developed in the context of climate change will provide a critical foundation for supporting the long-term sustainability of the agricultural sector.

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CHAPTER 5

ADAPTATION OF AGRICULTURAL PRODUCTION ACTIVITIES TO CLIMATE CHANGE EFFECTS

Assist. Prof. Dr. Hülya SAYĞI[1*]

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[1] Çukurova University Yumurtalık Vocational School, Department of Plant and Animal Production, Adana,
husaygi@gmail.com, ORCID:https://orcid.org/0000-0002-2327-566X
*Corresponding Author: husaygi@gmail.com

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1. INTRODUCTION

Although the modern world has managed to control many factors that may negatively affect the quantity and quality of products obtained in the agricultural production process with its advanced technological possibilities, it is largely dependent on environmental conditions (climate and related conditions) (Grigorieva et al. 2023). Agriculture, as a means of transforming and changing nature in order to establish its own civilization in the struggle of man with nature, is a structure that is dependent on the climatic conditions in the environment (nature) where man lives, is affected by it and also affects it (Saygı, 2022). The phenomenon of climate change is a reality that the modern world has to endure and has to adapt its agricultural production processes to this new situation. In many scientific studies conducted in the literature on the negative effects of climate change, negative effects such as decreases in product yield and quality due to climate change, water scarcity and water access problems, biodiversity, uncontrolled plant development due to increased carbon dioxide (CO2) levels in the agricultural production process are immediately striking issues (Akalın, 2015). In this sense, agricultural production activities need to be adapted to these new conditions in a way that will re-establish the natural balance by preserving product yield and quality. Accordingly, the main inputs in agricultural production are reduced soil tillage for soil quality; using plant nutrient inputs that will increase the amount of organic matter; rain harvesting for water access and irrigation; using drip irrigation systems for water saving; choosing the right plant species resistant to drought, pests and diseases in plant materials; producing drought-resistant species; benefiting from the solutions offered by technology; using natural enemies in pest control; and producing according to sustainable production principles and rules such as organic agriculture, a series of integrated applications are essential solutions in this process.

2. CLIMATE CHANGE AND AGRICULTURE

Climate change, which can be defined as changes in weather conditions in the average climate conditions prevailing in a region for a long time due to uncontrolled and excessive human activities, is a set of global problems consisting of natural disasters such as floods, landslides, forest fires, droughts, and extremely high temperatures that occur frequently and increase in intensity. It is a scientific fact that the most important factor causing climate change on Earth is the increase in global surface temperatures caused by greenhouse gas emissions from economic activities (primarily agricultural production activities) carried out to meet human needs (Sayği, 2022).

Scientific studies have shown that the world's surface temperature has increased by approximately 1.0 °C compared to the pre-industrial revolution period; if the same conditions continue, it will exceed the 1.5 °C limit between 2030-2050 and urgent measures should be taken to keep this temperature increase at least within the 1.5 °C limit (IPCC, 2018). A situation parallel to the global temperature increase in the world is also valid for Türkiye. While the average temperature in Türkiye was 13.5 °C between 1981-2010, it was 14.7 °C between 2010-2019 and the temperature increase between these periods was determined to be 1.2 °C (Tekeli, 2020). According to the report published by the IPCC in 2013, it is stated that the regions that will be most affected by the global temperature increase will be Europe and the Mediterranean basin (IPCC, 2013). The actual situation confirms this report.

Agriculture, one of the economic production activities, is the plant and animal production activities carried out in nature depending on climatic conditions. Climate-related conditions are the most important constraints in plant and animal production with their direct determining effect on whether a product will grow, its durability, unit production costs, product productivity and quality in agricultural production activities. Conventional agriculture, which is intensively carried out in agricultural production activities, causes climate change and is greatly affected by the consequences of this situation. For this reason, in the process of adaptation to climate change in agricultural production activities, it is necessary to address two different approaches, including, on the one hand, reducing greenhouse gas formation and transforming agricultural production processes; on the other hand, social, economic and agricultural investments and transformations that will ensure resilience in climate change for the sustainability of agricultural production and food security (TARDES, 2021).

As a result, it is a scientific fact that agricultural production activities, as an economic activity carried out in the climate and the environment shaped by the climate, have a structure that is directly affected/affects climate change.

Despite all these negativities that climate change has created on agricultural production activities, agricultural production activities are an activity that must be carried out without interruption as the basic production source of food that will ensure the continuation of human life. Accordingly, agricultural production activities must be carried out by adapting to new climate conditions with practices that are free from the effects that cause climate change, protect the current conditions and improve the negative effects. The purpose of this study is to evaluate possible solutions to reduce, improve and restore the negative effects of climate change on agricultural production activities.

3. ADAPTATION OF AGRICULTURAL PRODUCTION TO NEW CONDITIONS

In order to carry out agricultural production activities, suitable climatic conditions affecting soil, water, sunlight and temperature are needed. While climate change in nature has changed at a very low rate in long periods due to environmental effects, this situation has changed rapidly in a very short period of 100 years (2010-2019) due to uncontrolled and excessive economic production activities by humans with the industrial revolution (Tekeli, 2020). This situation causes agricultural production activities to be affected by drought, drying of water resources, unbalanced meteorological events, decrease in biodiversity, deterioration of soil structure, ecological change, decrease in product yield and quality, increase in pests and diseases, and the increase in the need for fertilization and pesticides, and the increase in production costs. These problems prevent the realization of sustainable agricultural activities as well as the production and transportation of safe food.

This negative picture created by humanity is not a fate. The humanity that created this negative picture also has sufficient knowledge and resources about what needs to be done for the solution. What needs to be done is to implement production processes compatible with nature instead of negative production processes in agricultural production activities. This means that production is carried out by taking environmental costs into account in production processes. In this sense, the nature (soil), plant nutrition material, irrigation, pest and disease control inputs used in agricultural production activities should be analyzed correctly. According to the results of this analysis, production processes compatible with new climate conditions should be created without being affected by the negative effects of climate change. Thus, while the current climate conditions are protected, the negative effects of climate change can be reduced and/or improved to reach a healthy state again.

3.1. Climate Change and Soil

Soil is a non-alternative natural source that terrestrial life is directly or indirectly dependent on with its minerals, organic substances, living microorganisms, air and water content. In this respect, soil is the most basic production source of agricultural production activities. Soil is an ecosystem with its structure consisting of elements, living organisms and water and interacting with other living things. This ecosystem provides a source of nutrients for plants in plant production and other living things. In the soil ecosystem, precipitation due to climate, changes in air temperature, soil health and the continuity of life of living things are closely related to climate. Drought, floods, storms, erosion, forest fires, soil salinization, very rapid changes in air temperature and adverse effects of extreme weather events due to climate change have significant effects on soil structure (AA, 2021).

Soil plays an important role in reducing carbon emissions that cause climate change and increasing carbon sequestration in the air. The map published by the Food and Agriculture Organization of the United Nations (FAO) showed that the top 30 cm of the world's soil contains twice as much carbon as the amount of carbon in the atmosphere (EEA, 2019). Soil, which surpasses forests and other vegetation in terms of its ability to capture carbon dioxide from the air, is the second largest natural carbon sink after the oceans (EEA, 2019). Soil is affected by temperature changes occurring due to climate change. In regions with frozen soils such as Siberia, CO2 in the soil is released and mixed into the air with the increase in temperature, accelerating the climate change process (EEA, 2019). The amount of CO2 transferred to the atmosphere by the decomposition of organic matter, which has the primary effect on the carbon cycle in the soil, and soil moisture, which is known to have a significant effect on plant productivity and production patterns, are negatively affected by climate change (Kaya and Bilgehan Aydın, 2017). The possible increase in temperature and decrease in precipitation as a result of climate change are parameters that directly affect soil moisture content. The increase in temperature decreases the soil moisture rate, and the living conditions of living beings in the soil that can live in humidity and suitable temperatures are negatively affected (Kaya and Bilgehan Aydın, 2017).

The presence of sufficient moisture in the soil for the plant throughout the plant development period is very important for yield. A decrease in soil moisture negatively affects the physical/chemical parameters in the soil structure, increases the need for irrigation and irrigation costs, and prevents the expected product yield and quality in agricultural production. Kayam et al. (2002) observed in a study conducted in the Aegean region that a 5% decrease in precipitation reduced wheat yield by 10%. In this respect, a soil management system suitable for the new climate conditions that emerged with climate change should be established.

According to the new climate conditions, soil moisture will be protected with protective agricultural practices that include reducing mechanical interventions to the soil and switching to direct planting without tillage, minimizing soil tillage activities; providing permanent soil organic cover with crop residues and/or cover crops; and protecting the soil plant nutrient balance by providing diversity in the crop pattern included in the crop rotation (Demircan et al. 2022). Preserving soil moisture will positively affect the soil physical/chemical structure and ensure the formation of a healthy and high-quality soil structure.

3.2. Climate Change Plant Nutrition

There are many techniques and practices used to achieve high productivity in modern agriculture. As the most vital component in a crop system with high quality and yield, plant nutrition practices are of great importance in achieving high productivity and providing the ideal soil structure for sustainable agricultural production (Hektaş, 2022).

Plant nutrition is the process of selecting the plant to be planted, analyzing the soil to be planted, and keeping the plant nutrients needed for the healthy growth, development and production of the plant ready in the soil until planting, growing and harvesting. Plant nutrition activities are carried out in a series of stages consisting of preparing the soil correctly, selecting and applying appropriate fertilizers, and determining the irrigation system according to the plant (Sector, 2024). Plant nutrition increases the yield by providing the macro (nitrogen, phosphorus, potassium) and micro (iron, copper, manganese) plant nutrients needed by the plants, which are reduced in the soil for various reasons. Plant nutrition has a positive effect on the healthy plant growth/development process and on the product yield and quality by increasing its quality, resistance and durability.

On the other hand, it is known that chemical plant nutrition inputs, which are used intensively in modern agricultural practices focused on getting the most efficiency per unit area, have a significant impact on the climate change process. The use of chemical plant nutrition inputs causes significant damage to the ecosystem by causing pollution of water and agricultural soils, increased salinity, and heavy metal accumulation (Akalın, 2015; AA, 2023). Depending on the substance in the structure of chemical plant nutrition inputs, greenhouse gas emissions (carbon dioxide and nitrous oxides, which are 300 times more effective than carbon dioxide) accelerate the climate change process in the atmosphere (Ağaçayak, 2021).

It is necessary to redesign plant nutrition processes against the negative effects of climate change and to adapt to new climate conditions. The subject covers the periods starting with the soil analysis of the land to be planted, preparing the soil for planting, selecting the right plant species suitable for soil properties, and the decision-making stages, and ending with plant cultivation until harvest. The most important issue is to provide the right plant nutrient material, in the right amount and with the right method. Organic, organomineral plant nutrient inputs that reduce the use of chemical plant nutrient inputs and protect/improve/develop the physical/chemical properties of the soil should be preferred (Saygı H. 2022b). Applying plant nutrients to the plant, especially after planting, with a drip irrigation system instead of a tractor, or with an agricultural unmanned aerial vehicle (AUAV) in liquid or solid form, will increase the effect of plant nutrition and reduce environmental damage.

3.3. Climate Change Irrigation

Irrigation is the activity of artificially giving the amount of water that the plant needs and cannot meet by natural means (rainfall, soil moisture, water vapor, etc.) to the soil in the required amount and with a suitable method (Demirci and Ortaakarsu, 2021). The main principle in irrigation activities is to irrigate the entire field with equal amounts and intensity with minimal loss. One of the most important issues among the strategies for adaptation to climate change in agricultural production activities is the irrigation methods to be applied (Atış et al. 2023). In agricultural production activities, potential risks that may arise regarding soil moisture lost as a result of insufficient rainfall are reduced by harmonizing irrigation practices (Cunha et al., 2014).

Climate change causes structural problems such as inadequate and untimely rainfall regimes, pollution of water resources and water scarcity. In particular, the solution to the water scarcity problem is the drip irrigation method, which will provide irrigation of large areas with a very small amount of water and can increase product yield per unit water volume used (Atış et al. 2023). The basic principle of the drip irrigation method is to provide sufficient amount of water each time by dripping it to the soil surface only to the plant roots through a pressurized pipe network at frequent intervals, without creating any stress in the plant due to lack of moisture (Gündüz, 2024). Drip irrigation is an effective method of providing water directly to the root zone and minimizes traditional losses such as deep percolation, surface runoff and soil erosion (Atış et al. 2023). Unlike surface irrigation, drip irrigation is considered more suitable and economical in areas with rugged topography, shallow and sandy soils, and water scarcity for high-value crops (Madhava Chandran and Surendran, 2016).

One of the innovations that will increase the efficiency of irrigation with technological developments is the drone technology AUAVs used in agricultural production activities. Despite some limitations, AUAVs can provide significant advantages in agricultural irrigation processes. AUAVs provide effective irrigation by performing precise irrigation activities in agricultural lands. AUAVs equipped with high-resolution cameras and sensors monitor the water needs of plants in real time, ensuring that water reaches the plant in the right place and at the right time. This contributes to the prevention of water waste and the efficient use of water resources.

3.4. Climate Change Pest and Disease Control

Pest and disease control are activities carried out to increase plant productivity and protect them from various pests (Altıkat, 2013). Organisms that feed on products produced by humans and cause the product to decrease are called pests. Today, the loss in agricultural areas due to diseases, pests and weeds is approximately 30%, which is equal to 23 million tons of wheat, which is the annual nutritional need of 150 million people. (Karaca, 2020). Pesticides are chemical substances used to destroy/control pests, unwanted weeds and insects that have the potential to harm plants and products in the agricultural production process (Altıkat, 2013). Pesticide, which is divided into classes according to its chemical structure and function, has varieties such as insecticide in insect control, herbicide in weed control and fungicide in fungal control (Altıkat, 2013). When used improperly or excessively, they mix with the environment and cause unhealthy conditions by polluting soil, water and air. Pesticide residues form in environmental foods and this is a significant problem for human health.

The greenhouse gas impact of pesticides throughout their entire life cycle (production, storage, transportation, application, degradation) is rarely taken into account (PAN, 2022). Although 99% of the production of all chemicals, including pesticides, is carried out from fossil fuels, less attention is paid to nitrogen fertilizers, which create dangerous levels of greenhouse gas emissions. Scientific studies have shown that approximately 10 times more energy is required to produce one kg of pesticide than one kg of nitrogen fertilizer (PAN, 2022). This means that pesticides also release greenhouse gases and accelerate the climate change process.

In the adaptation process to the effects of climate change, the first priority method of pest control should be the use of natural enemies. Historically, cats were used against mice that damaged stored products in Egypt, ants against insects that damaged citrus fruits in China, and the turning point in this regard was used all over the world as natural enemies against the ladybug, a citrus pest (Karaca, 2020). Using natural enemies reduces the use of chemicals and reduces the impact of climate change. In the fight against weeds, mulching systems, plant species change and crop rotation practices should be preferred over chemical use (TARFİN, 2023). In the fight against diseases, natural compounds such as copper compounds against fungicides, Bordeaux mixture fungicide against fungal diseases, lime-sulfur mixture against insecticides and acaricides should be applied to the plant in various forms (plant extracts, easily prepared preparations and biological drugs) (Yetgin, 2010). In all these processes, natural methods and in cases of necessity, the application of AUAV to plants to increase the effectiveness will reduce the harmful effects on the environment.

3.5. Climate Change Harvesting Processes

Harvesting is the act of separating the product from the plant when it reaches the desired maturity and quality in the agricultural production process and transporting it to a safer place for extraction, processing, consumption or storage (ASGEN, 2021). While the main factor determining the harvest time is the maturity of the crop, other factors such as weather, availability of harvesting equipment, collectors, packaging and storage facilities and transportation are also important issues (ASGEN, 2021). The movement of the machines used on the soil during the harvest periods affects the soil structure; the type of energy used accelerates the climate change process with greenhouse gas emissions. After harvest, the harvested plant residues should be left on the soil surface to protect the soil moisture and against the risk of erosion according to the time interval when the soil will be prepared for replanting.

4. SUSTAINABLE AND ORGANIC FARMING

Sustainability is used to design new nature-compatible production/consumption methods that will preserve the renewing properties of natural resources used to meet human needs and ensure that future generations benefit from these resources. The concept of sustainability has an application area in all economic activities carried out by humans (Brown JR. 2023). Sustainable agriculture is important for ensuring the continuation of healthy and sufficient food resources for future generations. Sustainable agriculture in the agricultural field is agricultural methods designed to meet environmental, economic and social criteria in a balanced way (Brown JR. 2023). These methods include measures such as organic agriculture that protects the health of the soil, savings in water management, reducing the use of fertilizers and pesticides, increasing diversity, using biological control methods, increasing animal welfare, and making agriculture compatible with global climate change.

Organic agriculture, which is a reflection of sustainable economic activities in agricultural production processes, is an agricultural production method that includes principles and rules that are friendly to nature, humans and other living beings in agricultural production processes (Saygı, 2023). Organic agriculture includes principles, rules and practices that will reduce the negative effects of climate change, repair the damages it causes and improve the capacity of agricultural resources. Organic agriculture is a production system with national/internationally organized private and public institutions/organizations, documenting the entire process and legal legislation covering the subject. Although there are negative criticisms about organic agriculture, it is a method that comprehensively addresses the problems in the agricultural field and suggests solutions (Saygı, 2022c). Organic agriculture includes practices that prohibit the use of chemical inputs that cause climate change in agriculture and take animal welfare into account in agriculture's own ecosystem. The wastes generated in agricultural production/consumption processes are evaluated in a way that they will be properly destroyed, preserved and used in the reproduction process. In short, organic agriculture is an agricultural production method that includes the restoration of the natural balance lost as a result of agricultural activities, including the above-mentioned practices.

5. CONCLUSION

The positive/negative effects of climate change caused by human activities on agricultural production activities are a scientifically proven fact. When the positive and negative effects of climate change are compared, it is seen that the negative effects are more dominant and that the negative effects are discussed in academic studies and other literature. Although it does not seem possible to avoid the negative effects of climate change on agricultural production activities in the short term, adapting agricultural production activities to these newly formed conditions is an important solution. In this way, while preventing agricultural production activities from being affected by the negative effects of climate change, it is also possible to correct these negativities. For this purpose, protective soil processing methods that will keep soil moisture in balance for a healthy and high-quality soil structure should be used during agricultural production activities. Organic plant nutrition materials (solid/liquid) should be used in plant nutrition according to soil analysis values and should be applied to the plant with drip irrigation and AUVA. Plant irrigation should be carried out effectively with drip irrigation systems or AUAVs due to insufficient and irregular rainfall and water scarcity. Considering biodiversity, the use of chemicals in the fight against diseases and pests should be minimized, natural enemies should be used in the fight against pests, natural methods should be used in the fight against diseases, and AUAVs should be used in cases where the use of chemicals is necessary. In harvesting processes, the right time for harvesting, the appropriate harvesting method should be selected, and the vegetation on the soil surface should be protected to preserve soil moisture. As a result, an organic agriculture production method that includes sustainable production activities that take all these processes into account should be implemented.

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CHAPTER 6

STRATEGIES FOR REDUCING GREENHOUSE GAS EMISSIONS IN AGRICULTURAL PRODUCTION FOR A SUSTAINABLE ENVIRONMENT

Res. Asst. Dr. Ferhat UĞURLAR[1*]

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[1] *Harran University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Sanliurfa, Türkiye. ORCID: 0000-0002-3663-3497, E-mail:ferhatugurlar@gmail.com
*Corresponding Author: ferhatugurlar@gmail.com

1. Introduction

Global warming and shifts in global climate patterns rank among the most pressing environmental challenges confronting humanity today. A primary driver of these phenomena is the rapid accumulation of atmospheric heat-trapping substances in the atmosphere. While the agricultural sector plays a crucial role in ensuring global food security, it is also a significant contributor to release of gases of heat-trapping gases. Potent atmospheric heat-trapping substances such as CH_4, CO_2, and N_2O are emitted throughout various stages of farming operations, intensifying the effects of shifts in global climate patterns. Consequently, implementing sustainable agricultural practices to mitigate release of gases of heat-trapping gases is essential for addressing this global issue (Smith and Olesen, 2010; Ramazanoglu et al., 2024).

Agricultural activities encompass various processes such as soil tillage, fertilization, livestock production, and irrigation, each of which contributes directly or indirectly to release of gases of heat-trapping gases (Bhatti et al., 2024). For instance, ruminant livestock is a primary source of CH_4 production, while the use of synthetic fertilizers containing nitrogen increases N_2O release of gases (Walling et al., 2020; Aan den Toorn et al., 2021). Additionally, fossil fuels used in agricultural machinery and deforestation significantly raise CO_2 release of gases (Raihan et al., 2022). Therefore, reducing release of gases of heat-trapping gases in agricultural production is not only vital for minimizing the sector's significant contribution to shifts in global climate patterns but also represents a key measure in the global effort to combat environmental challenges (Malhi et al., 2021; Panchasara et al., 2021).

Sustainable agriculture is at the forefront of strategies aimed at achieving environmental sustainability and holds significant potential for reducing release of gases. The adoption of innovative farming techniques that lower the carbon footprint, improved fertilizer management, and the use of sustainable energy sources sources can reduce release of gases of heat-trapping gases and enhance soil health (Saliu et al., 2023). Moreover, sustainable agricultural practices extend beyond emission reduction; they also maintain ecological balance by conserving biodiversity and efficiently managing water resources (Srivastav et al., 2021; Rehman et al., 2022).

Implementing these initiatives will enhance the sustainability of agricultural production on both local and global scales. The successful application of sustainability strategies in agriculture not only reduces release of gases of heat-trapping gases but also protects ecosystems and mitigates the adverse effects of shifts in global climate patterns. This book chapter will address strategies for reducing release of gases of heat-trapping gases in agricultural production, emphasizing the critical role of eco-friendly farming in the fight against shifts in global climate patterns.

2. Agriculture and Greenhouse Gas Emissions

Agricultural activities contribute significantly to global release of gases of heat-trapping gases, becoming one of the primary drivers of shifts in global climate patterns (Field et al. 2014). The main atmospheric heat-trapping substances released into the atmosphere in this process are potent gases like CO_2, CH_4, and N_2O. Agriculture causes the release of these gases into the atmosphere through various stages, such as fossil fuel usage, soil tillage practices, livestock farming, and fertilizer applications (Gołasa et al., 2021; Chataut et al., 2023). As of 2020, approximately 20% of global release of gases of heat-trapping gases are attributed to agriculture (Laborde et al., 2021; Panchasara et al., 2021). This proportion clearly indicates the need for sustainability in the agricultural sector and a reevaluation of agricultural production to combat shifts in global climate patterns (Tubiello et al. 2014; Gilbert 2012).

a) Carbon Dioxide Emissions: One of the primary contributors to CO_2 release of gases in agriculture is the energy consumption associated with machinery and infrastructure (Guan et al., 2023). The use of tractors, harvesters, irrigation systems, and other equipment is heavily dependent on fossil fuels such as diesel and gasoline. Similarly, controlled agricultural environments like greenhouses often require extensive energy for heating, cooling, and lighting, much of which comes from non-renewable sources. These processes collectively add a substantial amount of CO_2 to the atmosphere.

