
Soil Nutrients, Crop Yield, and Agricultural Practices: A Survey

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Abstract

This survey paper explores the complex interactions between soil nutrients, crop yield, and agricultural practices, emphasizing the importance of integrated management strategies for sustainable agriculture. Soil nutrients are fundamental to plant growth, influencing physiological processes and crop yield outcomes. The adoption of best management practices (BMPs) and the incorporation of beneficial plant microbiomes enhance soil health and productivity. Advanced technologies, such as machine learning and remote sensing, are pivotal in optimizing agricultural outputs by improving crop selection and yield predictions. The paper highlights the role of sustainable agricultural practices (SAPs) in mitigating environmental impacts, enhancing resilience against climate variability, and addressing contemporary agricultural challenges. Key findings include the effectiveness of agrivoltaic systems in promoting land use efficiency, the potential of biopesticides as sustainable alternatives to conventional pesticides, and the benefits of organic weed control methods. The survey underscores the need for adaptive strategies to overcome barriers to SAP adoption, such as economic constraints and inadequate knowledge dissemination. Future research directions focus on integrating traditional knowledge with modern practices, utilizing advanced modeling techniques, and fostering policy reforms to support sustainable agriculture. By leveraging these insights, the agricultural sector can enhance resilience, productivity, and sustainability, addressing the pressing challenges posed by climate change and resource limitations while ensuring food security for future generations.

1 Introduction

1.1 Interconnectedness of Soil Nutrients, Crop Yield, and Agricultural Practices

The interconnectedness of soil nutrients, crop yield, and agricultural practices is essential for sustainable agricultural systems. Soil nutrients are critical for plant growth, influencing physiological processes that directly affect crop yields. Integrating beneficial plant microbiomes into agricultural practices enhances soil health and crop yield, underscoring the interdependence of microbial communities and nutrient dynamics [1]. Furthermore, the adoption of best management practices (BMPs) is crucial for mitigating agricultural non-point source pollution, improving water quality, and ensuring sustainable crop production [2].

Optimizing agrivoltaic systems exemplifies the synergy between food and energy production, illustrating how integrated approaches can enhance land use efficiency [3]. This reflects the broader interconnectedness of agricultural practices with ecosystem services and socio-economic implications, as demonstrated by the Green Revolution's impact on ecosystem services in India [4].

Incorporating biopesticides into farming practices reduces the negative externalities of conventional pesticides [5], aligning with the need for sustainable practices that address challenges such as climate change and resource limitations [6]. Additionally, employing machine learning for crop selection

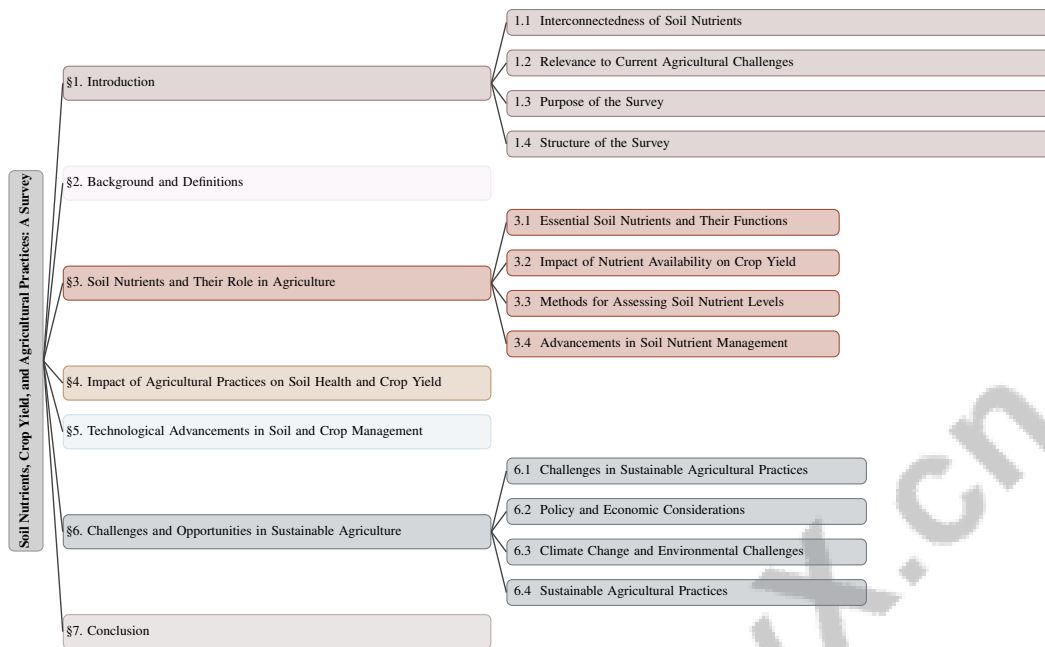


Figure 1: chapter structure

based on soil nutrient levels emphasizes informed decision-making to optimize resource use [7]. Such technological advancements are vital for enhancing crop productivity and sustainability.

The relationships between soil metabolites and physicochemical properties in intercropping systems, such as sugarcane/peanut, illustrate complex interactions among soil nutrients, crop yield, and agricultural practices [8]. These interactions are critical for developing strategies that enhance agricultural resilience and productivity. Moreover, a Bayesian hierarchical framework for crop yield modeling highlights the necessity of sophisticated approaches to emulate complex agricultural systems, further emphasizing the interconnectedness of soil nutrients, crop yield, and agricultural practices [9]. Understanding these intricate relationships is vital for advancing sustainable agricultural practices that adapt to the evolving demands of global food systems.

1.2 Relevance to Current Agricultural Challenges

The agricultural sector confronts multifaceted challenges, including climate change, resource scarcity, and the imperative to ensure food security for a growing global population. Innovative strategies that enhance crop production while promoting sustainability are essential. The adoption of sustainable agricultural practices (SAPs) is crucial for mitigating environmental impacts and improving resilience against climate variability. For instance, in Kentucky, SAP adoption has bridged knowledge gaps and overcome barriers to sustainable farming, demonstrating their potential to address contemporary agricultural challenges [10].

Advanced technologies, such as machine learning for crop selection and disease forecasting, are pivotal in optimizing agricultural outputs, especially in regions like Bangladesh where soil nutrition knowledge is limited [7]. Additionally, conservation agriculture (CA) has proven effective in enhancing food security among smallholder farmers in Mozambique, highlighting the importance of sustainable land management practices in addressing soil nutrient deficiencies and improving crop yields [11].

In organic farming, inorganic and organic weed control methods are vital for preventing yield losses and reducing reliance on harmful herbicides, thereby promoting more sustainable crop production systems [12]. The use of generative weather models in crop yield prediction underscores the necessity for accurate weather inputs, which are critical for adapting to climatic variability and ensuring reliable food production [13].

Agroecological approaches are increasingly recognized for their contributions to sustainable food systems, promoting biodiversity and ecosystem services essential for food security and nutrition [14]. Agricultural diversification strategies enhance financial profitability and ecosystem resilience over the long term [15]. Timely and accurate crop production estimations are vital for effective food security responses, as demonstrated by the need for early estimation accuracy in Senegal [16]. The adoption of BMPs is significant in combating agricultural non-point source pollution, which impacts water quality and necessitates sustainable agricultural solutions [2].

