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Empowering Crops: How Organic, Agronomic Practices and Technology Can Fortify Our Fields

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ABSTRACT

Global food security hinges on boosting crop productivity to meet the projected 44% surge in food demand by 2050. Current agricultural systems face significant challenges from both abiotic and biotic stressors. Abiotic factors like drought, heat, and salinity, and biotic factors such as pests, diseases, and weeds, severely limit crop yields. Drought alone can decimate wheat yields by up to 21% and maize yields by a staggering 40%. Healthy soil is paramount for robust crop production. Soil rich in organic matter fosters nutrient uptake, water retention, and beneficial microbial activity, all critical for plant growth. A thriving soil ecosystem supports strong root development, disease resistance, and improved soil structure, enhancing aeration and drainage. Research indicates that soil fertility contributes to as much as 60% of crop yield, highlighting its crucial role. However, climate change, population growth, and resource depletion strain agricultural systems. Water scarcity, pests, diseases, nutrient imbalances, and extreme weather events further threaten crop productivity. Addressing these challenges requires a

holistic approach centered on soil health. Sustainable soil management practices, including cover cropping, reduced tillage, and the use of organic amendments, are essential for restoring and maintaining soil health. These practices improve soil structure, water infiltration, and nutrient cycling, creating a more resilient and productive agricultural system. Precision agriculture, using technologies like remote sensing and GIS, optimizes resource use and crop management. Data analysis of soil, crop, and environmental factors enables targeted interventions and customized input application, maximizing yields and minimizing environmental impact. Integrating precision agriculture with soil health management builds resilient agricultural systems crucial for global food security. This combined approach supports a sustainable agricultural future capable of feeding the growing population while protecting the environment.

Keywords: Crop Productivity, Precision Agriculture, Data-Driven Farming, Food Security, Water Management, Organic Farming, Climate Change

1. INTRODUCTION

Crop health and productivity are key components of food security. The Intergovernmental Panel for Climate Change states that "research studies examined find that changes in the climate will increasingly be detrimental to agricultural productivity as levels of warming progress (high confidence)".

The existing global food system "supports the livelihoods of over 1 billion people and pleases the vast majority of people on the planet," hence this presents a serious concern. As can be seen from the search results, there has been a more than 30% rise in the amount of food available per person since 1961.

This growth has also been accompanied by an increase of over 100% in the amount of water used for irrigation and an increase of over 800% in the usage of nitrogen fertilizers. Nevertheless, 151 million kids younger than five suffer from malnutrition and an estimated 821 million adults remain undernourished despite these advancements. This underscores the need to further improve crop productivity and resilience to ensure adequate food availability and access for all (Gitz et al., 2016).

The World Bank's food security projects in regions like Honduras, Eastern and Southern Africa, and West Africa demonstrate how investments in climate-smart agriculture, value chain development, and food system resilience can boost crop productivity and enhance food security for vulnerable populations. Wageningen University's research and initiatives also highlight the importance of improving crop management, reducing food waste, and strengthening food system resilience to achieve global food security.

Increasing crop health and production is essential to supplying the world's expanding food demand, lowering hunger and malnutrition, and sustaining the lives of millions of people throughout the globe, according to the search results (Savary et al., 2017). Food security and general human well-being depend on ongoing efforts to improve crop resilience and sustainability.

The Connection Between Crop Productivity and Food Security

Crop productivity is essential in shaping global food security by directly influencing the availability, accessibility, and affordability of food.

1) Increased Food Availability

Global Agricultural Productivity Report in 2018 on “Prioritizing Productivity for Food Security”, highlights that higher crop productivity leads to an increased supply of food, which is essential for feeding the growing global population. According to research, agricultural productivity is the primary contributor to global agricultural output growth. The declining growth rates of total factor productivity (TFP), particularly in regions like sub-Saharan Africa, pose a severe danger to food security, where anticipated productivity growth would only satisfy 8% of food demand by 2030. Despite a 30%+ rise in per capita food supply since 1961, 821 million are undernourished, 151 million children stunted, and 2 billion adults overweight, highlighting food system inequalities amid rising fertilizer (800%) and water use (100%).

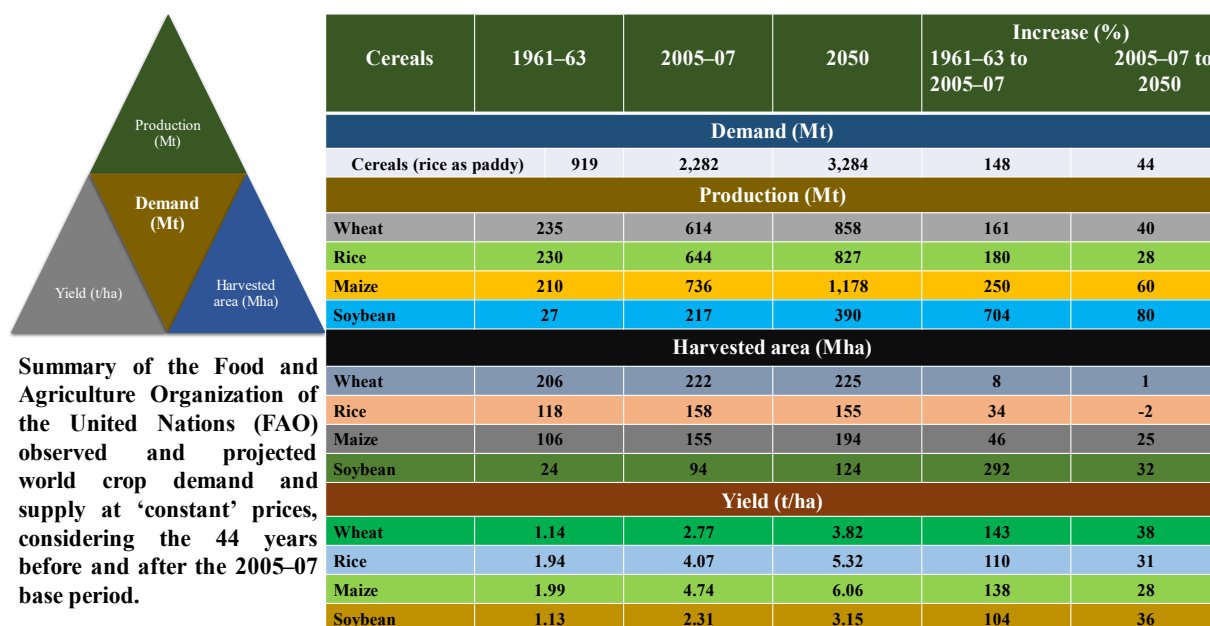


Figure 1. The demand for all cereals is predicted to rise by 44% overall between 2005–07 and 2050, according to this table. This translates to an annual compound growth rate of 0.83. Although some studies tend to assume higher values for the growth in demand for cereals and for all agriculture since the composition of demand changes as incomes rise, the growth in the value of overall agricultural production is projected to be closer to 60%.

(Source: Alexandratos and Bruinsma, 2012).

Economic Stability and Lower Food Prices

Enhanced productivity allows farmers to produce more food at lower costs, which can stabilize food prices. This is crucial for consumers, especially in low-income regions where food affordability is a major concern. As agricultural productivity increases, it helps mitigate the volatility of food prices, making food more accessible to vulnerable populations. A study of eight Asian economies (2000–2016) found a significant link between energy (oil) prices and food prices. Oil price shocks positively impact food prices. Biofuel prices also affect food prices, though explaining less than 2% of the variance (Taghizadeh-Hesary et al., 2019).

