# Enhancing soybean productivity through agroforestry, organic waste fertilization, and mulching: a review about climate change

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**Abstract.** Some issues that will threaten agriculture now and in the future are declining productivity and increased risks due to climate change. However, agroforestry, organic waste fertilizers, and mulching are promising ways to address these challenges. They offer approaches that increase productivity and improve land adaptability to climate extremes. This review explores the integration of agroforestry, organic fertilizer from local waste and mulching systems as strategies to increase soybean productivity while ensuring sustainability. Agroforestry reduced soil erosion by 50% and increased soil carbon stocks by 26-34% at various depths. Organic fertilizers combined with inorganic inputs increased yields by 12.8-32.5%, while mulching further increased yields by 38.6-44.2%. These practices improve soil health, reduce reliance on chemical inputs and provide ecosystem services that support adaptation and mitigation strategies for climate change. This combination is expected to increase soybean production to meet global demand. However, adoption remains limited due to economic and technical constraints, particularly among smallholder farmers. Future studies should address cost-effective solutions and identify optimal zones for implementation.

## 1 Introduction

The different facets of climate change have dire impacts on global agriculture and world food security. All across the globe, climate change is a threat to both food security and agricultural output. Increasing temperatures, changes in the distribution and amounts of rainfall, drought, and extreme weather events all contribute to disrupting traditional farming methods [1]. Increased temperatures due to climate change also result in soil compaction, acidification, reduced organic matter, and low soil biodiversity [2]. Data from Our World in Data from 2004 to 2024 shows an increase in monthly average temperature from 14.45°C to 16.82°C, indicating that the earth has warmed significantly over 20 years [3]. These changes are detrimental to the agricultural sector, especially agricultural systems that depend on nature. As climate variability increases, farmers face more significant uncertainty in crop

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yields. Some regions are even experiencing severe productivity declines. A study by Bobea et al. (2021) explains that there has been a 21% decline in global agricultural production efficiency since 1961. The impact is much more severe, with around 26-34% declines in warmer regions such as Africa, Latin America, and the Caribbean [4]. Evolving natural conditions require innovative and sustainable approaches to maintain and improve agricultural yields while addressing environmental concerns.

Climate change has made it imperative to adopt ecosystems-based sustainable agricultural practices. Agroforestry, the cultivation of crops with the management of forests, and the application of organic fertilizers have emerged as a more eco-friendly option than chemical fertilizers [5]. Furthermore, using mulch from organic materials such as leaves or straw effectively maintains soil moisture, reduces erosion, and maintains stable soil temperatures [6]. Studies by Mohanty et al. (2024) and Shahane and Shivay (2021) show that these techniques increase soil productivity and health and improve air retention and plant resistance to climate change and disease. These practices also play an essential role in mitigating climate change through carbon sequestration and reducing greenhouse gas emissions [7,8]. Holka et al. (2022) added that farmers who adopt these methods create more stable and adaptive farming systems to climate change and contribute to long-term food security. With the adoption of these sustainable practices, the farmers are also able to enhance the production efficiency while also maintaining an ecological system that is recovering and has a greater stability against disturbances [9].

Soybean, a widely grown crop worldwide, is susceptible to climate change. New research has indicated that soybean outputs will be reduced in several areas due to increasing temperatures and altered rainfall patterns. Li et al. (2024) determined that soybean plants suffered from various declines in years of exceptionally high temperatures. Plant height was reduced between 6.1 and 15 cm, and the number of main stem books was reduced by 0.1-2.9, while the number of pods per plant was reduced by 4.8-13.7. In addition, the number of seeds per plant was reduced by 13.5 - 32.6. The weight of seeds per plant also decreased by 3.8-6.9 grams, while the weight of 100 seeds was reduced by 0.1-4.5 grams [10]. High temperatures can cause damage to plant growth and development, including the cutting and dropping flowers and young pods. Temperatures above 35°C for 10 hours can reduce yield by up to 27% [11]. Water stress applied at vegetative and generative stages significantly affects dry weight and yield. Stress at 30/22 °C resulted in an average seed yield of 10.9 g/pl, which was reduced to 8.8 g/pl at 34/24 °C, 6.3 g/pl at 38/26 °C, and 3.9 g/pl at 42/28 °C. In addition, water stress at the vegetative stage can reduce yield by 28% and at the generative stage by 74% [12]. Developing climate-resilient soybean production practices is critical in the context of changing climate.