Transforming food systems to ensure food security and sustainable development requires addressing inadequacies in current agricultural policies, as highlighted in recent surveys [6]. Understanding intercropping effects on soil quality and crop yields further underscores the importance of sustainable practices in contemporary agriculture [8]. These integrated approaches are essential for overcoming the pressing challenges faced by the agricultural sector today.

1.3 Purpose of the Survey

This survey aims to synthesize and critically evaluate existing research on the complex interactions between soil nutrients, crop yield, and agricultural practices, focusing on leveraging advanced methodologies to improve prediction models and management strategies. By integrating zone-based heterogeneous datasets of soil and weather, the survey seeks to enhance the prediction accuracy of crop yields, particularly for winter wheat, which is vital for optimizing agricultural outputs [17]. Additionally, it examines the effectiveness and reliability of biofertilizers in augmenting crop yields and reducing dependency on chemical fertilizers [18].

The survey addresses challenges associated with providing accurate agricultural meteorological recommendations, often compromised by integrating diverse datasets leading to suboptimal advice [19]. In evaluating the physiological effects of sulfur on various crop species, the survey aims to elucidate its potential role in promoting sustainable agricultural practices [20].

Moreover, it investigates agrivoltaic systems' potential to balance crop yield with energy production, employing techno-economic optimization models to improve land use efficiency [3]. This is complemented by examining microclimatic conditions within agrivoltaic systems, which are crucial for assessing crop yield potential [21].

A significant component involves identifying research priorities for harnessing plant microbiomes to enhance sustainable agriculture [1]. The survey also highlights the negative externalities associated with conventional pesticides and explores biopesticides as a sustainable alternative [5]. It evaluates the efficacy of organic weed control prototypes, which have demonstrated high classification accuracy, contributing to sustainable agricultural practices [12].

Ultimately, this survey seeks to provide a comprehensive understanding of the factors influencing agricultural productivity and sustainability, informing future research directions and policy development. It addresses the need for transforming food systems to align with the 2030 Agenda for Sustainable Development [6], establishes accuracy requirements for early estimators of cropland area, crop area, and crop yield based on historical data trends and variability [16], and reviews factors influencing the adoption of BMPs while addressing existing knowledge gaps [2]. Additionally, it outlines a new intelligent agricultural decision-support system integrating soil nutrition, weather forecasting, and disease prediction [7], and addresses the impact of intercropping on soil nutrient dynamics and metabolite profiles [8].

1.4 Structure of the Survey

This survey is meticulously structured to provide a comprehensive exploration of the intricate relationships between soil nutrients, crop yield, and agricultural practices. The paper is organized into seven main sections, each focusing on a critical aspect of the topic. The introduction elucidates the interconnectedness of soil nutrients, crop yield, and agricultural practices, along with their relevance to current agricultural challenges, while outlining the survey's purpose and objectives.

The second section offers essential background and definitions, providing a detailed overview of key concepts such as soil nutrients, crop yield, and agricultural practices. It discusses the role of soil nutrients in crop production and examines the impact of various agricultural practices on soil health and crop yield.

The third section delves into soil nutrients and their agricultural roles, identifying essential nutrients and their functions, analyzing the impact of nutrient availability on crop yield, and reviewing methods for assessing soil nutrient levels. It highlights recent advancements in soil nutrient management, emphasizing innovative strategies for optimizing nutrient use.

The fourth section examines the impact of agricultural practices on soil health and crop yield, evaluating practices such as crop rotation, cover cropping, and conservation tillage. It also addresses challenges in measuring soil and crop dynamics, emphasizing the need for precise evaluation methods.

The fifth section explores technological advancements in soil and crop management, focusing on remote sensing, machine learning, and precision agriculture technologies that enhance soil nutrient management and crop yield prediction. It highlights the integration of technology and data for improved agricultural outcomes.

The sixth section identifies challenges and opportunities in sustainable agriculture, discussing barriers to sustainable practices, policy and economic considerations, and the impact of climate change and environmental factors. It explores sustainable agricultural practices that promote long-term soil health and crop productivity.

Finally, the conclusion summarizes the key findings of the survey, emphasizing the importance of integrated soil nutrient management and sustainable agricultural practices. It explores future research avenues and examines the transformative influence of emerging technologies, such as the Internet of Things (IoT) and remote sensing, on agricultural practices. The text synthesizes insights from various studies, highlighting how these technologies can enhance precision agriculture, optimize crop management, and contribute to sustainable farming practices. It also addresses the challenges of integrating advanced technologies with traditional agricultural methods, emphasizing the need for improved data management and the potential for increased productivity and environmental sustainability [22, 23, 24, 25]. The following sections are organized as shown in Figure 1.

2 Background and Definitions

2.1 Definitions of Soil Nutrients and Agricultural Practices

In agricultural sciences, defining soil nutrients, crop yield, and agricultural practices is essential for understanding their complex interactions and implications for sustainable agriculture. Soil nutrients include macronutrients like nitrogen, phosphorus, and potassium, which are needed in large amounts, and micronutrients such as iron, manganese, and zinc, required in trace amounts. These nutrients are crucial for plant growth, affecting physiological processes and crop yield, thereby necessitating efficient nutrient management to optimize crop selection and agricultural outputs [7].

Crop yield, the quantity of agricultural produce harvested per unit area, is a critical measure of productivity, influenced by soil fertility, climate, and agricultural practices [16]. Accurate crop yield assessments are vital for predicting food security outcomes and managing variability [16].

Agricultural practices include techniques aimed at maximizing crop production while maintaining soil health, from traditional methods with minimal environmental impact to modern industrial approaches [2]. Best management practices (BMPs) are crucial for improving water quality and mitigating pollution, highlighting the need for sustainable land management. Integrating beneficial plant microbiomes enhances soil health and crop yield, demonstrating the interdependence of microbial communities and nutrient dynamics [1].

Sustainable agricultural practices are critical for enhancing crop yield without adverse environmental impacts. Their adoption, as seen in Kentucky, underscores their importance in addressing contemporary agricultural challenges [10]. Innovative approaches like biopesticides offer sustainable alternatives to conventional pesticides, reducing negative externalities and promoting environmental health [5].

These definitions provide a foundation for exploring the dynamics of soil nutrients, crop yield, and agricultural practices, which are critical for advancing sustainable agricultural systems and addressing challenges posed by a growing global population and the inadequacy of current agricultural systems in meeting demands amidst climate change and resource depletion [14].

2.2 Role of Soil Nutrients in Crop Production

Soil nutrients are vital for plant growth and agricultural productivity, driving physiological and biochemical processes crucial for crop development and yield. Macronutrients such as nitrogen, phosphorus, and potassium are critical for key processes like photosynthesis, energy transfer, and nutrient uptake [26]. Phosphorus availability can limit growth in certain soils, such as alkaline soils, affecting crops like sugarcane [26].

Micronutrients, including zinc, copper, and manganese, though needed in smaller quantities, are essential for plant health and sustainability. Effective management of these nutrients is crucial for optimizing crop yields and achieving environmental sustainability. Enhancing soil quality through soil metabolites and improving physicochemical properties is significant in intercropping systems [8].

Agroecological practices enhance biodiversity, resilience, and social equity within food systems, supporting sustainable productivity [14]. These practices, along with agricultural diversification strategies, contribute to long-term profitability and biodiversity, emphasizing the importance of diverse cropping systems in maintaining soil health and productivity [15].