2) Resilience Against Climate Change

As climate change continues to threaten agricultural systems, enhancing crop productivity through sustainable practices becomes increasingly important. Studies indicate that climate change adversely affects crop yields, particularly in lower-latitude regions. Consequently, funding agricultural R&D to increase production can aid in reducing these effects and guaranteeing adequate nutrition in the midst of climatic unpredictability. Rising CO₂ is projected to increase global grain yields by 1.8% per decade, while warming may decrease them by 1.5%, with a potential range of 0-4%. This warming impact could offset half the expected 8% yield gain from technological advancements (Lobell & Gourdji, 2012). Global agricultural drought-affected areas have increased from 5-10% to 15-25% since the 1960s. Wheat yield losses per degree Celsius increase are projected at 5.5% (US), 9.1% (India), and 7.8% (Russia). Climate-smart agriculture and water management are crucial adaptations (Srivastav et al., 2021).

3) Global Trade Dynamics

Agricultural trade offers limited direct dynamic gains for farmers due to their limited influence on competitiveness. However, dynamic gains may arise from increased R&D investment by states or input suppliers. Intra-industry trade can also boost productivity by shifting resources to more efficient producers (Moon, 2022). Crop productivity also influences global trade patterns.

Regions with high productivity can export surplus food, contributing to global food security. For instance, North America is projected to produce 190% of its food demand by 2030, making it a key player in global food supply chains. Conversely, regions with lower productivity may rely on imports to meet their food needs, highlighting the interconnectedness of global food systems. Global agricultural trade network (ATN) analysis (1986-2018) reveals a shift from US-Asian dominance to a multipolar structure. While nodal stability increased, uneven stability across communities persists, highlighting the need for stronger trade relations to ensure food security (Wang et al., 2023).

4) Technological Advancements and Investment

Technological innovations in agriculture, such as improved seed varieties and efficient farming practices, are essential for increasing crop yields. Historically, agricultural research expenditures have resulted in notable increases in yield, especially for basic crops like rice and wheat. Maintaining productivity development and tackling the issues brought on by population increase and climate change require this continuous investment (Fischer, 2019). Ten crop models (including APSIM, DSSAT, AquaCrop, ORYZA) and one intercomparison project were reviewed.

Model ensembles and coupled models improve prediction accuracy. These models can effectively simulate crop growth, yield, and nitrogen dynamics, aiding food security assessments (Gavasso-Rita et al., 2024).

Crop production is therefore a key component of global food security. It influences food availability, economic stability, nutritional outcomes, resilience to climate change, and global trade dynamics. Realizing food security and enhancing the welfare of people everywhere depends on tackling the problems caused by slowing productivity development, especially in areas that are already at risk.

Briefly introduce the concept of stress factors affecting crop productivity (e.g., water scarcity, pests, diseases, nutrient deficiencies)

Abiotic and biotic stressors are two main categories of stress variables that have a considerable impact on crop yield. It is necessary to create strategies for dealing with these stresses in order to increase agricultural resilience and guarantee food availability.

A) Abiotic Stress Factors

1) Water Scarcity (Drought)

One of the most important abiotic stressors influencing agricultural yield is drought. It happens when plants do not receive enough water, which results in stunted development and lower harvests. Drought conditions can cause severe declines in crop yields, with studies indicating that wheat and maize can experience yield reductions of up to 21% and 40%, respectively, because of the across the world drought (Iqbal et al., 2022). Drought stress interferes with plant physiological processes, including photosynthesis and nutrient absorption, ultimately leading to significant yield losses (Kopecká et al., 2023).

2) Temperature Extremes (Heat Stress)

Heat stress, characterized by temperatures exceeding optimal levels for plant growth, is increasingly becoming a limiting factor for crop productivity, especially with climate change. High temperatures can damage plant proteins, disrupt enzyme activities, and negatively affect cell division, leading to reduced growth and yield. For example, it is predicted that worldwide wheat yield would decrease by around 6% for every degree Celsius that the temperature rises (Iqbal et al., 2022). Rising global temperatures due to human activity cause heat stress (HS), severely impacting plant growth and food security. Breeding, biotechnology, and molecular approaches aim to develop HS-tolerant crops. Improved crop management, including seed priming and nutrient management, also enhances HS resilience (Hassan et al., 2021).

3) Soil Salinity

Soil salinity is another abiotic stressor that adversely affects crop growth. Excessive levels of salt in the soil can cause osmotic stress, which hinders plants' ability to absorb nutrients and water. Soil salinity and sodicity affect irrigated and non-irrigated lands globally. Reclamation strategies require careful consideration of water quantity and quality, amendment types and amounts, and reclamation time. This condition can result in reduced germination rates, stunted growth, and ultimately lower crop yields. Salinity affects various physiological processes, including photosynthesis and transpiration, which are critical for plant health (Kopecká et al., 2023). Salt stress limits cereal crop productivity, with rice being most sensitive. Cereals employ various tolerance mechanisms, including Na^+ regulation and antioxidant systems. Biotechnology and hormone/osmolyte applications can mitigate salt stress effects (Alkharabsheh et al., 2021).

4) Nutrient Deficiencies

Nutrient deficiencies, such as inadequate levels of nitrogen, phosphorus, and potassium, can severely limit crop productivity. Plants require these nutrients for a number of purposes, like as photosynthesis, energy transfer, and overall growth. Deficiencies can lead to poor plant

development and reduced yields, making it essential for farmers to monitor and manage soil nutrient levels effectively (Ali et al., 2023). Secondary nutrient deficiencies (calcium, magnesium, sulfur) disrupt nitrogen balance in crops, reducing yields. Optimizing these nutrients, especially magnesium and sulfur, improves nitrogen use efficiency and productivity (Grzebisz et al., 2022). The excessive use of mineral fertilizers (N, P, K) in agriculture, while boosting food production, causes significant environmental pollution. This review examines fertilizer types, soil chemistry, application methods, environmental impacts, and sustainable alternatives like nano-fertilizers (Yahaya et al., 2023).

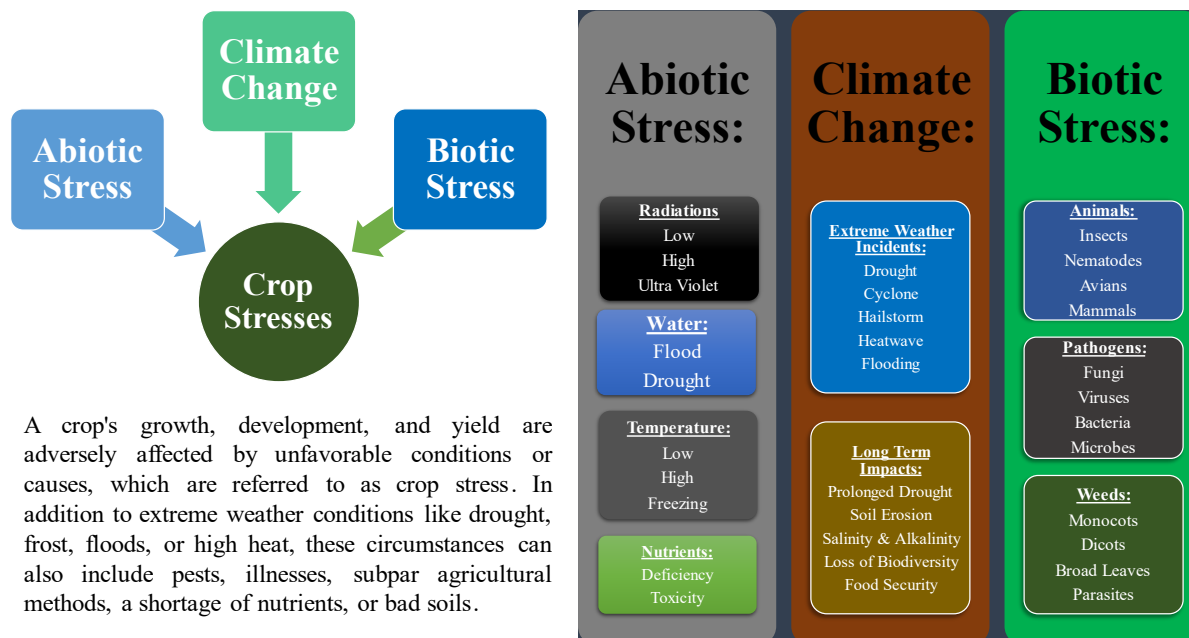


Figure 2. Main Factors of Stresses in Crops.

