Chapter

# Sustainable Intensification: Agroecosystem and Plant Nutrient Management in a Changing Climate

*Kwaku Onwona-Hwesofour Asante, Jeannette Aduhene-Chinbuah, Clement Oppong Peprah, Kennedy Agyeman, Felix Frimpong, Eric Owusu Danquah and Ralph Bam*

**Abstract**

This book chapter addresses the urgent need to shift from traditional practices to sustainable intensification, particularly in regions where environmental constraints and the impacts of climate change are pronounced. It provides an in-depth overview of sustainable intensification, focusing on its core principles to increase food production from existing farmland while minimizing environmental harm. Key aspects discussed include agroecosystem management, where the complex interactions between plants, soil, and microorganisms are explored, along with the critical role of soil biodiversity in maintaining ecosystem productivity. The chapter also emphasizes the importance of proper nutrient management, analyzing the effects of nutrient deficiency on plant health and productivity. It advocates for integrated nutrient management to optimize soil health and crop yields. Innovative practices such as breeding for nutrient use efficiency, crop rotation, intercropping, and advanced technologies like precision agriculture are also highlighted as vital strategies for sustainable intensification. Moreover, the chapter underscores the necessity of supportive policy frameworks and community engagement in promoting sustainable agricultural practices. The importance of sustainable intensification in ensuring food security and economic stability has been thoroughly discussed, offering practical recommendations for stakeholders to foster resilient and sustainable agroecosystems in the face of climate change.

**Keywords:** sustainable intensification, agroecosystem management, plant nutrient management, tropical agriculture, climate change adaptation

## 1. Introduction

The global challenge of ensuring food security is intensifying due to a rapidly expanding population and the corresponding surge in food demand. Projections indicate that by 2050, the global population will approach 10 billion, necessitating

a substantial increase in food production to meet these demands [1]. This challenge is compounded by environmental constraints that demand adopting sustainable agricultural practices. As the world grapples with feeding an ever-growing population, it becomes crucial to strike a delicate balance between enhancing food production and preserving environmental health [2]. The dual pressures of biodiversity loss and climate change further complicate this balance, posing significant challenges to sustainable food production systems. Biodiversity loss, often driven by agricultural expansion and intensification, undermines ecosystem resilience and their ability to provide essential services, such as pollination and pest control. Climate change, marked by rising temperatures, shifting precipitation patterns, and more frequent extreme weather events, directly threatens crop yields and food security. These interconnected challenges underscore the urgency of adopting sustainable agricultural practices that can adapt to and mitigate these threats.

In response to these challenges, the concept of sustainable intensification (SI) has emerged as a key strategy. Sustainable intensification focuses on increasing agricultural productivity while ensuring environmental sustainability [3]. This approach integrates the dual goals of boosting crop yields and maintaining or improving the ecological systems on which agriculture depends. Sustainable intensification prioritizes optimizing resource use efficiency and reducing the environmental footprint of agriculture, thereby fostering a more harmonious relationship between agricultural practices and the natural world [4]. Within this context, the importance of sustainable nutrient management becomes evident. Effective nutrient management is critical in mitigating the adverse effects of climate change on agriculture [5]. Farmers can enhance soil fertility, increase crop resilience to climate variability, and reduce greenhouse gas emissions by adopting sustainable practices. These practices support higher and more stable food production and contribute to broader environmental objectives, such as carbon sequestration and biodiversity conservation. This chapter explores the principles and practices of sustainable nutrient management within the framework of SI. Through an examination of current research and practical applications, we aim to highlight the importance of integrating productivity with environmental health in modern agriculture.

## 2. Sustainable intensification

### 2.1 Historical evolution

Agriculture has historically relied on monoculture cropping, where the same crop is planted continuously, leading to soil nutrient depletion and increased pest vulnerability. This approach, combined with poor soil management, resulted in significant declining soil fertility over time [6]. To counter these issues, sustainable intensification emerged as a critical approach. It focuses on increasing food production from existing farmland while minimizing environmental impact, incorporating innovative practices and technologies to ensure long-term sustainability. Key elements of sustainable intensification include diversification, which enhances crop diversity through intercropping, crop rotation, and mixed farming, improving soil health and resilience to climate variability [7]. Precision agriculture is another vital development, leveraging technology like soil sensors and GPS to optimize resource use, reduce waste, and minimize environmental impact. These advancements are essential for meeting the growing global food demand while maintaining ecological balance [8].

## 2.2 Key milestones and developments

### *2.2.1 The Green Revolution and shift toward agroecology*

The Green Revolution of the mid-twentieth century, led by figures like Norman Borlaug, introduced high-yielding crop varieties, synthetic fertilizers, and advanced irrigation techniques, significantly boosting food production and preventing famines [9]. However, it also led to environmental and social challenges, such as soil degradation and reduced biodiversity due to intensive chemical use [10]. These issues prompted a shift toward agroecology, which integrates ecological principles into farming, emphasizing sustainability and resilience. This shift was driven by both scientific research and grassroots movements advocating for environmentally sustainable and socially equitable farming practices [11].

### *2.2.2 The rise of precision agriculture*

Precision agriculture (PA) has emerged as a cornerstone of sustainable farming in the twenty-first century. While PA technologies have existed since the 1980s, their adoption was initially slow. By 2012, only about 30–50% of US corn and soybean acres utilized PA, a low figure partly due to the complexity of the required technology and the migration of skilled individuals to urban areas [12]. Despite these challenges, PA adoption varies regionally, as seen in **Table 1**. Technological advancements, including GPS-guided machinery and soil sensors, have enabled data-driven decision-making, improving efficiency and sustainability. For example, PA has been shown to reduce nitrogen use by up to 20% in the United States while maintaining or improving crop yields [20].

| Agroecological zone | Region | Precision agriculture tools usage | References |
|---|---|---|---|
| Tropical | Latin America | High usage of drones, satellite imaging, and GPS-guided machinery | [13] |
| Tropical | Sub-Saharan Africa | Limited usage of precision agriculture tools but growing adoption of mobile apps and SMS-based services | [14] |
| Temperate | North America | Widespread adoption of precision agriculture tools, including drones, satellite imaging, and precision irrigation | [15] |
| Temperate | Europe | High usage of precision agriculture tools, including GPS-guided machinery and precision irrigation | [16] |
| Arid | Middle East and North Africa | Limited usage of precision agriculture tools but growing adoption of drought-tolerant crops and precision irrigation | [17] |
| Arid | Australia | High usage of precision agriculture tools, including drones and satellite imaging, to manage water resources | [18] |
| Mountainous | Asia | Limited usage of precision agriculture tools but growing adoption of terracing and contour farming | [19] |

**Table 1.**
*Regional variation in precision agriculture tools usage across different agroecological zones.*

*2.2.3 Integration of sustainable practices, policy support, and community-led initiatives*

In recent years, we have witnessed a significant integration of sustainable practices into mainstream agriculture, supported by national and international policies. Examples include the UN's Sustainable Development Goals (SDGs), the Paris Agreement, and the Global Alliance for Climate Smart Agriculture, which emphasize the importance of sustainable practices [21]. National policies, including the European Union's Common Agricultural Policy (CAP) and Brazil's Low Carbon Agriculture Plan, also play a critical role [22]. Community-led initiatives, such as the System of Rice Intensification (SRI) and the "Push-Pull" pest management strategy in East Africa, highlight the effectiveness of involving local communities in agricultural innovation [23]. Initiatives like Participatory Irrigation Management (PIM) in India and community seed banks globally further demonstrate the benefits of local participation in managing resources and preserving biodiversity.