Technological advancements have improved soil nutrient management. Developing suitable metrics for monitoring and evaluating food systems transformation is crucial for optimizing nutrient management strategies and ensuring sustainable practices [6]. Leveraging these advancements, agronomic practices evolve, providing pathways for more sustainable and productive agricultural systems.

2.3 Impact of Agricultural Practices on Soil Health and Crop Yield

Agricultural practices significantly influence soil health and crop yield. Anthropogenic actions affect soil ecosystems and food webs, posing challenges in assessing ecological stability [27]. Sustainable farming practices, often underutilized due to a lack of awareness of soil organic carbon dynamics, are essential for maintaining soil fertility and structure [28]. Intensive methods may boost immediate productivity but can lead to soil degradation, emphasizing the need for practices prioritizing long-term sustainability.

Intercropping systems offer an alternative to monoculture, enhancing nutrient levels and microbial diversity, thus improving soil health and resilience. This approach supports soil structure and fertility while optimizing resource use. The complexity of microbial communities and their role in nutrient transformations are critical, with variations in soil conditions and fertilization practices complicating the linkage of specific taxa to nutrient cycling processes [29].

Biopesticides provide an environmentally friendly alternative to conventional pesticides, reducing toxicity and negative externalities [5]. This shift aligns with sustainable pest management strategies that bolster soil health and productivity.

Technological innovations, such as the Intelligent Crop Management System (ICMS), utilize language model-based reinforcement learning to adjust crop management policies, enhancing adaptability and yield outcomes [30]. Integrating machine learning for predictive irrigation scheduling optimizes water use efficiency, enhancing crop yields and resource conservation [31].

Conservation agriculture (CA) practices, influenced by socio-economic factors like household size, animal ownership, and communication assets, significantly impact soil health and yield [11]. These practices, including minimal soil disturbance and crop residue retention, improve soil structure and fertility, supporting sustainable productivity.

Environmental challenges, including climate change, pests, and diseases, necessitate adaptive management strategies to maintain crop resilience and yield stability [32]. Integrating detailed models with abstract representations in simulating food security dynamics underscores the importance of comprehensive approaches in understanding and managing agricultural systems [33].

3 Soil Nutrients and Their Role in Agriculture

3.1 Essential Soil Nutrients and Their Functions

Essential soil nutrients are fundamental to plant development, significantly impacting physiological and biochemical processes that underpin crop growth. Key macronutrients include nitrogen, phos-

phorus, and potassium. Nitrogen is crucial for synthesizing amino acids, proteins, and chlorophyll, thereby enhancing photosynthesis and plant vigor [34]. Phosphorus is vital for energy transfer, particularly in ATP synthesis, and supports root development and flowering [26]. Potassium is involved in enzyme activation and osmoregulation, essential for maintaining plant water balance and stress tolerance [35].

Micronutrients such as zinc, copper, and manganese, though needed in trace amounts, are equally vital for plant health, acting as cofactors in enzymatic reactions that influence nutrient assimilation and metabolic pathways [36]. Zinc and selenium also mitigate cadmium toxicity, highlighting the importance of micronutrients in sustaining productivity [36].

To further illustrate these concepts, Figure 2 categorizes essential soil nutrients into macronutrients and micronutrients, highlighting key nutrients and their roles. This figure also presents innovative methods for nutrient management, emphasizing advanced technologies and sustainable practices.

Microbial communities, including bacterial taxa like Gemmatimonas and Arenimonas, play a crucial role in nutrient cycling and availability [29]. Advanced technologies, such as UAV-based multispectral imaging combined with laser-induced breakdown spectroscopy (LIBS) and machine learning, enhance soil nitrogen estimation accuracy, facilitating precise nutrient management [37].

Traditional practices like intercropping and crop rotation leverage the ecological benefits of diverse cropping systems to improve soil fertility and nutrient dynamics [38]. Innovative methods, such as the Physics-Constrained Deep Learning (P-DL) approach, integrate physics-informed neural networks with sensor data to model soil moisture dynamics, supporting sustainable agriculture [39].

Mobile chemical analysis systems using colorimetric paper sensors for soil pH measurement offer high spatial resolution and rapid feedback, aiding effective nutrient management [40]. These advancements drive agronomic practices toward more sustainable and productive agricultural systems.

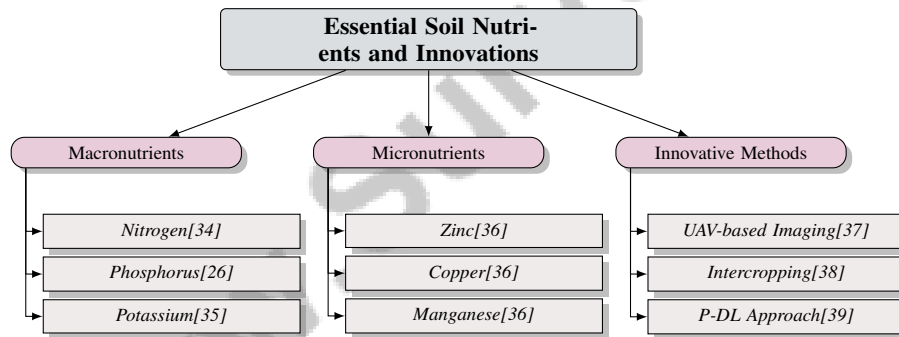


Figure 2: This figure illustrates the categorization of essential soil nutrients into macronutrients and micronutrients, highlighting key nutrients and their roles. It also presents innovative methods for nutrient management, emphasizing advanced technologies and sustainable practices.

3.2 Impact of Nutrient Availability on Crop Yield

Nutrient availability is crucial for crop yield, directly influencing physiological and biochemical processes essential for plant growth. The availability of nitrogen, phosphorus, and potassium is vital for optimizing crop productivity. Advanced modeling techniques, including machine learning, analyze the complex relationships between nutrient availability and crop yield, offering insights into optimizing these interactions for improved agricultural outcomes [7].

The application of humic acid alongside phosphorus fertilizers significantly enhances phosphorus uptake in sugarcane, particularly in alkaline soils where phosphorus is often limited [26]. This combined approach not only boosts nutrient absorption but also increases crop yields, emphasizing the importance of targeted nutrient management strategies.

Machine learning models have proven instrumental in predicting crop yield based on nutrient availability, adeptly capturing the non-linear interactions between soil nutrients and environmental factors [7]. These models facilitate precision agriculture, empowering farmers to make informed nutrient management decisions that enhance yield and sustainability.

Integrating nutrient management strategies with environmental factors, such as soil type and climate, is essential for optimizing crop yield. Enhanced phosphorus uptake methods in sugarcane cultivation exemplify how tailored nutrient management can address specific soil nutrient limitations, improving agricultural productivity [26].

3.3 Methods for Assessing Soil Nutrient Levels

Benchmark	Size	Domain	Task Format	Metric
CNN[41]	5,692	Agriculture	Yield Prediction	RMSE, MAE
MLYF[42]	1,139	Agriculture	Yield Forecasting	rRMSE, R2
DG-Benchmark[43]	1,896	Agriculture	Adoption Prediction	Accuracy, F1-score
SICKLE[44]	2,398	Agriculture	Crop Yield Prediction	RMSE
CropNet[45]	2,362,000	Agriculture	Crop Yield Prediction	RMSE, R2
CCDS[46]	78,536	Agriculture	Image Classification	Accuracy, F1-score
pH-MCAS[40]	805	Soil Chemistry	Soil PH Classification	Accuracy, Turnaround Time
SoilNutrientMap[35]	59,000	Soil Science	Spatial Prediction	R-square, RMSE

Table 1: Table ef presents a comprehensive overview of various benchmarks used for predicting agricultural and soil-related outcomes. The table includes information on the benchmark name, dataset size, domain, task format, and evaluation metrics, highlighting the diversity of approaches within the field. These benchmarks are integral for advancing methodologies in soil nutrient assessment and agricultural yield prediction.