B) Biotic Stress Factors

1) Pests and Diseases

Significant obstacles to agricultural yield are presented by biotic stresses, such as pests and diseases. Pests can directly damage plants by feeding on them, while diseases caused by pathogens can lead to widespread crop failure. To lessen the effects of these biotic stresses, effective management techniques are essential. These include the adoption of resistant crop types and integrated pest management (IPM). Biotic stress from microbes significantly impacts global agriculture. Endophytic bacteria and fungi offer a sustainable solution, promoting plant growth, nutrient uptake, and pathogen defense through various mechanisms, thus improving crop and soil health (Chaudhary et al., 2022). Legumes are valuable crops but suffer significant yield losses from biotic (especially fungal diseases) and abiotic stresses. Fungal diseases, including rust, powdery mildew, and root rot, can cause complete crop failure. Various control methods are used to manage these diseases (Mahmoud, 2021). A article give reviews on current methodologies for detecting biotic stress (pathogens and pests) in crops, including nucleic acid,

immunological, imaging, spectroscopic, and remote sensing techniques, highlighting their strengths and limitations (Kashyap & Kumar, 2021).

2) Weeds

Weed competition for essential resources like light, water, and nutrients has a significant influence on crop production. Effective weed management is essential to minimize competition and maximize crop productivity. The interplay of abiotic and biotic stress factors significantly influences crop productivity. Given the world's expanding population and shifting climate, it is imperative to address these issues through technical advancements and sustainable farming methods in order to improve food security. Macronutrient fertilization can benefit weeds as well as crops, impacting crop yield.

Weed biomass and height often respond strongly to N, P, and K. A conceptual framework highlights key factors like emergence timing and relative nutrient responsiveness to predict weed-crop interaction outcomes. Nutrient source also plays a crucial role (Little et al., 2021). Current weed management heavily relies on herbicides and tillage, facing resistance and environmental concerns. This review advocates for ecologically-based strategies, manipulating crop diversity, management, and resources to suppress weeds while promoting diversity, offering a more sustainable approach (MacLaren et al., 2020).

2. MATERIALS AND METHODOLOGY

Concept of Precision Agriculture and its Data-Driven Approach

Precision agriculture is a cutting-edge method that maximizes crop yield by utilizing technology and data to optimize agricultural methods. Precision farming helps farmers make educated decisions and distribute resources as effectively as possible at the local level by gathering and evaluating real-time data from several sources. This data-driven approach to agriculture has the capacity to completely transform how we manage agricultural resources and cultivate crops.

Key Components of Precision Agriculture

1) Data Collection

Precision agriculture relies on the collection of data from various sources, including:

- Yield monitoring systems that track crop yields across a field.
- Remote sensing tools like drones and satellite images.
- Soil sensors that measure parameters like moisture, pH, and nutrient levels.
- Weather stations that offer up-to-date information on precipitation, temperature, and other meteorological factors.

2) Data Analysis

Following collection, sophisticated methods like machine learning and predictive analytics are used to examine the data. Farmers are able to make data-driven decisions because to these techniques, which assist in locating patterns, trends, and linkages within the data. Machine learning algorithms can be used for tasks like:

- Predicting future crop yields and quality
- Identifying areas within a field that require specific management practices
- Optimizing fertilizer and pesticide application based on soil and crop needs

3) Site-Specific Management

The precision agriculture allows for site-specific management, where farmers may apply the right amount of resources (such pesticides, fertilizer, and water) at the right time and place. With this focused approach, waste is minimized and the environmental effect of agricultural activities is reduced. By applying resources precisely, farmers can optimize yields while conserving natural resources.

Data-Driven Precision Agriculture's Advantages

- Increased Productivity:** Precision agriculture has the potential to improve crop quality and yields by streamlining management techniques and resource allocation.
- Reduced Costs:** Targeted application of inputs like fertilizers and pesticides can result in cost savings for farmers.
- Improved Sustainability:** Precision farming minimizes trash and its negative effects on the environment to encourage sustainable activities and conserving natural resources.
- Improved Decision-Making:** Farmers may make better judgments and adjust to changing circumstances more skillfully thanks to data-driven insights.

Challenges and Limitations

- High Initial Investment:** Adopting precision agriculture technologies can require significant upfront costs for equipment and infrastructure.
- Data Management:** Large data sets produced by precision agricultural equipment can be difficult to handle and analyze, requiring specialist knowledge.
- Interoperability:** Ensuring seamless integration and compatibility between various precision agriculture technologies and systems is crucial for effective implementation.

Notwithstanding these difficulties, precision agriculture is a viable strategy for effective and sustainable crop production due to its potential advantages. As technology continues to advance and costs decrease, the adoption of data-driven precision farming practices is expected to grow, transforming the future of agriculture.

Precision agriculture's use of remote sensing and geographic information systems (GIS)

Technologies for remote sensing and geographic information systems (GIS) are essential in precision agriculture by providing critical data and analytical capabilities that enhance decision-making processes. Farmers may better manage their crops and resources with the help of these technologies, and ultimately increase productivity while minimizing environmental impacts. Below is an elaboration on the role of GIS and remote sensing in precision agriculture.

Precision Agriculture Relying on Geographic Information Systems (GIS)

1) Integration and Management of Data

GIS is a computer-based system that captures, stores, analyzes, and visualizes spatial data related to geographic locations. In precision agriculture, GIS integrates various data types,

including soil characteristics, weather patterns, crop yields, and management practices. By visualizing and analyzing geographical linkages and trends, this integration enables farmers to make more informed decisions about resource allocation and crop management.

2) Spatial Analysis and Mapping

GIS enables farmers to conduct spatial analyses that identify variability within fields, such as differences in soil fertility, moisture levels, and crop health. Farmers can apply site-specific management techniques suited to the particular circumstances of several sections within a field by producing thorough maps. This focused strategy optimizes input use (e.g., fertilizers, water) and enhances overall crop productivity.

3) Decision Support Systems

GIS serves as the foundation for decision support systems connected to agriculture. These systems utilize spatial data to provide recommendations on crop selection, planting schedules, and resource management. For example, GIS can analyze historical yield data alongside current soil and weather conditions to suggest the best times to grow and the best kinds of crops, thereby improving yield potential.

Remote Sensing in Precision Agriculture

1) Real-Time Monitoring

Drones and other remote sensing technology, such as satellite photography, provide real-time crop status monitoring and environmental factors. These technologies can capture high-resolution images that provide information on the health of crops, their development phases, and stressors (e.g., drought, pest infestations). By analyzing this data, farmers can make timely measures to reduce hazards and improve crop performance (Tantalaki et al., 2019).