### 2.3 Core principles

*2.3.1 Enhancing productivity with a minimal environmental footprint*

One core principle of sustainable intensification is enhancing productivity while minimizing environmental impact. Precision nutrient management, supported by regular soil testing and integrated nutrient management (INM), optimizes nutrient use and improves soil health [24]. Integrated pest management (IPM) combines biological control, cultural practices, and reduced chemical pesticide use to manage pests effectively, protecting non-target organisms and reducing environmental contamination. Conservation agriculture, including minimum tillage and cover cropping, preserves soil structure, reduces erosion, and maintains organic matter, contributing to soil health and productivity. Agroforestry integrates trees with crops, enhancing biodiversity, providing ecosystem services, and improving soil fertility [25].

### 2.4 Balancing economic, social, and environmental goals

Balancing economic, social, and environmental goals is fundamental to sustainable intensification. Ensuring market access, fair prices, and strengthening value chains for sustainable agricultural products support farmers' livelihoods [26]. Social equity ensures that the benefits of sustainable intensification reach smallholders, women, and marginalized communities. Empowering farmers through knowledge sharing and capacity building is essential for inclusive and equitable agricultural development [27]. Promoting ecosystem services through agroecological practices helps achieve these goals. Economic balance is demonstrated by organic certification programs and Fairtrade initiatives, which provide market access and fair wages, ensuring profitability for farmers [28]. Social goals are further supported by initiatives like Farmer Field Schools, which enhance knowledge sharing and empower marginalized groups, promoting social equity.

## 3. Agroecosystem management

Agroecosystem management involves applying ecological and agronomic principles to optimize interactions between plants, soil, and microorganisms for sustainable

production. This approach is crucial for maintaining ecological balance and enhancing agricultural productivity. Agroecosystems are complex networks of plants, soil, and microorganisms, all of which play vital roles in ecosystem stability and productivity. Biodiversity within these systems is key to promoting resilience and reducing dependency on chemical inputs, contributing to sustainable agricultural practices [29].

### 3.1 Soil health and biodiversity and agroecosystem services

Soil organisms are integral to nutrient cycling and crucial for soil fertility and plant growth. Conventional farming practices, reliant on chemical inputs and monoculture, often degrade soil health by reducing biodiversity and disrupting nutrient cycling [30]. In contrast, sustainable practices such as crop rotation, organic amendments, and reduced tillage lead to healthier, more productive soils. Agroecosystem services, including pollination, pest control, and nutrient recycling, are vital for sustainable agriculture. Practices like conservation tillage and cover cropping preserve soil structure, reduce erosion, and improve water retention and organic matter [31].

### 3.2 Integration of agroforestry and permaculture principles

Agroforestry and permaculture integrate ecological principles into farming, enhancing both economic outputs and ecological services. Agroforestry, for instance, provides timber, fruit, and habitat for wildlife, while also contributing to carbon storage and water cycle regulation. Permaculture, on the otherhand, focuses on mimicking natural ecosystems to create sustainable, self-sufficient agricultural systems, emphasizing diversity, stability, and resilience. For instance, in sub-Saharan Africa, the push-pull strategy integrates specific crops to repel pests and attract beneficial insects. This strategy reduces pest damage and increases yields without chemical pesticides, offering a promising path toward sustainable agriculture. Adapting these practices to local contexts through community engagement is crucial for the success and sustainability of agricultural interventions [32, 33].

### 3.3 Challenges and opportunities

Adopting agroecosystem management practices can be challenging due to limited access to information, financial resources, and understanding of long-term benefits, especially for smallholder farmers [34]. Additionally, inadequate policy frameworks and institutional support often hinder the implementation of sustainable practices. Emerging technologies, such as precision agriculture, satellite imagery, and artificial intelligence (AI), offer opportunities to optimize agroecosystem management, improving planning, resource allocation, and productivity. Enhanced collaboration among researchers, farmers, policymakers, and NGOs can facilitate knowledge transfer, resource sharing, and policy advocacy, fostering innovation and scaling successful practices more effectively.

## 4. Plant nutrient management in sustainable intensification

Sustainable intensification emphasizes efficient plant nutrient management to boost productivity while minimizing environmental impacts. This approach integrates biodiversity, soil health, and ecological interactions, utilizing practices like cover cropping,

integrated crop-livestock systems, and strategic use of legumes to maintain ecological balance and resilience [35]. Macronutrients such as nitrogen, phosphorus, and potassium are critical for plant functions, including growth and resilience. Though needed in smaller quantities, micronutrients are vital for processes like enzyme function and photosynthesis. For example, nitrogen is central to amino acid synthesis, while phosphorus is crucial for energy transfer. Micronutrients like iron, zinc, and manganese play roles in chlorophyll synthesis, enzyme function, and photosynthesis [36]. Nutrient cycling involves the movement and availability of essential nutrients, like nitrogen and phosphorus, which are often limited in agroecosystems. Processes like nitrogen fixation by legumes and phosphorus mobilization by soil microorganisms enhance nutrient availability. However, nutrients can be lost through leaching, erosion, and gaseous emissions, necessitating careful soil fertility management [37].

Nutrient deficiencies and abiotic stresses, such as drought and salinity, negatively impact plant productivity. These stresses can exacerbate deficiencies, and effective management strategies, including foliar nutrient applications and the use of protective agents, are essential to improve plant resilience under challenging conditions [38].

## 5. Plant-soil interaction

Plant-soil interactions are fundamental in sustaining plant growth and maintaining soil health, forming a complex and dynamic relationship where plants influence the soil environment impacting their development. These interactions are mediated through various biophysical, chemical, and biological processes that vary across spatial and temporal scales. Understanding these interactions is critical for enhancing agricultural productivity and ensuring ecosystem stability.

### 5.1 Plant-soil feedback (PSFs)

Plant-soil feedbacks (PSFs) describe the reciprocal interactions between plants and soils that can either enhance or inhibit plant growth and soil health (example as seen in **Figure 1**). These feedbacks involve a complex network of interactions among plant roots, soil microbes, and the surrounding soil environment.

Positive PSFs occur when plants modify the soil in ways that enhance their growth or that of similar species. For instance, leguminous plants establish symbiotic relationships with nitrogen-fixing bacteria, enriching soil nitrogen content, which benefits subsequent plantings. Mycorrhizal fungi also form mutualistic relationships with plant roots, increasing nutrient and water uptake, particularly phosphorus [40].