The production and application of synthetic fertilizers represent another major source of CO_2 release of gases (Xu et al., 2023). The manufacturing of nitrogen-based fertilizers, which is vital for modern high-yield farming, relies on energy-intensive processes such as the Haber-Bosch method (Braun et al., 2022). This process uses natural gas both as an energy source and a raw material, making it a significant contributor to release of gases. Beyond production, the transportation and application of fertilizers further increase fossil fuel use, compounding their overall carbon footprint (Jaiswal and Agrawal, 2020). Fertilizers not only contribute directly to CO_2 release of gases but also play a role in other greenhouse gas processes, such as N_2O release (Galic et al., 2020).

Deforestation for agricultural expansion is a particularly damaging contributor to carbon release of gases (Raihan et al., 2022). When forests are cleared for cropland or pasture, the carbon stored in trees and vegetation is released into the atmosphere, often through burning. This not only adds large amounts of CO_2 but also diminishes the natural carbon storage capacity of the landscape. Furthermore, these cleared lands often lose their ability to sequester carbon in the long term, exacerbating shifts in global climate patterns impacts. In tropical regions with high deforestation rates, the impact is particularly severe. Additionally, changes in land use, such as the conversion to olive cultivation areas, further highlight the interplay between agricultural practices and carbon dynamics (Erdal et al., 2021).

Soil management practices, including conventional tillage, also play a critical role in CO_2 release of gases from agriculture. Tillage disrupts soil structure, exposing organic matter to oxygen and accelerating its decomposition, which releases stored carbon into the atmosphere (Hussain et al., 2021; Chudasama et al., 2023). In contrast, environmentally friendly management of soil health practices, such as reduced tillage and organic amendments, have been shown to enhance soil biological properties. For example, Celik et al. (2023) reported significant improvements in microbial biomass carbon and nitrogen content, as well as enzyme activities, under horticultural systems that avoided soil disturbance and synthetic applications. These biological properties are sensitive indicators of soil health and contribute to the sustainability of agricultural systems. Over time, continuous tillage depletes soil organic carbon reserves, reducing the soil’s ability to act as a carbon sink (Kalyani et al., 2024). Poor management of soil health practices not only contribute to immediate release of gases but also threaten the sustainability of agricultural systems by degrading soil health (Cárceles Rodríguez et al., 2022).

Finally, post-harvest activities such as transportation, processing, and storage are additional sources of CO_2 release of gases. The logistics of moving agricultural products to markets or processing facilities often rely on fossil-fueled vehicles, while processing and packaging require energy-intensive operations. In many regions, crop residues are burned in the field as a quick and cost-effective method of clearing land for the next planting season. This practice releases large amounts of CO_2 and other atmospheric heat-trapping substances directly into the atmosphere, further contributing to the agricultural sector's carbon footprint.

b) Methane Emissions: Ruminant animals such as cattle, sheep, and goats produce CH_4 through enteric fermentation, a natural digestive process where microbes in their stomachs break down feed (Cholewińska et al., 2020). This process generates CH_4 as a byproduct, which is released into the atmosphere. Manure management is another significant source, particularly when animal waste is stored or treated in anaerobic conditions, such as liquid manure systems (Liu and Wang, 2020). These environments facilitate CH_4 production by microorganisms. Additionally, rice cultivation contributes heavily to CH_4 release of gases (Rajendran et al., 2024). The flooded fields used in rice farming create anaerobic conditions ideal for the decomposition of organic matter, leading to substantial CH_4 release (Das et al., 2023).

Methane's impact on the environment is particularly significant due to its high potency as a greenhouse gas, with a heat-trapping capacity approximately 25 times greater than that of CO_2 over a 100-year time frame (Gerber et al., 2013). As a result, addressing CH_4 release of gases is a key priority in agricultural climate mitigation strategies. Effective approaches include enhancing feed efficiency in livestock to reduce enteric fermentation, adopting advanced manure management techniques, and applying alternate wetting and drying methods in rice paddies. These practices collectively hold great potential for lowering CH_4 release of gases and minimizing the agricultural sector's overall contribution to shifts in global climate patterns.

c) Nitrous Oxide Emissions: Nitrous oxide is a potent greenhouse gas emitted predominantly from farming operations, particularly through the use of synthetic fertilizers and management of soil health practices involving organic materials. During the nitrogen cycle, microbial processes such as nitrification and denitrification convert nitrogen in the soil into N_2O, which escapes into the atmosphere (Robertson and Groffman, 2024). Excessive application of synthetic fertilizers is a key driver of these release of gases, as it provides an abundance of nitrogen that intensifies microbial activity, leading to higher N_2O production (Xing and Wang, 2024). Organic amendments, such as manure or compost, can also contribute to N_2O release of gases under certain soil conditions, especially when oxygen levels are limited (Guenet et al., 2021).

The environmental significance of N_2O lies in its extreme climate heating potential—approximately 298 times greater than that of CO_2 over a 100-year period (Tian et al., 2023). Its long atmospheric lifespan and high warming capacity make it a critical target for mitigation strategies in agriculture. Effective approaches include optimizing fertilizer application rates, adopting precision farming techniques, improving soil drainage, and incorporating cover crops to enhance nitrogen uptake and reduce excess availability in the soil. These measures not only reduce N_2O release of gases but also improve overall nitrogen use efficiency in farming systems.

d) Impact of Agricultural Emissions on Climate Change: Agricultural production is a major source of release of gases of heat-trapping gases, making it one of the most significant contributors to shifts in global climate patterns (Laborde et al., 2021). The emission of CO_2, CH_4, and N_2O from various farming operations significantly increases atmospheric greenhouse gas concentrations. This results in global temperature rise, shifts in precipitation patterns, and an increase in the frequency and severity of extreme weather events, including droughts, floods, and heatwaves. Such climatic changes disrupt ecosystems, intensify environmental degradation, and heighten vulnerabilities in both natural and human systems, posing a severe challenge to global sustainability.

Agriculture is not only a driver of shifts in global climate patterns but also one of the sectors most vulnerable to its effects. Rising temperatures, changing rainfall patterns, and extreme weather can reduce crop yields, lower livestock productivity, and degrade soil fertility, posing severe risks to food security (Ahmed et al., 2023). Water scarcity, in particular, threatens irrigated agriculture, while high temperatures can directly affect plant growth and increase pest and disease pressures (Skendžić et al., 2021). These compounding effects underline the urgent need to address agricultural release of gases to mitigate shifts in global climate patterns and protect global food systems.

e) Role of Sustainable Agriculture: Sustainable agriculture plays a vital role in reducing release of gases of heat-trapping gases and addressing shifts in global climate patterns. By emphasizing the efficient use of natural resources and minimizing environmental impacts, sustainable farming practices offer a pathway toward climate resilience (Das and Ansari, 2021). Key strategies include minimizing soil tillage to preserve soil carbon, using organic fertilizers to reduce synthetic input reliance, and integrating sustainable energy sources sources into agricultural operations (Agbelusi et al., 2024). These practices not only lower release of gases of heat-trapping gases but also enhance soil health and ecosystem stability.

By adopting such approaches, the agricultural sector can achieve more sustainable production processes while contributing to a healthier environment. Reducing release of gases through these methods not only mitigates shifts in global climate patterns but also ensures long-term agricultural productivity and food security (Balasundram et al., 2023). Sustainable agriculture thus serves as a cornerstone for balancing the need for increased food production with the imperative to protect the planet.

3. Soil and Fertilizer Management

Soil and fertilizer management play a critical role in ensuring the sustainability of agricultural production and reducing its negative environmental impacts. Proper management of soil health not only enhances agricultural productivity but also contributes to reducing release of gases of heat-trapping gases. Practices such as increasing carbon sequestration capacity, using organic matter, and effective fertilizer management can significantly reduce release of gases while improving soil health (Lal, 2021).

3.1. Importance of Soil Management

Soil is a natural carbon reservoir capable of storing large amounts of carbon (Aminu et al., 2017). However, improper management of soil health practices and intensive farming operations reduce this capacity, causing carbon to be released into the atmosphere (Chowdhury et al., 2021). Traditional soil tillage methods rapidly deplete organic matter and reduce soil fertility while also increasing CO_2 release of gases, thereby negatively contributing to shifts in global climate patterns (Rahman et al., 2020). Practices like minimal tillage, however, help retain organic matter in the soil, promoting carbon sequestration (Robertson and Vitousek, 2009).

Moreover, soils rich in organic matter improve water retention, enabling plants to access water more readily during dry periods and enhancing agricultural productivity (Gavrilescu, 2021). To protect soil health and ensure sustainability in agricultural production, strategies to increase organic matter content in soil should be implemented (Cárceles Rodríguez et al., 2022). The use of materials such as biochar increases soil carbon content and contributes to reducing atmospheric greenhouse gas concentrations (Gupta et al., 2020).

3.2. Fertilizer Management and Greenhouse Gas Emissions

Fertilizer management is crucial for reducing agricultural release of gases. The overuse of nitrogen-based fertilizers significantly increases N_2O release of gases by stimulating microbial activity in the soil. N_2O is particularly concerning because its climate heating potential is approximately 298 times greater than that of CO_2 (Tian et al., 2023). Therefore, efficient fertilizer application is essential for minimizing release of gases in agriculture while maintaining productivity.

Precision fertilization methods play a key role in preventing excessive fertilizer use by addressing the specific nutrient requirements of plants. Utilizing soil analysis to guide fertilization strategies, combined with the application of nitrogen inhibitors, can improve fertilizer efficiency and reduce unnecessary nitrogen losses (Barłóg et al., 2022). Moreover, replacing synthetic fertilizers with organic alternatives offers additional environmental benefits. Organic fertilizers not only reduce release of gases associated with synthetic fertilizers but also enrich the soil with organic matter, providing a sustainable and long-term source of nitrogen (Owusu et al., 2024).

4. Emission Reduction Methods in Livestock Farming

The livestock sector is a major contributor to release of gases of heat-trapping gases in agriculture, particularly through the release of CH_4 and N_2O (Gerber et al., 2013). These release of gases stem primarily from enteric fermentation in ruminant animals and manure management practices, which together significantly impact shifts in global climate patterns and pose challenges to the environmental sustainability of agriculture (Cholewińska et al., 2020). Addressing these release of gases through sustainable practices is critical for mitigating the agricultural sector's contribution to climate heating and ensuring long-term viability.

Methane is 25 times more potent than CO_2 as a greenhouse gas, making the reduction of its release of gases crucial for mitigating shifts in global climate patterns (Shivanha, 2022). Effective strategies to achieve this include dietary modifications and feed additives. Adding fat-based supplements or tannic acid to animal diets can significantly lower CH_4 production, while improving the digestibility of feed enhances energy efficiency and further reduces release of gases (Shibata and Terada, 2010). Studies suggest that these approaches can decrease CH_4 release of gases in livestock by up to 20% (Lascano and Cárdenas, 2010). In addition, genetic selection offers a long-term solution by breeding animals that naturally produce less CH_4, creating a sustainable pathway to mitigate release of gases (Pickering et al., 2015).

Nitrous oxide release of gases, another significant issue in livestock farming, largely result from improper manure management. Manure stored under anaerobic conditions can release N_2O, a gas with a climate heating potential 298 times greater than CO2 (Tian et al., 2023). Proper manure management strategies are therefore essential to reducing release of gases. Biogas production offers a sustainable solution by processing manure in anaerobic digesters, which capture CH_4 for use as a sustainable energy sources source. This approach not only mitigates release of gases but also supports on-farm energy needs and minimizes the environmental impact of waste (Gerber et al., 2013). Additionally, composting manure under suitable conditions can reduce both CH_4 and N_2O release of gases while creating a nutrient-rich soil amendment that supports eco-friendly farming (Singha and Singha, 2024).

Beyond these targeted strategies, sustainable livestock practices provide a holistic approach to emission reduction. For instance, rotational grazing enhances pasture productivity, prevents overgrazing, and supports soil carbon sequestration, which contributes to lowering release of gases of heat-trapping gases (Teague et al., 2011). Integrating waste recycling systems into livestock farming aligns with circular economy principles by converting waste into valuable resources, thereby minimizing environmental impacts and improving overall efficiency. These integrated approaches not only reduce release of gases but also improve animal welfare, enhance soil health, and provide economic benefits, contributing to a more sustainable agricultural model (Gerber et al., 2013).

5. Use of Renewable Energy

The use of sustainable energy sources in activities such as agricultural production and livestock farming has great potential for increasing energy efficiency and reducing release of gases of heat-trapping gases. Dependence on traditional energy sources amplifies the environmental impact of farming operations, with fossil fuel usage leading to significant release of gases of heat-trapping gases, particularly CO_2 (Wang and Azam, 2024). In this context, utilizing sustainable energy sources sources in agriculture is a critical strategy for promoting environmental sustainability and reducing energy costs (Burney et al., 2010).

5.1. Types of Renewable Energy and Their Use in Agriculture

a) Solar Energy: Solar energy is one of the most commonly used sustainable energy sources sources in agricultural production. Solar panels installed on farms can generate electricity to power irrigation systems, storage facilities, and agricultural machinery (Burney and Naylor, 2012). By significantly reducing fossil fuel usage, solar energy helps lower the carbon footprint of agricultural operations. Additionally, solar-powered irrigation systems can be automated, promoting efficient water usage and enhancing agricultural productivity (Kabir et al., 2018).

b) Wind Energy: Wind energy holds significant potential for meeting energy needs in agricultural areas, particularly in regions with abundant wind resources. Wind turbines installed on farmland can generate sustainable energy sources to power farming operations, greatly reducing release of gases of heat-trapping gases (Esteban et al., 2011). Wind energy not only lowers energy costs but also enhances environmental sustainability by minimizing reliance on fossil fuels. Additionally, wind turbines allow for efficient land use, as the land beneath them remains available for farming operations, maximizing productivity without sacrificing farmland (Davis and Daniels, 2012).

c) Biogas: Biogas production is an effective method for converting agricultural waste into energy. Animal manure, plant residues, and other organic waste materials can be processed in biogas facilities to produce CH_4 gas, which can be used for electricity generation or directly as an energy source for farming operations (Weiland, 2010). Additionally, biogas production enhances the efficient use of fertilizers by recycling nutrient-rich waste, thus reducing release of gases and promoting agricultural sustainability (Holm-Nielsen et al., 2009). This process not only aids in waste management but also supports sustainable practices in agriculture.

d) Bioenergy: Bioenergy is derived from agricultural biomass, including agricultural and forestry waste. By burning organic materials, energy can be produced for heating, electricity generation, and other agricultural applications. Bioenergy is often considered a carbon-neutral energy source, as the CO_2 released during biomass combustion is balanced by the amount absorbed during the growth of the biomass (Tilman et al., 2006). Consequently, bioenergy contributes significantly to sustainable energy management in agricultural production, supporting both energy needs and environmental goals.

5.2. The Role and Benefits of Renewable Energy in Agriculture

The adoption of sustainable energy sources sources in agriculture offers significant environmental and economic benefits. By reducing dependency on fossil fuels, sustainable energy sources systems lower release of gases of heat-trapping gases and help mitigate shifts in global climate patterns (Pimentel and Pimentel, 2007). This shift decreases the carbon footprint of agricultural production and enhances the sustainability and resilience of farming systems. Renewable energy systems, such as solar, wind, and biogas, also address the energy needs of agricultural machinery, irrigation systems, and other operations, reducing production costs and promoting economic sustainability (Burney et al., 2010).

In addition to economic advantages, the use of sustainable energy sources mitigates the negative environmental impacts of traditional agricultural practices. By decreasing CO_2 release of gases and improving energy efficiency, sustainable energy sources sources contribute to a more sustainable agricultural sector. This transition is critical for achieving global climate goals and supporting long-term productivity in agriculture (Kabir et al., 2018). Through the integration of sustainable energy sources, agriculture can align with sustainable development principles, benefiting both current and future generations.

6. Conclusion

Agricultural production plays a crucial role worldwide, not only in terms of economic development and food security but also as a significant source of release of gases of heat-trapping gases. Powerful atmospheric heat-trapping substances such as CO_2, CH_4, and N_2O are released into the atmosphere during various agricultural processes, directly contributing to shifts in global climate patterns. Reducing agriculture's environmental impact and developing a sustainable production model require controlling release of gases of heat-trapping gases.

Sustainable agricultural practices are essential for reducing release of gases in agricultural production. Soil management techniques can increase carbon sequestration, while precision strategies in fertilizer application significantly reduce N_2O release of gases. In the livestock sector, methods such as feed additives and biogas production help reduce CH_4 release of gases, thereby minimizing agriculture’s environmental footprint. Furthermore, the use of sustainable energy sources sources in agriculture replaces fossil fuels, lowering release of gases of heat-trapping gases from energy consumption.

Reducing release of gases of heat-trapping gases in agricultural production is crucial for ensuring environmental sustainability and combating shifts in global climate patterns. Strategic approaches in agriculture control release of gases, enhance the efficiency of production processes, and ensure the long-term sustainability of farming. Promoting sustainable agricultural policies and adopting eco-friendly production techniques will help create a livable environment and ensure food security for future generations.

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CHAPTER 7

INNOVATIVE NITROGEN MANAGEMENT FOR SOIL HEALTH IN CLIMATE-IMPACTED SYSTEMS

Res. Asst. Fatma Nur KILIÇ[1]
Prof. Dr. Osman SÖNMEZ[2]
Assist. Prof. Dr. Somayyeh RAZZAGHI[3*]

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[1] Department of soil Science and Plant Nutrition, Faculty of Agriculture, Erciyes University, Kayseri/Turkey, Address, OrcID: 0000-0003-3498-2455
E-mail: fatmanur@erciyes.edu.tr

[2] Department of soil Science and Plant Nutrition, Faculty of Agriculture, Erciyes University, Kayseri/Turkey, Address, OrcID: 0000-0002-9134-6466
E-mail: osmansonmez@erciyes.edu.tr

[3*] Department of soil Science and Plant Nutrition, Faculty of Agriculture, Erciyes University, Kayseri/Turkey, Address, OrcID: 0000-0002-8028-452X
E-mail: srazzaghi@erciyes.edu.tr
*Corresponding Author: srazzaghi@erciyes.edu.tr

1. Introduction

Owing to abnormal temperature fluctuations, irregular rainfall, and alteration of weather events, climate change has severe adverse impacts on agricultural production. At recent times, it is an essential consideration threatening continuity and efficiency in the agricultural systems (Bibi & Rahman, 2023; Anh et al., 2023). This sudden and constant change in temperature and rainfall affects the health of the soil and the yield of the crops through alteration in planting dates, harvest dates, crop yield potential, and quality (Pareek, 2017; Balasundram et al., 2023). In addition, climate is the main factor governing the formation of the soil which affected the structure of the soil, fertility, water retention capacity, and erosion resistance (Karmakar et al., 2016; Al-Tawaha et al., 2021).

It considers the capacity of the soil to sustain biological productivity while preserving or improving the quality of the environment through air and water quality protection in support of animal, plant and human health (Patil & Lamnganbi, 2018). The concept of soil health integrates the characteristics of the soil concerning its biology, chemistry, and physics with the quality index to get information concerning its functional performance (Davis et al., 2023). Nutrients are one of the important parameters in soil quality indices, when it comes to farming crops and food security are apprehensive (Bashir et al., 2023).

Among all the parameters of soil health, soil nitrogen (N) has privileged position regarding fertility and has emerged as one of the most significant factors in the processes of agricultural production. Nitrogen is a essential nutrient for plant growth and development, directly affecting productivity. In this respect, recent works insist more and more on the crucial role played by N in the development of a healthy soil ecosystem (Wade et al., 2020; Naasko et al., 2024). Some of the main types are which nitrogen exists in soil: organic and inorganic. The organic one refers to more than 90% of the total N in soils, which includes complex compounds like polyphenols and high-molecular-weight amino acids. The uptake of this form by plants directly is limited, mainly to simple amino acids and amides. Most organic N must be transformed by microorganisms before it is available to plants; hence, the bioavailability and utilization of this form of nitrogen fundamentally depends on microbial activity in the soil. Active management of soil N is thus crucial for sustainability in agricultural productivity and maintaining soil health (Tan et al., 2018).

Accordingly, inefficient N management, the overuse of N application caused pollution in groundwater and surface water, eutrophication, loss of enhance greenhouse gas emissions and biodiversity (Reay et al., 2012; Zhang et al., 2015; Zhu et al., 2024). Global warming and irregular precipitation in connection with climate change are nowadays causing disequilibrium in the gains and losses of soil N (Bai et al., 2013; Yuan et al., 2017). This balance, with increasing human activities, goes on to become more important. Innovative N management strategies combined with agricultural practices have the potential for minimum N losses. Get the application exactly when and how much is better to ensure that the sustainability of the N gain-loss balance is done. These management strategies are believed to help in mitigating the effects of climate change on agriculture (Kanter et al., 2016).

The key role of N with respect to soil health and its important function regarding productivity and sustainability in agricultural production will be overviewed in depth within the present chapter. Possible influences of global climatic change will also be assessed on the N cycle and on the management of soil N for its effects on ecosystem equilibria and agroecosystems. It is for this reason that this review will focus on innovative N management strategies developed for optimization in agricultural activities in ensuring productivity efficiency, environmental sustainability, and economic benefits.

2. Importance of Nitrogen in Soil Health

2.1. The Fundamental Role of Nitrogen

Amino acids are the major constituent of N, they can be considered vital in forming the biological structures of organisms. Amino acids in turn are the units of proteins, which have functions as wide-ranging from stability in cell shape to acting as enzymes, carrying out regulatory functions, and catalyzing a wide array of biochemical reactions. Therefore, N is important to keep living organisms alive, enable normal growth, and support complex metabolic processes in living things (The et al., 2021). Further, N participates in biosynthesis of nucleic acids-DNA and RNA, energy transport molecule ATP, hormones, chlorophyll, and primary and secondary metabolites (Naeem et al., 2020; Gupta, 2020).

Organically, it influences the whole soil in its chemical, physical and biological properties. Physically, the soil organic matter (SOM) enhances the structure of the soil, with better water-holding capacity and increased resistance to erosion. Besides that, SOM increases the porosity of the soil, creating a more favorable environment for the development of the root and access of oxygen required by plants (Lehmann et al., 2020). The chemical effect is that N and other nutrients in SOM are converted into available forms which can easily be uptaken by the plants; hence, it increases the fertility of the soil. There is a healthy development of plants with high yields (Hoffland et al., 2020). Biologically, SOM acts as a basis for energy for microorganisms in the soil. This consequently supports the diversity and activities of the organisms. Microorganisms play a significant role in the decomposition of nutrients to make them available for plants. All these biological processes balance nutrient cycling within the soil for fertility and sustainability (Banerjee & Van Der Heijden, 2023).

2.2. Soil Nitrogen Dynamics

As we know, all the nutrient cycles significant in terrestrial ecosystems, but among them the N cycle is one the important ones in which N goes through a series of transformations with different forms in the ecosystem through a variety of chemical processes. Whereas about 78% of the volume of the atmosphere consists of nitrogen gas (N_2), less than 1% of the total N which has very limited biological availability, contained in the Earth's oceans, sedimentary rocks, silicate minerals, and clays (Marty et al., 2013; Zhang et al., 2020; Sardar et al., 2023). The N cycle processes involve ammonification, fixation, assimilation of N, nitrification and denitrification stages, in which N gain and loss were balanced (Fig. 1) (Mahmud et al., 2021).