Assessing soil nutrient levels is crucial for effective agricultural management, guiding fertilizer application and crop selection to optimize yield and sustainability. Traditional soil testing methods, such as chemical extraction and spectrophotometric analysis, provide quantitative assessments of nutrient concentrations essential for evaluating soil fertility and identifying deficiencies. However, these methods can be costly and time-consuming, leading to the exploration of alternative techniques like machine learning and spatial modeling. Recent studies demonstrate that advanced approaches can accurately predict soil nutrient content across diverse agricultural contexts, revealing significant relationships between soil characteristics and crop yields. Moreover, different cropping systems and soil amendments can substantially influence nutrient loss due to erosion, emphasizing the need for tailored agronomic practices for sustainable soil management [47, 48, 35, 49]. Table 1 provides a detailed overview of representative benchmarks utilized in the field of soil nutrient assessment and agricultural forecasting, demonstrating the integration of machine learning and spatial modeling techniques.

Technological advancements have introduced innovative methods for soil nutrient assessment, enhancing accuracy and efficiency. Remote sensing technologies utilize spectral data to estimate soil properties and nutrient levels over vast areas, enabling comprehensive soil health monitoring. These technologies are complemented by machine learning algorithms that refine the interpretation of spectral data for actionable nutrient management insights [16].

Integrating historical production data into assessment frameworks enhances the accuracy of early estimators in agricultural forecasting, leveraging past data trends to inform current evaluations [16].

Mobile sensing technologies and field-based diagnostic tools have emerged as practical solutions for real-time soil nutrient assessment. Equipped with sensors and data processing capabilities, these tools allow for on-site analysis of soil properties, providing immediate feedback on nutrient levels. Real-time data derived from advanced technologies, such as remote sensing, IoT, and machine learning, enhance precision agriculture practices by facilitating targeted interventions that optimize nutrient application and maximize crop yield while minimizing environmental impacts and resource waste [50, 51, 52, 53].

Methods for assessing soil nutrient levels are diverse and evolving, driven by technological advancements and the demand for sustainable agricultural practices. By integrating traditional practices, such as intercropping and organic farming, with modern innovations like mobile soil analysis and IoT monitoring, farmers and researchers can gain a nuanced understanding of soil nutrient dynamics. This comprehensive approach enhances agricultural productivity through improved crop yields and soil health while promoting environmental sustainability by increasing biodiversity and carbon sequestration. Long-term studies indicate that such diversified practices yield significant socioeconomic

and ecological benefits, supporting the dual goals of food security and climate change mitigation [40, 15, 54, 22, 29].

3.4 Advancements in Soil Nutrient Management

Recent innovations in soil nutrient management increasingly focus on integrating advanced technologies to enhance nutrient availability and optimize agricultural productivity. A notable advancement is the development of a smartphone-based method for assessing fertilizer stress through trichome density measurement, facilitating real-time monitoring of plant health and timely interventions for nutrient deficiencies [55].

The Internet of Things (IoT) and other smart technologies have transformed traditional agricultural practices into data-driven systems, enabling real-time monitoring and decision-making [22]. These technologies facilitate the collection and analysis of vast data sets, providing insights into soil nutrient dynamics and informing effective management strategies.

Incorporating dual-band illumination and deep learning techniques for weed classification has also advanced soil nutrient management by reducing reliance on chemical herbicides and promoting sustainable practices [12]. This innovation enhances precision in weed control while supporting soil health by minimizing chemical inputs.

Furthermore, integrating sensor data with image processing techniques has improved nutrient status monitoring precision, allowing for early deficiency detection and targeted interventions. This approach enhances sustainability by optimizing nutrient use and minimizing waste, as evidenced by studies highlighting the role of incentives and digital technologies in promoting sustainable agriculture [56, 23].

These advancements in agricultural technology, particularly the integration of IoT and mobile soil analysis systems, signify a transition toward more sustainable and efficient soil nutrient management practices. This shift is characterized by real-time data use and advanced sensors for precise monitoring and optimization of soil health, enhancing crop yields while minimizing environmental impact. As agriculture increasingly adopts these digital technologies, it is better equipped to address challenges such as global warming and resource conservation, ultimately contributing to a more sustainable agricultural ecosystem [23, 40, 49, 22, 57]. Leveraging these innovations allows agricultural systems to improve resilience and productivity, addressing contemporary challenges like climate change and food security while ensuring long-term sustainability.

4 Impact of Agricultural Practices on Soil Health and Crop Yield

4.1 Agricultural Practices and Soil Health

Agricultural practices significantly influence soil health, a cornerstone of sustainable farming. Diverse cropping systems, such as intercropping, enhance nutrient cycling and soil enzyme activities, promoting soil structure and microbial diversity [8]. Strategies for agricultural diversification address both socioeconomic and ecological challenges, emphasizing the enhancement of soil health and resilience through a framework incorporating socioeconomic factors, biological communities, soil quality, and climate change mitigation [15].

Conservation tillage and cover cropping improve soil organic carbon (SOC) levels and microbial diversity, offering ecological alternatives to conventional methods. These practices reduce dependency on chemical fertilizers, thereby promoting long-term environmental sustainability. Research demonstrates that organic farming, cover cropping, conservation tillage, and agroforestry not only enhance SOC storage but also foster beneficial microbial activity and nutrient cycling, leading to increased agricultural productivity and economic viability [56, 28]. However, the adoption of sustainable agricultural practices (SAPs) is hindered by barriers such as insufficient knowledge, perceived implementation difficulties, and lack of appropriate technologies.

Innovative methods that improve phosphorus absorption efficiency in crops like sugarcane can reduce fertilizer inputs, supporting soil health and sustainability. Integrating advanced technologies such as AI-driven soil analysis, mobile chemical testing, and remote sensing with regenerative agricultural practices significantly enhances soil health, productivity, and long-term sustainability. These innovations enable precise SOC level monitoring and real-time soil condition assessments,

facilitating data-driven decisions that improve environmental outcomes and resilience against climate change. Furthermore, agricultural diversification yields substantial socioeconomic and ecological benefits over time, supporting sustainable food production [15, 58, 25, 40].

As illustrated in Figure 3, the hierarchical categorization of key agricultural practices and innovations influencing soil health underscores the importance of sustainable practices, technological advancements, and the challenges that remain. This visual representation enhances our understanding of the interconnectedness of these elements and their collective impact on soil health.

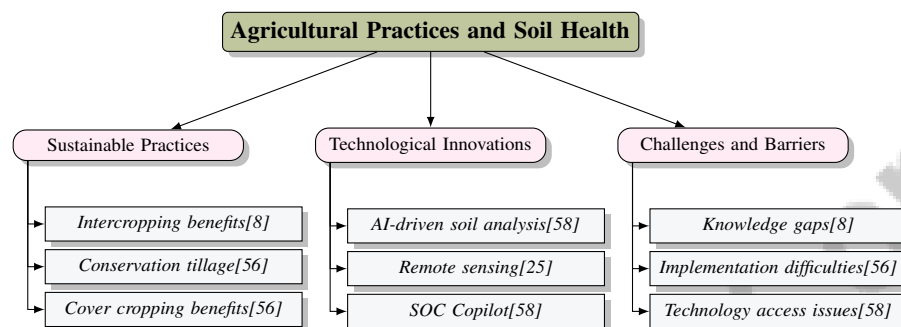


Figure 3: This figure illustrates the hierarchical categorization of key agricultural practices and innovations influencing soil health, highlighting sustainable practices, technological advancements, and existing challenges.