Negative PSFs arise when plants alter the soil environment in ways that reduce their growth or that of subsequent plants. This can occur through pathogen buildup, allelopathy (the release of harmful chemicals by plant roots), or nutrient depletion. Continuous monocropping of species like maize can lead to the accumulation of specific pathogens, such as *Fusarium oxysporum*, which can significantly reduce yield [41].

### 5.2 Mechanisms of soil-plant interactions

Plants release various organic compounds, including sugars, amino acids, and organic acids, into the soil through their roots. These exudates serve as a food source for soil microbes, stimulating microbial activity and enhancing nutrient cycling and

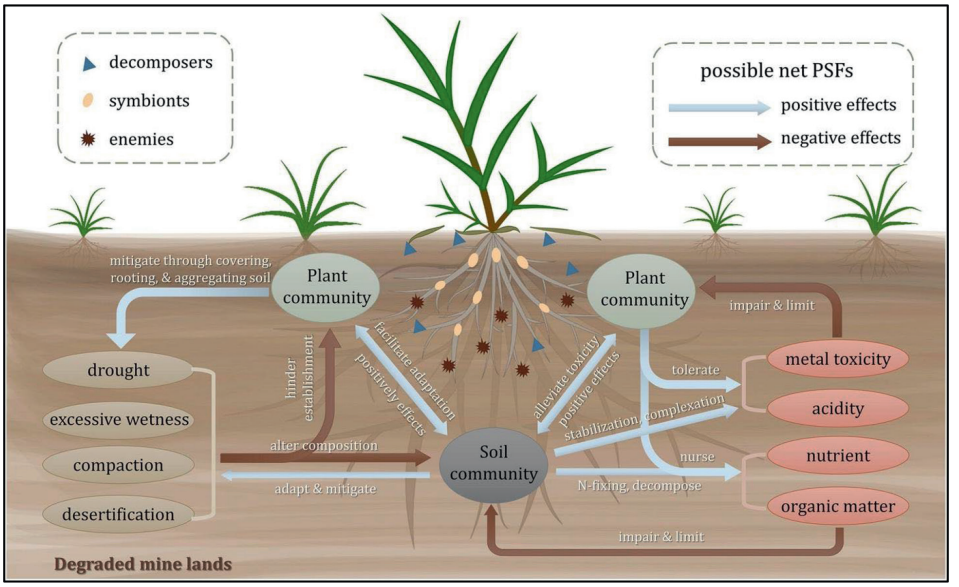


**Figure 1.**
*Plant-soil interaction diagram [39].*

availability [42]. Additionally, root exudates are crucial in soil aggregation, improving soil structure and water retention [43].

Additionally, the soil microbiome, comprising bacteria, fungi, and other microorganisms, plays a vital role in plant health. Beneficial microbes can suppress soil-borne pathogens, fix atmospheric nitrogen, and solubilize phosphorus, thereby making these nutrients more available to plants. The interactions between plant roots and these microbes are essential for maintaining soil fertility and plant productivity [44]. Soil texture, structure, and porosity directly influence plant growth. Well-structured soils with adequate porosity allow for better root penetration, water infiltration, and nutrient uptake. Conversely, compacted soils can restrict root growth and reduce the availability of essential nutrients [45].

The availability of nutrients in the soil is influenced by several factors, including pH, organic matter content, and cation exchange capacity (CEC). Soil pH, for instance, affects nutrient solubility, with most nutrients being more available in slightly acidic to neutral pH ranges. CEC, on the other hand, determines the soil's ability to retain and supply essential cations like potassium and calcium to plants [46]. These factors are crucial considerations in sustainable agriculture.

### 5.3 Managing plant-soil interactions for sustainable agriculture

Effective management of plant-soil interactions is key to sustainable agriculture. Practices such as crop rotation, intercropping, and the use of cover crops can balance positive and negative PSFs, promoting long-term soil health and agricultural productivity. Additionally, the application of organic amendments, such as compost and biofertilizers, can enhance soil microbial diversity and function, further supporting sustainable plant-soil interactions [47]. Advanced PSF management strategies involve manipulating soil microbial communities to favor beneficial interactions. For example, inoculating soils with mycorrhizal fungi or nitrogen-fixing bacteria can enhance

nutrient availability and plant growth. Adjusting soil pH through liming or the use of acidifying agents can also optimize nutrient availability and microbial activity [48].

Plant-soil interactions significantly contribute to the resilience and stability of agricultural ecosystems. By improving soil structure, enhancing nutrient cycling, and promoting microbial diversity, these interactions help maintain soil fertility and reduce the need for chemical inputs. Moreover, healthy plant-soil interactions can mitigate environmental impacts, such as nutrient runoff and soil erosion, contributing to the long-term sustainability of agricultural systems [49].

## 6. Fertilization strategies for crop production

Fertilization is crucial for agricultural productivity, especially given the global need for higher crop yields and the decreasing availability of arable land. While fertilizers, particularly inorganic ones, are key to enhancing productivity, their widespread use presents significant environmental challenges, such as pollution and soil degradation. The uneven distribution of fertilizer use globally underscores the necessity for more sustainable and equitable practices. To address these issues, a shift in fertilization strategies has been advocated, focusing on a deeper understanding of nutrient roles, sources, and plant uptake processes [50].

### 6.1 Inorganic fertilization

Inorganic fertilization involves using synthetic fertilizers to supply plants with essential nutrients, such as nitrogen (N), phosphorus (P), and potassium (K) along with other micronutrients like sulfur, iron, and zinc. Regions like Africa face a pressing need to boost food production by 4% annually to meet the growing population's demands. This necessitates a significant increase in chemical fertilizer use, from an average of 10 to 50 kg/ha, requiring an 18% annual rise in fertilizer usage. Research indicates that Africa heavily relies on inorganic fertilizers to address nutrient losses, which can exceed 10 kg of nitrogen, 4 kg of phosphorus, and 10 kg of potassium per hectare annually in most sub-Saharan African countries. East Africa experiences the highest depletion rates, with losses surpassing 40 kg of nitrogen, 15 kg of phosphorus, and 40 kg of potassium per hectare [51]. Proper application of fertilizers, informed by soil and crop production knowledge, can help mitigate environmental impacts. Various commercial fertilizers are available, differing in nutrient content and release mechanisms, and can be categorized into nitrogen, phosphorus, potassium, sulfur, calcium, and magnesium fertilizers, some containing multiple nutrients [52].