2) Vegetation Indices

Vegetation indices, such the Normalized Difference Vegetation Index (NDVI), are frequently used in remote sensing techniques to assess the health and vigor of plants. NDVI is calculated using spectral data from satellite or drone imagery and provides a quantitative measure of vegetation cover and health. This information is crucial for identifying areas within a field that may require additional attention or resource.

3) Water and Soil Management

Assessing irrigation requirements and tracking soil moisture levels are two further uses for remote sensing. By integrating remote sensing data with GIS, farmers can develop precise irrigation schedules that optimize water use and reduce waste. This capability is particularly important in regions facing water scarcity, as it enables more efficient management of this vital resource. Precision agriculture, which combines GIS and remote sensing technology, is a major development in farming methods. By leveraging spatial data and real-time monitoring, growers can maximize use, enhance the crop management, and improve overall productivity while minimizing environmental impacts. As these technologies continue to evolve, their role in supporting sustainable agricultural practices will become increasingly important in tackling the issues brought on by an increasing world population and climate change.

3. RESULTS AND DISCUSSIONS

Define mitigation strategies and their role in enhancing crop resilience

Mitigation strategies are essential strategies intended to reducing the negative impacts of stress factors on crop productivity, thereby enhancing crop resilience. When it comes to tackling the problems caused by climate change, these tactics are essential, pests, diseases, and nutrient deficiencies, ensuring sustainable agricultural practices and food security. Some key mitigation strategies are;

- i) Development of Climate-Resilient Crop Varieties.
- ii) Improved Water Management Practices.
- iii) Integrated Pest Management (IPM).
- iv) Nutrient Management.
- v) Adoption of Sustainable Agricultural Practices.
- vi) Use of Bio-stimulants and Priming Techniques.

1) Creation of Crop Varieties Resistant to Climate Change

Climate warming accelerates crop development, potentially reducing yields. By century's end, 39% of global cropland (under high warming) may need new varieties. With low warming, 85% could adapt by shifting existing varieties. Variety availability significantly impacts adaptation effectiveness (Zabel et al., 2021). Breeding and creating crop varieties that are adaptable to shifting climatic conditions is one of the main mitigating measures. This involves breeding crops that are resistant to heat, disease, and drought. Research has shown that such varieties can significantly improve yields under stress conditions, thereby enhancing food security. For instance, the National Initiative on Climate Resilient Agriculture (NICRA) in India focuses on developing these resilient varieties through strategic research and technology demonstrations. Some climate resilient field crops are given in the Table no.2, of South Asia which are developed by different institutes of Pakistan and India.

2) Improved Water Management Practices

Sharma et al., (2013) reported that efficient water management is critical in mitigating the effects of water shortage on crop productivity. Crop stress may be minimized and water consumption optimized with the use of methods like drip irrigation, rainwater collection, and the application of soil amendments that retain moisture. By guaranteeing sufficient moisture during crucial growth phases, efficient water management not only preserves water resources but also improves crop resilience. In Lebanon's Upper Litani Basin, crop water footprint is more sensitive to climate than soil. Mulching reduced blue water footprint by 3.6%, and combined with drip irrigation, by 4.7%, saving 6.3 and 8.3 million m³/year, respectively, but not enough for sustainable levels (Nouri et al., 2019). Climate change and drought stress necessitate efficient resource use in agriculture. Water deficit reduces crop yield by impacting nutrient uptake, assimilation, and radiation use efficiency. Improving water, nitrogen, and radiation use efficiency is crucial, especially in dry areas, to maintain food production under changing climate conditions (Ullah et al., 2019).

3) Integrated Pest Management (IPM)

Biological, cultural, physical, and chemical methods are all combined in integrated pest management (IPM) to effectively control diseases and pests. Through encouraging biodiversity

and using resistant crop varieties, IPM reduces reliance on chemical pesticides, thereby enhancing the resilience of crops against biotic stresses. This approach is essential for sustainable agriculture, as it minimizes environmental impacts while maintaining crop productivity. Water and herbivory are key factors limiting plant growth. This review examines the interactions between water, plants, and insects, exploring how integrated water management can improve pest control strategies and enhance plant resilience and agricultural sustainability, considering farming types and regional differences (Lin et al., 2024). Climate change significantly impacts plant pests and IPM effectiveness. Climate-smart pest management (CSPM) is a proposed solution, integrating all stakeholders to address pest challenges under changing climate conditions.

4) Nutrient Management

In 2024, Dr. Werner proclaimed in her report that addressing nutrient deficiencies through balanced fertilization and soil health management is vital for enhancing crop resilience. Crop health and soil fertility may be increased by using methods including crop rotation, soil testing, and the use of organic amendments. Global population growth necessitates increased food production. Abiotic stresses (temperature, salinity, moisture) negatively impact plant growth at all levels. Plant nutrition, including macro, micro, and beneficial nutrients, can effectively mitigate these stress effects and improve crop yields (Kumari et al., 2022). This, in turn, leads to better yields and increased resistance to stress factors. Intensive agriculture, while boosting food production, degrades soil and harms the environment. Sustainable agriculture, incorporating various management strategies (SCMS), is crucial for balancing food needs with environmental protection (Shah & Wu, 2019).

5) Adoption of Sustainable Agricultural Practices

Organic farming practices that focus on reduced tillage and cover cropping can significantly improve soil health and climate resilience, according to the research:

Reduced Tillage

It has been researched that improving soil organic matter, soil structure, and water-holding capacity in organic systems involves reducing the frequency, depth, and severity of tillage (Krauss et al., 2022). For example, one study found that "continuously reduced tillage in organic farming has been proven to enhance soil quality" by increasing topsoil organic carbon by 25% and microbial biomass and activity by over 30% (Krauss et al., 2020). Techniques like chisel plowing and double-layer plowing can provide similar benefits to full inversion plowing, while minimizing soil disturbance (Zikeli et al., 2013). Sustainable agriculture balances profitable farming with natural resource preservation. It's not limited to low-input or organic methods but requires increased energy efficiency alongside higher energy input, particularly in tillage, which must be tailored to specific soil conditions.

Cover Cropping

Incorporating cover crops into organic rotations is another key practice for building healthy, climate-resilient soils. Boosted organic matter, better soil structure, improved water penetration, and soil cover are all facilitated by cover crops (Zikeli et al., 2013). As one resource states, cover crops "help build soil organic matter, which improves soil structure, water-holding

capacity, and nutrient cycling". This enhances the soil's ability to withstand both droughts and heavy rainfall events. By combining reduced tillage and cover cropping, organic farmers can create a synergistic effect, further enhancing soil health and climate resilience. As the research indicates, these practices "have the potential to increase total soil carbon stocks" and improve overall soil quality and productivity (Krauss et al., 2020).



Figure 3. Significance of Soil Health and Major Constituents of Soil Organic Matter.

Reduced Carbon Sequestration and Greenhouse Gas Emissions

According to current research, organic farming methods may greatly enhance carbon sequestration and reduce greenhouse gas emissions in a number of important ways, including:

Reduced Greenhouse Gas Emissions

Dr. Brook in 2022, exemplified in her report at NRDC that organic farming avoids the use of synthetic fertilizers and pesticides, which are highly energy-intensive to produce and contribute to greenhouse gas emissions like nitrous oxide (N₂O). Studies show that organic farming can reduce direct agricultural greenhouse gas emissions by around 20% compared to conventional systems.