The influences that affect the N cycle are soil, climate, and plants. It is very important to manage such influences effectively in order to come up with better ways of increasing N use efficiency, ensuring that N applications managed and assessing N losses arising from agriculture (Kumawat et al., 202

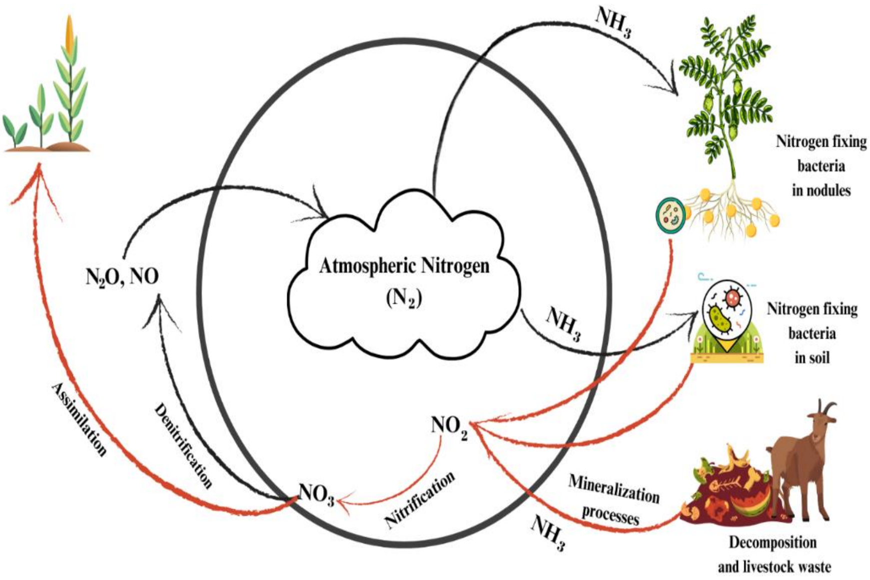

Fig. 1. Nitrogen transformation dynamics in the ecosystem

2.3. Nitrogen Fixation

Nitrogen fixation is the reduction of atmospheric N_2 into ammonia (NH_3), carried out by diverse prokaryotic groups such as bacteria and actinomycetes through nitrogenase enzyme complexes containing molybdenum-iron protein denitrogenase and vanadium/iron protein dinitrogenase reductase. This occurs either symbiotically in plant root nodules or freely in the rhizosphere (Hoffman et al., 2014; Stein & Klotz, 2016). Some of the major prokaryotic groups contributing to N fixation include bacteria from the families *Rhizobiaceae* and *Burkholderiaceae*, commonly referred to as rhizobia and are mostly involved in N_2 reduction in leguminous plants. Cyanobacteria from the genus *Nostocaceae*; actinobacteria from the genus *Frankia*. Several free-living bacteria like *Azospirillum*, *Azotobacter*, *Beijerinckia*, *Burkholderia*, *Clostridium* along with some archaea are also reposible for N_2 fixation (Timofeeva et al., 2023; Sepp et al., 2023). Associated with this biological N fixation, is industrial N fixation whereby free N_2 is converted into NH_3 through a Haber-Bosch process under conditions of high temperature and pressure. The process greatly provides a large amount of the mineral N used in agriculture, thereby reducing the requirement for N by crops (Smith et al., 2020; Salvagiotti et al., 2008; Ladha et al., 2022).

2.4. Nitrogen Mineralization

Nitrogen mineralization consists of the microbial processes involved in aminization, ammonification, and nitrification, which transform organic N-soil forms, such as proteins and amino acids into inorganic or mineral forms (Cruz et al., 2021; Zhang et al., 2024). Aminization denotes the complex enzymatic activity of heterotrophic bacteria, fungi and actinomycetes, and exudates from plant roots that degrade proteins and other N-rich compounds into amino acids or amines in biological remnants (Pruthviraj et al., 2024). Ammonification is executed by bacteria of the genera *Bacillus, Clostridium, Proteus,* and *Pseudomonas*; actinomycetes belonging to the genus *Streptomyces*; and fungi belonging to the genera *Alternaria* and *Aspergillus* through the conversion of organic amino acids into ammonium-an inorganic N form (Giri & Varma, 2020). The process of nitrification entails the oxidation of ammonium into nitrite by the bacteria genera *Nitrosomonas* and *Nitrosococcus* and further into nitrate by the genus *Nitrobacter*. While NO_3^- is the preferred form of N by plants, its anionic nature puts it vulnerable to leaching in the soil profile driven by many factors including rainfall and irrigation (Lee et al., 2022; Bonton et al., 2011).

Nitrogen mineralization supplies up to 47-68% of the net N inquiry in terrestrial biomes (Cleveland et al., 2013). Soil pH, moisture, and temperature affect organisms' existence and actions accountable for mineralization processes.

2.5. Nitrogen Assimilation

Assimilation represents the process by which these inorganic N forms, including NH_4^+ and NO_3^-, are converted into organic forms, such as amino acids, within fungi, phytoplankton, plants, and other microorganisms with the aid of enzymes such as glutamate synthase and glutamine synthetase that assist in incorporating N into the body tissues (Leigh & Dodsworth, 2007). In plants, the sources of N are coordinately assimilated with photosynthesis and carbon metabolism, thereby improving N use efficiency in support of energy balance.

The energy balance is attained through an equivalent mechanism in this pathway in microorganisms (Xu et al., 2012).

2.6. Denitrification

In turn, denitrification is the opposite of nitrification under anaerobic conditions whereby NO_3^- and NO_2^- are reduced, by bacteria like *Thiobacillus denitrificans, Pseudomonas, Micrococcus, Achromobacter, Bacillus* outcome in the production of nitric oxide (NO) and nitrous oxide (N_2O) to yield finally dinitrogen (N_2) (Naeem et al., 2020; Cruz et al., 2021). Nitrous oxide as the special concern of scientists as greenhouse gas (GHG) by its long atmospheric lifetime and higher heat-trapping ability compared to CO_2 (Mohanty et al., 2020 can also reacts with oxygen to deplete the ozone layer. While these gases are emitted through natural soil processes at significant rates, the proportion to the anthropogenic emissions from industrial activities and use of fossil fuel is disproportionately lower (Mahmud et al., 2021).

3. Climate Change and Nitrogen Dynamics

It is believed that climate change, through increased temperatures, indistinctive precipitation, and altered climatic events, largely enhances microbial N transformation processes in soils, such as mineralization, nitrification, and denitrification, and increases N losses (Elli et al., 2022). Changes in the balance of N gain-loss due to climate change are anticipated to enhance the emissions of N-based GHG, influencing the overall process (Xu, 2024).

3.1. Impact of Rising Temperatures on Nitrogen Dynamics

Global warming affects the size of N pools, the plant availability of N, and altered N_2O production or consumption through denitrification processes in terrestrial ecosystems (Hui et al., 2024). Studies have indicated that temperature fluctuations significantly affect the N cycle (Niu et al., 2010; Mooshammer et al., 2014). All these activities of N-cycling organisms and enzymes and decomposition of SOM would enhance with increased temperatures (Li et al., 2022). The consequence of this is that mineralization would proceed at a faster pace, which consequently generates additional N available to plants and microorganisms. While this may encourage soil nutrient cycling in the short run, reduced water retention capacity, increased vulnerability to erosion, as well as N loss resulting from volatilization and leaching, thus reducing soil health (Wei et al., 2023; Lyu et al., 2024). According to Fowler et al. (2015), increased temperatures, through increased mineralization, were seen to have the potential of reduction of N resources by 5-10%. Furthermore, increased temperatures facilitate the process of nitrification in transforming NH_4^+ to NO_3^- by enhancing the activities of bacteria (AOB) and ammonia-oxidizing archaea (AOA). Increased mobility of NO_3^- may lead to transport via rainfall or irrigation into groundwater and surface waters, causing pollution and eutrophication (Yilin et al., 2022; Hui et al., 2024). While, with the rise in temperatures, denitrification decreases NO_3^- to N_2O, increasing NO_2, NO, N_2O, and N_2 emissions (Wei et al., 2023; Schlüter et al., 2024). N_2O concentration in the atmosphere has been increasing at a rate of ~2% per decade, and ~70% of this is due to anthropogenic sources, like agriculture (as one of the major anthropogenic sources) in the form of increased application of fertilizers and irrigation, which both enhanc the rates of denitrification (Tian et al., 2020; Naeem et al., 2020).

3.2. The Impact of Rainfall İrregularities on Nitrogen Dynamics

Rainfall variations are indeed one of the most important features of climate change, seriously affecting agriculture. For instance, increased rainfall can facilitate the leaching of both inorganic and organic N into groundwater and surface waters, while insufficient rain disrupts microbial activity, slowing mineralization processes (Jiang et al., 2021b; Gervasio et al., 2024). Excess rainfall brings nitrates into the aquatic environments - nitrates (NO_3^-), critical inorganic N compounds whose absorption by aquatic plants, algae, and bacteria is very efficient, thus eventually promoting healthy growth and nitrate accumulation. This subsequently causes reduced oxygen levels and death in aquatic life, due to eutrophication (Gilliam et al., 2019; Hu et al., 2023). Moreover, various studies still show conflicting findings about the impact of N_2O emission, since several of these find an increase in N_2O emissions with increased rainfall, while others observe a decrease in cases where rainfall is limiting (Homyak et al., 2017; Yan et al., 2018; Li et al., 2020).

4. Innovative Nitrogen Management Approaches

The utilization of N, due to its beneficial effects on plant productivity and soil fertility, has become one of the common features of agriculture. However, excessive application of N fertilizer promotes crop lodging, and susceptibility to pests and diseases, and therefore is more costly during all crop cycles (Lehari et al., 2016). This also accelerates the mineralization of organic matter, lowers the soil pH, and reduces fertilizer efficiency at higher rates than optimum. This results in NO_3^- runoff and leaching into water bodies, reducing oxygen levels in them by the decomposition processes, deterioration of water quality, eutrophication, and mortality of aquatic life. All these processes are also linked with human health risks that include methemoglobinemia and some cancers, such as colon cancer (Payne et al., 2013; Singh et al., 2018; LR et al., 2020). A reduction in N use by about 50% is suggested to help address both environmental pollution and human health protection (Steffen et al., 2015). Traditional N management practices cannot fulfill the requirements of optimum crop production since they are associated with losses and environmental damage (Mohanty et al., 2020). Though there are several existing approaches to N analysis, including Kjeldahl analysis, chromatography, Fourier-transform infrared spectroscopy (FTIR), and high-performance liquid chromatography (HPLC) and all of the mentioned methods are capable of measuring the amount of N in the soil, developed, less expensive approaches is still highly needed to reduce time and cost (Lehari et al., 2016; Miao et al., 2023; Swathy et al., 2024). Hence, innovative approaches to N monitoring attempt to minimize losses from fertilizer applications, optimize application rates, and ensure precise timing of nitrogen use (Hedley, 2015). Such innovative N management practices aim at mitigating the adverse impacts of climate change and fostering sustainable and productive agricultural practices.

4.1. Nitrification Inhibitors and Slow-Release Fertilizers

Fertilizers that involve slow-release and nitrification inhibitors can reduce the velocity of N transformation and regulate the process, hence minimizing NO_3^- and N_2O losses effectively (Yadav et al., 2017). Slow-release fertilizers are isobutylidene diurea (IBDU), urea formaldehyde (UF), and crotonylidene diurea (CDU), which have several advantages over conventional methods. By applying this kind of fertilizer maintaining as a steady N source during the growth period, few applications are required, also these fertilizers minimize NH_3 volatilization and NO_3 leaching (Beig et al., 2018).

The nitrification inhibitor fertilizers include dicyandiamide (DCD), nitrapyrin (NP), and 3,4-dimethyl pyrazole phosphate (DMPP). These types of fertilizers impede NH_4^+ oxidation by ammonia-oxidizing bacteria (AOB) and archaea (AOA), reducing N_2O loss, particularly via the process of denitrification (Wang et al., 2021). The ^{15}N isotope labeling technique application and the use of nitrification inhibitors are powerful in determining ^{15}N distribution in the N cycles for different agricultural production systems. It provides precise information on the rate at which the quantity of N applied as fertilizer is taken up by plants and how much remains in the soil. It presents a more detailed analysis than the traditional method and does not neglect the other distributions of applied N (Li et al., 2019). Meng et al. (2020) reported that inhibitor-containing fertilizers were more effective in promoting rice plant growth in contrast to the control (Fig. 2).

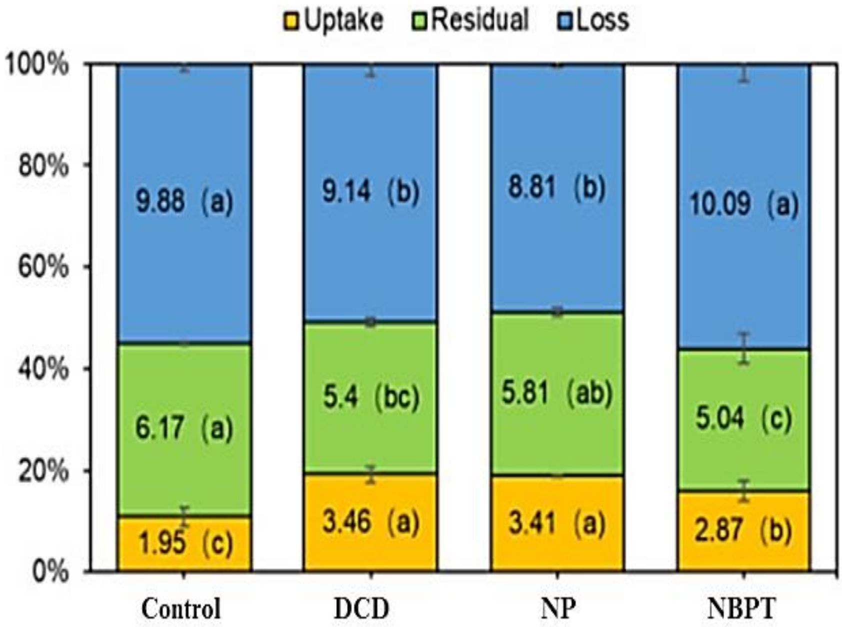

Fig. 2. The impact of inhibitors (nitrification and urease) on rice growing (Meng et al., 2020).

4.2. Precision Agriculture Practices

Precision agriculture is a farming system aimed at maximizing profitability, sustainability, and the preservation of land structure by identifying and analyzing spatial and temporal variations in production, enabling accurate seeding and input application at the right place and time (Ghadirnezhad Shiade et al., 2024). Technologies such as remote sensing, geographic information systems (GIS), global positioning systems (GPS) and variable rate applicators (VRA) allow for data-driven and precise monitoring of N-use efficiency (NUE) and crop growth (Fig. 3). The GPS provides accurate location data that facilitate the effective distribution of soil and crop information, which can then be integrated into farm equipment through GIS to guide application strategies. The correct identification of plant needs for nutrients is further enhanced by the remote sensing sensors (Javed et al., 2022). The technologies demonstrate utility with data for assessment fertilizer-N ratios through plant management and leaf chlorophyll measurement methods as depicted by Raper et al. (2015), and Denora et al. (2022).

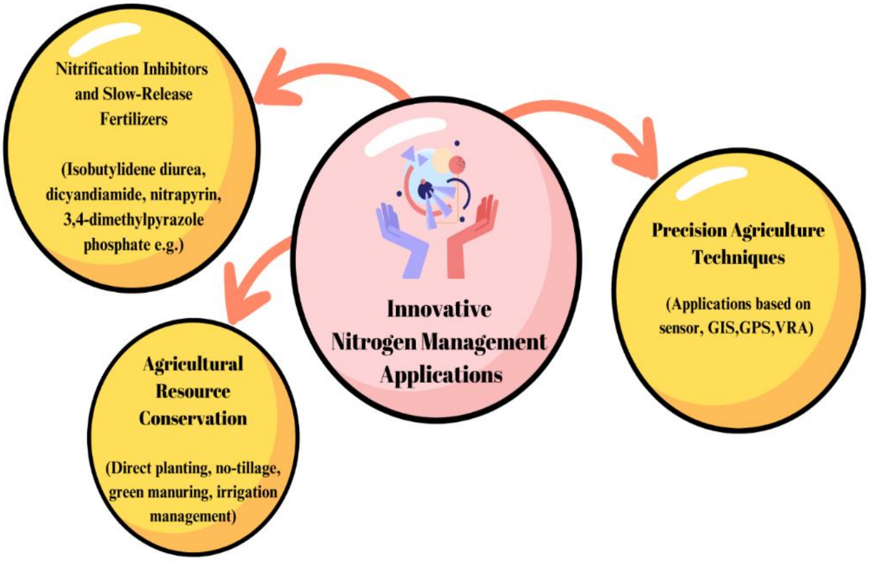

Fig. 3. Innovative N management techniques

4.2.1. Applications Based on Sensor Usage

Sensor-based methodologies have empowered agriculture in optimizing data-driven decisions by the farmer related to resource management and agricultural best practices with immediate information regarding soil conditions, climate, and plant health (Sishodia et al., 2020). Sensors in the soil, monitor the moisture, temperature, and nutrient levels to help improve irrigation and fertilization strategies. Precision farming uses such technology for early detection of stress, diseases, and nutrient deficiencies through crop yield sensors in order to timely corrective measures may be undertaken. More recent soil nutrient sensors offer even more accurate observing of the most essential elements, N, phosphorus, and potassium, for a more effective nutrient management approach (Dhanaraju et al., 2022).

4.2.1.1. Leaf Based Sensors

Leaf-based sensors provide a practical and rapid substitute for standard laboratory analyses by removing the necessity for sample processing. Since chlorophyll levels measured in leaves often indicate N concentration in plants, these sensors offer significant insights into plant health and nutritional status by remotely monitoring leaf chlorophyll content (Narmilan et al., 2022). However, the accuracy of information provided by these sensors can be influenced by factors such as plant diversity, growth stages, leaf thickness, and abiotic or biotic stressors (Zhang et al., 2016).

4.2.1.2. Ground Canopy Sensors

Canopy sensors, used at the crop level, offer a compelling alternative to leaf-based sensors for boosting agricultural efficiency and operate through two main methods: active and passive measurement (Sishodia et al., 2020). Passive sensors measure light reflected from the plant canopy using natural sunlight, whereas active sensors utilize their own light sources to assess green wavelengths and near-infrared reflections, which helps identify plant stress and N deficiencies (Colaço & Bramley, 2018).

These sensors offer several advantages, including the derivation of accurate plant biomass estimates and chlorophyll content, hence enabling more informed and optimized fertilization timing within the season. Limitations include susceptibility to such influences as the angle of the sun, dust, and clouds, added to their higher cost (Dhanaraju et al., 2022; Swathy et al., 2024).

4.2.1.3 Unmanned Aerial Vehicles (UAVs) and Remotely Piloted Aircraft Systems (RPAS)

Lately, unmanned aerial vehicles (UAVs) and remotely piloted aircraft systems (RPAS) have been emerging as credible tools for the precision management of N in farming. With remote-sensing sensors on board, they can accomplish quick and accurate acquisition of data cost-effectively over an extensive area for monitoring the level of N and determining different chemical and physical parameters in agricultural fields (Yang et al., 2017; Näsi et al., 2018). These methods will improve plant health, stress levels, and nutrient distribution through thermal and multispectral imaging (Hunt Jr & Daughtry, 2018). In this respect, Fiorentini et al. (2021) aimed to observe the growth and yield characteristics of durum wheat by employing UAVs under different soil tillage and N fertilization conditions. Their findings suggested that UAVs could be a promising technique for managing sowing systems and fertilizer applications (Figure 4).

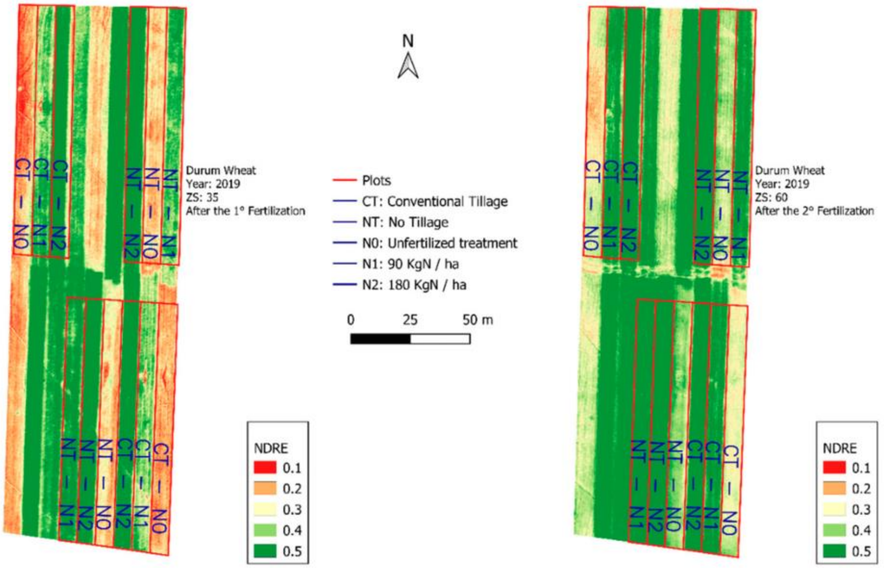

Fig. 4. Using multispectral imagery from UAVs to generate NDRE vegetation index maps at specific growth stages of cereals on the Zadoks scale (ZS:35 stem elongation, ZS:60 flowering) (Fiorentini et al., 2021).

4.2.2. Geographic Information Systems (GIS) and Global Positioning Systems (GPS)

The integration of Global Positioning Systems (GPS) and Geographic Information Systems (GIS) in precision agriculture enhances data-driven decision-making, which is an important ingredient in increased agricultural efficiency (Ghosh & Kumpatla, 2022). GIS technology helps in the accurate mapping of field differences in soil characteristics and topography which are very critical in the strategic planning of nutrient management. While GIS provides a clear and more graphic representation of the field conditions, the integration of GPS makes accessible precise location information that aids in the effective guidance and management of farming equipment. It is attained by using GIS and GPS integration to avail location-based applications in farming with increased precision, thereby facilitating a more even distribution of fertilizers and, in turn, enhancing productivity (Beriya et al., 2019).

4.2.3. Variable Rate Application (VRA)

Variable-rate applications (VRA) in precision agriculture were developed to provide an opportunity for synchronizing inputs, such as pesticide application, seeding, and fertilization, with field variability. It is supposed to offer better efficiency in the use and conservation of resources (Pawase et al., 2023). Variable-rate applications involve sensors, GPS, GIS, data analytics, machine learning in mapping at high resolutions that can give farmers all the information they need on soil quality, nutrient levels and all properties of each field. This application uses these detailed maps in conjunction with real-time data to optimize input rates, enhancing precision in agricultural operations and allowing the development of even more optimal utilization of resources (Ahmad et al., 2018).