4.2 Challenges in Measuring Soil and Crop Dynamics

Assessing soil and crop dynamics involves significant challenges due to the complex interplay of biophysical and environmental factors and the limitations of current measurement techniques. A major challenge is accurately estimating population variance and mean when aggregated measurements are used as individual observations, potentially leading to inaccuracies [59].

Predicting soil characteristics, such as pH, is difficult due to insufficient comprehensive data for new fields, limiting the effectiveness of existing prediction methods that rely on detailed soil profiles [48]. Traditional agricultural monitoring often involves labor-intensive manual processes, delaying timely interventions needed to protect crops from pests or adverse conditions [60].

Empirical studies face difficulties in disentangling the effects of correlated environmental variables like temperature and vapor pressure deficit (VPD) on crop yields, complicating the interpretation of individual impacts [61]. Moreover, existing yield prediction methods frequently overlook spatial relationships among neighboring points, leading to inaccuracies in understanding crop dynamics across larger areas [62].

Variability in crop responses to temperature changes, alongside uncertainties in climate models and socio-economic factors, further complicates the assessment of agricultural practices' impacts on soil and crop dynamics [63]. These challenges underscore the need for integrated approaches that incorporate spatial and temporal data, leverage advanced technologies, and consider socio-economic contexts to enhance the accuracy and reliability of soil and crop dynamic assessments. Addressing these challenges will enable researchers and practitioners to develop more effective strategies for sustainable agricultural management.

5 Technological Advancements in Soil and Crop Management

The integration of advanced technologies is pivotal in modernizing soil and crop management practices. Table 2 presents a detailed summary of the key technological advancements and methodologies utilized in modern soil and crop management, emphasizing their contributions to improving agricultural practices. Additionally, Table 5 presents a comprehensive comparison of various technological advancements in soil and crop management, detailing their specific applications, components, and integration methods. This section explores key technological advancements that are transforming traditional agricultural methodologies, with a particular focus on remote sensing technologies that

Category	Feature	Method
Remote Sensing Technologies	Collaborative Technologies	RL-POMDP[64], HA[65]
Machine Learning and AI in Crop Yield Prediction	Hybrid Modeling Approaches	GWM[13], CSM[7]
Precision Agriculture and Data-Driven Approaches	Model Enhancement Techniques	CNN-RNN[66]
	Predictive Algorithms	CYP-ML[67]
	Data Accuracy Improvement	GSFD[68], MFAR[16]
Technological Innovations and Data Integration	Data Utilization Strategies	RFR[69], MMP[70], WMSN[71]
	Model Interpretability	ECYP[72]

Table 2: This table provides a comprehensive overview of various technological categories and their corresponding features and methods, as applied in soil and crop management. It highlights the integration of remote sensing technologies, machine learning, AI, precision agriculture, and data integration techniques, showcasing their roles in enhancing agricultural productivity and sustainability.

have significantly enhanced agricultural resource monitoring. These innovative tools provide crucial insights into soil conditions and crop health, thereby facilitating informed decision-making. Figure 4 illustrates the hierarchical structure of these technological advancements in soil and crop management, highlighting key categories such as remote sensing technologies, machine learning and AI in crop yield prediction, precision agriculture and data-driven approaches, as well as technological innovations and data integration. Each category is further divided into specific applications, challenges, techniques, innovations, technologies, models, integration methods, and data-driven approaches, showcasing the multifaceted impact of these advancements on modern agriculture. The following subsection delves into remote sensing technologies and their applications in contemporary agriculture.

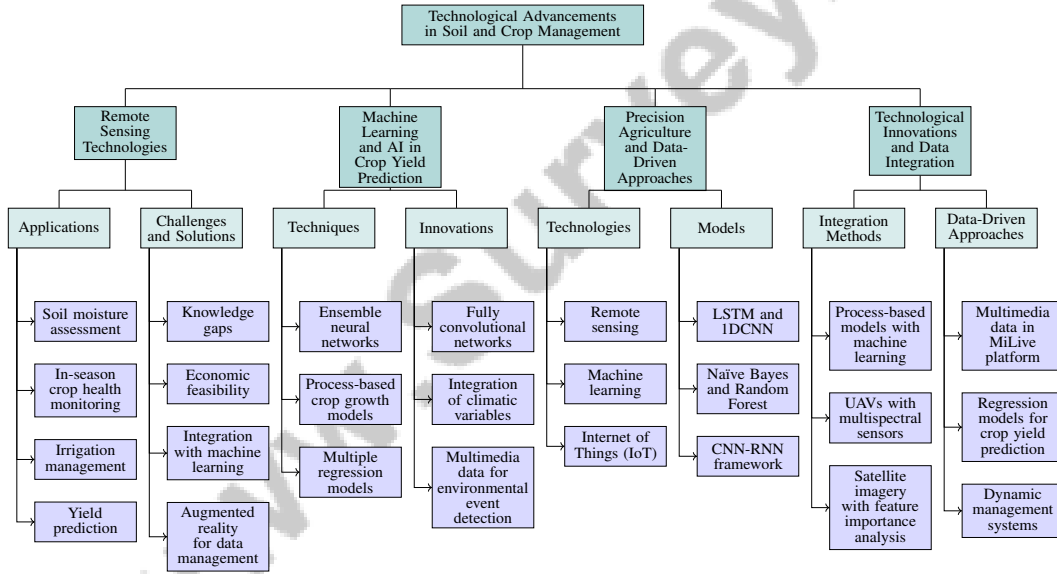


Figure 4: This figure illustrates the hierarchical structure of technological advancements in soil and crop management, highlighting key categories such as remote sensing technologies, machine learning and AI in crop yield prediction, precision agriculture and data-driven approaches, and technological innovations and data integration. Each category is further divided into specific applications, challenges, techniques, innovations, technologies, models, integration methods, and data-driven approaches, showcasing the multifaceted impact of these advancements on modern agriculture.

5.1 Remote Sensing Technologies

Remote sensing technologies have revolutionized the monitoring of soil and crop conditions by providing high-resolution data essential for precision agriculture. These tools enable early detection of agricultural issues, allowing timely interventions to prevent productivity declines. Advancements in sensor technologies and data analytics have expanded remote sensing applications, including soil moisture assessment, in-season crop health monitoring, irrigation management, and yield prediction. However, challenges such as knowledge gaps regarding effectiveness and economic feasibility impede full implementation. The increasing use of unmanned aerial systems (UASs) and other

Method Name	Technological Components	Application Areas	Integration and Enhancement
WMSN[71]	Multimedia Sensors	Environmental Event Detections	Cooperative Processing
CYP-ML[67]	Naive Bayes	Crop Yield Prediction	Machine Learning
HA[65]	Microsoft Hololens 2	Precision Agriculture Tasks	Augmented Reality Headset
RL-POMDP[64]	Stochastic Weather Generator	Nitrogen Fertilization Optimization	Probabilistic ML Model

Table 3: Overview of remote sensing technologies and their integration in precision agriculture, highlighting the technological components, application areas, and enhancements. The table outlines various methods, including WMSN, CYP-ML, HA, and RL-POMDP, emphasizing their contributions to environmental event detection, crop yield prediction, precision agriculture tasks, and nitrogen fertilization optimization, respectively.

remote sensing methods underscores their importance in optimizing crop production while addressing sustainability and profitability concerns [53, 25]. A variety of sensors, including optical, multispectral, hyperspectral, thermal, and microwave, are employed on platforms like satellites, manned aircraft, and UAS, offering comprehensive datasets that inform agricultural management decisions.