A study categorizes that port measures for reducing greenhouse gas emissions and improving energy efficiency. Research is concentrated on developed countries, and a combination of measures is crucial for port decarbonization (Alamouh et al., 2020). Geothermal technologies, ranging from 7 °C to 350 °C, offer cost-efficient, low-carbon baseload energy. With a social cost of carbon of \$25, geothermal needs to be below 50 kg (CO₂)/MWh and \$30-60/MWh to compete with coal and CCGT (Ball, 2021).

Enhanced Carbon Sequestration

Wetlands are crucial for carbon sequestration, but their potential is declining. This review analyzes measures to enhance wetland carbon sequestration, focusing on ecological and socio-economic impacts. Conservation and incentivizing non-manipulative measures are recommended, considering potential risks to wetland ecosystems (Were et al., 2019). Soil organic matter may be increased by using organic farming techniques such as cover crops, less tillage, and organic amendments and the soil's capacity to sequester and store atmospheric carbon (Jorgen et al., 2022). Additionally, Dr. Brook in 2022 disclosed that soils may potentially absorb more carbon than the farming sector as a whole emits between 2020 and 2100 if organic and other agroecological methods were widely adopted. Improved soil management is crucial for food security and climate change mitigation. Practices increasing carbon input (e.g., compost) or reducing losses can sequester up to $714 \text{ kg C ha}^{-1} \text{ y}^{-1}$. Subsoil carbon sequestration and socio-economic factors need further study (Tiefenbacher et al., 2021).

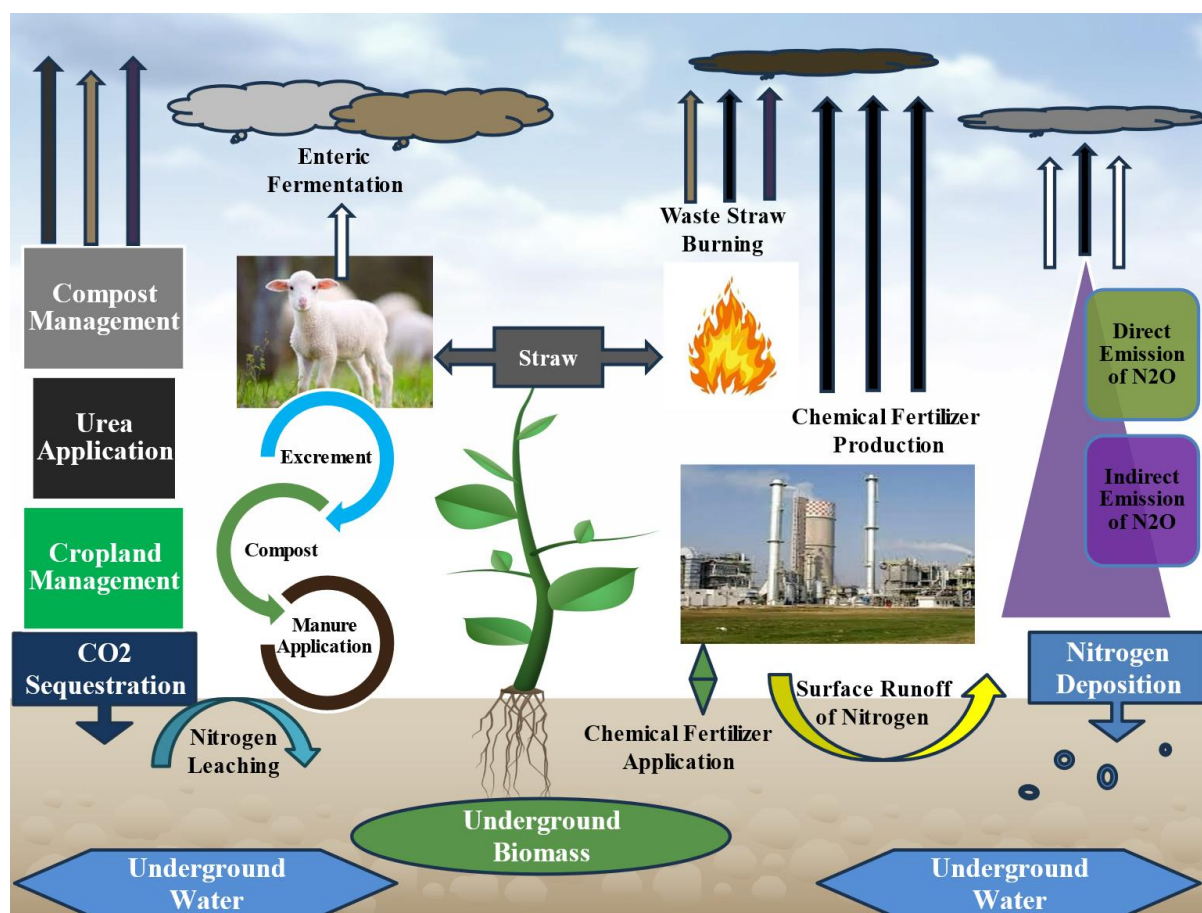


Figure 4. Detailed Elaboration of Green House Gas Emissions and Sequestrations.

Reduced Reliance on Fossil Fuels

Dr. Vinopal in Oct., 2019, reported in her article, titled; “How More Organic Farming Could Worsen Global Warming” that the organic farming is less dependent on fossil fuel-based

inputs like synthetic fertilizers and pesticides, making it more resilient to supply chain disruptions and price volatility. Farmers may benefit from this as a buffer against the effects of climate change and other shocks to the world. In summary, the study shows that by lowering greenhouse gas emissions, raising carbon sequestration, and creating more resilient agricultural systems, organic farming methods may significantly contribute to climate change adaptation and mitigation. Using sustainable farming techniques may improve soil health, retain more water, and boost biodiversity. Examples of these techniques include conservation tillage, cover crops, and agroforestry. These practices help mitigate the impacts of abiotic stresses like drought and salinity, contributing to overall crop resilience (Karri et al., 2024).

6) Use of Bio-stimulants and Priming Techniques

Biostimulants, as well demonstrated by 2024, Dr. Werner in 2024, are the substances that enhance plant growth and stress tolerance. They can improve nutrient uptake, stimulate root development, and enhance resistance to environmental stresses. Additionally, priming techniques prepare seeds for better performance under stress conditions, improving germination and early growth. Mitigation strategies play a crucial role in enhancing crop resilience against various stress factors, ensuring sustainable agricultural production and food security. By focusing on developing resilient crop varieties, improving water and nutrient management, and adopting sustainable practices, farmers are more able to handle the challenges posed by climate variabilities and other stressors. Agricultural systems are more sustainable overall when these tactics are implemented, in addition to increasing crop yields.

Agronomic Practices for Mitigation

A) Water Management

Discuss traditional irrigation methods and their limitations

Traditional irrigation methods have been used for centuries, but they often suffer from limitations that may affect the efficiency of water consumption and agricultural output. Some of the traditional irrigation methods are well explained in the Figure 3.

Limitations of Traditional Irrigation Methods:

- i. Water Inefficiency:** Due to evaporation, runoff, and deep percolation, traditional techniques frequently cause large water losses, which results in low water usage efficiency (Florafex.com 2023).
- ii. Uneven Water Distribution:** Uncontrolled water application can cause some areas to be over-irrigated while others remain under-irrigated, leading to uneven crop growth and reduced yields (Housing.com 2023).
- iii. Labor-Intensive:** Many traditional methods, such as pulling ropes or manually operating valves, require significant human labor and time (Housing.com 2023).
- iv. Potential for Waterlogging and Salinization:** Crop development and yield can be significantly impacted by waterlogging and soil salinization caused by improper management of conventional irrigation systems (Geeksforgeeks.com 2024).
- v. Limited Suitability for Sloping Terrain:** Some traditional methods, like furrow irrigation, are challenging to implement on sloping terrain and require significant land leveling efforts (Florafex.com 2023).