4.3. Approaches to Conservation of Farming Resources

The incorporation of crop residues into the soil after harvest will not only reduce soil degradation but also provide a long-term source of N. One of the best examples of agricultural residues that can effectively act as N sources is leguminous crops, due to their elevated N content and diminished C/N ratio (Yadav et al., 2021; Meena et al., 2018). Another important practice is cropping rotation, which can reduce demand for N-based fertilizers while improving the accessibility of available N and reducing leaching of NO_3^- into water bodies (De Notaris et al., 2018). These practices, along with conservation agriculture methods, assistance for enhancement of the structure of the soil and nutrient cycling. Techniques include leaving plant residues on the soil surface, direct seeding, and zero tillage to offset the intensive removal of plant residues under conventional farming. Conservation agriculture methods prevent soil organic matter loss, and erosion, enhance water retention capacity and microbial population activity for sustaining productivity (Somasundaram et al., 2020; Yadav et al., 2021). This is especially applicable in drip irrigation systems that can also be combined with fertilization, forming an effective alternative to flood irrigation that normally causes nutrient leaching. These systems supply the nutrients directly to the plant root zone for better nutrient uptake. It enhances water use efficiency and general soil and crop efficiency (Li et al., 2021).

5. Case Studies of Successful Practices

Studies investigating the effects of innovative application methods on N dynamics are included in Table 1.

Table 1. Studies on Innovative Application Methods in N Dynamics

Innovative Practice	**Impact on Nitrogen Management & Soil Health**	**References**
Precrop/Crop Rotation and Residue Management	Rotation systems and especially residues of legume plants have 🔴 NUE	(Vaziritabar et al.,2024)
Precision Farming Techniques (UAV)	Obtaining and mapping the normalized vegetation difference index enabled timely estimation of 🔴 NUE	(Jiang et al.,2021a)
Nitrification Inhibitor (DCD)	DCD cumulative ● NO_2 emissions compared to chemical fertilizer	(Changhua et al., 2024)

Precision Agriculture Techniques (Variable Rate Fertilization Method (VRF))	🔴NUE and economic efficiency of 🔴VRF compared to conventional N applications	(Wang et al., 2023)
Protection of Agricultural Resources (Pivot Irrigation)	1- Plant 🔴 water use efficiency and 🔴 partial efficiency of N fertilizer with pivot irrigation in wheat 2- Risk of ⚫ NO_3 leaching into deeper layers	(Cai et al.., 2023)
Controlled Release Urea (CRU)	1- Compared to conventional urea, CRU 🔴 NUE by %24.1 , 🔴 corn yield by %5.3 2- ⚫ N_2O emission (%23.8), leaching (%27.1) and ⚫ NH_3 volatilization (%39.4)	(Zhang et al., 2019)
Crop Rotation	1- Wheat 🔴 yield and 🔴 soil quality 2- Potential mineral ⚫ N loss in soil	(Yang et al., 2024)
No-Tillage with Maize Mulch	No-till corn-wheat rotation system 🔴 mineral N	(Yang et al., 2023)
Protection of Agricultural Resources (Green Manure)	Green manuring application in the citrus catchment area ⚫ NO_3 leaching	(Luo et al., 2023)
Precision Farming Techniques (UAV)	Control of 🔴 N availability in the growing stages of rice plant using unmanned aerial vehicle (UAV)-based remote sensing method	(Zha et al.,2020)

🔴: high or increased, ⚫: low or less

6. Future Perspectives

The current research highlights significant efforts being directed at enhancing N management in agricultural practices in light of stress imparted by climate change, while it also highlights certain areas where such gaps exist. This should now be followed by research addressing precision agriculture, smart fertilization strategies, biotechnology-driven materials, and resource conservation techniques to offer sustainable farming and soil health with a more profound comprehension of the dynamics of N. Given the realizations above, a whole understanding of the complex interactions of climate change and soil systems is urgently needed, together with innovative approaches that minimize N losses. Future studies should be guided to address the following priorities:

1- Full-Spectrum Monitoring of N Cycle Microbial Processes: The development of climate-resilient N management practices needs to concentrate on the following continuum: "soil-plant-climate interaction-N cycle-greenhouse gas emissions-N use efficiency." Long-term laboratory and field studies monitoring microbial processes and mechanisms within the N cycle can give enormous insights into their impact on soil health and ecosystems. This will provide a sound scientific basis for sustainable agricultural practices.

2- Improvement of Precision Agriculture Through New Fertilization Methods: Some of the new precision agriculture methodologies, along with new types of fertilizers and inhibitors, might improve N management and mitigate N problems arising result from climate change. The full utilization of potential sustainable applications preserving soil stability, reducing the environmental impact of N, and addressing socio-economic issues shall aid in furthering the cause of agriculture.

3-Tapping into Advanced Technologies for Monitoring and Modeling: The integration of smart sensors with artificial intelligence (AI) has the potential to realize active monitoring of soil N dynamics impacted by climate change. Thus, an integrated monitoring system with data collection, predictive modeling, and real-time assessments will contribute to soil health, economic sustainability, and increased crop productivity. This approach will provide a comprehensive adaptive management strategy foundational to sustainable agriculture.

These strategic focuses will serve to fill key knowledge gaps and establish the foundation for effective approaches to N management that meet environmental and agricultural needs in a changing climate.

7. Conclusion

In fact, faced with the effects of climate change, effective N management is important in terms of soil health and sustainability of agriculture. Nitrogen represents the most vital plant nutrient, playing key roles in all kinds of biochemical reactions related to photosynthesis and synthesis of amino acids. Nitrogen has proved to be one of the most essential elements for improving soil fertility and maintaining ecological balance. However, an increase in temperature and anomaly rainfall patterns are among the factors in climate change that affect N dynamics and the retention capacity of the soil for N. While the temperature fluctuations and changes in the amount of rainfall can directly affect the activity of soil microbes and processes of N transformation that can make N more mobile in the soil, the increased mobility of NO_3^- can result in its leaching to the groundwater, contamination thereof, and emissions of such greenhouse gases as N_2O and NO into the atmosphere, contributing to the aggravation of atmospheric pollution. Simultaneously, new methods of N management provide important solutions for "softening" negative impacts of climate change while maintaining agricultural productivity and preserving soil health. Key approaches include precision agriculture techniques, for example the use of slow-release and inhibitor-enriched fertilizers, green manuring, efficient irrigation management, and minimal resource-conserving tillage. Advanced sensors and remote sensing technologies are employed in precision agriculture techniques for monitoring soil and plant N levels and for real-time and site-specific fertilizer management. This, in turn, allows more accurate prediction of crop N requirements and controlled applications that can enhance both efficiency and effectiveness of N use. Application of slow-release fertilizers and nitrification inhibitors has the potential for controlled release of N when compared to conventional types of fertilizers. This will finally reduce nitrogen leaching and volatilization, besides leading to better long-term availability of N within the soil. The other conservationist method involves green manuring that increases the organic matter content in the soil and helps in the improvement of the soil structure, thus allowing the natural buildup of N within the soil. Effective irrigation management can optimize water use in agricultural production, ensuring that N movement within the soil is managed and hence improving the N use efficiency. Reduced or no-till farming and crop rotation support the structure of the soil, reduces erosion, and protects against N losses.

Given the complex feedback and interactions between climate change and N dynamics, various innovative strategies in N management and conservation-oriented practices have emerged. The list includes precision agriculture, slow-release fertilizers and inhibitors, green manuring, efficient irrigation management, and reduced tillage. Application of these technologies tends to enhance agricultural productivity with minimum loss of N for ecosystem sustainability. These are integrated approaches to soil health, predicated on the long-term aim of conservation and probably the better way for the balance of agricultural production in the future with ecological stability.

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CHAPTER 8

BENEFITS OF MYCORRHIZAL FUNGI IN SUNFLOWER CULTIVATION UNDER CLIMATE CHANGE SCENARIOS

PhD Candidate Suat CUN[1]*

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[1] Harran University, Faculty of Agriculture, Department of Field Crops, Sanliurfa, Turkey, e-mail: suatcun@harran.edu.tr, https://orcid.org/0000-0001-6607-8263
*Corresponding Author: suatcun@harran.edu.tr

1. Introductıon

Sunflowers (*Helianthus annuus* L.) represent the fourth most significant oilseed crop globally, valued particularly for their high drought tolerance, making them a prime choice for production in semi-arid regions (Vilvelt et al., 2018). A critical challenge facing modern agriculture is the reduction in crop productivity due to environmental changes, particularly those exacerbated by climate change. The increasing frequency and severity of extreme weather events—droughts, blizzards, floods, heatwaves, and cyclones, among others—have brought drastic shifts in ecosystems, which, in turn, place significant stress on plant health. This shift contributes to annual crop losses valued in millions of euros, with potential production losses estimated at approximately 50% per year (Eisenach, 2019; IPCC et al., 2014).

Recent research highlights the potential of soil microorganisms in bolstering crop productivity in a sustainable manner. These organisms, by enhancing nutrient availability and reducing reliance on synthetic fertilizers, offer resilience against various stress factors such as pests and diseases. A prominent example is arbuscular mycorrhizal fungi (AMF), commonly referred to as biofertilizers due to their natural symbiosis with plant roots (Begum et al., 2019; Kuila & Ghosh, 2022). Despite extensive studies on AMF, a comprehensive synthesis detailing the responses of various mycorrhizal fungi groups to climate factors remains limited. Like all organisms, AMF exhibit distinctive traits that govern their response to climate change pressures (Treseder & Lennon, 2015). AMF are poised to influence plant distribution and productivity and are anticipated to play a crucial role in ecosystem responses to, or mitigation of, climate impacts (Classen et al., 2015).

Several studies have illustrated that AMF inoculation enhances resilience against abiotic stressors like drought, heat, salinity, and extreme temperatures. This resilience is achieved through AMF's facilitation of tolerance mechanisms in host plants while simultaneously preventing the downregulation of critical metabolic pathways (Oliveira et al., 2022; Qin et al., 2021; Nanjareddy et al., 2017). In addition to these functions, AMF also supply vital inorganic nutrients to host plants, promoting enhanced growth and yield under both optimal and stress-laden conditions (Begum et al., 2019).

Climate change can indirectly impact AMF by altering soil properties and affecting the composition of neighboring microbial communities. Key soil elements such as nitrogen, phosphorus, potassium, and carbon, along with pH levels, are subject to shifts induced by changes in temperature, precipitation, and atmospheric composition (Cotton, 2018). These alterations can also affect root exudates, which are modified by environmental stress factors, influencing the interactions between AMF and other soil microorganisms. Such interactions are vital for maintaining functional diversity in agricultural soils, which has significant implications for soil health and crop resilience (Goss, 2017).

2. Mycorrhizal Fungi (AMF) and Their Effects on Agricultural Production

Arbuscular mycorrhizal fungi (AMF) are symbiotic organisms that form a close relationship with their host plants through specialized fungal structures known as arbuscules in the root cortex cells (Rillig et al., 2002). These fungi are believed to have co-evolved with their host plants since the Ordovician period, over 430 million years ago, when plants began to colonize land (Strullu-Derrien et al., 2018). Around 80% of terrestrial plant species are in mutualistic associations with AMF, benefiting from improved nutrient uptake, increased biomass and productivity, and enhanced tolerance to abiotic stresses like drought and soil salinity (Yang et al., 2023; Sheteiwy et al., 2023).

AMF play a vital role in improving soil structure, stability, and function by promoting growth and increasing biomass through their host plants' root systems. One of the ways they achieve this is by producing glomalin, a glycoprotein that binds soil particles and helps form microaggregates (Pohanka and Vlcek, 2020). In addition, the branched networks of AMF mycelium extend through the soil, producing exploration hyphae that help them discover new areas (Lu et al., 2018). This process allows the hyphae to encircle and stabilize microaggregates, promoting the formation of larger, more stable macroaggregates and contributing to soil erosion control by wind and water (Wilkes et al., 2021). However, land management practices can either preserve or disrupt the mycorrhizal networks, their symbiotic interactions with plants, and their positive effects on soil properties (Jiang et al., 2011).

AMF, along with other soil microorganisms, play a critical role in helping plants cope with drought stress. Although the interactions between plants and microbes under drought conditions are not yet fully understood, ongoing research is focused on this area. Some studies have demonstrated that

AMF mycelial networks, which often extend through soil pores not explored by the plant roots, can help increase water absorption and transport water to the host plant (Liu et al., 2018; Li et al., 2019). Furthermore, research by Duc et al. (2018) and Augé et al. (2014) has shown that an increase in stomatal conductance leads to higher transpiration rates, pulling more water from AMF networks into the plant, which helps mitigate the impacts of drought on crop yields.

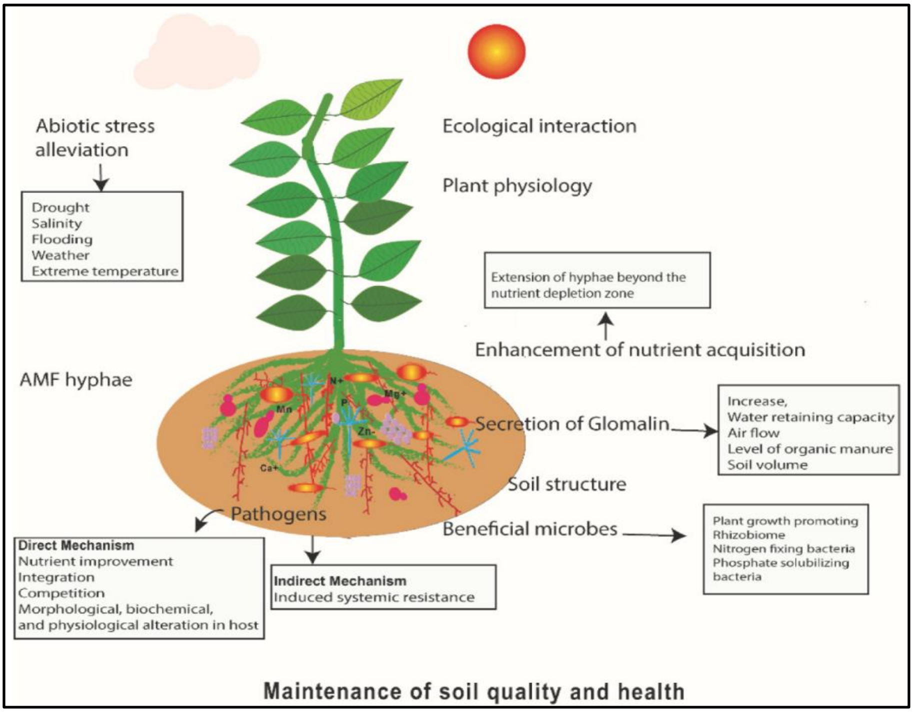

Figure 1. Mechanisms for preserving soil quality and health with AMF to enhance plant productivity (Kalamulla et al., 2022).

Crops can adapt to or withstand drought stress through a mutualistic association with arbuscular mycorrhizal (AM) fungi (Oyewole et al., 2017). AM fungi, in exchange for carbohydrates derived from photosynthesis, improve the absorption of vital nutrients, notably nitrogen and phosphorus, and enhance plant resilience to both biotic and abiotic stressors (Li et al., 2013). This enhancement occurs through mechanisms that either directly boost plant metabolism (Langeroodi et al., 2020) or modify the rhizosphere environment

(Gianinazzi et al., 2010). Insight into these mechanisms highlights the potential of AM fungi as a resource for promoting plant growth, particularly in drought-prone regions or under limited irrigation conditions (Gholamhoseini et al., 2013). Moreover, the ecosystem services provided by AM fungi can reduce dependence on synthetic fertilizers (Langeroodi et al., 2020), making them well-suited for integration with sustainable agricultural practices.

3. The Importance of Mycorrhiza Under Changing Climate Conditions

Salt and drought are among the most frequent and intense abiotic stresses that ecosystems face. These conditions adversely affect various physiological and biochemical processes, ultimately hindering plant growth and development (Boutasknit et al., 2020). The use of beneficial soil microorganisms is recognized as one of the most effective strategies for promoting sustainable agriculture and environmental health (Vimal et al., 2017). Several studies emphasize the role of soil microbes in enhancing plant nutrition and growth under stressful conditions (Paymaneh et al., 2019). One of the key soil microorganisms that form beneficial symbiotic relationships with plants is arbuscular mycorrhizal fungi (AMF).

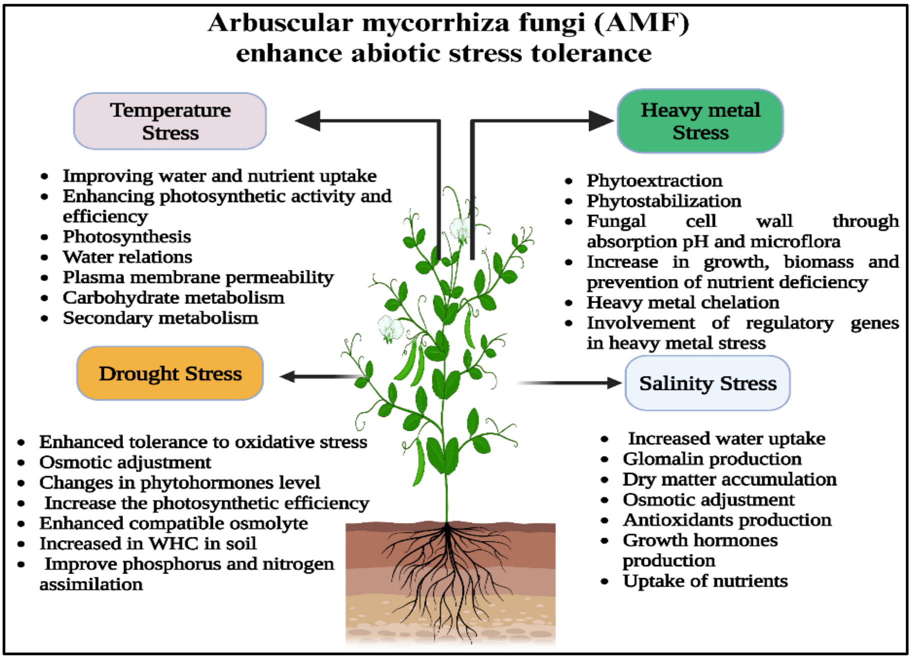

Figure 2. A schematic illustration of the various mechanisms through which arbuscular mycorrhizal fungi (AMF) improve plant tolerance to abiotic stresses (Wahab et al., 2023).

Mycorrhizae play a pivotal role in ecosystem restoration and biodiversity conservation (Pepe et al., 2020). Arbuscular mycorrhizal fungi (AMF) establish symbiotic relationships with plants by colonizing their roots, completing their life cycle using carbon supplied by the host plant. In return, the plant receives enhanced access to nutrients and water acquired by AMF, resulting in a mutually advantageous symbiosis (Mitra et al., 2021). Studies demonstrate that AMF can improve plant resilience to salt and drought stress by supporting growth, maintaining ion balance, activating antioxidant enzymes, triggering hormonal signaling, and enhancing photosynthetic efficiency (Huang et al., 2020; Junli et al., 2020). Through close interaction with plant roots, AMF extend nutrient transfer networks, sometimes reaching several centimeters beyond the root zone, in dense mycelial structures (Ma et al., 2021). These networks function as conduits, delivering nutrients like nitrogen and phosphorus to the host plant, which in turn fosters growth and biomass production (Liu et al., 2023).

4. The Impact of Climate Change on Sunflower Cultivation

Sunflower, from an agricultural perspective, is widely cultivated under drought conditions due to its capacity to withstand water scarcity. Additionally, it possesses a higher drought tolerance compared to other crops, owing to its early planting, short growth cycle, and deep root system (Hussain et al., 2018). As a rain-fed plant, sunflower exhibits tolerance to water stress by presenting a highly investigational root system (Sadras et al., 1991). Although the molecular mechanisms underlying this tolerance remain unclear, recent studies have reported increased expression of genes associated with photosynthesis under water stress conditions, alongside higher levels of sugars, osmoprotective amino acids, and ionic nutrients in sunflower plants (Moschen et al., 2017). Despite its drought tolerance, water remains crucial for sunflower growth, particularly during the flowering and seed-filling stages (Rondanini et al., 2006).

Due to its ability to grow in various environments and its moderate tolerance to drought (and salinity), sunflower could become one of the preferred oilseed crops in the future, especially when considering global climate change (Miladinović et al., 2019). Seiler et al. (2017) suggested that sunflower's survival capacity in diverse agricultural ecological environments makes it a promising industrial crop for the future. García-Vila et al. (2012) emphasized that future preference for sunflower is closely linked to its adaptation to climatic diversity. Although sunflower is considered to have moderate tolerance to both drought and salinity, it is necessary to investigate the performance of various sunflower genetic lines under different water management and salinity conditions. This research is essential for predicting yield productivity and input-output analyses under diverse climatic and soil conditions, particularly given the adverse impacts of climate change on agricultural productivity.

5. The Interaction of Mycorrhizal Fungi with Sunflower Roots

Research on the mycorrhizal status of sunflowers remains limited, with most studies focusing on growth responses and phosphorus uptake (Thompson, 1987; Chandrashekara et al., 1995), or their ability to tolerate heavy metals (Ultra et al., 2007; Ker & Charest, 2010). As far as we know, there is no available data on the variation in AM fungal root colonization across different sunflower genotypes (Turrini et al., 2016).

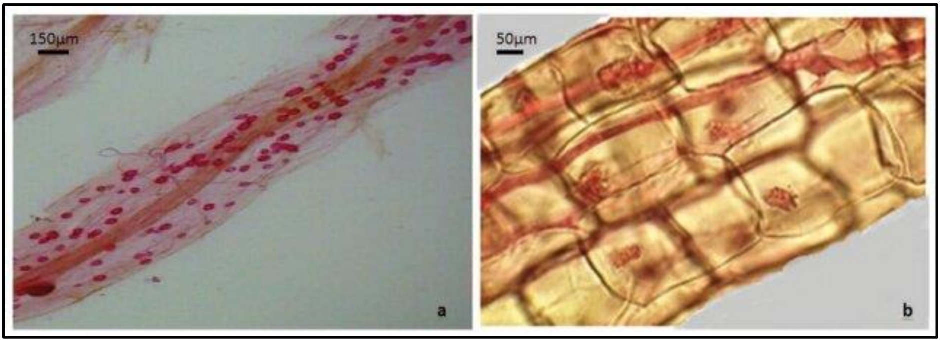

Figure 3. Microscopic images of AMF root colonization in sunflower (İbrahim, 2019).

The AMF mixture enhances both mycorrhizal dependency and the success of mycorrhizal inoculation in sunflowers, indicating its potential as an effective inoculant to support sunflower growth and yield in sustainable agricultural practices (Ibrahim, 2019). Combining AM fungi with biochar is also recommended as a water-saving approach for sustainable sunflower cultivation in semi-arid areas. Further investigation is needed to understand the broader impact of these treatments on different crops and environmental conditions. Ramasamy et al. (2011) observed that mycorrhizal colonization significantly increased in sunflower roots of AMF-inoculated plants, leading to a decrease in infection sites. This decrease is attributed to competition for nutrients and spatial resources between AMF and pathogens, which ultimately protects root tissues from pathogenic invasion. Abobaker et al. (2018) proposed that the symbiotic relationship between sunflower roots and AMF may moderately enhance leaf chlorophyll levels, particularly in nutrient-deficient conditions, thereby fostering plant growth. This improvement likely results from the lower nutrient concentrations in certain fertilizers or their constituents, as well as the type of application—whether applied alone or in combination.