#### *6.1.1 Nitrogen, phosphorus, and potassium fertilizers*

Nitrogen fertilizers, crucial for plant growth and leaf development, are widely used in Africa. Common sources include ammonium sulfate, ammonium phosphates, and urea. Urea, as shown in **Figure 2**, contains 45–46% nitrogen and, is particularly valued for its cost-effectiveness and ability to convert to ammonium in the soil, reducing leaching risks. Phosphorus fertilizers, such as rock phosphates and superphosphates (SSP and TSP), are vital for plant root development and energy transfer. Rock phosphates are more effective in acidic soils, while superphosphates provide readily available phosphorus, essential for various crops. Potassium fertilizers, such as potassium chloride (KCl) and potassium sulfate ($K_2SO_4$), support plant processes like



**Figure 2.**
*An example of commonly used inorganic fertilizers. (a) Sodium nitrate. (b) Urea. (c) Muriate of potash.*

water regulation and enzyme activation. Potassium chloride is the most widely used potassium fertilizer due to its high solubility and effectiveness.

### *6.1.2 Benefits and potential environmental risks of inorganic fertilizers*

While inorganic fertilizers are crucial for global food production, their overuse poses significant environmental risks. Intensive application can lead to air, water, and soil pollution, land degradation, and increased greenhouse gas emissions. Long-term use affects soil microbiology, altering pH and impacting bacterial diversity and soil microbial activity. Moreover, excessive nitrogen fertilization can lead to nutrient leaching, contributing to water eutrophication, soil acidity, and reduced crop yields [53]. Therefore, while inorganic fertilizers are key in boosting agricultural productivity, their use must be carefully managed to avoid adverse environmental consequences. Combining them with organic fertilization and adopting practices such as INM can enhance nutrient use efficiency and promote sustainable farming systems.

## 6.2 Organic fertilization

Organic fertilizers are derived from animal wastes, plant residues, treated sewage sludge, and leguminous plants. Organic amendments improve soil nutrient availability, organic matter content, and microbial activity, thereby enhancing crop yield and growth [54]. About 2.4 million farmers globally practice organic agriculture on 50.9 million hectares, representing 1.1% of total agricultural land [55]. The choice of organic fertilizers depends on crop type, season, soil chemistry, and farmers' experiences. Research has explored the agronomic potential of various organic fertilizers on crops and animal-based organic fertilizers [56]. Organic fertilizers support a diverse soil ecosystem, providing essential nutrients for beneficial microorganisms that maintain healthy soil and suppress harmful pathogens. They enhance soil fertility by improving porosity and water-holding capacity while promoting microbial activity. The slow release of nutrients from organic materials ensures a steady supply of essential elements, preventing nutrient depletion and promoting balanced nutrient levels in the soil [57].

## 6.3 Integrated nutrient management

Integrated nutrient management practices have gained significant attention in agriculture due to their potential to enhance crop productivity and sustainability. By combining different nutrient sources, farmers can improve soil health, increase nutrient availability to crops, and reduce the reliance on synthetic fertilizers. This improves the economic viability of farming and contributes to environmental conservation.

Research has demonstrated that INM can lead to better nutrient utilization by crops, improved soil structure and fertility, reduced greenhouse gas emissions from synthetic fertilizer use, and decreased risk of nutrient runoff into water bodies [58, 59]. However, the successful implementation of INM requires careful consideration of various factors such as soil type, crop type, climate conditions, availability of inputs, and farmer knowledge. Adequate training and support are essential for farmers to adopt INM practices effectively.

### 6.4 Best practices for maximizing nutrient use efficiency and minimizing environmental impact

Combining organic and inorganic fertilizers can optimize soil fertility and crop productivity. Organic fertilizers, like manure and compost, enhance soil structure and provide a long-term nutrient supply, while inorganic fertilizers offer a rapid source of essential nutrients. Integrated Nutrient Management (INM) effectively combines these benefits, ensuring sustained crop nutrition and addressing immediate nutrient deficiencies. INM not only provides a sustainable and economical approach to nutrient management but also helps reduce reliance on chemical fertilizer [60]. However, while the individual effects of INM on crop productivity and soil quality are well-documented, its overall impact on factors such as soil bulk density and microbial biomass carbon is still not fully understood. Proper fertilizer management, including balanced fertilization based on soil testing, is crucial for maximizing nutrient use efficiency and minimizing environmental impacts like greenhouse gas emissions and nutrient runoff. Precision agriculture technologies and practices like cover cropping and crop rotation further enhance nutrient management, reducing waste and protecting aquatic environments; application of fertilizer in croplands is a major source of anthropogenic greenhouse gas emissions [61].

## 7. Innovative practices for sustainable intensification

### 7.1 Enhanced crop varieties

Recent advancements in crop breeding focus on developing varieties that utilize nutrients more efficiently and are resilient to climate stresses, ensuring stable yields [62]. For example, the development of drought-resistant maize in sub-Saharan Africa has significantly increased food security in the region [63]. These advancements in crop breeding have the potential to transform agriculture, enabling farmers to produce more with fewer resources while minimizing environmental impact. As research advances, we can expect to see even more innovative solutions that address the pressing challenges of food security and sustainability. In addition, biotechnology, in recent years, has also facilitated the creation of crops with precise genome modifications, allowing for targeted improvements in yield, disease resistance, and nutritional quality. Notable examples include Golden Rice, which is enriched with beta-carotene to combat vitamin A deficiency [64].

### 7.2 Agroecological practices

Diversifying crop species helps buffer against market and climatic risks, promoting a more resilient agricultural system. Agroforestry, which integrates trees and shrubs

with crops and livestock, offers numerous benefits including improved soil fertility, enhanced biodiversity, and better microclimates. Trees in agroforestry systems can act as windbreaks, reduce soil erosion, and enhance water infiltration. Additionally, they can provide shade for crops and livestock, creating a more favorable microclimate. Intercropping, or growing multiple crops together, maximizes resource use and reduces pest pressures [65]. For example, integrating nitrogen-fixing trees with staple crops in Zambia has significantly improved yields and soil health. Such systems also provide additional products like fruits, fodder, and timber, which can diversify income sources for farmers and improve their livelihoods [66]. Moreover, these practices contribute to carbon sequestration, aiding in climate change mitigation. Agroforestry systems, for instance, have a higher capacity for carbon storage than traditional farming systems.

### 7.3 Conservation tillage

Conservation tillage techniques, such as no-till and reduced-till farming, are revolutionizing agricultural practices by maintaining soil structure, enhancing organic matter content, and significantly reducing erosion. For instance, in the United States, conservation tillage practices have reduced soil erosion by up to 90% in some areas [67]. The benefits of conservation tillage extend beyond soil preservation. By minimizing soil disturbance, these techniques help maintain the habitat for beneficial soil organisms, which play a critical role in nutrient cycling and soil health. This approach conserves soil moisture, which is crucial during dry periods and reduces farmers' fuel and labor costs, making it an economically viable option. Moreover, conservation tillage is pivotal in mitigating climate change. Reducing the need for frequent plowing, lowers greenhouse gas emissions from farm machinery. Additionally, the increased organic matter in the soil acts as a carbon sink, sequestering carbon dioxide from the atmosphere. This dual benefit of enhancing soil health while combating climate change makes conservation tillage a cornerstone of sustainable agriculture. In practice, farmers adopting conservation tillage have reported improved crop resilience to drought and extreme weather events [68]. This resilience is particularly vital in the face of global climate change, ensuring food security and sustainable farming livelihoods.