To address these limitations, modern irrigation methods have been developed that offer greater control, efficiency, and suitability for various terrain and crop types. In comparison with conventional irrigation techniques, these strategies—like drip irrigation and sprinkler systems - can greatly increase agricultural yields, lower labor costs, and improve water usage efficiency.

Explore Advanced Irrigation Techniques

Advanced irrigation techniques are revolutionizing water management in agriculture by improving water use efficiency and crop productivity. Among these methods are drip irrigation, sprinkler irrigation, and other cutting-edge systems that minimize water loss through evaporation and runoff by supplying water directly to the root zone of crops.

1) Drip Irrigation

In 2024, a reported is generated by the Farm Raise site, which explained how drip irrigation, often referred to as micro-irrigation, uses a system of emitters, pipes, tubing, and valves to administer water gradually and directly to the plant's root zone. This technique allows for precise water application, reducing water waste and promoting efficient use of water resources. In comparison to more conventional techniques like flood irrigation, drip irrigation may improve water consumption efficiency by up to 90%.



Figure 5. Central Pivot System at Nishat Agri. Farm (Pvt.) Ltd., Pindi Bhattian, Hafizabad, Pakistan.

2) Sprinkler Irrigation

Sprinkler irrigation systems use revolving nozzles attached to pipelines to spray water over the crop canopy, mimicking natural rainfall. These systems are suitable for irregular-shaped fields and can be adapted to various terrain types. Sprinkler irrigation can achieve water use efficiencies of 70-90%, depending on factors such as wind, evaporation, and system design.

3) Subsurface Drip Irrigation (SDI)

Installing drip lines or emitters beneath the soil's surface, usually between 10 and 50 cm, is known as subsurface drip irrigation. This technique minimizes evaporation losses, reduces weed growth, and allows for uninterrupted field operations. SDI can achieve water use efficiencies of 80-95% and is particularly useful for high-value crops and orchards.

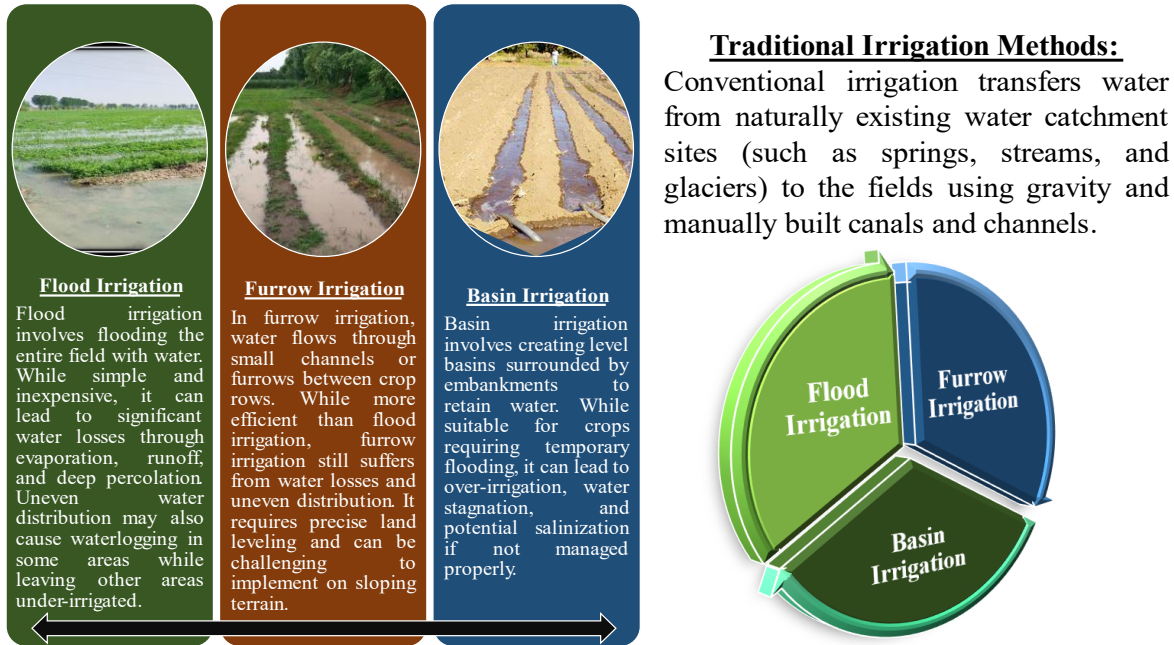


Figure 6. Traditional Irrigation Methods
(Source: Florafex.com).

4) Precision Irrigation

In 2024, a reported is generated by the Farm Raise site, as explained above that precision irrigation techniques, such as variable-rate irrigation (VRI) and sensor-based irrigation, use advanced technologies to optimize water application based on real-time data. In sensor-based systems, irrigation events are triggered by soil moisture sensors; in VRI systems, throughout the field, water application rates are modified based on crop water needs, terrain, and soil type.

5) Alternate Furrow Irrigation

The alternate furrow irrigation, water is applied to every other furrow, allowing the dry furrows to act as a pathway for air and facilitating better root growth. When compared to traditional furrow irrigation, this method can save 30–50% of the water use while preserving yields.

To overcome these challenges, governments and organizations are providing financial incentives, technical support, and capacity-building programs to encourage the adoption of advanced irrigation techniques. Farmers may maximize water consumption, boost output, and support the sustainability of agricultural systems by adopting these cutting-edge techniques.

Table 1. Benefits, Challenges and Limitations are briefly described in Table.

Sr. No.	Benefits of Advanced Irrigation Techniques	Challenges and Limitations
1	Improved water uses efficiency and reduced water consumption.	High initial investment costs for advanced irrigation systems.
2	Enhanced crop yields and quality.	Potential for clogging of emitters and drip lines.
3	Reduced nutrient leaching and improved fertilizer use efficiency.	Increased management complexity and the need for skilled labor.
4	Decreased labor requirements and energy costs.	Compatibility issues with certain soil types and crop systems.
5	Increased resilience to drought and climate variability.	-----

B) Crop Management Strategies

Crop rotation and its advantages (disease suppression, nutrient cycling, improved soil structure)

Crop rotation is a technique used in agriculture whereby different crops are grown on a given plot of land over several growing seasons. This method is widely recognized for its numerous advantages, particularly in terms of disease suppression, nutrient cycling, and improved soil structure. Below is an exploration of these benefits.

1) Disease Suppression

Crop rotation is an effective strategy for managing soil-borne diseases. A lot of viruses are crop-specific and can linger in the soil for a long time. Crop rotation allows farmers to disrupt the life cycles of these pathogens, which lowers disease incidence and their populations. When non-host crops are planted in rotation, for example, studies show that crop rotational variety improves the soil's ability to suppress disease by lowering pathogen abundances. This practice can significantly lower the severity of diseases such as Fusarium wilt and root rot in subsequent crops (Peralta et al., 2018).

2) Nutrient Cycling

In 2023, it was reported that the nutrients that each crop needs and contributes to the soil vary. For example, legumes are well recognized for fixing nitrogen from the atmosphere, which enriches the soil for crops that may need more nitrogen later on. This natural nutrient cycling enhances soil fertility and reduces the need for synthetic fertilizers. Studies have shown that incorporating legumes into crop rotations can improve nitrogen availability and overall soil health, leading to better crop performance in subsequent seasons.