In a related study, Yadav et al. (2015) showed that AM fungal inoculation increased both AM colonization and spore counts, which subsequently enhanced nutrient uptake, especially of phosphorus (P), and optimized soil rhizosphere conditions by producing plant growth hormones and altering the sunflower's physiological and biochemical traits. Additionally, Ibrahim (2018) highlighted the role of native AMF under semi-arid conditions as a biofertilizer that improved the seed quality of a confectionery-type sunflower crop. The native AMF effectively colonized sunflower roots and outperformed treatments without AMF by promoting better plant growth. The native AMF mixture (G. viscosum, G. intraradices, and G. mosseae) yielded sunflower seeds with higher N, P, and protein content compared to a single-species inoculum (G. viscosum). Consequently, this mixed AMF inoculum proved more effective than a single-species application, supporting its suitability for sustainably producing nutrient-dense, high-quality seeds in sunflower cultivation under semi-arid conditions.

6. The Effect of Mycorrhiza on Nutrient Uptake in Sunflower

The colonization of plant roots by arbuscular mycorrhizal fungi (AMF) is essential for enhancing plant growth, as it boosts the absorption of immobile nutrients, especially phosphorus (P) and zinc (Zn) (Fernandez et al., 2009). Sunflower serves as an exemplary plant model for exploring this interaction. Numerous studies have shown that AMF inoculation in sunflowers significantly raises spore density, root colonization rates, total plant dry biomass, flowering onset, and phosphorus concentration in plant tissues during maturation (Chandrashekara et al., 1995). Koide (1985) reported that lower phosphorus levels encourage greater AMF colonization, resulting in an increased leaf area relative to non-colonized plants, whereas high soil phosphorus concentrations tend to reduce AMF colonization. Although inorganic fertilizers can produce comparable results, sustainable alternatives are often preferred. A similar reduction in AMF colonization has been observed in soils with high nitrogen (N) content.

Research indicates that elevated phosphorus levels from chemical fertilizers can reduce AMF colonization and weaken the symbiotic relationship between AMF and their host plants (Johnson, 2010). Nitrogen-rich fertilizers also indirectly influence the formation and mutual benefits of AMF symbioses. Mäder et al. (2000) noted that intensive agricultural practices or nutrient enrichment with nitrogen and phosphorus reduce the mycorrhizal fungi’s nutrient absorption capabilities, thereby limiting their benefits. They further observed that host plants exposed to high nutrient levels often restrict or even cease providing resources to their fungal partners, leading to diminished mycorrhizal colonization. Additionally, Asad (2002) and Asad et al. (2003)

highlighted that sunflowers are highly sensitive to low boron (B) levels, which negatively impact vegetative growth and reproductive organ development. McIlrath and Skok (1964) found that boron-fertilized sunflowers showed notable increases in plant height and internode length compared to unfertilized control plants. Furthermore, Farokhi et al. (2014) observed that boron supplementation enlarged sunflower head diameter. Additional studies are needed to clarify whether increased sunflower productivity at varying nitrogen levels is linked to improved boron nutrition.

Conclusıon

The impacts of climate change pose significant challenges for sensitive agricultural crops, such as sunflower. Rising temperatures, irregular rainfall, water scarcity, and disruptions in nutrient cycling in the soil adversely affect the growth cycle and yield of sunflower plants. These challenging conditions highlight the need for strategies that enhance plant stress tolerance. In this context, mycorrhizal fungi play a critical role in strengthening the adaptation of strategic crops like sunflower under climate change conditions.

Mycorrhizal fungi establish a symbiotic relationship with plant roots, supporting both water and nutrient uptake while enhancing soil fertility. Through this interaction, sunflower plants gain more efficient access to water and nutrients present in the soil. Particularly, the transfer of vital nutrients like phosphorus, which are crucial for growth, facilitates root development and, in turn, increases the plant's resilience to drought stress. The expanded root network formed by mycorrhiza supports water and mineral absorption, enabling the sunflower to continue growing even under drought conditions.

Moreover, mycorrhizal fungi strengthen stress management mechanisms in sunflowers. For instance, they reduce the harmful effects of oxidative stress, enhancing cellular resilience in plants. Mycorrhiza not only promotes better development of the plant's root system but also supports microbial diversity in the root zone, which offers critical benefits for plant health and the balance of soil ecosystems. This symbiotic relationship enhances the sunflower’s adaptation to challenging conditions caused by climate change, such as water scarcity, while promoting more sustainable and resilient agricultural practices.

In conclusion, the effects of mycorrhizal fungi on sunflower plants offer a promising solution for reducing crop loss and supporting plant health under climate change conditions. Sunflowers supported by mycorrhiza become more resilient to stresses like drought and nutrient deficiencies, while playing a significant role in sustaining sustainable agricultural practices.

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CHAPTER 9

THE POTENTIAL OF SOIL AMENDMENTS TO IMPROVE SOIL HEALTH

PhD Candidate Zemzem FIRAT[1*]

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[*1] Harran University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Sanliurfa, Turkey, e-mail: zemzemfirat63@gmail.com, https://orcid.org/0000-0003-4549-9389
*Corresponding Author: zemzemfirat63@gmail.com

1. Introductıon

Agriculture aims to harness the biological productivity of plant and animal populations in a structured and intentional way to supply society with both food and raw materials (Gürler, 2008). From the dawn of human history to the present, agriculture has remained a critical livelihood and a focal sector in the evolution of economic disciplines, maintaining its relevance through every era. Today, agriculture faces a dual challenge: addressing the urgent food needs of a rapidly growing population while ensuring the sustainability of ecosystem services such as carbon sequestration, nutrient cycling, and water regulation in soils (Foley et al., 2011).

One of the fundamental factors for sustaining agriculture is undoubtedly the preservation of soil health. Soil, a natural and dynamic layer covering the upper lithosphere, is formed through the decomposition of rocks and organic matter and serves as a habitat for life. It is composed of water, minerals, organic materials, and soluble salts and ions in variable proportions (Yildiztekin et al., 2019; Khomiakov, 2020; Yadav et al., 2021). Traditional agricultural practices, with their heavy reliance on fertilizers and pesticides, have contributed substantially to meeting global food demands but have also led to unintended negative consequences. These include soil degradation, reduced fertility, lowered crop yields, and compromised ecosystem health. Efforts to boost crop productivity have often relied on practices that, while effective in the short term, involve indiscriminate synthetic agrochemical inputs, unsustainable water use, and alterations to soil ecosystems, thereby gradually eroding the soil’s inherent properties and its self-renewal capacity (Bender et al., 2016). Soil fertility decline can be attributed to various physical limitations, such as surface crusting, subsurface compaction, reduced permeability, and erosion driven by wind and water (Thakur et al., 2023).

Nutrient cycling within the soil is crucial for supporting healthy crop growth (Prasad et al., 2021). Soil amendments can quickly boost certain components, such as organic carbon, but they also require additional nitrogen to support microbial decomposition, which is necessary to maintain a balanced carbon-to-nitrogen (C/N) ratio. Additionally, soil microorganisms play a key role in releasing mineral nutrients from amendments by breaking them down and recycling them, thereby enhancing nutrient availability for plants and improving soil fertility (Liu et al., 2023). Research has shown strong links between bacterial diversity and factors like soil organic carbon (SOC), total nitrogen (TN), and overall nutrient cycling in sandy and coastal wetland ecosystems (Liu et al., 2021). In the process of forest conversion, fungi may contribute more significantly than bacteria to nutrient cycling in the soil (Jin et al., 2019; Li et al., 2023).

2. Soil Health

Soil health is frequently defined as "the ongoing ability of soil to function as a dynamic, living ecosystem that supports plants, animals, and humans" (USDA, 2021). Alternatively, it can be described as "the capacity of soil to operate within ecosystem boundaries to maintain or enhance crop and livestock productivity, promote environmental sustainability, and improve global human health" (Yang et al., 2020). Another perspective identifies six key characteristics of healthy soil: (1) high biodiversity, (2) resilience to chemical and biological degradation with potential for self-repair, (3) the ability to maintain nutrient cycling and energy flow, (4) suppression of pests and pathogens, (5) the capacity to promote plant health, and (6) preservation of water and air quality (Wang & Hooks, 2011).

These definitions are conceptual in nature, aiming to outline the attributes of healthy soil rather than providing a direct method of measurement. On the other hand, operational definitions focus on identifying indicators of soil health. In assessing soil health, it is essential to consider its physical, chemical, and biological properties (Bünemann et al., 2018). Soil health depends on a delicate balance of biological, chemical and physical parameters, each of which affects the overall vitality and productivity of the soil ecosystem. Biological parameters include organism populations, microbial diversity and enzyme activity (Sakin et al., 2024). Ideally, these indicators should be relevant to the soil processes involved and responsive to changes in management practices and environmental conditions (Yang et al., 2020). There is no universal set of ideal soil characteristics, and their interpretation is always context-dependent (Fierer et al., 2021).

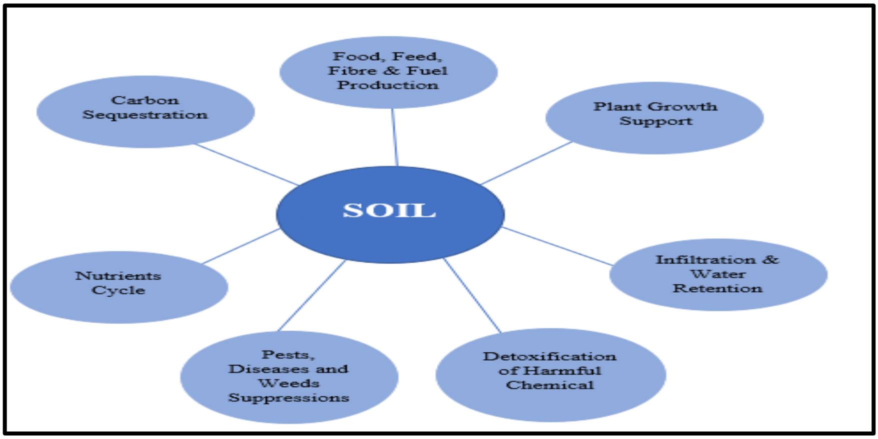


Figure 1. Core functions of soil (Moebius-Clune et al., 2016)

Understanding soil health is essential for promoting sustainable management practices in agricultural ecosystems. Soil health is a multifaceted, functional concept that cannot be directly measured in the field or laboratory. Instead, it is assessed indirectly by evaluating specific soil indicators (Mukherjee & Lal, 2014). These indicators are measurable characteristics of soil that affect its functioning and the ecosystem services it provides (Cherubin et al., 2016).

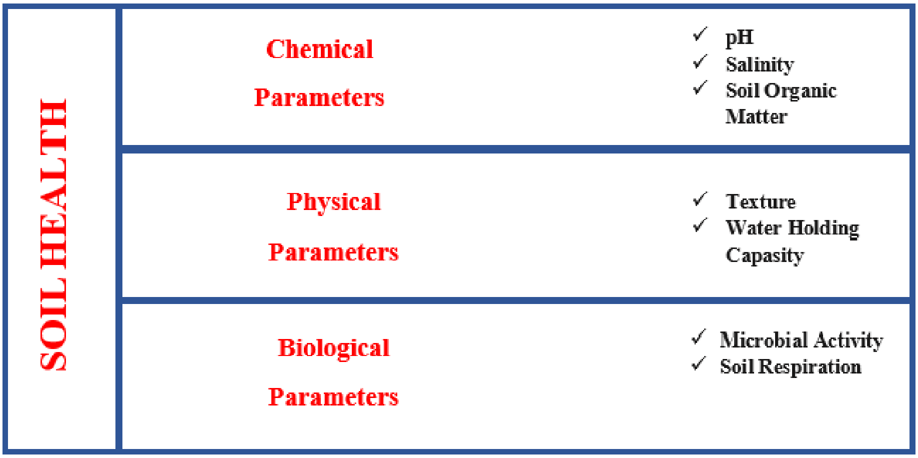
Soil health is influenced by a variety of factors, which can be categorized into physical, chemical, and biological components (Bünemann et al., 2018).

Physical components of soil: These refer to the soil's properties such as texture, structure, depth, and water retention capacity. Factors like aeration, infiltration rate, and drainage also impact root development and microbial activity.

Chemical components of soil: These include soil pH, electrical conductivity (EC), cation exchange capacity (CEC), and nutrient levels. Chemical properties affect nutrient availability, metal toxicity, and microbial processes.

Biological components of soil: This category encompasses the diversity and activity of soil microorganisms, as well as the presence of earthworms, nematodes, and other soil organisms, along with the content of organic matter.

Soil biota play an essential role in breaking down organic matter, cycling nutrients, and forming soil structure (Hendrix et al., 2020).



SOIL HEALTH	Chemical Parameters	✓ pH ✓ Salinity ✓ Soil Organic Matter
	Physical Parameters	✓ Texture ✓ Water Holding Capasity
	Biological Parameters	✓ Microbial Activity ✓ Soil Respiration

Figure 2. Soil Health Parameters

Healthy soils rich in organic matter and inhabited by diverse microbiota facilitate nutrient cycling, ensuring sufficient nutrient supply to crops. They also maintain good soil structure, which enhances water infiltration and root penetration, leading to improved water use efficiency and potentially higher crop yields. Beyond crop production, healthy soils provide a foundation for various ecosystem services: Water filtration and regulation—soils with good structure and high organic matter content serve as effective filters, purifying water and regulating its movement, thus reducing the risk of flooding and groundwater contamination (Timmis & Ramos, 2021).

3. Soil Degradation

The degradation of soil quality resulting from the loss of its physical, chemical, and biological properties is referred to as "soil degradation." Soil characteristics, which include the content of plant nutrients, water retention capacity, organic matter content, pH (acidity), depth of the upper soil layer, salinity, and the biomass in the soil, influence plant productivity. Significant changes in these characteristics are considered indicators of soil degradation (Scherr, 1999).

Soil degradation can be classified into three types: physical, chemical, and biological degradation. Examples of physical degradation include the deterioration of soil structure, reduced infiltration capacity, and loss of organic matter. Chemical degradation involves the disruption of the salt balance, alkalization, changes in pH, leaching, and the accumulation of certain elements such as aluminum (Al) and manganese (Mn) to toxic levels in the soil solution. Biological degradation is characterized by the proliferation of soil pathogens. Furthermore, the excessive presence of clay and sand in the soil can also contribute to soil-related issues (Göl and Dengiz, 2006).

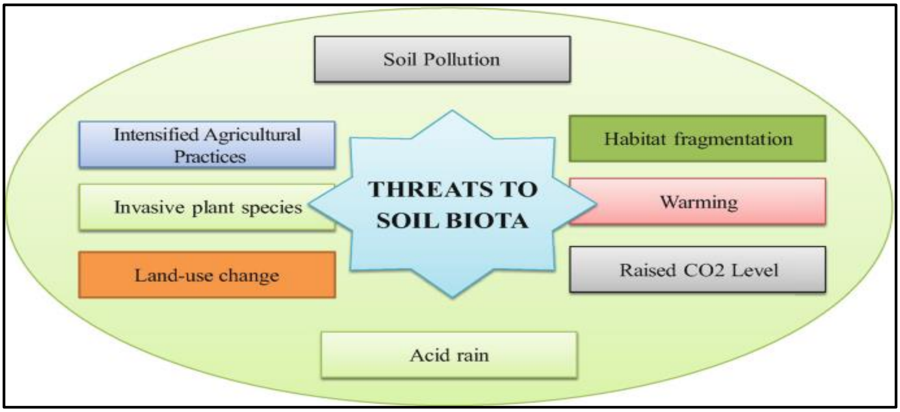


Figure 1. Threats to soil biota (Yatoo et al., 2020).

Degraded soils extend over approximately 6 billion hectares globally. As the world's population continues to grow, agricultural land is diminishing due to degradation. It is estimated that 30% of forests, 20% of agricultural land, and 10% of pastures are severely affected by land degradation (Ayub et al., 2020). Degraded soils are typically the result of intensive management, inadequate soil conservation measures, and the decline in soil fertility caused by climate change. Numerous studies have highlighted the detrimental effects of intensive annual crop farming on soil health. In fact, the growing interest in regenerative agriculture today (Giller et al., 2021) has made soil health restoration a central focus (Schreefel et al., 2020).

Several specific aspects of intensive annual crop production contribute to soil degradation, such as frequent disturbances like tillage, the lack of continuous vegetation cover throughout the year, the absence of deep-rooted plants, limited crop functional diversity, and nutrient imbalances. Furthermore, climate change, including global warming and altered rainfall patterns, has intensified or worsened soil degradation in regions increasingly prone to flooding and drought (Debonne, 2019). Erosion has been particularly severe, with up to 1% of the topsoil being lost annually in many areas (Montgomery, 2007). This erosion is driven by factors such as intensive tillage, overgrazing, and the growing frequency of extreme weather events, which accelerate both wind and water erosion.

Figure 4. Images of degraded soils

4. Soil Amendments for the Restoration of Degraded Soils

Soil conditioners are substances used to improve soil properties and boost crop productivity. Their primary objectives include improving soil conditions by enhancing nutrient and water availability for plants, reducing soil moisture loss, supporting high microbial activity, and facilitating efficient nutrient uptake by plants (Tu et al., 2006; Tejada et al., 2009; Xu et al., 2015; El-Alsayed & Ismail, 2017; De Oliveira et al., 2018). Additionally, soil conditioners contribute to soil structure enhancement by stabilizing soil aggregates, modifying soil bulk density, and optimizing the air-water balance within the soil (Tejada et al., 2009; El-Alsayed & Ismail, 2017; Manirakiza & Sęker, 2020). The environmental advantages of natural soil conditioners are also significant. These materials assist in improving ecosystem health by reducing soil toxicity, restricting heavy metal mobility, preventing fertilizers and pollutants from leaching into water bodies and plant tissues, lowering soil salinity, regulating soil pH, increasing CO2 storage in soil, and decreasing greenhouse gas emissions (Oster, 1982; Parmar et al., 2016; Sun et al., 2019; Bossolani et al., 2020).

The prolonged use of organic soil conditioners also supports carbon sequestration and enhances food security (Parmar et al., 2016). Furthermore, both the quantity and quality of organic conditioners are vital factors influencing microbial biomass in the soil (Tu et al., 2006). A related study found that microbial biomass carbon content in soils enriched with compost at a rate of 80 Mg ha^{-1} year^{-1} was 33% greater compared to soils treated with 20 Mg ha^{-1} year^{-1} (García-Gil et al., 2000).

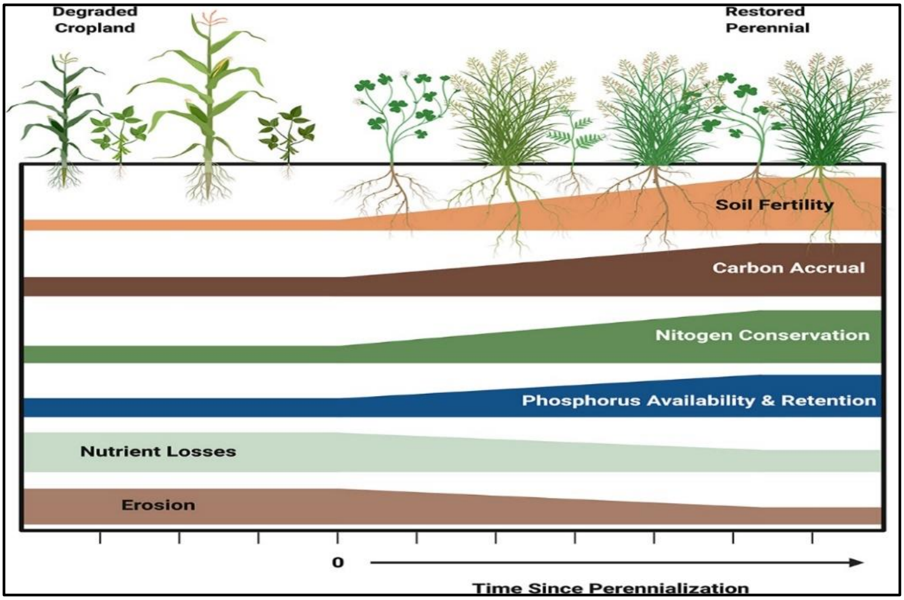


Figure 5. Patterns of key agronomic and biogeochemical process changes during the restoration of soil fertility via perennialization of degraded cropland (Mosier et al., 2021).

5. The Importance and Role of Soil Amendments

- Soil conditioners play a critical role in regulating soil pH, particularly in challenging soils such as acidic or alkaline ones.
- They enhance the physical, chemical, and biological properties of the soil.
- They support soil aeration, water retention capacity, root development, and the maintenance of a healthy soil ecosystem.

- By attracting beneficial microorganisms and earthworms that contribute to soil health, they create an optimal soil environment.
- Soil conditioners can be used to revitalize infertile soils and rehabilitate soils damaged by improper management.
- They contribute to nutrient enrichment, replenishing essential elements needed for plant growth, thereby promoting healthier and more productive plant development.
- They help prevent soil compaction by reducing the formation of hard layers and alleviating compaction that occurs over time.
- By enhancing soil fertility, they help maintain soils at optimal health and functional levels (Thakur et al., 2023).

6. Soil Amendments

Soil conditioners are specialized materials that contain essential nutrients for plants. These materials improve the physical, chemical, and biological properties of the soil, making it suitable for plant growth and addressing various soil-related issues. They can be derived from natural sources such as plants and microorganisms, or from synthetic materials like polymers and industrial waste products. Soil conditioners enhance soil structure, providing a conducive environment for healthy plant growth. By addressing nutrient deficiencies in the soil, they promote plant vitality and growth. Some commonly used soil conditioners include compost, farmyard manure, green manure, peat moss, humates, gypsum, fly ash, and lime (Thakur et al., 2023). Soil conditioners are classified into two main categories based on their composition: organic and inorganic soil conditioners.

7. Organic Soil Amendments

Organic soil conditioners are used to enhance water infiltration and retention, promote soil aggregation, boost microbial activity, and increase the soil's resistance to compaction and its ability to bind with organic matter (SOM) (Shinde et al., 2019; Karamina and Fikrinda, 2020). Examples of organic conditioners include materials such as crop residues, fertilizers, peat, biochar, bone meal, blood meal, coffee grounds, compost tea, coconut coir, sewage sludge, farmyard manure, and sawdust.

Figure 6. Images of organic soil amendments

8. Inorganic Soil Amendments

Inorganic soil conditioners are substances, either natural or synthetic, derived from mining or industrial processes, that are used to improve the physical properties of soil, thereby enhancing the effective use of soil and water resources (Shinde et al., 2019). Examples of inorganic conditioners include gypsum, lime, limestone, pyrite, crushed rocks, fly ash, sulfur, zeolites, dolomite, and phosphogypsum. These materials are often applied to modify soil acidity and improve soil quality, as they are rich in elements such as Si, Ca, K, and Mg, particularly in alkaline soils (Yang et al., 2020).