Recent developments in remote sensing have been further enhanced by machine learning techniques, which facilitate complex dataset analysis and improve crop yield predictions. For example, UAV-based multispectral sensing solutions equipped with multispectral cameras provide actionable insights for nutrient management, particularly in estimating soil total nitrogen [73]. The MiLive platform, which integrates scalar and multimedia sensors, supports precision agriculture by enhancing environmental data collection and event detection [71].

High-resolution satellite imagery, such as that from the Sentinel-2 satellite constellation, models spatial and temporal agricultural landscape variations, offering insights into crop health and soil properties. The synergy between remote sensing data and advanced computational methods, such as integrating canopy spectral information from satellite imagery with UAV data, optimizes agricultural outcomes [67].

As illustrated in Figure 5, the hierarchical structure of remote sensing technologies in agriculture categorizes key applications, technologies, and challenges. This figure highlights the role of various technologies such as UASs and satellite imagery in enhancing agricultural practices, while also addressing challenges like knowledge gaps and economic feasibility. Moreover, the integration of augmented reality (AR) with remote sensing technologies introduces new opportunities for real-time interaction and data management in agriculture. Teleoperating legged robots via AR headsets allows dynamic engagement with the agricultural environment, enhancing data collection and management practices [65].

Despite these advancements, challenges persist, particularly regarding the loss of detailed information and mixed pixels in remote sensing data. Continuous development of sophisticated algorithms and data processing techniques is essential to improve the accuracy of remote sensing applications in agriculture. By leveraging remote sensing technologies, agricultural systems can achieve more precise monitoring and management of soil and crop conditions, ultimately enhancing productivity and sustainability [64].

Table 3 provides a comprehensive overview of remote sensing technologies utilized in precision agriculture, detailing their technological components, application areas, and integration methods to enhance agricultural outcomes.

5.2 Machine Learning and AI in Crop Yield Prediction

Machine learning and AI techniques have transformed crop yield prediction, enhancing the precision and efficiency of forecasts. Machine learning models, such as ensemble neural networks, utilize diverse soil and environmental parameters to refine yield prediction accuracy, illustrating AI's role in elucidating complex genotype-environment interactions [7]. This methodology is crucial for optimizing crop yield predictions and facilitating informed agricultural management decisions.

Advanced approaches, including the integration of process-based crop growth models with data-driven machine learning techniques, enhance yield predictions. This meta-model framework combines mechanistic understanding with empirical data, improving the reliability of forecasts [70]. Multiple regression models, such as Linear Regression, Gradient Descent, Gradient Boosting, K-Nearest

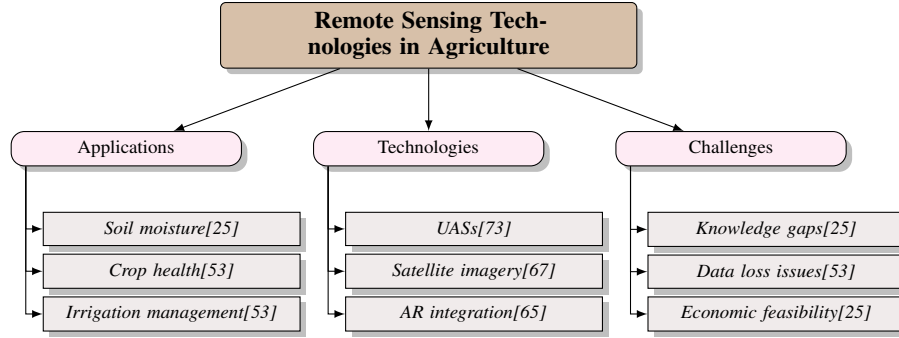


Figure 5: This figure illustrates the hierarchical structure of remote sensing technologies in agriculture, categorizing key applications, technologies, and challenges. It highlights the role of various technologies such as UASs and satellite imagery in enhancing agricultural practices, while also addressing challenges like knowledge gaps and economic feasibility.

Neighbors, and Random Forest, have also been employed to predict crop yields based on key parameters, demonstrating the adaptability of machine learning in agricultural forecasting [69].

Fully convolutional networks for generating realistic weather inputs further improve yield prediction accuracy by providing precise environmental data [13]. Integrating climatic variables into yield prediction models is essential for understanding environmental impacts on agricultural productivity.

The MiLive platform, utilizing multimedia data alongside scalar data, enhances the detection of environmental events such as plant diseases and pest presence, thereby supporting precision agriculture practices [71]. This innovative use of multimedia data highlights AI's potential to tackle diverse agricultural challenges, from pest management to environmental adaptation.

5.3 Precision Agriculture and Data-Driven Approaches

Precision agriculture represents a paradigm shift in modern farming, employing data-driven methodologies to enhance agricultural practices through diverse dataset integration. This approach leverages advanced technologies, including remote sensing, machine learning, and the Internet of Things (IoT), to optimize crop yield predictions and inform strategic decision-making. By utilizing neural network architectures like LSTM and 1DCNN, precision agriculture systems can process seasonal time series data, enabling accurate crop yield forecasting that accommodates temporal variations [74].

Machine learning models, such as Naïve Bayes and Random Forest algorithms, refine yield predictions by analyzing extensive agricultural datasets encompassing a wide range of input features [67]. These models effectively capture spatial correlations among neighboring counties, enhancing the reliability and accuracy of yield forecasts [68].

Incorporating historical variability and official statistics collection timelines into prediction frameworks ensures early estimators meet realistic accuracy thresholds, providing timely insights for agricultural planning [16]. Ensemble learning methods, such as Random Forest Regression, construct multiple decision trees to yield a mean prediction, thereby bolstering the robustness of multivariate agricultural forecasting [69].

Integrating crop simulation models with machine learning techniques fosters a comprehensive understanding of crop growth dynamics, allowing for precision management strategies tailored to specific environmental and agronomic conditions. Remote sensing technologies play a critical role in this process, delivering high-resolution imagery and environmental data that systematically inform precision agriculture practices [75].

Furthermore, fusing various data types, including satellite imagery and environmental factors, through advanced models like the CNN-RNN framework captures spatial and temporal dependencies, providing sophisticated tools for predicting crop yields [66]. These innovations underscore the transformative potential of precision agriculture, paving the way for increased productivity and resilience amid environmental challenges. By harnessing data-driven approaches, precision agriculture optimizes farming practices and supports the development of sustainable agricultural systems.

5.4 Technological Innovations and Data Integration

Method Name	Data Integration	Technological Applications	Model Complexity
MMP[70]	Synthetic And Real	Convolutional Neural Network	Convolutional Neural Network
ECYP[72]	Additional Data Modalities	Satellite Imagery	Lstm Models
WMSN[71]	Multimedia Sensor Integration	Multimedia Data	-
RFR[69]	Real-time Data	-	Simpler Regression Models

Table 4: Overview of various technological methods in agriculture, highlighting their data integration strategies, technological applications, and model complexities. This table illustrates the diverse approaches employed to enhance agricultural outcomes through advanced data utilization and machine learning techniques.