3) Improved Soil Structure

Dr. Davidson in 2024, from Taurus Agricultural Marketing, presented that crop rotation contributes to improved soil structure through the diversity of root systems that different crops

develop. Deep-rooted crops can break up compacted soil layers, enhancing aeration and water infiltration, while shallow-rooted crops can improve surface soil structure. This diversity promotes better soil aggregation and increases the organic matter content as different crops contribute varying amounts of biomass. Improved soil structure facilitates better water retention and reduces erosion, ultimately leading to healthier and more productive soils.

In nut shells, crop rotation is a vital agricultural practice that offers significant benefits, including disease suppression, enhanced nutrient cycling, and improved soil structure. By strategically planning crop rotations, a more robust agricultural system that encourages farmers to sustainability and productivity. The integration of these practices enhances agricultural production while also promoting the soil's and the environment's long-term health.

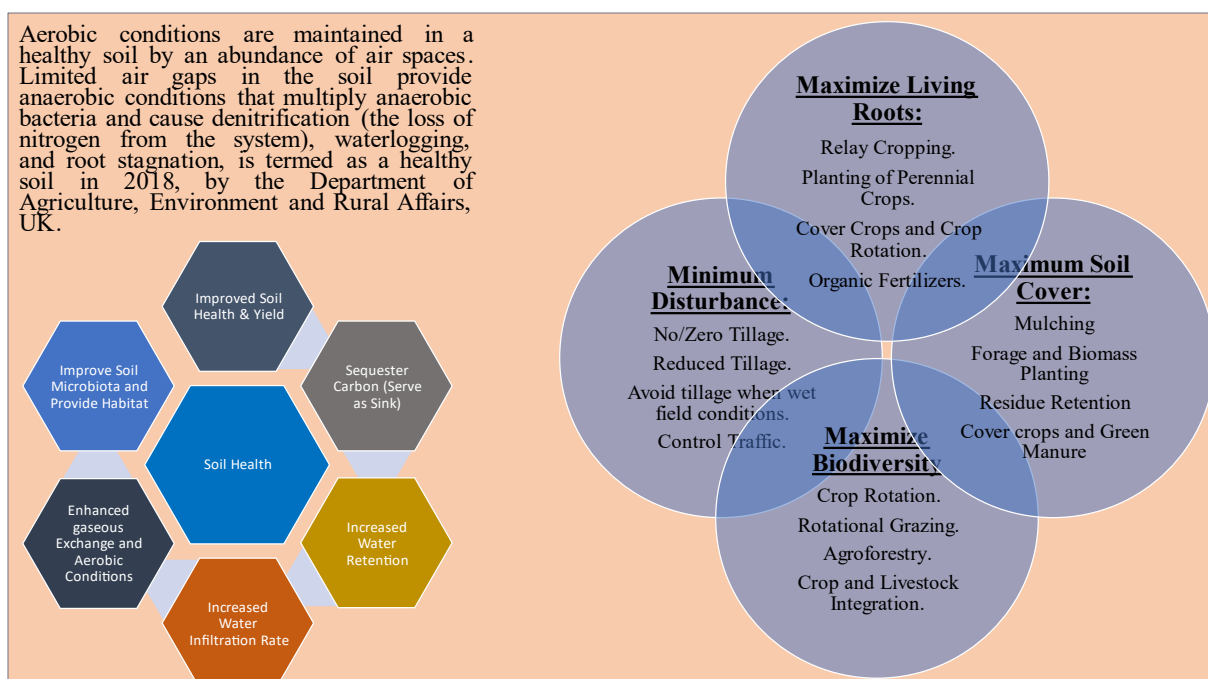


Figure 7. Soil Health by adding Organic Matter.

Figure 8. Principles of Soil Health.

Fundamentals of Soil Health

The Nguyen in December 2023 provides a clear demonstration of the fundamentals of soil health.

1) Reduce Uneven Soil Surfaces

Reduce soil disturbance by mechanical, chemical, and physical means by using techniques such as reduced tillage and no-till farming. safeguards soil organisms that provide natural fertility, minimizes erosion, and maintains the structure of the soil.

2) Maintain Soil Coverage

To prevent erosion from wind and water, always keep the soil covered by plants or leftovers. Provides food and habitat for soil organisms and prevents moisture evaporation.

3) Maximize Biodiversity

In the soil ecosystem, aim for a diversity of plant and animal species. Improves ecological function, with each species contributing to the upkeep of healthy soil.

4) Maintain a Living Root

For as long as possible throughout the year, keep live roots in the soil. Living roots create habitat for soil organisms, connect the soil with stabilizing fibers, and absorb water.

Selection of Stress-Tolerant Crop Varieties

In contemporary agriculture, choosing crop types that can withstand stress is essential, especially in light of climate change and the rise in abiotic stressors like heat, salt, and drought. These varieties are bred to withstand adverse environmental conditions, ensuring food security and agricultural sustainability. An overview of the significance and benefits of selecting stress-tolerant crop varieties, is given below.

1) Mitigating Climate Change Impacts

As climate change intensifies, traditional crops may struggle to adapt to new environmental conditions. Stress-tolerant varieties are essential for maintaining agricultural productivity under these changing conditions. To improve resilience among smallholder farmers confronting climate variability, the CGIAR, for example, has created a number of rice, maize, and wheat varieties with greater tolerance to climatic shocks. These varieties have been implemented in places like Africa and Asia.

2) Enhancing Food Security

Particularly in areas vulnerable to harsh weather events, stress-tolerant cultivars are essential for guaranteeing food security. Research indicates that drought-tolerant maize varieties can yield approximately 20% more under stress-prone conditions compared to traditional varieties, significantly contributing to food availability and stability in vulnerable areas. In sub-Saharan Africa, this is especially crucial, where over 200 stress-tolerant maize varieties have been released, impacting millions of households and improving food security.

3) Improving Nutritional Quality

In addition to resilience against environmental stresses, many stress-tolerant varieties are being developed with enhanced nutritional profiles. For example, biofortified crops like pro-vitamin A rich maize, orange-fleshed and sweet potato varieties not only address climate resilience but also contribute to improved nutrition in populations suffering from micronutrient deficiencies. This dual benefit of stress tolerance and nutritional enhancement is vital for combating malnutrition.

4) Economic Benefits for Farmers

The adoption of stress-tolerant varieties can lead to significant economic gains for farmers. Increased yields and reduced variability in crop production can enhance household incomes. For instance, the introduction of drought-tolerant rice varieties in Senegal has resulted

in substantial yield increases, translating to higher incomes for adopters. The economic internal rate of return for these investments is estimated at 72%, highlighting the financial viability of adopting stress-tolerant crops.

5) Sustainability and Resource Efficiency

Stress-tolerant varieties contribute to more sustainable agricultural practices by improving resource use efficiency. For instance, crops that can thrive in saline soils or under drought conditions reduce the need for irrigation and fertilizers, leading to lower environmental impacts and better resource management. In dry and semi-arid areas where water shortage is a major worry, this is especially pertinent (Boraiah et al., 2023).

The selection of stress-tolerant crop varieties is a vital component of contemporary agricultural strategies aimed at enhancing resilience to climate change, ensuring food security, and improving nutritional outcomes. A changing climate can provide issues for agricultural systems, but they can also be used to make them more resilient by development and application of these types. Achieving these objectives requires both the distribution of these types to farmers and ongoing investment in research and development.