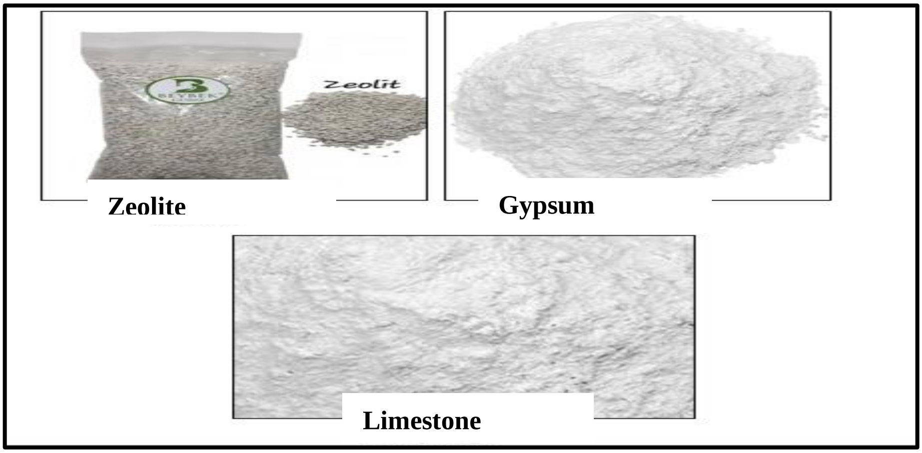


Figure 7. Images of ınorganic soil amendments

9. The Effects of Soil Amendments on the Physical Properties of Soil

Both organic and inorganic soil conditioners influence the physical properties of soil, supporting chemical and biological factors that enhance soil health. Organic conditioners, in particular, improve soil structure, promote better aggregation, increase water retention, help maintain optimal soil temperatures, reduce bulk density, and enhance porosity, all of which favor root development and nutrient uptake. Furthermore, organic conditioners boost microbial activity, and the release of exopolysaccharides contributes to better soil structure, while compounds such as hyphae enhance soil aggregation and stability (Yazdanpanah et al., 2016).

10. The Effects of Soil Amendments on the Chemical Properties of Soil

The application of organic fertilizers, such as farmyard manure, compost, vermicompost, and green manures, alongside chemical fertilizers, plays a crucial role in enhancing soil health. Adding organic fertilizers to the soil promotes carbon accumulation, which, over time, boosts the organic carbon content in the soil, thus supporting the sustainability of cropping systems. Organic fertilizers, like farmyard manure and compost, help maintain higher levels of soil organic carbon compared to mineral fertilizers. These fertilizers influence soil pH and cation exchange capacity, indirectly affecting the bioavailability of essential nutrients and directly impacting soil fertility (Abbott et al., 2018). The composition and maturity of soil fertilizers have a significant impact on soil reactions. Fertilizers high in calcium or basic cations can cause a 'liming effect,' raising soil pH (Mijangos et al., 2010). Supporting this, a study found that biochar, a common organic soil conditioner, directly increased soil pH and organic matter content, while also reducing bulk density and extractable salt content, thereby enhancing nitrate availability (Roberts et al., 2015; Ghosh et al., 2020; Das et al., 2021). As a result, liming can enhance soil microbial activity and diversity in acidic soils. In contrast, some organic fertilizers may lower soil pH, primarily due to the release of humic acids during the degradation of the carbon pool and the nitrification of ammonium in the fertilizer (Antolin et al., 2005).

11. The Effects of Soil Amendments on the Biological Properties of Soil

Soil organisms are vital for enhancing nutrient availability through processes like mineralization, immobilization, and nutrient cycling, making them key to maintaining soil health (Kumawat et al., 2021). The addition of organic conditioners improves biological soil properties by stimulating microbial growth, energy production, and nutrient availability, which in turn supports plant growth and development. These conditioners also promote biodiversity, leading to functional changes that enhance plant growth and suppress diseases. Furthermore, increased structural and functional biodiversity strengthens the soil ecosystem, increasing its resilience to both natural and human-induced stresses (Kumar et al., 2014).

Soil enzyme activity serves as an indicator of microbial health and is sensitive to various factors, such as climate, soil moisture, temperature, soil properties, and crop management practices. However, chemical degradation of soils, such as salinization and alkalization, hampers biological processes like mineralization, enzyme activity, and microbial biomass carbon and nitrogen, thereby reducing crop productivity. Consequently, applying organic amendments—such as green manures, crop residues, farmyard manure, compost, and vermicompost—emerges as one of the most effective management strategies for degraded soils (Leogrande and Vitti, 2019).

The structural and functional diversity of soil organisms, including bacterial richness, can be improved by adding organic amendments to the soil (Aparna et al., 2014). Thus, these organic changes enhance biological soil properties, supporting soil health and ensuring the sustainability of crop production (Sulok et al., 2021).

Conclusion

Soil conditioners are essential tools that support the sustainability of agricultural production and contribute to the conservation of natural resources. These conditioners directly enhance soil health in several ways, such as improving soil structure, increasing water retention capacity, making nutrient elements more available for soil use, and enriching the soil microbiota. Additionally, soil conditioners provide long-term benefits, including increasing organic matter levels, reducing erosion risks, and enhancing carbon storage capacity. In these respects, soil conditioners offer both environmentally friendly and sustainable solutions to global issues such as climate change and environmental degradation.

However, several factors influence the effectiveness of soil conditioners. Variables such as the type of soil conditioner applied, dosage, regional climate conditions, soil type, and plant species directly determine the impact of these conditioners. Therefore, to ensure the optimal use of soil conditioners, application protocols tailored to the needs of each region and plant species must be developed. Regular measurement and monitoring of soil health indicators such as pH, organic matter content, and microorganism populations will provide clearer long-term assessments of the effects of conditioners.

For the broader adoption of soil conditioners in agricultural production, it is crucial for local authorities, scientists, and farmers to collaborate. Educating farmers about the benefits of these conditioners, implementing incentivizing policies, and facilitating access to conditioners will be significant steps toward improving soil health. Additionally, more scientific studies are needed to explore the long-term effects of organic and inorganic soil conditioners in agricultural systems. This research will provide broader knowledge on their environmental impacts, economic sustainability, and practical applicability, enabling the development of evidence-based strategies for effective use.

In conclusion, the effective and proper use of soil conditioners holds great potential for enhancing agricultural productivity and preserving ecosystem health. The correct application of these conditioners will maintain the natural balance of the soil, ensuring the sustainability of future agricultural production processes. Particularly in the face of the negative impacts of climate change, soil conditioners play a vital role in strengthening ecosystems and enabling agriculture to adapt to climate change. Therefore, the increasing use of soil conditioners in the future will make it possible to maintain both agricultural sustainability and environmental balance.

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CHAPTER 10

PRESERVING SOIL HEALTH AND ENHANCING PRODUCTIVITY THROUGH ORGANIC MATTER MANAGEMENT

Res. Asst. Dr. Ferhat UĞURLAR[1*]

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[1] Harran University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Sanliurfa, Türkiye. ORCID: 0000-0002-3663-3497, E-mail:ferhatugurlar@gmail.com
*Corresponding Author: ferhatugurlar@gmail.com

1. Introduction

Soil is the fundamental building block of the life cycle of living organisms and is the most critical natural resource for the sustainability of agricultural production. However, factors such as increasing population pressure, intensive agricultural practices, and environmental alterations are posing an ever-greater threat to land vitality (Seleiman et al., 2021). To preserve soil productivity in the long term, a holistic approach to soil management is essential to secure both economic and ecological sustainability. In this context, biological soil components management lies at the core of strategies for maintaining land vitality and enhancing productivity.

Soil biological soil components is a component that plays a crucial role throughout the plant growth cycle and directly affects the soil's physical, chemical, and biological properties (Hoffland et al., 2020; Voltr et al., 2021; Gerke, 2022). Organic matter acts as a carbon reservoir within the soil, serves as an energy source for microorganisms, and increases the soil's moisture conservation capacity, helping plants become more resilient during droughts (Navarro-Pedreño et al., 2021; Elbasiouny et al., 2022). Additionally, by contributing to soil structure improvement, it reduces soil displacement risks and supports root development. Nevertheless, many agricultural lands today are impoverished in terms of biological soil components content, leading to both productivity loss and soil degradation (Hossain et al., 2020).

Traditional farming practices, improper irrigation, and excessive use of chemical fertilizers have contributed to reduced biological soil components levels, causing soils to become less fertile over time (FAO, 2015). Therefore, implementing effective biological soil components management strategies is a critical necessity to maintain land vitality and increase productivity. These strategies not only support sustainable agricultural practices but also play an important role in preventing environmental degradation.

Organic matter management maintains land vitality, improves plants’ access to essential nutrients, increases the soil’s water-holding capacity, and supports soil microorganism activities, thus promoting biodiversity within agricultural ecosystems (Rahman et al., 2020). Practices aimed at increasing biological soil components, such as decomposed organic material application, cover crop incorporation, residue management, and the use of organic fertilizers, enhance soil productivity and lay the foundation for eco-conscious farming (Bhat et al., 2021;

Meena et al., 2023; Panday et al., 2024). These methods not only ensure the long-term productivity of agricultural lands but also reduce dependency on chemical fertilizers.

2. Effects of Organic Matter on Soil Properties

Organic matter in soil is a critical component for farming output and sustainability. Formed through both natural processes and human activities, biological soil components provides diverse benefits to soil structure (Hoffland et al., 2020). While enhancing land vitality, it also facilitates plant access to essential nutrients and contributes to the sustainability of soil biota (Lehmann and Kleber, 2015). These effects are essential for soil management and sustainable agricultural practices. The impact of biological soil components on soil should be examined across physical, chemical, and biological dimensions (Voltr et al., 2021).

2.1. Effects on the Physical Structure of Soil

The physical structure of soil is a crucial parameter for agricultural production, and biological soil components plays a beneficial role in improving this structure (Voltr et al., 2021). Organic matter enhances soil aggregate formation by creating bridges between soil particles, thus strengthening the aggregate structure (Sarker et al., 2022). Soil aggregates improve soil aeration and increase water-holding capacity, while also enhancing resistance to soil displacement. Erosion is one of the most significant threats to the productivity of agricultural lands, especially in semi-arid, soil displacement-prone regions (Quinton and Fiener, 2024). Increasing biological soil components content in such areas significantly reduces soil displacement risk by stabilizing the soil structure (Smith et al., 2022).

Organic matter strengthens soil aggregate stability, allowing plant roots to penetrate the soil more easily. Strong root development allows plants to use water and nutrients more efficiently (van der Bom et al., 2020). Compacted soils, in particular, tend to convert rainwater rapidly into surface runoff, while soils rich in biological soil components minimize this issue by enhancing water infiltration, thus preventing both water loss and soil displacement (Du et al., 2022).

2.2. Contributions to the Chemical Structure of Soil

One of the most important effects of biological soil components on soil is increasing the cation exchange capacity (CEC), thereby enhancing the soil's ability to store essential nutrients for plant growth (Bashir et al., 2021). CEC enables clay minerals and biological soil components within the soil to hold and release nutrients as needed. Soils rich in biological soil components retain nutrients for longer periods, providing a continuous nutrient source for plants (Coonan et al., 2020).

In addition, biological soil components plays a crucial role in regulating soil pH. The release of organic acids into the soil buffers pH, preventing extreme acidic or alkaline conditions (Adeleke et al., 2017). By stabilizing soil pH, biological soil components applications create optimal growth conditions for plants. Therefore, biological soil components is vital not only for soil fertility but also for maintaining the soil's chemical balance (Rastogi et al., 2023).

2.3. Supporting Microbial Activity and Soil Biota

The biological activity of soil is directly dependent on biological soil components. Soil microorganisms play essential roles in the decomposition of biological soil components (Wu et al., 2024). While biological soil components provides a source of energy and nutrients for the soil biota, microorganisms break down these organic compounds, releasing essential nutrients that plants require for growth (Michael, 2021). This fertility recycling is crucial for both healthy plant development and the continuity of the soil ecosystem.

The microbial biomass of soil increases in parallel with biological soil components levels. Soils rich in biological soil components host a more diverse and dense community of microorganisms (Murphy, 2015). This community establishes symbiotic relationships within the soil, enhancing nutrient uptake by plant roots (Das et al., 2022). Mycorrhizal fungi, for example, improve plant access to nutrients like phosphorus, which are otherwise difficult to absorb (Khaliq et al., 2022). In soils with low biological soil components content, microbial activity declines, negatively impacting the diversity and health of the soil biota (Bashir et al., 2021).

High microbial activity also helps suppress soil pathogens. Organic matter supports the proliferation of beneficial microorganisms, which in turn naturally inhibit the effects of pathogenic organisms, serving as a form of biological control

(Bonanomi et al., 2018). This reduces the need for chemical pesticides and promotes environmental sustainability (Ray et al., 2020; Suman et al., 2022).

2.4. Increasing Water-Holding Capacity

Organic matter enhances water-holding capacity, improving water management in agricultural production. Due to its hydrophilic properties, biological soil components allows water to be retained in the soil for longer periods (Hayes and Swift, 2020). This is especially important in arid and semi-arid regions where efficient use of water resources is crucial. Soils low in biological soil components lose water quickly after rainfall, while organic-rich soils retain water and deliver it gradually to plant roots (Ankenbauer and Loheide, 2017).

This capacity to hold water not only boosts farming output but also increases the chances of plant survival during drought periods (Seleiman et al., 2021). Additionally, the more homogeneous distribution of water within the soil profile enables plant roots to access water more easily. In contrast, a lack of biological soil components can lead to rapid water loss through drainage, resulting in stress for plants. Enhancing soil water-holding capacity through biological soil components applications has thus become essential for eco-conscious farming (Lal, 2020).

2.5. Carbon Sequestration and Combating Climate Change

Organic matter plays a vital role in combating global environmental alterations due to its carbon storage capacity. Soil acts as a carbon sink by capturing carbon dioxide from the atmosphere. Adding biological soil components to soil helps reduce the concentration of greenhouse gases in the atmosphere, mitigating the adverse effects of environmental alterations (Thangarajan et al., 2013). Through sustainable agricultural practices, effective biological soil components management increases soil's carbon storage capacity, thereby reducing the environmental footprint of agricultural lands.

Furthermore, soils rich in biological soil components are more resilient to extreme weather conditions brought on by environmental alterations. Despite fluctuations in temperature and precipitation, these soils retain water more effectively, enhance nutrient availability to plants, and sustain microbial activity. Organic matter management thus plays a key role not only in improving soil fertility but also in helping the agricultural sector adapt to environmental alterations (Bayu, 2020).

3. Organic Matter Management Strategies

Organic matter management is a crucial approach to maintaining land vitality and enhancing farming output. By employing effective strategies, the biological soil components content of soil can be enriched, leading to improved productivity and sustainability of agricultural lands in both the short and long term (Gerke, 2022). In this context, biological soil components management is a systematic process achieved through various techniques and applications. Below are some of the most common and effective biological soil components management strategies detailed (Stockmann et al., 2013).

3.1. Compost Application

Compost is one of the most widely used practices in biological soil components management. Produced through the controlled decomposition of plant and animal waste, decomposed organic material serves as a rich source of biological soil components for the soil. It improves soil structure, increases water-holding capacity, retains essential nutrients for longer periods, and promotes soil biota activity (Larney and Angers, 2012; Ramasamy et al., 2024). The decomposed organic materialing process relies on microorganisms to break down organic waste. For effective decomposed organic material production, it is essential to balance the carbon-to-nitrogen ratio, maintain adequate oxygen levels, and control moisture content. Compost is especially rich in macronutrients such as nitrogen, phosphorus, and potassium, providing an additional nutrient source for agricultural production (Bernal et al., 2009; Koc et al., 2021; Bellitürk et al., 2022). Furthermore, decomposed organic material helps reduce the need for chemical fertilizers, thereby minimizing adverse environmental impacts.

Regular use of decomposed organic material increases the soil's biological soil components content and helps control soil-borne pathogens. For this reason, decomposed organic material is regarded as an indispensable strategy in eco-conscious farming, essential for maintaining land vitality and productivity (Hettiarachchi et al., 2020).

3.2. Green Manuring

Green manuring is another widely used strategy in biological soil components management. This practice involves incorporating growing plants, particularly legumes, back into the soil to enrich it with biological soil components and nutrients. Once these plants reach maturity, they are plowed back into the soil, enhancing the soil's organic content and nutrient availability. Green manuring improves soil physical structure, reduces soil displacement risk, and boosts soil biota activity (Singh and Kumar, 2023).

The use of legumes is especially beneficial for increasing soil nitrogen content, as these plants host symbiotic bacteria in their roots that convert atmospheric nitrogen into a form usable by plants. Green manure crops also help control weeds by covering the soil during their growth cycle, thus promoting biological soil components accumulation on the soil surface. The regular application of green manure supports long-term productivity in agricultural lands (Melander et al., 2020).

This strategy is particularly valuable in ecological farming practices, as it reduces the need for chemical fertilizers and pesticides. Green manuring also ensures the sustainable use of agricultural lands, allowing continuous renewal of soil biological soil components content (Baiyeri and Olajide, 2023).

3.3. Stubble Management

Stubble management is a method that involves returning post-harvest agricultural residues to the soil. When remnants such as roots and stalks of harvested plants are left as biological soil components, they contribute to improving soil structure. In conventional agriculture, stubble burning is a common practice, but it leads to a rapid loss of soil biological soil components and decreases soil fertility. Through stubble management, however, these residues are left to decompose in the soil, thus increasing biological soil components levels (Pradhan et al., 2024).

Incorporating stubble residues into the soil provides a nutrient source for soil microorganisms, boosting biological activity. Additionally, stubble left on the soil surface helps prevent water runoff after rainfall, promoting moisture conservation within the soil and helping prevent soil displacement (Wang et al., 2017). This practice supports improved water management and reduces soil soil displacement.

Incorporating stubble into the soil also helps prevent compaction, promoting a looser soil structure. This enables plant roots to penetrate more deeply, enhancing their access to water and nutrients. Thus, stubble management not only maintains soil biological soil components levels but also sustainably enhances soil fertility (Gerke, 2022).

3.4. Mulching

Mulching is an essential technique in biological soil components management, involving the placement of a layer of organic material on the soil surface. Mulch conserves soil moisture, gradually integrates into the soil as biological soil components, and improves land vitality over time. By moderating temperature fluctuations on the soil surface, mulching creates a more favorable microclimate around plant root zones (Mangani et al., 2022).

This practice is particularly effective in arid climates for reducing water loss and preserving soil moisture. Mulching also suppresses weed growth, reducing competition for resources and enabling plants to grow more effectively. Organic-rich mulches steadily increase soil biological soil components levels and support soil biota activity, promoting a healthier soil ecosystem (El-Beltagi et al., 2022).

3.5. Crop Rotation and Fallowing

Crop rotation is a key strategy for maintaining biological soil components levels and enhancing soil fertility. By alternating different crop types, the soil can utilize nutrients more evenly, reducing nutrient depletion. Leguminous crops, in particular, contribute to biological soil components content by fixing atmospheric nitrogen, which increases the nitrogen available for subsequent crops (Kumar et al., 2020).

The practice of fallowing involves leaving agricultural land unplanted for certain periods to allow the soil to replenish its biological soil components and provide a rest period for the soil biota. During this time, the soil naturally accumulates biological soil components and maintains its biological activity. Both crop rotation and fallowing are essential biological soil components management strategies for agricultural sustainability, as they help maintain land vitality and productivity over the long term (Karlen and Cambardella, 2020; Shah et al., 2021).

4. Consequences of Organic Matter Deficiency

Soil biological soil components is a critical component for land vitality and farming output. However, the loss of biological soil components has become a widespread issue in modern agricultural practices. A deficiency in biological soil components has adverse effects on both farming output and environmental sustainability. This section provides a detailed examination of the primary problems caused by biological soil components deficiency.

4.1. Erosion Risk and Degradation of Soil Structure

Organic matter is a fundamental component that regulates the physical structure of soil. A lack of biological soil components leads to the destabilization and breakdown of soil aggregates. When soil aggregate structure deteriorates, the soil's resistance to wind and water soil displacement decreases. Erosion causes the loss of the fertile topsoil layer, significantly reducing farming output. In sloped areas especially, a deficiency in biological soil components increases the risk of soil displacement and, over time, can lead to desertification of agricultural lands (Lynch et al., 2021).

The degradation of soil structure also reduces the soil's water-holding capacity. The spaces between soil particles shrink, leading to compaction issues. As a result, rainwater is more likely to run off the surface rather than infiltrate into the soil. Soil compaction makes it harder for plant roots to penetrate the soil, which in turn limits their access to water. Thus, biological soil components deficiency negatively impacts soil physical structure, directly lowering farming output (Cotrufo et al., 2022).

4.2. Decreased Water-Holding Capacity

Organic matter is one of the primary components that enables soil to retain water. A deficiency in biological soil components significantly reduces the soil's water-holding capacity, which jeopardizes farming output, especially in arid and semi-arid regions. Organic matter enhances soil's moisture conservation capacity, reducing the risk of water loss through evaporation or drainage. In its absence, soils are less able to retain water, leading to plant water stress and potential yield losses (Nasir and Toth, 2022).

A reduction in water-holding capacity also leads to excessive drying of the soil. This means that there is insufficient moisture in the root zone, negatively impacting plant growth. Soils with weakened water management become more vulnerable during drought periods, making it difficult for plants to access the water they need. This situation poses a particular threat to sustainable farming output in regions experiencing water scarcity (Shakoor and Ullah et al., 2024).

4.3. Nutrient Loss

Soil biological soil components plays a critical role in storing and releasing essential nutrients for plants. A deficiency in biological soil components reduces the soil’s capacity to retain nutrients, making it harder for plants to access the nutrients they need (Havlin, 2020). This is particularly problematic for macronutrients like nitrogen, phosphorus, and potassium, whose loss can significantly hinder plant growth (Yuan et al., 2024).

Moreover, a lack of biological soil components decreases the soil's CEC. CEC is essential for retaining plant nutrients in the soil and releasing them gradually as needed. When biological soil components levels are low, CEC is reduced, causing plants to either consume available nutrients more quickly or lose them to leaching. This often leads to a higher reliance on chemical fertilizers in agriculture. However, the continuous use of chemical fertilizers can, in the long run, further degrade land vitality (Pahalvi et al., 2021).

4.4. Decline in Microbial Activity

Organic matter is the primary energy and nutrient source for soil microorganisms. A deficiency in biological soil components leads to a reduction in soil microbial biomass and a weakening of biological activity. Microorganisms play a crucial role in decomposing biological soil components, releasing essential nutrients for plants, and maintaining a healthy soil biota. However, a lack of biological soil components disrupts this cycle, leading to an inadequate supply of nutrients necessary for plant growth (Gavrilescu, 2021).

A decrease in soil microorganisms also promotes the spread of pathogenic organisms in the soil. The suppression of beneficial microorganisms allows pathogens to proliferate, leaving plants more vulnerable to diseases. This results in yield losses and various issues in agricultural production. Furthermore, the decline in soil microbial populations slows down the decomposition of biological soil components, disrupting the biological soil components cycle and affecting land vitality and fertility over time (Zhan, 2024).

4.5. Decline in Soil Fertility

A deficiency in biological soil components is a key factor that directly impacts overall soil fertility. The deterioration of soil structure, reduction in water and nutrient retention capacities, and decrease in microbial activity contribute to the long-term loss of soil productivity. Fertile soils are essential for agricultural production; however, a lack of biological soil components undermines the soil's ability to sustain farming output (Rastogi et al., 2023).

This deficiency also increases the need for chemical inputs in agricultural practices, raising farming costs in the long term. Furthermore, the absence of biological soil components slows down the soil's natural regeneration processes, accelerating soil degradation and desertification. Soil health, which is crucial for agricultural production, becomes increasingly difficult to restore once biological soil components levels decline, leading to irreversible damage in some cases (Montgomery, 2021).