### 7.4 Technological advances

Integration artificial intelligence (AI), big data analytics, and remote sensing technologies has revolutionized the monitoring and management of agroecosystems. These technologies enable real-time data collection and analysis, which helps predict crop performance, identify pest and disease outbreaks, and optimize irrigation and nutrient applications. Such innovations lead to more sustainable and efficient farming practices. For instance, in California's Central Valley, remote sensing data from satellites is used to monitor crop health and water usage, optimize irrigation practices and conserve water. AI has enabled the development of predictive models that analyze vast datasets to forecast agricultural trends, improve crop management decisions, and enhance resilience to climatic variability. Practical tools include AI-driven platforms like Climate FieldView, which provides farmers with detailed insights into field conditions, and Plantix, an app that uses AI to diagnose plant diseases from photos taken by farmers, offering treatment recommendations [69, 70]. These digital tools support sustainable agricultural practices by minimizing resource wastage and environmental degradation. As these technologies advance, they promise to transform agriculture into a more efficient, sustainable, and resilient industry.

## 8. Enhancing policy and institutional frameworks for sustainable agriculture in Africa

Enhancing the policy and institutional frameworks for sustainable agriculture for example in Africa is crucial given the continent's heavy reliance on agriculture for economic stability, food security, and environmental sustainability. Robust frameworks are necessary to provide the guidelines, incentives, and regulations to effectively promote sustainable agricultural practices. These frameworks are instrumental in integrating sustainable agriculture into national strategies by ensuring both vertical alignment with international directives and horizontal integration across various governmental sectors.

### 8.1 Vertical and horizontal policy coherence

In the African context, aligning international and local policies is critical. International agreements, such as the Paris Agreement and the Sustainable Development Goals (SDGs), serve as overarching frameworks guiding national policies. For African nations, this involves adapting global standards to local conditions, which vary widely in terms of ecology, economy, and society [71]. Horizontal integration, on the other hand, ensures that agricultural policies are in harmony with policies from other sectors like water management, economic development, and environmental protection. This coherence is essential for ensuring sustainable agricultural policies contribute to broader development goals without compromising environmental sustainability or social equity [72].

### 8.2 Global policies and agreements

Global organizations, including the Food and Agriculture Organization (FAO) and the Consultative Group on International Agricultural Research (CGIAR), play pivotal roles in global agricultural policies. They set standards and provide technical support to facilitate the implementation of sustainable practices across Africa. These organizations ensure that policies are scientifically sound and practically viable [73]. Agreements like the Paris Agreement and the SDGs significantly influence national policies across Africa. These global frameworks drive efforts to reduce agricultural emissions, enhance carbon sequestration, and promote sustainable land and soil management practices that can adapt to the continent's climatic challenges [74].

### 8.3 National and local policies

At the national level, policies such as Kenya's Climate Smart Agriculture Strategy and Ethiopia's Green Economy Strategy provide frameworks to support sustainable agricultural practices through financial and technical assistance. These strategies are akin to similar programs found in countries like the United States and Germany [75]. Local governance and community involvement are key to effectively implementing sustainable practices. Policies must be grounded in local realities to ensure their effectiveness and acceptance. Community-led initiatives, such as Tanzania's community forest management, highlight the potential of local involvement in enhancing ecosystems and providing sustainable livelihoods [76]. Africa faces significant challenges in coordinating policies across different government levels and sectors, often resulting in conflicts, delays, and inefficiencies. Resistance to change and limited adaptation of policies to local conditions further hinder their effectiveness. Frequently, policies

do not consider the unique ecological, social, and economic conditions of local areas, rendering them less effective or even irrelevant [77].

### 8.4 Strategies for effective policy frameworks

Developing policies through inclusive processes involving all stakeholders is essential. These policies must be flexible, adaptive, and capable of evolving with new scientific findings and changing circumstances. Regular scientific reviews and the establishment of bridging institutions can enhance the integration of scientific research into policymaking, ensuring that policies are up-to-date with the latest advancements in agricultural science [78]. The future of sustainable agricultural policies in Africa will likely involve increased integration of digital tools in policy implementation. Technologies like AI, big data, and remote sensing are being employed to improve the precision and efficiency of policy enforcement and monitoring across the continent. As global challenges such as climate change intensify, regulatory frameworks are expected to evolve to provide greater support for green technologies and align more closely with global climate agendas, ensuring a unified response to these challenges [79].

## 9. Future directions and research needs

Several key research areas and future directions are crucial to advance sustainable intensification. First, expanding the adoption of precision agriculture, particularly in regions reliant on traditional practices, requires focusing on affordable, scalable technologies for smallholder farmers. Integrating AI, machine learning, and big data into agriculture can enhance predictions for crop health and resource use [80]. With climate change intensifying, research into climate resilience is critical. Developing drought, heat, and flood-resistant crops and optimizing nutrient management under varying climates are priorities. Soil health and biodiversity also need deeper investigation, focusing on the interactions between soil microorganisms, plant roots, and sustainable practices like conservation agriculture and agroforestry [81].

Refining Integrated Nutrient Management (INM) strategies for different agro-ecological zones and exploring biofertilizers are essential for sustainable nutrient management [82]. Additionally, research should explore supportive policies and community-led initiatives that integrate traditional knowledge with modern practices, ensuring that strategies are locally appropriate and widely adopted. These initiatives will help ensure that policies and practices are well-suited to local conditions and widely adopted. Finally, understanding the economic viability and social impacts of sustainable intensification, including labor dynamics and gender roles, is vital for designing economically and socially sustainable interventions [83].

## 10. Conclusions

Sustainable intensification represents a vital paradigm shift in agriculture, aiming to balance the increasing global food demand with the need to preserve environmental health. This approach is not just about increasing productivity, but about doing so in a way that maintains and enhances the ecological systems upon which agriculture depends. Key principles such as diversification, precision agriculture, and integrated nutrient management are central to this approach. These practices, when effectively

implemented, can lead to enhanced productivity with minimal environmental impact, improved soil health, and increased resilience to climate change. The integration of agroecological practices, such as agroforestry and conservation agriculture, further supports the sustainability of agricultural systems by promoting biodiversity and ecological balance. However, the success of sustainable intensification relies heavily on supportive policies, community engagement, and ongoing research and innovation. Policies that incentivize sustainable practices and participatory approaches involving local communities, are essential for the widespread adoption of sustainable intensification.

Additionally, research focusing on refining sustainable practices, understanding the socio-economic impacts, and developing new technologies will be crucial in addressing the challenges of global food security and environmental sustainability. In conclusion, sustainable intensification offers a promising pathway to meet the dual challenges of feeding a growing global population and preserving the planet's ecological balance. Integrating productivity and environmental health provides a framework for resilient and sustainable agriculture in the face of climate change and other global challenges. Continued research, innovation, and collaboration across sectors will be key to realizing the full potential of a sustainable and resilient future.