C) Soil Health Management

Importance of Soil Health for Crop Productivity and Stress Resilience

Crop productivity and resistance to environmental shocks are significantly influenced by soil health. Healthy soils not only support plant growth but also enhance the ability of crops to withstand adverse conditions such as drought, flooding, and nutrient deficiencies. Exploration of the importance of soil health for crop productivity and stress resilience, described as following.

The Value of Healthy Soils for Crop Production

- 1) Availability of nutrients
- 2) Infiltration and Retention of Water
- 3) Aeration and Structure of the Soil
- 4) Microbial Activity and Biodiversity

Healthy soils are rich in organic matter, which plays a vital role in nutrient cycling and availability. In addition to strengthening the soil's structure and retaining water, organic matter in the soil releases nutrients that are essential for plant growth. Research indicates that up to 60% of crop yield can be attributed to soil fertility, highlighting the importance of maintaining healthy soil for optimal productivity. Soil health significantly impacts its ability to retain and infiltrate water. Healthy soils with high organic matter content can hold more water, which is crucial during dry spells. For instance, every 1% increase in soil organic matter can enhance water retention by approximately 25,000 gallons per acre. This capacity is vital for sustaining crops during periods of drought and reducing the impact of extreme weather occurrences, as seen by the U.S., drought of 2012, where fields with healthy soils showed better resilience compared to those managed with conventional tillage practices (Kaisi et al., 2016).

Good soil health promotes optimal soil structure, which is essential for root development and nutrient uptake. Diverse root systems from various crops improve soil aggregation and porosity, enhancing aeration and water movement within the soil. Improved soil structure leads

to better root growth, which is crucial for accessing nutrients and water, thereby increasing crop resilience to stress. A varied population of microorganisms that promote soil fertility, disease prevention, and nutrient cycling are found in healthy soils. Strong microbial communities accelerate the decomposition of organic debris and release nutrients that are easily absorbed by plants. Furthermore, diverse microbial populations can help suppress soil-borne diseases, reducing the need for chemical inputs and enhancing crop resilience to pathogens (Stokes et al., 2023).

Importance of Soil Health for Stress Resilience

1) Drought Resistance

Healthy soils can significantly improve a crop's ability to withstand drought conditions. The enhanced water-holding capacity of soils rich in organic matter allows crops to access moisture during dry periods, reducing stress and maintaining productivity. Studies have shown that crops grown in healthy soils exhibit greater resilience to drought, resulting in higher yields compared to those in degraded soils (Miner et al., 2020).

Table 2. Drought and Heat Tolerant Crops.

Crop Type	Scientific Names	Varieties	Source
Wheat	<i>Triticum aestivum</i>	Chakwal-86, Rawal-87, Pothwar-93, Kohsar-95, Chakwal-97, G.A-2002, Chakwal-50, Bars-09, Dharabi-11, Ehsan-16, Fateh Jang-16, Barani-17, MA-2021, Shiraz-23.	Barani Agricultural Research Institute, Chakwal, Punjab, Pakistan.
Maize	<i>Zea mays</i>	PEHM-1 Pratap, Makka-3 Pratap, Makka-5 Pratap, Hybrid Makka-1, Mukta.	Indian Agricultural Research Institute, New Delhi, India.
Pearl Millet	<i>Pennisetum glaucum</i>	Raj-171, GHB-538, RHB-177, HHB-67 (I), RBH-177, RBH-173, RBH-154.	Rajasthan Agricultural Research Institute, Jaipur, India.
Barley	<i>Hordeum vulgare</i>	RD-2660, RD-2592, JB-58	Rajasthan Agricultural Research Institute, Durgapura, India.
Sorghum	<i>Sorghum bicolor</i>	M-35-1, Phule Chitra, Phule Vasudha, Phule Panchami, CSH19R, CSV-18, Phule Anuradha, Phule Roshani (RPASV-3), Phule Madhur (RSSGV-46)	Mahatma Phule Krishi Vidyapeeth (Agriculture University), Rahuri, Ahmednagar, India.

Sugarcane	<i>Saccharum officinarum</i>	Co-86032, Co-85019, Co-94008, Co-94004, Co-94012, Co-2001-13, Co-0218, Co-0403, Co-06027, Co-09004 (Amritha), Sugarcane Co-06022, Uphar (Co-10026)	ICAR-Sugarcane Breeding Institute, Coimbatore, Tamil Nadu, India.
Chickpea	<i>Saccharum officinarum</i>	JG-16, JG-6, JAKI-9218, JG-11, RVG-201, Raj Vijay Gram (RVG-202), RVG-203, JSC-55, JSC-56	Rajmata Vijayaraje Scindia Krishi Vishwavidyalaya, (Agriculture University) Gwalior, India.
Soybean	<i>Glycine max</i>	JS-95-60, JS-9305, JS-335	Jawaharlal Nehru Krishi Vishwa Vidyalaya, Jabalpur, India.
Cotton	<i>Gossypium arboreum</i>	SVPR-4, SVPR-1 (TSHH-0629) Hybrid	Cotton Research Station, Srivilliputhur, Tamil Nadu, India.
Rice	<i>Oryza sativa</i>	IR-64 Drt I (IET 22836) (DRR Dhan 42) IR-64 Drt I (IET 22836) (DRR Dhan 42) IR-64 Drt I (IET 22836) (DRR Dhan 42) IR-64 Drt I (IET 22836) (DRR Dhan 42)	Indian Institute of Rice Research, Hyderabad, India.

Some Varieties of Major Field Crops of Asia, which are Drought & Heat-Tolerant.

2) Flood Tolerance

In addition to drought resistance, healthy soils can better manage excess water during heavy rainfall events. Well-structured soils with good infiltration rates can reduce surface runoff and reduce the possibility of waterlogging, which can severely damage crops. This ability to manage water effectively is crucial in the face of increasingly variable weather patterns connected to the changing climate (Kaisi et al., 2016).

3) Nutrient Cycling and Stress Mitigation

Healthy soils enhance nutrient cycling, ensuring that crops have access to essential nutrients even under stress conditions. For example, the presence of beneficial soil microbes can improve nutrient availability during periods of stress, enabling crops to maintain growth and yield despite adverse conditions. This nutrient resilience is particularly important in regions where soil fertility is challenged by climatic extremes.

In short, soil health is fundamental to achieving high crop productivity and resilience against environmental stresses. By keeping soils healthy using techniques like organic amendments, minimal tillage, and cover crops, farmers can enhance nutrient availability,

improve water retention, and foster beneficial microbial communities. In the face of climate change, these methods not only promote short-term crop yields but also long-term agricultural sustainability and food security.

4. CONCLUSION

In conclusion, maintaining healthy soil is paramount for achieving sustainable and resilient agricultural systems. Farmers may grow crops that are more resilient to environmental challenges like drought, floods, and nutrient deficits by encouraging techniques that improve soil health, such as cover crops and less tillage. This not only translates to higher crop yields and improved food security but also fosters a more sustainable agricultural approach. Furthermore, advancements in precision agriculture offer powerful tools to optimize resource use and mitigate stress factors. By leveraging data collected through various sources (soil sensors, remote sensing) and analyzed with machine learning, Farmers are able to allocate resources at a fine level with knowledge. This targeted, data-driven approach minimizes waste, reduces environmental impact, and ultimately enhances crop productivity. The combined focus on soil health management and the adoption of precision agriculture technologies presents a promising pathway for ensuring long-term agricultural sustainability. By adopting these tactics, farmers can guarantee food security for everyone while making a substantial contribution to reducing the effects of climate change and an expanding world population.

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