4.6. Reduced Carbon Sequestration Capacity and Climate Change

Soil serves as a major global carbon reservoir, with biological soil components playing a crucial role in sequestering atmospheric carbon dioxide. Acting as a carbon sink, soil biological soil components mitigates environmental alterations by storing carbon that would otherwise contribute to rising atmospheric CO_2 levels (Navarro-Pedreño et al., 2021). The depletion of biological soil components not only compromises the soil's carbon storage potential but also makes agricultural lands increasingly vulnerable to environmental alterations impacts. Soils with low biological soil components struggle to retain water and nutrients, which exacerbates challenges posed by shifting temperature and precipitation patterns, such as drought and nutrient depletion (Naorem et al., 2023). Managing biological soil components effectively enhances the soil's ability to sequester carbon and plays a critical role in global environmental alterations mitigation. Without sufficient biological soil components, this potential is lost, further intensifying the adverse effects of environmental alterations and threatening long-term agricultural sustainability (Paustian et al., 2016).

5. Conclusion

Soil health and farming output are the fundamental elements for ensuring the continuity of eco-conscious farming. However, modern agricultural practices, improper soil management methods, and excessive dependence on chemical inputs have led to severe losses in soil biological soil components levels. This has resulted in a reduction in agricultural production capacity, degradation of the soil's physical and chemical structure, and weakening of soil biota. In this context, biological soil components management stands out as an indispensable tool for preserving land vitality and enhancing productivity.

Through strategies such as decomposed organic material applications, cover crop incorporation, stubble management, organic fertilizer use, and mulching, the biological soil components content of soil can be increased, and the regular application of these methods improves soil moisture conservation capacity, allowing for more efficient use of nutrients. These strategies also support soil microbial activity, contributing to the strengthening of the soil's biological structure. Organic matter, which improves the physical structure of the soil, prevents water and wind soil displacement and ensures sustainability in agricultural production.

Neglecting soil biological soil components management endangers not only farming output but also long-term environmental sustainability. A deficiency in biological soil components leads to soil degradation, a reduction in CO2 absorption capacity, and an increase in the adverse effects of environmental alterations. Therefore, biological soil components management is critically important for enhancing productivity in agricultural production and protecting global environmental health.

Organic matter management in agricultural production is a vital strategy for preserving the biological, chemical, and physical structure of soil, creating a sustainable production system, and ensuring that agricultural lands remain productive in the future. Organic matter management not only improves land vitality but also helps agricultural systems become more resilient to global challenges such as environmental alterations. Thus, the adoption and implementation of biological soil components management strategies are key to ensuring the future sustainability of the agricultural sector and environmental health.

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CHAPTER 11

THE ROLE OF SUGAR BEET IN SUSTAINABLE AGRICULTURE

PhD Candidate Suat CUN[1]*

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[1] Harran University, Faculty of Agriculture, Department of Field Crops, Sanliurfa, Turkey, e-mail: suatcun@harran.edu.tr, https://orcid.org/0000-0001-6607-8263

*Corresponding Author: suatcun@harran.edu.tr

1. Introductıon

One of the major challenges that farmers currently face is the reduction in agricultural output, largely due to environmental changes. This issue has intensified in recent years because of climate change, which has drastically modified ecosystems, resulting in extreme weather phenomena such as droughts, snowstorms, floods, heatwaves, and cyclones. These conditions create stress for crops, leading to annual losses in production valued at millions of euros and causing approximately 50% of potential crop yields to be lost each year (Eisenach, 2019). Moreover, climate change impacts not only crop yields but also critical natural resources required for agriculture, including soil and water. Although climate change is expected to diminish water availability, agricultural water usage is anticipated to rise by 19% by 2050 (UN-Water, 2013).

The global population is projected to reach 9.7 billion by 2050 (Desa, 2019), necessitating a significant increase in crop production to satisfy this demand while also reducing environmental harm (Hunter et al., 2017). It is vital to integrate mitigation strategies aimed at lowering greenhouse gas emissions with adaptation measures that address the negative impacts of climate change and exploit possible advantages. Climate change and population growth are pivotal factors affecting future food security. Thus, ensuring global food security will demand alterations in farming practices, crop types, public policies, and societal perspectives (Anderson et al., 2020).

Salinity and drought are particularly daunting for the agricultural industry. Salinity impairs plants' ability to absorb water, leading to diminished growth and yield, while drought reduces productivity due to insufficient water supply. These challenges are exacerbated by climate change, urging farmers to adopt effective adaptation strategies. Implementing agricultural methods such as cultivating salt-resistant crop varieties, preserving soil health, and employing organic fertilizers will be essential for sustainable management.

Sugar beet (Beta vulgaris L.), belonging to the Chenopodiaceae family, is primarily cultivated in temperate climates (Bojović et al., 2022). This crop is grown across 41 countries, encompassing a total cultivated area of approximately 8.1 million hectares worldwide (Mehdikhani et al., 2011). The principal producers of sugar beet are the Russian Federation, France, Germany, the United States, Turkey, Poland, China, Egypt, Ukraine, and the United

Kingdom (FAO, 2019). Biancardi et al. (2010) report that the annual consumption of sugar beet has risen by roughly 1.5%, especially in densely populated countries such as China and India.

Sugar beet contains approximately 16% sugar, contributing to 20% of the global sugar supply (Wimmer and Sauer, 2020). It is also utilized for energy production in forms such as ethanol, bioethanol, molasses, cattle feed, pulp, and pectin. In contrast to sugarcane, which is cultivated over a longer duration (12-14 months), sugar beet has a shorter growing period of 5-6 months, making it a more efficient crop. The sucrose content in sugar beet ranges from 14-20%, surpassing the 10-12% found in sugarcane. Additionally, the resources required for growing sugar beet, such as water and fertilizers, are considerably lower than those needed for sugarcane, and beet products exhibit a remarkable adaptability to varying climatic conditions (Mioduszewska et al., 2020). There is a pressing need to enhance sugar production by growing sugar beets in saline-sodic and drought-affected soils without compromising sugar quality.

2. Effects of Saline Soils on Sugar Beet Plants

Salinity is a major abiotic factor that notably impedes agricultural productivity worldwide (Ma et al., 2020). In the face of such detrimental environmental factors, promoting crop growth and yields becomes a significant challenge in contemporary agriculture. The adverse impacts of salinity on farming are intensified by its presence in water resources, the effects of climate change, and the rising demand for food (Ullah et al., 2021).

Figure 1. The negative effects of salinity on agricultural lands

Over the past five decades, soil salinization has emerged as a significant challenge for agricultural practices (Dewi et al., 2022). Currently, approximately 33% of the globe's arable land is impacted by salinization, leading to notable reductions in agricultural productivity (Devkota et al., 2022). Increased salt concentrations adversely affect the physiological and biochemical functions of plants, thereby impeding the growth and development of both root and shoot systems (Ran et al., 2021). The accumulation of salts induces two main types of stress in plants: osmotic stress and ionic stress (Khare and Jain, 2021). The reduction in water potential linked to elevated levels of soil salinity results in diminished water absorption by plant roots.

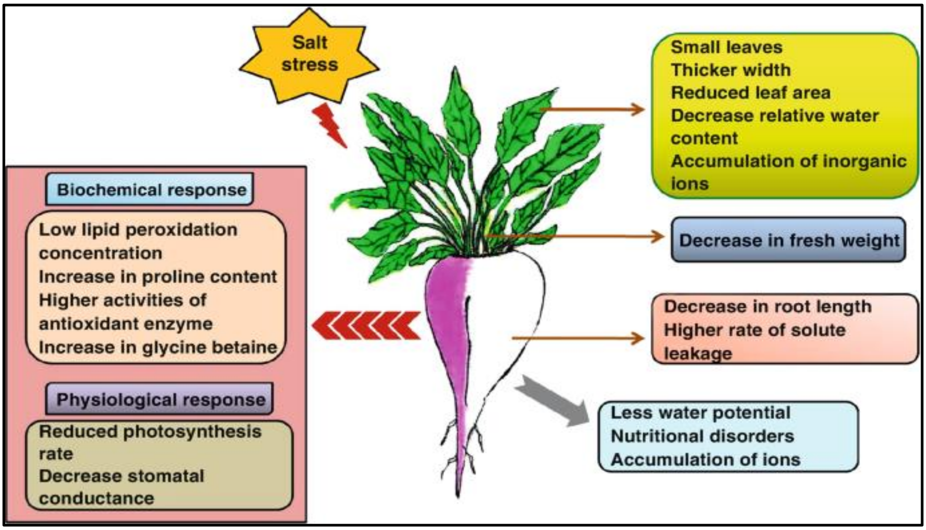

Figure 2. Biochemical, physiological, and morphological changes induced by salt stress in sugar beet plants (Misra et al., 2020).

Among the various beet cultivars, sugar beet is recognized for its ability to tolerate salinity, withstanding levels between approximately 40 and 120 mM NaCl (Pinheiro et al., 2018). In addition to its salt tolerance, sugar beet exhibits superior drought resistance compared to other cereal crops. The primary abiotic stressors, including salinity and drought, typically induce a range of morpho-physiological alterations in sugar beets. These alterations may manifest as growth inhibition, leaf wilting, reduced stomatal conductance, diminished photosynthetic rates and transpiration, a decrease in relative water content, lower concentrations of leaf photosynthetic pigments, decreased root biomass, lipid peroxidation resulting in membrane damage, accumulation of compatible solutes, a decline in white sugar yield, and an increase in specific leaf weight and water content index (Wiśniewska et al., 2019; Vitali et al., 2021). The observed growth reduction following salt stress may be attributed to ion toxicity, as photosynthetic rates can remain elevated even under conditions of high salinity (Daoud et al., 2008). Initially, salt stress decreases water absorption due to osmotic changes (osmotic phase) and subsequently induces ionic stress from the accumulation of salts within the leaves (Munns, 2002).

3. The Effect of Drought Stress on Sugar Beet Plants and Their Root Systems

Plants can acclimate to environments with limited water availability through several strategies, such as drought avoidance (for instance, rapid maturation), tolerance to tissue desiccation (like the accumulation of proline), and mechanisms that enhance water use efficiency (Jones et al., 2003). Effective utilization of soil moisture not only ensures high yields but also extends the plants' survival in regions with limited rainfall. Furthermore, selecting drought-tolerant cultivars strengthens the adaptive capacity of agricultural crops to climate change (Tardieu, 2012).

The risks associated with sustainable sugar beet production are expected to escalate due to climate change. Although elevated atmospheric CO_2 concentrations may enhance photosynthesis and productivity via the CO_2 fertilization effect, rising temperatures increase atmospheric water demand, intensify canopy transpiration, and heighten (nighttime) respiratory losses (Pidgeon et al., 2001). The total water requirement of sugar beet is highly dependent on environmental conditions. It can vary from as low as 385 mm in cool, humid environments with low evaporation to as high as 1043 mm in hot climates with high atmospheric water demand (Morillo-Velarde and Ober, 2006). A simulation study demonstrated that drought-induced losses and the interannual variability in sugar beet yields are projected to increase from 7% and 10% (1961–1990) to 18% and 15%, respectively, by 2021–2050 (Demmers-Derks et al., 1998). Therefore, it is crucial to understand the fundamental mechanisms underlying the plant’s response to water limitation to identify traits that can enhance drought resilience.

Figure 3. Negative effects of drought on sugar beet plants

In Europe, sugar beet is commonly grown in fertile soils, particularly chernozems, which are characterized by their high water retention capacity and profound rooting ability (Märländer et al., 2003). These pedological conditions necessitate the efficient use of groundwater reserves accumulated during the winter months, serving as a buffer against the increasingly frequent and anticipated intermittent droughts experienced in Central Europe during May and June (Trnka et al., 2015). Consequently, the root system emerges as a significant trait in sugar beet breeding programs.

The characteristics of the root system play a critical role in both mitigating water deficits within the plant and optimizing the utilization of available soil moisture (Blum, 2009). In soils with substantial water retention, the allocation of deep roots is regarded as a key trait that differentiates water-efficient root systems (Tron et al., 2015). Recognized for its capacity to reach deep water sources during drought conditions, sugar beet is classified as a deep-rooted species (Bodner et al., 2015). This deep rooting can result in anisohydric behavior, which enables the maintenance of open stomata and continued transpiration even during extended periods of water scarcity, a process linked to the accumulation of osmolytes within leaf and root tissues (Barratt et al., 2021).

4. Development and Utilization of New Cultivars Against Changing Climate Conditions

Numerous researchers are focusing on enhancing agricultural resilience to abiotic stressors such as heat, drought, flooding, and soil salinity, with the goal of making agriculture more climate-smart (Hickey et al., 2019). Scientists are utilizing transgenic and gene-editing methods to cultivate crops with better tolerance to these stresses, including maize, rice, wheat, beans, and other varieties (Eshed and Lippman, 2019). Recently, notable progress has been achieved in the development of crops with enhanced nutrient-use efficiency (Bailey-Serres et al., 2019). Furthermore, both transgenic and non-transgenic strategies are being employed to boost the yield potential of crops by improving their growth and photosynthetic performance. While the genetic factors influencing yield are intricate, recent research suggests that relatively straightforward, region-specific modifications can lead to significant yield improvements, regardless of the growing conditions (Wu et al., 2019).

By gathering and categorizing the morpho-physiological and genetic characteristics of various sugar beet cultivars under conditions of drought or salinity stress, breeders can devise effective strategies to produce new varieties that withstand these challenges (Taghizadegan et al., 2019; Islam et al., 2020). Creating stress-tolerant sugar beet varieties may enhance yield, boost productivity, and allow for the expansion of cultivation areas. To reduce yield losses from stress in sugar beets, it is essential for plant breeders to prioritize the development of varieties that demonstrate high germination and establishment rates, even under stressful conditions (Ghaffari et al., 2021).

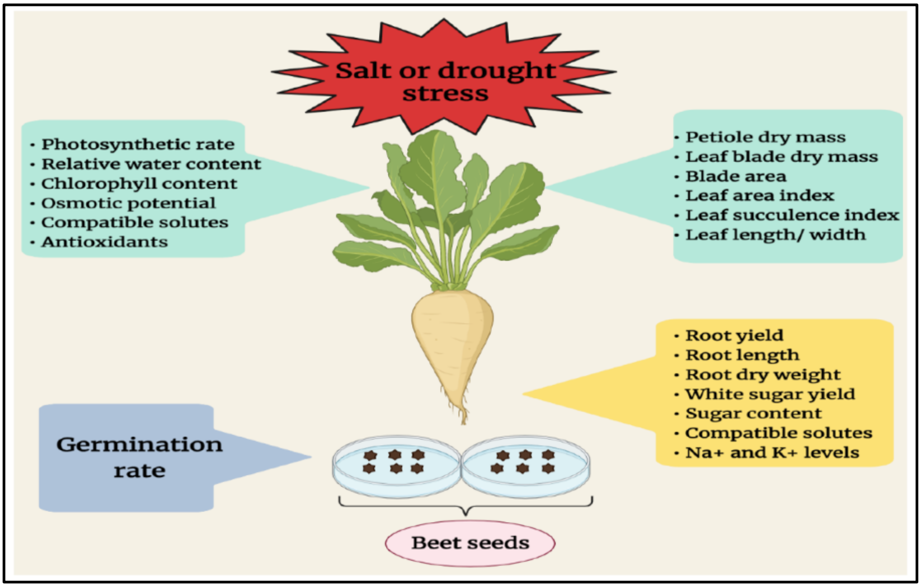

Figure 4. Morpho-physiological and biochemical parameters used in the selection of salt and drought-resistant beets (Yolcu at el., 2021)

5. Effects of Sugar Beet Cultivation on Soil

Sugar beet is a significant crop, valued not only for its sugar yield but also for its resilience in various environmental conditions (Shanmuganathan et al., 2023). Its ability to flourish in temperate climates and adapt to a wide range of soil types makes it an essential asset in agricultural production (Stevanato et al., 2019). Furthermore, its capacity to succeed in adverse conditions highlights its importance in areas dealing with soil salinity challenges (Mosaad et al., 2022).

The increase in root biomass of sugar beet can have a direct positive impact on soil carbon levels in fields where it is cultivated. In the soil environment, root biomass tends to remain stable for a more extended period compared to the aboveground residues of the crop (Poeplau et al., 2021). However, due to the relatively low amount of fibrous root biomass associated with sugar beet (Pacholski et al., 2015), it might be viewed as less advantageous for carbon retention and for maintaining current soil carbon levels in agricultural systems. Enhancing the root biomass of sugar beet could be beneficial for evaluating its role in climate change mitigation strategies (Grunwald et al., 2023). In addition, improvements in land use, the promotion of crop rotation, direct seeding into the residue, and reduced soil tillage practices can help decrease field intensity and enhance soil quality (Çelik et al., 2017)

6. Use of Biological Fertilizers in Sugar Beet Agriculture

The growing variability in weather patterns is increasingly affecting sugar beet yields through various abiotic factors (Ober and Rajabi, 2010). These factors contribute to yield reductions in both organic and conventional farming systems, often resulting in what is identified as a limiting factor. To counteract the detrimental effects of these adverse abiotic conditions, it is essential to enhance the soil's physical attributes, structure, and its content of moisture and organic matter.

Effective fertilization strategies are vital for unlocking the full yield potential of sugar beet (Hergert, 2010). The utilization of compost derived from organic materials such as plant residues and animal manure provides a sustainable approach to improving both soil fertility and structure (Pergola et al., 2018). In the absence of organic livestock production, farms can incorporate mineral fertilizers, including green manure, compost, and commercially available organic nitrogen sources like Bioilsa N 12.5, alongside naturally sourced potassium and phosphorus fertilizers.

The incorporation of compost in saline-sodic soils not only enhances the organic matter content and structural integrity of the soil but also stimulates microbial activity, which can help alleviate the negative impacts of salinity and sodicity (Majbar et al., 2021; Rekaby et al., 2023). Additionally, compost supplies critical nutrients necessary for the growth and development of sugar beet, thus improving overall crop productivity (Rerhou et al., 2023).

7. Protection and Support of Microbial Communities in Soils

Soil acts as a fundamental substrate for plant development, supplying essential nutrients and serving as a habitat for diverse soil microorganisms (Leloup et al., 2018). These microorganisms play a crucial role in sustaining the stability of soil structure, enhancing microbial diversity, and maintaining ecological balance. Additionally, they serve as significant indicators for the preservation of soil fertility (Kirk et al., 2004).

Soil microorganisms constitute a fundamental component of the soil ecosystem, functioning as key agents in the transformation and cycling of nutrients within this environment (Dai et al., 2021). The diversity and composition of microbial communities in the soil are significantly correlated with the prevalence of soil-borne diseases (Tan et al., 2021). These microbial communities engage in interactions with plants, contribute to essential nutrient cycling, and are integral to the promotion of plant growth and overall health (Schmid et al., 2018; Li et al., 2019).

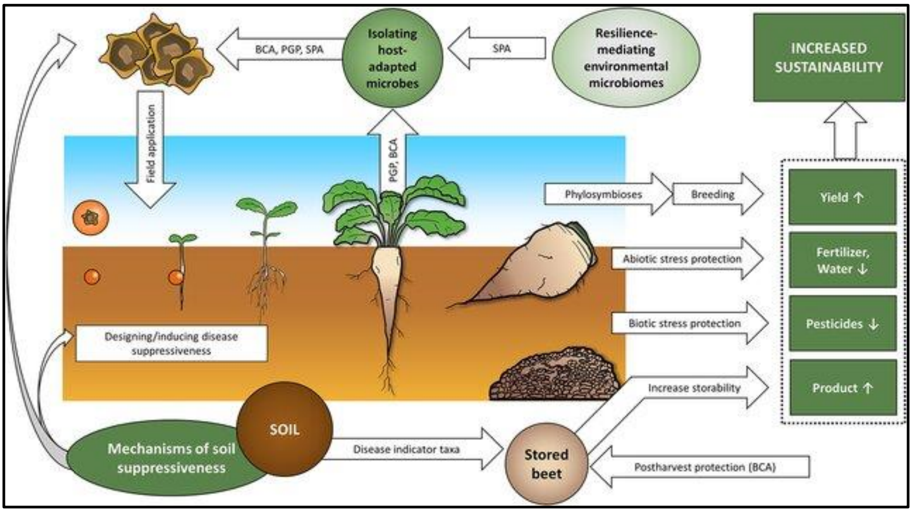

Figure 5. Effects of soil microbiomes on enhancing sustainability in sugar beet agriculture (Wolfgang et al., 2023).

Additionally, they are crucial for soil formation processes, influencing changes in fertility and supporting plant development, thereby serving as key indicators of soil quality (Brubaker et al., 1992). Consequently, the characteristics of soil microorganisms are intrinsically linked to agricultural productivity (Lupwayi et al., 2018).

Conclusion

Drought and salinity stress are two fundamental environmental factors that severely negatively affect the growth, physiological processes, and productivity of sugar beet. These stress conditions disrupt the water balance and nutrient uptake of plants, leading to a reduction in leaf area, decreased root length, and loss of fresh weight. Particularly, the decline in photosynthesis rate and reduction in stomatal conductance limit carbon assimilation, hindering plant development. Disruptions in water and nutrient uptake from the roots lead to a decrease in plant water potential and an increase in solute leakage from cells. This situation disturbs intracellular ion balance, resulting in inorganic ion accumulation and nutritional disorders.

However, sugar beet develops various biochemical and physiological responses to adapt to stress conditions. The accumulation of osmolytes, such as proline and glycine betaine, increases for osmotic regulation. At the same time, the activity of antioxidant enzymes rises to mitigate the damage caused by oxidative stress, and lipid peroxidation is limited. Although these adaptation mechanisms can partially alleviate the negative effects of stress, yield loss in plants becomes inevitable under prolonged or severe stress conditions.

The development of drought and salinity-resistant sugar beet varieties is an important strategy to reduce these adverse effects. Additionally, suitable agricultural practices, such as optimizing irrigation management, soil improvement, and nutrient supplementation, can alleviate the severity of stress. These approaches will contribute to supporting sustainable sugar beet production, preserving agricultural productivity, and enhancing resilience to climate change.

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CHAPTER 12

THE ROLE OF HEAVY METAL CONTAMINATION IN SOIL ON AGRICULTURAL PRODUCTION: ISSUES AND PROPOSED SOLUTIONS

PhD Candidate Zemzem FIRAT[1*]

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[1] Harran University, Faculty of Agriculture, Department of Soil Science and Plant Nutrition, Sanliurfa, Turkey, e-mail: zemzemfirat63@gmail.com, https://orcid.org/0000-0003-4549-9389
*Corresponding Author: zemzemfirat63@gmail.com

1. Introductıon

Soil constitutes the upper layer of the lithosphere, a dynamic and natural structure that forms through the decomposition of rocks and organic matter, resulting in varying proportions of its components. It contains water, minerals, organic compounds, soluble salts, and ions essential for supporting various forms of life (Yildiztekin et al., 2019; Khomiakov, 2020; Yadav et al., 2021). This complex composition allows soil to fulfill multiple critical functions. Among these are its roles in sustaining life, providing a habitat for humans, animals, plants, and other organisms, and maintaining essential ecological processes. Additionally, soil is integral to water and nutrient cycles, offers limited protection for groundwater reserves, preserves historical, natural, and cultural footprints, conserves mineral resources and raw materials, and serves as a foundation for food production as well as social and economic activities (Castelo-Grande et al., 2010).