## Acknowledgements

The authors gratefully acknowledge the Climate and Clean Air Coalition (CCAC) of the United Nations Environment Program for their generous funding and indispensable support, which were pivotal to the success of this research. The authors acknowledge the use of Grammarly, ChatGPT, and Perplexity AI for language polishing and reference support in the manuscript.

## Conflict of interest

The author declares no conflict of interest.

## Author details

Kwaku Onwona-Hwesofour Asante, Jeannette Aduhene-Chinbuah,
Clement Oppong Peprah, Kennedy Agyeman, Felix Frimpong, Eric Owusu Danquah and Ralph Bam*
Council for Scientific and Industrial Research-Crops Research Institute, Kumasi, Ghana

*Address all correspondence to: ralphbam@yahoo.com

## References

[1] Foley JA et al. Solutions for a cultivated planet. Nature. 2011;**478**(7369):337-342. DOI: 10.1038/nature10452

[2] Tscharntke T, Klein AM, Kruess A, Steffan-Dewenter I, Thies C. Landscape perspectives on agricultural intensification and biodiversity-ecosystem service management. Ecology Letters. 2005;**8**(8):857-874. DOI: 10.1111/j.1461-0248.2005.00782.x

[3] Tilman D, Balzer C, Hill J, Befort BL. Global food demand and the sustainable intensification of agriculture. Proceedings of the National Academy of Sciences. 2011;**108**(50):20260-20264. DOI: 10.1073/pnas.1116437108

[4] Campbell BM, Thornton P, Zougmoré R, van Asten P, Lipper L. Sustainable intensification: What is its role in climate smart agriculture? Current Opinion in Environment Sustainability. 2014;**8**:39-43. DOI: 10.1016/j.cosust.2014.07.002

[5] Pretty J et al. Global assessment of agricultural system redesign for sustainable intensification. Nature Sustainability. 2018;**1**(8):441-446. DOI: 10.1038/s41893-018-0114-0

[6] Pretty J, Toulmin C, Williams S. Sustainable intensification in African agriculture. International Journal of Agricultural Sustainability. 2011;**9**(1):5-24. DOI: 10.3763/ijas.2010.0583

[7] Veste M et al. The need for sustainable agricultural land-use systems: Benefits from integrated agroforestry systems. In: von Maltitz GP, et al., editor. Sustainability of Southern African Ecosystems under Global Change. Ecological Studies. Vol. 248. Cham: Springer; 2024. pp. 587-623. DOI: 10.1007/978-3-031-10948-5_21

[8] McBratney A, Whelan B, Ancev T, Bouma J. Future directions of precision agriculture. Precision Agriculture. 2005;**6**(1):7-23. DOI: 10.1007/S11119-005-0681-8/METRICS

[9] Evenson RE, Gollin D. Assessing the impact of the green revolution, 1960 to 2000. Science (1979). 2003;**300**(5620):758-762. DOI: 10.1126/science.1078710

[10] Pinstrup-Andersen P, Hazell PBR. The impact of the green revolution and prospects for the future. Food Reviews International. 1985;**1**(1):1-25. DOI: 10.1080/87559128509540765

[11] Hou D, Bolan NS, Tsang DCW, Kirkham MB, O'Connor D. Sustainable soil use and management: An interdisciplinary and systematic approach. Science of the Total Environment. 2020;**729**:138961. DOI: 10.1016/j.scitotenv.2020.138961

[12] Delgado JA, Short NM, Roberts DP, Vandenberg B. Big data analysis for sustainable agriculture on a geospatial cloud framework. Frontiers in Sustainable Food Systems. Jul 2019;**3**:54. DOI: 10.3389/fsufs.2019.00054

[13] Krishna KR. Agricultural Drones. Waretown, NJ: Apple Academic Press; 2018. DOI: 10.1201/9781315195520

[14] Lowenberg-DeBoer J, Erickson B. Setting the record straight on precision agriculture adoption. Agronomy Journal. 2019;**111**(4):1552-1569. DOI: 10.2134/agronj2018.12.0779

[15] Erlangga E, Machuku O, Jun Dahino C. A review article on the impact and challenges of mobile phone usage on agricultural production in

Africa. Cogent Food & Agriculture. Dec 2023;**9**(2):2273634. DOI: 10.1080/23311932.2023.2273634

[16] Cisternas I, Velásquez I, Caro A, Rodríguez A. Systematic literature review of implementations of precision agriculture. Computers and Electronics in Agriculture. 2020;**176**:105626. DOI: 10.1016/j.compag.2020.105626

[17] Philippine Economic Update, December 2012: Accelerating Reforms to Sustain Growth. Manila. Available from: https://hdl.handle.net/10986/26742: World Bank; 2012 [Accessed: July 15, 2024]

[18] Raj R, Kar S, Nandan R, Jagarlapudi A. Precision agriculture and unmanned aerial vehicles (UAVs). In: Unmanned Aerial Vehicle: Applications in Agriculture and Environment. Cham: Springer International Publishing; 2020. pp. 7-23. DOI: 10.1007/978-3-030-27157-2_2

[19] Lampach N, To-The N, Nguyen-Anh T. Technical efficiency and the adoption of multiple agricultural technologies in the mountainous areas of northern Vietnam. Land Use Policy. 2021;**103**:105289. DOI: 10.1016/j.landusepol.2021.105289

[20] Surendran U, Nagakumar KCV, Samuel MP. Remote sensing in precision agriculture. In: Digital Agriculture. Cham: Springer International Publishing; 2024. pp. 201-223. DOI: 10.1007/978-3-031-43548-5_7

[21] Nakai J. Food and Agriculture Organization of the United Nations and the sustainable development goals. Sustainable Development (Rome). 2018;**22**:1-450

[22] Souza Piao R, Silva VL, Navarro del Aguila I, de Burgos Jiménez J. Green growth and agriculture in Brazil. Sustainability. 2021;**13**(3):1162. DOI: 10.3390/su13031162

[23] Van den Berg H, Jiggins J. Investing in farmers—The impacts of farmer field schools in relation to integrated pest management. World Development. 2007;**35**(4):663-686. DOI: 10.1016/j.worlddev.2006.05.004

[24] Mäder P, Fließbach A, Dubois D, Gunst L, Fried P, Niggli U. Soil fertility and biodiversity in organic farming. Science (1979). 2002;**296**(5573):1694-1697. DOI: 10.1126/SCIENCE.1071148

[25] Francis C et al. Agroecology: The ecology of food systems. Journal of Sustainable Agriculture. Jul 2003;**22**(3): 99-118. DOI: 10.1300/J064v22n03_10

[26] das Nair R, Landani N. Making Agricultural Value Chains more Inclusive Through Technology and Innovation. Finland: UNU-WIDER; 2020. DOI: 10.35188/UNU-WIDER/2020/795-8