Technological innovations and data integration are pivotal for advancing agricultural outcomes, enhancing both precision and efficiency in farming practices. Table 4 provides a comprehensive comparison of different technological methods used in agriculture, emphasizing their integration of data, technological applications, and model complexity. The fusion of machine learning models with traditional agricultural data has revolutionized crop yield prediction and resource management. For instance, integrating process-based models to generate synthetic data for pretraining machine learning models, followed by fine-tuning with real observational data, exemplifies how combining diverse data sources can enhance predictive accuracy and robustness [70].

UAVs equipped with multispectral sensors have been instrumental in establishing relationships between vegetation indices and crop parameters, providing granular insights into crop health and facilitating precise nutrient management [73]. This technology highlights UAVs' role in capturing high-resolution data that informs agricultural management decisions.

Leveraging satellite imagery and additional data modalities to train models and elucidate predictions through feature importance analysis underscores remote sensing technologies' potential in agriculture [72]. By utilizing these data sources, agricultural systems can deepen their understanding of factors influencing crop yields, thereby improving prediction accuracy and resource allocation.

The MiLive platform's integration of multimedia data significantly enhances detection capabilities, surpassing existing scalar Wireless Sensor Networks (WSN) [71]. This innovation emphasizes multimedia data's importance in comprehensive environmental monitoring, crucial for precision agriculture.

Moreover, employing regression models for crop yield prediction, as opposed to more complex deep learning models, offers a simplified yet effective approach to modeling agricultural outcomes [69]. This strategy illustrates the potential for maintaining accuracy while reducing the computational complexity of predictive models.

The integration of advanced technologies—such as sensors, communication protocols, and data analytics—highlights these innovations' transformative potential by enabling the collection and analysis of extensive agricultural data from diverse sources. This data-driven approach empowers farmers and agronomists to make informed decisions that enhance crop yield, improve operational efficiency, and promote sustainability, ultimately contributing to food security and the resilience of agricultural ecosystems. By normalizing and integrating various data sources, this methodology supports precision agriculture practices and empowers stakeholders to optimize resource management effectively [76, 24]. Dynamic management systems that incorporate both temporal and spatial data allow agricultural practices to adapt to changing conditions more effectively, leading to improved productivity and sustainability. These advancements provide a robust framework for addressing modern agriculture's challenges, ensuring technological progress translates into tangible benefits for agricultural systems and food security.

6 Challenges and Opportunities in Sustainable Agriculture

Sustainable agriculture development is influenced by complex challenges and opportunities. This section examines the barriers to adopting sustainable agricultural practices (SAPs) and potential strategies for their implementation. Understanding these challenges is crucial for developing effective strategies that support sustainability in agricultural systems. The following subsection focuses on

Feature	Remote Sensing Technologies	Machine Learning and AI in Crop Yield Prediction	Precision Agriculture and Data-Driven Approaches
Application Area	Soil And Crop Monitoring	Yield Prediction	Farming Optimization
Technological Components	Sensors And Satellites	Neural Networks	IoT And Sensors
Integration Method	Data Analytics	Data-driven Models	Data Fusion

Table 5: This table provides a comparative analysis of three key technological domains in modern agriculture: remote sensing technologies, machine learning and AI in crop yield prediction, and precision agriculture with data-driven approaches. It highlights the application areas, technological components, and integration methods associated with each domain, underscoring their roles in enhancing soil and crop management practices.

obstacles to implementing SAPs, laying the groundwork for a thorough exploration of the hurdles that must be overcome to achieve sustainable agricultural objectives.

6.1 Challenges in Sustainable Agricultural Practices

The widespread adoption of sustainable agricultural practices (SAPs) is hindered by various challenges. A significant barrier is the lack of long-term data to reassure risk-averse farmers and policymakers about the benefits of diversified agricultural systems, complicating efforts to promote agricultural diversification crucial for ecosystem resilience and productivity [15]. Economic constraints and governance issues further exacerbate these challenges, especially in resource-limited regions, where financial pressures, social inequities, and environmental degradation impede SAP adoption [14].

Advanced technologies like machine learning and precision agriculture face hurdles due to inadequate infrastructure and high costs. The complexities of soil metabolomics and extensive data requirements for assessing intercropping impacts on soil health and crop yields highlight the difficulties in transitioning to sustainable practices. Intercropping systems' beneficial changes in rhizosphere soil nutrients and metabolites underscore agricultural diversification's role in enhancing soil quality and carbon sequestration. Moreover, mobile soil analysis advancements are vital for optimizing sustainable practices while minimizing environmental impacts [40, 15, 8, 28].

Social and educational barriers significantly impact SAP adoption, as farmers' decisions are often influenced by social norms and economic pressures, discouraging sustainable practices. Inadequate agricultural policies and governance structures further challenge food security and sustainable development, emphasizing the need for policy reforms to support sustainable agriculture [14].

Addressing these challenges necessitates adaptable strategies and leveraging technological advancements. Promoting SAPs involves fostering an ecosystem that encourages long-term data sharing, implements economic incentives, and strengthens governance frameworks. Effective incentives can enhance sustainable practices adoption, leading to improved income, productivity, and environmental sustainability. Digital technologies can transform agricultural operations, facilitating better resource management and climate change resilience, thus reinforcing sustainability within the agricultural value chain [56, 23].

6.2 Policy and Economic Considerations

Policy and economics are pivotal in promoting sustainable agriculture by providing frameworks and incentives for adopting SAPs. Policies that encourage positive attitudes and awareness of conservation programs are crucial in fostering farmers' willingness to engage in sustainable practices by highlighting their long-term benefits [77].

Economic considerations, including market-based, non-market-based, and regulatory incentives, are essential for promoting SAPs. Market-based incentives, such as subsidies and financial support for sustainable technologies, ease farmers' financial burdens. Non-market-based incentives, including educational programs and technical assistance, equip farmers with the knowledge and skills to implement SAPs effectively. Regulatory incentives, such as environmental regulations and compliance requirements, drive sustainable practices adoption by establishing standards and guidelines [56].

Integrating advanced technologies, like deep learning and machine learning, into agricultural policy frameworks can enhance SAP effectiveness. These technologies improve phenology estimation and crop yield predictions, providing valuable insights for policymakers and farmers. However, challenges

persist in generalizing predictive models across diverse geographical regions and temporal contexts, particularly where data availability is limited, and agronomic practices vary widely. Incomplete adoption of remote sensing tools due to knowledge gaps regarding their suitability and economic feasibility further complicates the landscape, necessitating efforts to address these issues to enhance decision-making and optimize crop production sustainably [69, 25]. Future research should focus on improving model generalization and exploring deep learning integration to enhance predictive accuracy in diverse agricultural contexts.

6.3 Climate Change and Environmental Challenges

Climate change significantly challenges sustainable agriculture, impacting vital environmental factors for crop production and soil health. Changes in temperature and precipitation alter soil nutrient dynamics, influencing plant growth and productivity, making it crucial to address nutrient availability across ecosystems [57]. Applying fractal geometry to understand soil pore structure and its functional properties offers insights into greenhouse gas emissions and climate change mitigation strategies [78].