With the rapid economic development observed since the 20th century, human activities have driven an unprecedented demand for land resources (Cheng et al., 2015). This increased demand has led to significant soil degradation and pollution, resulting from both natural processes and anthropogenic influences. A growing global population has further exacerbated the pressure on land by necessitating higher agricultural productivity, compelling the adoption of intensive, technology-driven farming practices. While these advancements have bolstered food production, the improper, excessive, and uninformed application of agricultural practices—such as chemical fertilizers, pesticides, irrigation, and soil tillage—has contributed to pressing environmental and health issues (Eryılmaz & Kılıç, 2019; Bagheri, 2010).

As population and economic activities surge, so do environmental pressures, including food demand, consumption, and industrial production. These developments have intensified environmental pollution (Mikhailenko et al., 2020), with urbanization and industrialization contributing to rising contamination levels in soil. This contamination has now reached levels that pose significant risks to biodiversity and human health (Oztürk et al., 2017; Turan et al., 2020; Yilmaz et al., 2021). The pervasive impact of soil contamination is particularly concerning due to its effect on various organisms through the food chain, revealing the critical nature of this issue (Ozyigit et al., 2021). Technological progress, though beneficial for food security, has led to progressively polluted soils, reducing the area available for cultivating fruits, vegetables, and other agricultural products (Syed, 2005).

Among the most concerning contaminants, heavy metal pollution now presents an urgent challenge within natural ecosystems, as these metals reach humans through the food chain and cause significant health complications. As soil is the primary medium through which these metals enter ecological and human systems, early detection of heavy metals in soil and proactive measures are essential to prevent and mitigate their detrimental effects on health and the environment.

2. Soil Pollution

Soil pollution has undeniably become a global issue today (Çağlarırmak & Hepçimen, 2010). Over the past few decades, soil contamination has increased significantly, emerging as a major global concern (FAO, 2015). For example, recent data from the European Environment Agency (EEA, 2014) indicate that Europe hosts more than 2.5 million potentially contaminated sites, with approximately 340,000 considered severely polluted. Soil pollution is defined as the degradation of soil's physical, chemical, biological, or fertility properties due to substances originating from soil formation processes or external additions, including improper agricultural practices. The main sources of soil contamination include agricultural chemicals (such as pesticides and fertilizers), industrial waste, nuclear waste, medical waste, domestic waste, and mining residues (Syed, 2005).

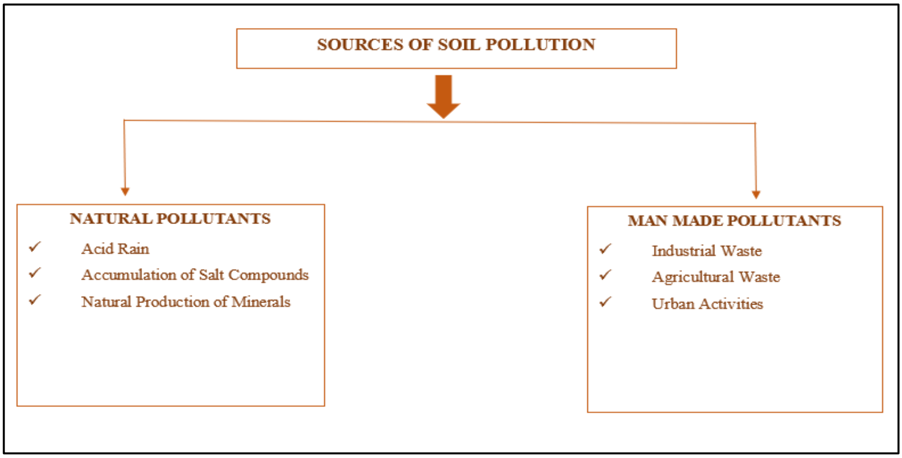

Figure 1. Sources of soil pollution (Verma, 2022)

Due to the increasing significance of heavy metal pollution compared to other contaminants, recent studies have focused on addressing this issue (Haktanır et al., 1995).

3. Heavy Metals

Heavy metals are elements found in the periodic table from the third period onward, distinguished by having a density greater than 5 g/cm^3. This category encompasses over 60 metals, with key examples including lead, cadmium, chromium, iron, cobalt, copper, nickel, mercury, and zinc (Kahvecioğlu et al., 2004). The concept of "heavy metals" was initially introduced in the scientific literature in relation to environmental pollution (Sönmez & Kılıç, 2021).

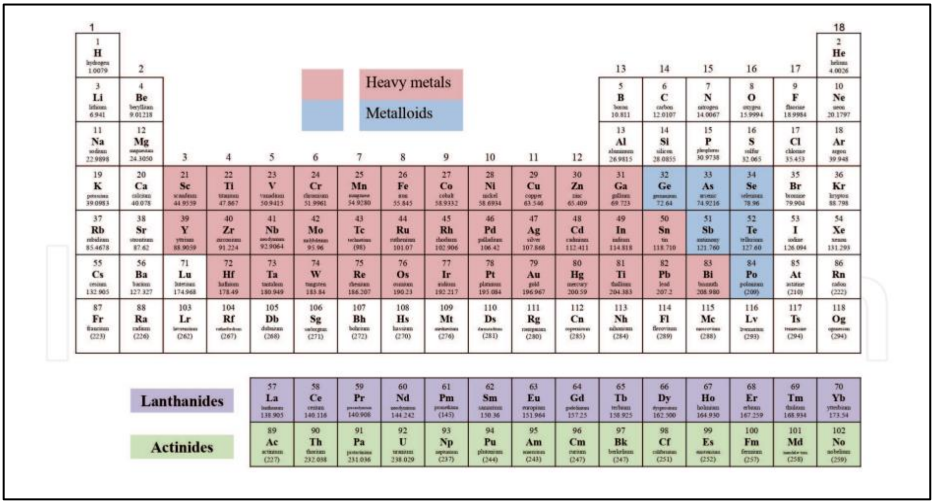

Figure 2. Positions of heavy metals in the periodic table (Ali et al., 2021)

Metals are commonly categorized into heavy metals, light metals, and metalloids. Depending on their physical, chemical, and physiological properties, metals are further divided into several groups:

Transition metals refer to a specific group of elements, including chromium (Cr), manganese (Mn), iron (Fe), cobalt (Co), nickel (Ni), copper (Cu), and molybdenum (Mo). These elements are known for their ability to form a wide range of compounds due to their variable oxidation states. In addition to transition metals, there is a group called post-transition metals. This category includes elements such as aluminum (Al), zinc (Zn), cadmium (Cd), mercury (Hg), and lead (Pb), which are often characterized by their softer and more malleable nature compared to transition metals.

Another significant classification is the alkaline earth metals, which are essential in many biological and geological processes. This group consists of elements like calcium (Ca), magnesium (Mg), beryllium (Be), and barium (Ba). These elements are typically found in compounds that contribute to the structural integrity of organisms, such as bones and shells. Alkali metals, which include lithium (Li), sodium (Na), potassium (K), and cesium (Cs), are highly reactive and play important roles in biological and chemical processes, especially in regulating cellular functions.

Finally, metalloids, a group of elements that exhibit both metallic and non-metallic characteristics, include boron (B), silicon (Si), arsenic (As), and antimony (Sb). These elements have properties that make them useful in various applications, such as semiconductors and materials science (Pourret & Hursthouse, 2019).

Heavy metals are known for their high density and can be harmful to living organisms even at very low concentrations (Ackova, 2018). Both heavy metals and metalloids are significant pollutants in agricultural soils, as their elevated concentrations can adversely affect crop health and yield (Maksymiec et al., 2007; Shahid et al., 2015).

4. Heavy Metal Pollution in Soils

Heavy metal pollution in soil poses a threat to the ecological environment, food security, and the development of sustainable agriculture (Yao et al., 2012). The threat to food security and sustainable agricultural development arises from the fact that metals cannot be biologically degraded; they can only be transferred from one chemical state to another and are highly persistent in the soil (Naila et al., 2019; Sun et al., 2020).

Heavy metals reaching the soil through natural processes and human activities can be immobilized in the soil by cation exchange capacity, iron and aluminum oxides, clays, and organic matter, thereby reducing their accumulation. Additionally, various factors such as organic carbon, soil texture, soil temperature, water content, clay type, phosphorus, bicarbonates, and carbonates also influence the active movement of heavy metals in the soil formation process (Yerli et al., 2020).

Soils with high clay content and rich in organic matter, which possess a high capacity for exchangeable cations in the soil solution, can retain significant amounts of heavy metals. These types of soils tend to exhibit higher levels of heavy metal contamination. Due to the binding of heavy metals to clay and organic matter, they are concentrated in the upper layers of the soil (Kızıloğlu et al., 2008). The pollution caused by heavy metals can easily transfer from one ecosystem to another through the food chain. Pollution in the ecosystem chain, when absorbed by organisms, leads to numerous negative effects (Vareda et al., 2016).

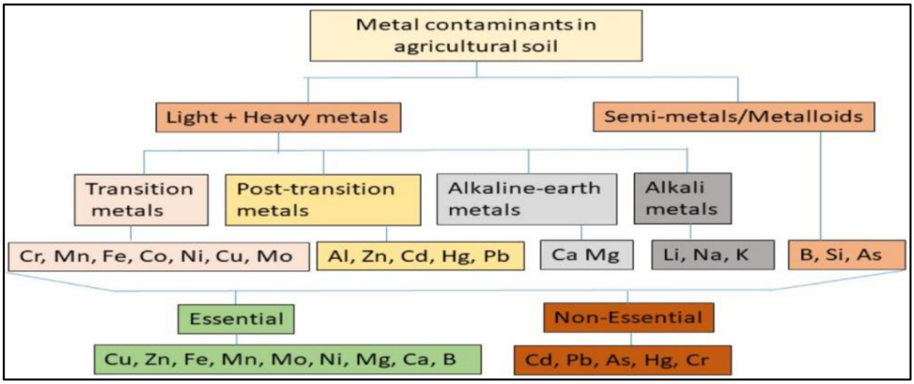

Figure 3. The categorization of common metallic and non-metallic elements found in agricultural soils (Raşhid et al., 2023)

The concentrations of heavy metals in soils can vary widely, with global averages differing. For instance, copper (Cu) is typically found at 20 mg kg^{-1}, cadmium (Cd) at 0.06 mg kg^{-1}, chromium (Cr) ranges from 20 to 200 mg kg^{-1}, lead (Pb) from 10 to 150 mg kg^{-1}, nickel (Ni) at 40 mg kg^{-1}, and zinc (Zn) between 10 and 300 mg kg^{-1}. In soils that are rich in metals, these concentrations can be 10 to 1000 times higher, often due to the composition of the parent material or contamination (He et al., 2005). Toxic metals such as arsenic (As), cadmium (Cd), chromium (Cr), copper (Cu), mercury (Hg), lead (Pb), and zinc (Zn) are some of the most common contaminants in soils. These metals are characterized by their persistence, inability to degrade, potential for bioaccumulation, and ability to biomagnify within the food chain. The chemical forms and species of these metals play a critical role in determining how they behave and move through the soil.

5. Sources of Heavy Metal Pollution in Soils

The swift pace of global industrial growth has greatly heightened the risk of environmental contamination by heavy metals. Accelerated industrialization, unchecked urban expansion, and the extensive use of fertilizers and pesticides over extended periods have contributed to the buildup of harmful substances in the soil, water, and air (Kumar et al., 2015; Rodrigues et al., 2017).

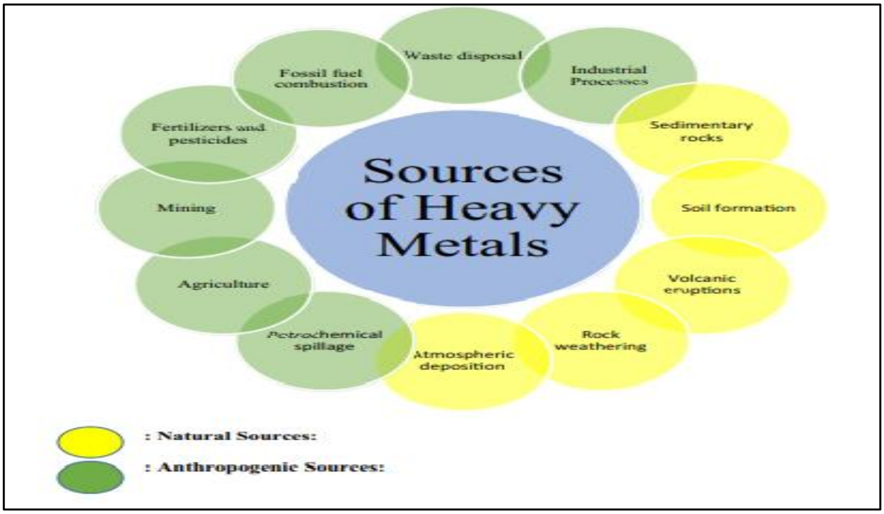

Figure 4. Sources of heavy metal contamination in soils, both natural and human-induced (Nnaji, D et al., 2023).

Agricultural soil is an essential, non-renewable resource. While natural processes contribute to contamination, human activities are significant drivers of heavy metal pollution, including substances such as cadmium (Cd), lead (Pb), chromium (Cr), arsenic (As), mercury (Hg), copper (Cu), nickel (Ni), zinc (Zn), and aluminum (Al). Natural sources of contamination include the weathering of rocks containing metals, as well as rainwater and atmospheric deposition. Human-induced sources include industrial activities (such as mining, tanning, textiles, and petrochemicals), the disposal of metal-laden waste, vehicle emissions, and agricultural practices (Hasnine et al., 2017; Kumar et al., 2019). Regardless of the origin of contamination, the ongoing accumulation of heavy metals in agricultural land can make soils toxic, thus impairing plant growth and crop productivity.

Both inorganic and organic fertilizers are significant contributors to heavy metal contamination in agricultural soils. Other sources include the use of lime, sewage sludge, irrigation water, and pesticides (Nagajyoti et al., 2010).

6. Effect of Heavy Metal Contaminated Soil on Plant Growth

Heavy metals that are available for plant uptake are found in the soil solution in soluble forms and can be easily dissolved by root exudates (Blaylock et al., 2000). The plants' ability to accumulate essential metals also allows them to absorb non-essential, potentially toxic metals (Djingova et al., 2000). Since metals are non-biodegradable, excessive concentrations in plants can have both direct and indirect detrimental effects.

Direct toxic effects from high metal concentrations include the inhibition of cytoplasmic enzymes and damage to cellular structures caused by oxidative stress (Jadia & Fulekar, 2009). Additionally, heavy metals can indirectly impact plant growth by harming soil microorganisms. For example, a reduction in beneficial microorganisms due to high metal concentrations can slow down the decomposition of organic matter, leading to a decrease in soil nutrient levels. Heavy metals can also interfere with essential enzymatic processes in soil microorganisms, which are crucial for plant metabolism. These toxic effects, whether direct or indirect, can significantly hinder plant growth and may even result in plant death (Schaller et al., 1991).

7. Remediation Methods for Heavy Metals in Soil

Several methods have been developed to remediate heavy metal contamination in soils. These methods are generally classified into two categories: in-situ remediation, which involves the treatment of contaminated soil at its location, and ex-situ remediation, which involves removing contaminated soil and treating it elsewhere (Gomes et al., 2013). Remediation techniques are carried out through physical, chemical, and biological processes. **Physical remediation methods** involve techniques that use physical technologies to mitigate or halt the damage caused to the soil. These include soil replacement, isolation, capping, and thermal treatment methods (Yao et al., 2012).

Chemical remediation methods involve the use of chemicals to remove or stabilize pollutants in contaminated soils. Various chemical remediation techniques include soil washing and immobilization methods (solidification/stabilization, vitrification, and electrokinetic methods). Soil washing techniques involve washing contaminated soil with clean water, reagents, and other liquids to flush out contaminants (Derakhshan Nejad et al., 2018). Various substances, including water (Dermont et al., 2008), saponins (Maity et al., 2013), organic acids (Kim et al., 2013), chelating agents (Jiang et al., 2011), surfactants (Sun et al., 2011), and low molecular weight organic acids (Almaroai et al., 2012), have been shown to affect the desorption of contaminants from soils.

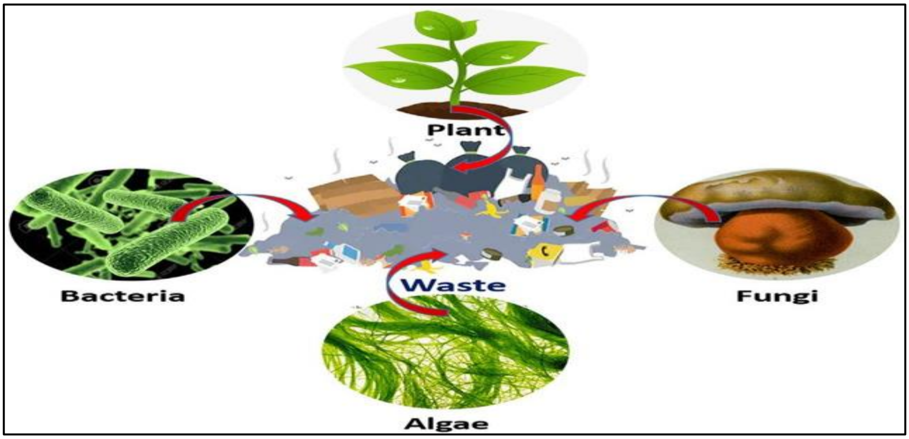

Figure 5. Demonstration of the Bioremediation Principle (Kumar and Tyagi, 2020)

Bioremediation Methods: Bioremediation processes are methods based on the use of plants, macro, and microorganisms to remediate contaminated environments in an environmentally friendly manner (Dindar et al., 2017). In bioremediation processes, biological mechanisms of plants and microorganisms are utilized to remove, degrade, or immobilize contaminants from polluted environments (Ayangbenro & Babalola, 2017). Compared to other physical and chemical techniques, bioremediation is a cost-effective and environmentally friendly method for large areas (Blaylock et al., 1997). Bioremediation techniques can be influenced by factors such as temperature, pH, moisture, and oxygen levels (Dandan et al., 2007; Yao et al., 2012).

The microorganisms used for cleaning polluted environments do not break down heavy metals directly, but they can transform them into various physical and chemical forms and incorporate them into their cells (Bosecker, 1999). Typically, bacteria and fungi are the microorganisms used for removing heavy metals from contaminated soils, although yeasts and algae can also be employed for heavy metal removal (Coelho et al., 2015). The combined use of plants and microorganisms for the remediation of contaminated environments often leads to faster and more effective results (Vangronsveld et al., 2009). In addition, Soil health and quality, along with processes of chemical degradation and restoration, can be effectively assessed using enzyme activities as indicators, particularly dehydrogenase, catalase, and urease. These enzymes serve as valuable markers for ecosystem functioning, especially in soils contaminated or at risk of contamination by heavy metals. Due to the high sensitivity of these enzymatic activities, they tend to decline rapidly when exposed to elevated concentrations of heavy metals (Sakin et al., 2024).

8. Phytoremediation Technologies

Phytoremediation is a technique used to clean contaminated soils by immobilizing or adsorbing pollutants to reduce their concentration (Yao et al., 2012). Various phytoremediation technologies include phytoextraction, rhizofiltration, phytostabilization, phytovolatilization, and phytodegradation (Kong & Glick, 2017).

For cleaning organic pollutants in the soil, methods such as rhizodegradation, phytovolatilization, and phytodegradation can be applied (Aybar et al., 2015). These techniques involve using plant roots and associated microorganisms to degrade, stabilize, or remove contaminants from the soil, providing an eco-friendly and cost-effective solution for soil remediation.

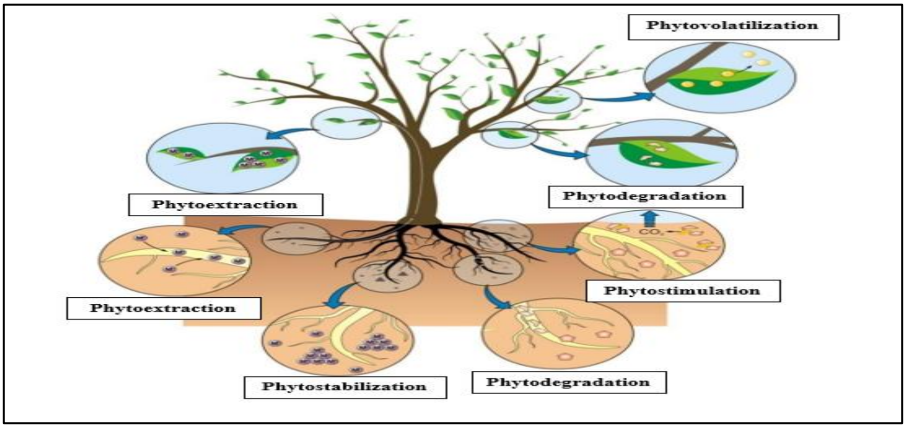

Figure 6. Schematic representation of phytoremediation types (Favas et al., 2014)

Accumulator plants are those that, despite the presence of metals in the soil, can accumulate higher levels of metals in their above-ground parts. These plants are used for soil remediation of heavy metals (Baker & Walker, 1990). Hyperaccumulator plants, on the other hand, are capable of accumulating 50 to

500 times higher metal concentrations in their above-ground parts compared to the metal levels in the soil (Clemens, 2006). Some of the most well-known hyperaccumulator plants include Thlaspi, Chenopodium, Urtica, Polygonum sachalase, and Allyssum, which have the potential to accumulate metals such as cadmium, nickel, copper, zinc, and lead in their plant tissues (Mulligan et al., 2001). These plants play a crucial role in phytoremediation by removing toxic metals from contaminated soils.

Conclusıon

Heavy metal contamination in soil is a significant concern for agricultural production, presenting both environmental and public health challenges. The presence of toxic metals such as lead, cadmium, arsenic, and mercury in soils disrupts soil fertility, affects microbial diversity, and inhibits plant growth. These metals can enter the food chain through contaminated crops, leading to severe health consequences. The primary sources of contamination include industrial activities, the overuse of fertilizers and pesticides, and the disposal of sewage sludge and wastewater. In regions affected by mining and industrial pollution, soil contamination poses even greater risks to agricultural productivity.

Addressing this issue requires a multi-pronged approach that includes phytoremediation, which uses plants to absorb and detoxify heavy metals, and soil amendments like biochar and compost to reduce metal bioavailability. Bioremediation, leveraging microorganisms to transform heavy metals into less harmful forms, also offers a promising solution. Additionally, improving agricultural practices by regulating the use of chemical inputs and encouraging sustainable farming methods can prevent further contamination. Remediation techniques such as soil washing, alongside regular monitoring and risk assessments, are essential for identifying contamination levels and guiding effective interventions.

Ultimately, addressing soil heavy metal contamination is crucial for ensuring the long-term sustainability of agriculture and the protection of human health. A combination of innovative techniques, regulatory measures, and continuous monitoring can help mitigate the impacts of this environmental threat, fostering safer and more resilient agricultural systems for the future.

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