[27] Snapp SS et al. Participatory action research generates knowledge for Sustainable Development Goals. Frontiers in Ecology and the Environment. 2023;**21**(7):341-349. DOI: 10.1002/fee.2591

[28] Shawki N, Schnyder M. Understanding polycentrically organized movements: An analysis of the Slow Food and Fair Trade movements in Europe. Journal of Civil Society. 2023;**19**(2):156-174. DOI: 10.1080/17448689.2023.2206153

[29] Marten GG. Productivity, stability, sustainability, equitability and autonomy as properties for agroecosystem assessment. Agricultural Systems. 1988;**26**(4):291-316. DOI: 10.1016/0308-521X(88)90046-7

[30] Belete T, Yadete E. Effect of mono cropping on soil health and fertility management for sustainable agriculture practices: A review. Journal of Plant Sciences. 2023;**11**:192-197

[31] Shah KK et al. Diversified crop rotation: An approach for sustainable agriculture production. Advances in Agriculture. 2021;**2021**:1-9. DOI: 10.1155/2021/8924087

[32] Chain-Guadarrama A, Martínez-Salinas A, Aristizábal N, Ricketts TH. Ecosystem services by birds and bees to coffee in a changing climate: A review of coffee berry borer control and pollination. Agriculture, Ecosystems and Environment. 2019;**280**:53-67. DOI: 10.1016/j.agee.2019.04.011

[33] Khan ZR et al. Achieving food security for one million sub-Saharan African poor through push–pull innovation by 2020. Philosophical Transactions of the Royal Society, B: Biological Sciences. 2014;**369**(1639):20120284. DOI: 10.1098/rstb.2012.0284

[34] Shiferaw BA, Okello J, Reddy RV. Adoption and adaptation of natural resource management innovations in smallholder agriculture: Reflections on key lessons and best practices. Environment, Development and Sustainability. 2009;**11**(3):601-619. DOI: 10.1007/s10668-007-9132-1

[35] Lazali M et al. CROSYMED project: Enhancing nutrient use efficiency through legumes in agroecosystems of the Mediterranean Basin. Sustainability. 2021;**13**(9):4695. DOI: 10.3390/su13094695

[36] Rumpel C et al. The 4p1000 initiative: Opportunities, limitations and challenges for implementing soil organic carbon sequestration as a sustainable development strategy. Ambio. 2020;**49**(1):350-360. DOI: 10.1007/s13280-019-01165-2

[37] Andrews SS, Karlen DL, Cambardella CA. The soil management assessment framework. Soil Science Society of America Journal. 2004;**68**(6):1945-1962. DOI: 10.2136/SSSAJ2004.1945

[38] Rusan MJ. Soil and nutrient management under saline conditions. In: Biosaline Agriculture as a Climate Change Adaptation for Food Security. Cham: Springer; 2023. pp. 71-85. DOI: 10.1007/978-3-031-24279-3_4

[39] Zhu S-C et al. Plant-soil feedbacks for the restoration of degraded mine lands: A review. Frontiers in Microbiology. Jan 2022;**12**:751794. DOI: 10.3389/fmicb.2021.751794

[40] Koudahe K, Allen SC, Djaman K. Critical review of the impact of cover crops on soil properties. International Soil and Water Conservation Research. 2022;**10**(3):343-354. DOI: 10.1016/j.iswcr.2022.03.003

[41] Bennett JA, Klironomos J. Mechanisms of plant–soil feedback: Interactions among biotic and abiotic drivers. New Phytologist. 2019;**222**(1):91-96. DOI: 10.1111/nph.15603

[42] Dakora FD, Phillips DA. Root exudates as mediators of mineral acquisition in low-nutrient environments. In: Food Security in Nutrient-Stressed Environments: Exploiting Plants' Genetic Capabilities. Developments in Plant and Soil Sciences. Vol. 95. Dordrecht: Springer; 2002. pp. 201-213. DOI: 10.1007/978-94-017-1570-6_23

[43] Jones DL, Nguyen C, Finlay RD. Carbon flow in the rhizosphere: Carbon trading at the soil-root interface.

Plant and Soil. 2009;**321**(1-2):5-33. DOI: 10.1007/S11104-009-9925-0/METRICS

[44] Parnell JJ et al. From the lab to the farm: An industrial perspective of plant beneficial microorganisms. Frontiers in Plant Science. 2016;**7**(AUG2016):209596. DOI: 10.3389/FPLS.2016.01110/BIBTEX

[45] Brady N, Weil R. Elements of the Nature and Properties of Soils [Online]. 2004. Available from: http://faculty.washington.edu/zabow/ESC210/210Syllabus_2007.doc [Accessed: August 21, 2024]

[46] Tisdale S, Nelson W, Beaton J. Soil Fertility and Fertilizers [Online]. 1985. Available from: https://www.cabidigitallibrary.org/doi/full/10.5555/19851998321 [Accessed: August 21, 2024]

[47] Li Y, Tian D, Feng G, Yang W, Feng L. Climate change and cover crop effects on water use efficiency of a corn-soybean rotation system. Agricultural Water Management. 2021;**255**:107042. DOI: 10.1016/j.agwat.2021.107042

[48] Page V, Feller U. Heavy metals in crop plants: Transport and redistribution processes on the whole plant level. Agronomy. 2015;**5**(3):447-463. DOI: 10.3390/agronomy5030447

[49] Lal R. Soil carbon sequestration impacts on global climate change and food security. Science (1979). 2004;**304**(5677):1623-1627. DOI: 10.1126/SCIENCE.1097396/SUPPL_FILE/LAL.SOM.PDF

[50] Tilman D, Clark M. Food, agriculture & the environment: Can we feed the world & save the earth? Daedalus. 2015;**144**(4):8-23. DOI: 10.1162/DAED_a_00350

[51] Bindraban PS, Dimkpa C, Nagarajan L, Roy A, Rabbinge R. Revisiting fertilisers and fertilisation strategies for improved nutrient uptake by plants. Biology and Fertility of Soils. 2015;**51**(8):897-911. DOI: 10.1007/s00374-015-1039-7

[52] Amalu UC. Food security: Sustainable food production in sub-Saharan Africa. Outlook on Agriculture. 2002;**31**(3):177-185. DOI: 10.5367/000000002101294029

[53] Færge J, Magid J. Evaluating NUTMON nutrient balancing in sub-Saharan Africa. Nutrient Cycling in Agroecosystems. 2004;**69**(2):101-110. DOI: 10.1023/B:FRES.0000029680.97610.51

[54] Kumar R, Prakash OG. The Impact of Chemical Fertilizers on Our Environment and Ecosystem [Online]. Available from: https://www.researchgate.net/publication/331132826 [Accessed: August 07, 2024]

[55] Ren N, Wang Y, Ye Y, Zhao Y, Huang Y, Fu W, et al. Effects of continuous nitrogen fertilizer application on the diversity and composition of rhizosphere soil Bacteria. Frontiers in Microbiology. 2020;**11**:1948