Extreme weather events, such as droughts and floods, exacerbate challenges faced by agricultural systems, resulting in reduced crop yields and increased vulnerability to pests and diseases. The Bivariate Gaussian Model captures the relationship between temperature, precipitation, and maize yield, predicting potential yield decreases with rising temperatures [79]. This highlights the need for adaptive strategies to mitigate climate variability's adverse effects on agricultural productivity.

Machine learning-based nutrient applications present promising solutions for optimizing resource use and enhancing crop resilience to environmental stressors. However, privacy concerns regarding these technologies could hinder their widespread adoption [52]. Future research should focus on integrating remote sensing data and developing models that account for extreme weather variability, improving crop yield predictions under changing climatic conditions [80].

The uncertainty surrounding wheat's response to extreme temperatures and the lack of comprehensive data on climate factors' interactions highlight critical gaps in understanding crop-climate interactions [81]. Addressing these gaps is vital for developing robust agricultural forecasting models that inform sustainable management practices [69].

Optimizing energy efficiency in agricultural technologies, such as the MiLive architecture, is essential for promoting sustainable practices in the face of climate change [71]. Enhancing agricultural systems' resilience to environmental challenges contributes to developing sustainable food systems better equipped to withstand climate change impacts.

6.4 Sustainable Agricultural Practices

Sustainable agricultural practices are crucial for enhancing soil health, increasing crop productivity, and ensuring environmental sustainability. These practices integrate traditional and modern techniques, leveraging advanced technologies to optimize resource use and minimize environmental impacts. Agrivoltaic systems exemplify sustainable practices by promoting land efficiency and supporting renewable energy goals, enabling dual land use for agriculture and solar energy production [3].

As illustrated in Figure 6, the categorization of sustainable agricultural practices highlights key technological integrations, such as machine learning and meta-modeling, alongside resource efficiency strategies like agrivoltaic systems and nanoscale sulfur. Additionally, it showcases innovative pest management methods, including biopesticides and the Rapid Unnatural Dual Component Selective Illumination Protocol (RUDCIP), which represents an innovative approach to organic weed control, utilizing low-level UV-A and near-IR radiation to selectively damage weeds while minimizing harm to crops and the environment [12]. This figure emphasizes the interconnectedness of these strategies in promoting sustainable agricultural practices.

The integration of machine learning (ML) in agriculture provides actionable insights to maximize yield while effectively managing soil nutrition, thereby promoting sustainability [7]. ML techniques combined with decision-making frameworks enhance seed variety selection and yield predictions, supporting sustainable practices [10]. Meta-modeling can facilitate ML uptake in agriculture by

combining process-based and data-driven approaches, offering a robust framework for sustainable agricultural management [70].

The use of biopesticides provides a viable alternative to synthetic pesticides, reducing environmental toxicity and promoting sustainable pest management strategies [5]. This aligns with sustainable agriculture's broader goals by minimizing negative externalities and supporting environmental health. Additionally, integrating nanoscale sulfur in agricultural systems reduces reliance on synthetic pesticides and enhances nutrient efficiency, contributing to more sustainable farming practices [20].

Agroecology is increasingly recognized as a viable pathway for achieving sustainable food systems, emphasizing inclusive, context-specific transition pathways [14]. Key takeaways include the importance of agroecological practices in promoting biodiversity, resilience, and social equity within food systems, underscoring the potential of tailored information dissemination and social norms in fostering sustainable agricultural practices [2].

Future research should explore the synergies and trade-offs between agricultural practices and ecological health, integrating machine learning approaches to refine ecosystem service valuations [4]. By adopting these sustainable practices, the agricultural sector can address contemporary challenges, promote environmental sustainability, and ensure food security for future generations. The survey emphasizes sustainable agricultural practices as integral to transforming food systems, advocating for integrated strategies that address social, economic, and environmental outcomes [6].

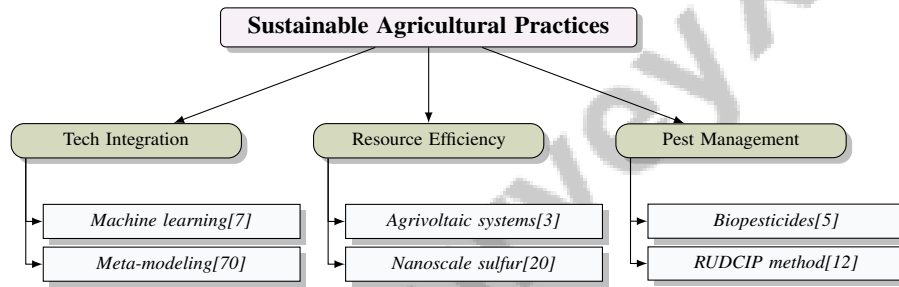


Figure 6: This figure illustrates the categorization of sustainable agricultural practices, highlighting key technological integrations like machine learning and meta-modeling, resource efficiency strategies such as agrivoltaic systems and nanoscale sulfur, and innovative pest management methods including biopesticides and the RUDCIP method.

7 Conclusion

This survey highlights the critical importance of integrating soil nutrient management with sustainable agricultural practices to enhance productivity and ensure environmental sustainability. Advanced modeling techniques, such as the GNN-RNN framework, improve crop yield predictions by effectively utilizing geospatial and temporal data. These technologies are crucial in addressing future challenges posed by climate change and increasing global food demands. The role of the SOC Copilot in advancing soil health and promoting regenerative agriculture marks a significant shift towards more sustainable agricultural practices.

Future research should focus on merging traditional knowledge with modern agricultural techniques to enhance food security and sustainability. The QRF-SJ method offers superior yield forecasting capabilities, aiding decision-making processes for farmers and stakeholders. The use of organic fertilizers, such as those derived from fishpond sediment, has demonstrated potential in enhancing maize growth while promoting resource efficiency and reducing environmental impacts. Bayesian models simplify complex crop yield analyses, providing high prediction accuracy and further advancing agricultural methodologies.

Hybrid approaches offer promising advancements for future agricultural practices, particularly in adapting to climate change. The TALSTM model's success over traditional methods provides insights into the temporal dynamics of yield prediction, essential for sustainable agricultural research. Integrating satellite data with traditional agricultural methods can significantly enhance agricultural statistics, paving the way for more sustainable practices.

Key findings underscore the necessity of a data-driven approach in agriculture, highlighting the potential of technology to boost productivity while overcoming socio-economic challenges. The distinct responses of soil microbiomes to environmental changes facilitate nutrient cycling, with microbial communities playing vital roles across soil layers. The effectiveness of soil-based metrics over plant or remote sensing metrics suggests a need for further research into nutrient metrics across diverse ecosystems. Training on smaller, relevant datasets has shown better outcomes than using larger, unrelated datasets, pointing to future research directions in agricultural practices and yield predictions. Hybrid machine learning models hold significant potential for improving crop yield predictions and supporting global food security. Selecting suitable biochar types for specific soil conditions is crucial for maximizing benefits and minimizing negative impacts on soil health and crop yields. Understanding population dynamics in agricultural contexts presents opportunities for future research into resource management. Early stress detection methods, including smartphone-based technologies, promise to enhance precision agriculture. Future research efforts will focus on refining methodologies, expanding datasets for diverse crops and regions, and validating techniques across various agricultural contexts. Integrating physics-based principles with deep learning is vital for advancing soil moisture modeling, contributing to sustainable agriculture practices.

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