[56] Jote CA. The impacts of using inorganic chemical fertilizers on the environment and human health. Organic and Medicinal Chemistry International Journal. 2023;**13**(3):555864

[57] García-Orenes F, Roldán A, Morugán-Coronado A, Linares C, Cerdà A, Caravaca F. Organic fertilization in traditional Mediterranean grapevine orchards mediates changes in soil microbial community structure and enhances soil fertility. Land Degradation and Development. 2016;**27**(6):1622-1628. DOI: 10.1002/ldr.2496

[58] The World of Organic Agriculture 2024. FAO [Online]. Available from: https://www.fao.org/family-farming/detail/en/c/1678159/ [Accessed: August 07, 2024]

[59] Magid J, Pedersen KE, Hansen M, Cedergreen N, Brandt KK. Comparative assessment of the risks associated with use of manure and sewage sludge in Danish agriculture. Advances in Agronomy. 2020;**164**:289-334

[60] Campbell CA, Biederbeck VO, Selles F, Schnitzer M, Stewart JWB. Effect of manure and P fertilizer on properties of a black Chernozem in Southern Saskatchewan. Canadian Journal of Soil Science. 1986;**66**(4):601-614. DOI: 10.4141/cjss86-060

[61] Paramesh V, Mohan Kumar R, Rajanna GA, Gowda S, Nath AJ, Madival Y, et al. Integrated nutrient management for improving crop yields, soil properties, and reducing greenhouse gas emissions. Frontiers in Sustainable Food Systems. 2023;7:1173258

[62] Rahman MM et al. Integrated nutrient management enhances productivity and nitrogen use efficiency of crops in acidic and Charland soils. Plants. 2021;**10**(11):2547. DOI: 10.3390/plants10112547

[63] Chaubey AK, Mishra S, Singh SK, Chaubey C, Pandey KP. Integrated nutrients management for future production: A review. International Journal of Environment and Climate Change. 2023;**13**(11):1770-1779. DOI: 10.9734/ijecc/2023/v13i113333

[64] Selim MM. Introduction to the integrated nutrient management strategies and their contribution to yield and soil properties. International Journal of Agronomy. 2020;**2020**:1-14. DOI: 10.1155/2020/2821678

[65] Tester M, Langridge P. Breeding technologies to increase crop production in a changing world. Science (1979). 2010;**327**(5967):818-822. DOI: 10.1126/science.1183700

[66] Gebre GG, Rahut DB, Aryal JP, Mawia H. Potential impact of scaling adaptation strategies for drought stress: A case of drought-tolerant maize varieties in Tanzania. International Journal of Agricultural Sustainability. 2023;**21**(1):2189396

[67] Bouis HE, Saltzman A. Improving nutrition through biofortification: A review of evidence from HarvestPlus, 2003 through 2016. Global Food Security. 2017;**12**:49-58. DOI: 10.1016/j.gfs.2017.01.009

[68] Brookes G, Barfoot P. Environmental impacts of genetically modified (GM) crop use 1996-2016: Impacts on pesticide use and carbon emissions. GM Crops & Food. 2018;**9**(3):109-139. DOI: 10.1080/21645698.2018.1476792

[69] Huss CP, Holmes KD, Blubaugh CK. Benefits and risks of intercropping for crop resilience and pest management. Journal of Economic Entomology. 2022;**115**(5):1350-1362. DOI: 10.1093/jee/toac045

[70] Garrity DP et al. Evergreen agriculture: A robust approach to sustainable food security in Africa. Food Security. 2010;**2**(3):197-214. DOI: 10.1007/s12571-010-0070-7

[71] Kumar V, Mahajan G, Dahiya S, Chauhan BS. Challenges and opportunities for weed management in no-till farming systems. In: No-Till Farming Systems for Sustainable Agriculture. Cham: Springer International Publishing; 2020. pp. 107-125. DOI: 10.1007/978-3-030-46409-7_7

[72] Shrestha JIBAN, Subedi SUBASH, Timsina KP, Chaudhary A, Kandel M, Tripathi S. Conservation agriculture as an approach towards sustainable crop production: A review. Farming and Management. 2020;**5**(1):7-15

[73] Hampf AC, Nendel C, Strey S, Strey R. Biotic yield losses in the Southern Amazon, Brazil: Making use of smartphone-assisted plant disease diagnosis data. Frontiers in Plant Science. 2021;**12**:621168

[74] Tiefenbacher A, Sandén T, Haslmayr HP, Miloczki J, Wenzel W, Spiegel H. Optimizing carbon sequestration in croplands: A synthesis. Agronomy. 2021;**11**(5):882

[75] Vargas VR, Lawthom R, Prowse A, Randles S, Tzoulas K. Implications of vertical policy integration for sustainable development implementation in higher education institutions. Journal of Cleaner Production. 2019;**235**:733-740. DOI: 10.1016/j.jclepro.2019.07.022

[76] Pawlak K, Kołodziejczak M, Xie Y. Horizontal integration in the agricultural sector as a factor increasing its competitiveness—Experience from Poland. Eastern European Countryside. 2019;**25**(1):195-232. DOI: 10.12775/eec.2019.008

[77] Pingali P, Kelley T. The role of international agricultural research in contributing to global food security and poverty alleviation: The case of the CGIAR. In: Handbook of Agricultural Economics. Vol. 3. Elsevier; 2007. pp. 2381-2418

[78] Nhemachena C, Matchaya G, Nhemachena C, Karuaihe S, Muchara B, Nhlengethwa S. Measuring baseline agriculture-related sustainable development goals index for southern Africa. Sustainability. 2018;**10**(3):849. DOI: 10.3390/su10030849

[79] Ogemah VK. Sustainable agriculture: Developing a common understanding for modernization of agriculture in Africa. African Journal of Food, Agriculture, Nutrition and Development. 2017;**17**(1):11673-11690. DOI: 10.18697/AJFAND.77.16560

[80] Esteves AM, Genus A, Henfrey T, Penha-Lopes G, East M. Sustainable entrepreneurship and the sustainable development goals: Community-led initiatives, the social solidarity economy and commons ecologies. Business Strategy and the Environment. 2021;**30**(3):1423-1435. DOI: 10.1002/bse.2706

[81] Jastrzębska M, Kostrzewska M, Saeid A. Sustainable agriculture: A challenge for the future. In: Smart Agrochemicals for Sustainable Agriculture. Netherland: Elsevier; 2022. pp. 29-56. DOI: 10.1016/B978-0-12-817036-6.00002-9

[82] Snyder KA, Miththapala S, Sommer R, Braslow J. The yield gap: Closing the gap by widening the approach. Experimental Agriculture. 2017;**53**(3):445-459. DOI: 10.1017/S0014479716000508

[83] Ehlers M-H, Huber R, Finger R. Agricultural policy in the era of digitalisation. Food Policy. 2021;**100**:102019. DOI: 10.1016/j.foodpol.2020.102019