The focus of this review is on fostering agroforestry practices, organic waste fertilization, and mulching in order to improve the productivity of soybeans. A growing body of literature suggests that under different climate conditions, some management practices of eco-friendly agricultural systems can be quite effective in growing soybeans. In addition, this review will explore the potential contribution of integrated systems (agroforestry, organic fertilizer, and mulching) to climate change mitigation and adaptation strategies in agriculture. The detailed analysis will provide practical information to researchers, policymakers, and farmers oriented toward developing improved and sustainable soybean production systems in the face of climate change.

## 2 Agroforestry as a Sustainable Agricultural System

Agroforestry is a land management system integrating trees, crops, and livestock on the same land area [13]. Soybean cultivation in an agroforestry system involves strategically combining trees or shrubs with soybean fields to create a multifunctional agricultural

landscape. The approach adopts the principle of ecological synergy and relies on interrelations between the woody, non-woody, and other components aimed at increasing productivity and providing other environmental services. The basic principles of agroforestry applied to soybean cultivation include spatial and temporal arrangements that optimize resource utilization, minimize competition, and maximize complementarity among system components [14].

Integrating agroforestry into soybean production has many advantages, mainly in dealing with climate change and soil degradation challenges. One of them is soil erosion control and the enhancement of soil properties. Trees and shrubs situated adjacent to or interspersed in the rows of soybeans serve as windbreaks and assist in soil anchoring. A study conducted in Western India over four years revealed that cultivation of a mustard-based agroforestry system reduced total runoff and soil loss by 19.1% and 37.1%, respectively [15]. A literature review conducted by Muchane et al. (2020) revealed that agroforestry trees reduced soil erosion by 50% [16]. Leaf litter and tree root systems also contribute to increased organic matter content and improve soil fertility, which can increase soybean yields over time [17]. Switching from traditional agriculture to agroforestry increases soil carbon stock levels by 26% at 0-15 cm depth, 40% at 0-30 cm depth, and 34% at 0-100 cm soil depth [18].

Agroforestry systems reduce emissions while enhancing carbon sequestration, which is why they are also significant in addressing climate change. Introducing trees into soybean fields drastically expands the carbon-storage potential of the agricultural landscape. This is adequately discussed in a literary review by Ghale et al. (2022) [19]. Agroforestry systems in South Asia, such as alley cropping and tree plantations, can contribute significantly to carbon sequestration. Agroforestry systems lock up more than 24 metric tons of carbon per hectare in Bangladesh, a significant amount in Haryana, India, and Punjab, Pakistan. Cocoa-based agroforestry systems in Brazil have been shown to sequester up to 302 metric tons of carbon per hectare, offering a potential source of income for farmers. In addition, in its agroforestry systems, low rainfall in Australia has seen an average carbon sequestration rate of 9.5 metric tons per hectare per year. The increased carbon sequestration helps the global mitigation strategies for climate change while boosting the resilience of the agricultural systems to the impacts of climate change [20].

The agroforestry microclimate has exceptional advantages for soybean cultivation within dry and heat-stressed regions. If it gets too hot, trees are around to provide shade and block out some sunlight. This reduction in sunlight intensity means reduced evapotranspiration of plants and water in the soil; hence, the water requirement is more minor. Also, trees provide some protection from wind, which in turn helps protect soybean plants from extreme weather. Research by Riyadh et al. (2018) in Bangladesh reported a 3.37-9.25% decrease in soil temperature, a 10-20% increase in soil moisture, and a 9-19% increase in total soil nitrogen in various crops associated with jackfruit-based agroforestry systems when compared to open seasonal crop fields. This proves that trees have a role in buffering extreme climate impacts [21].

Case studies from various regions have demonstrated the potential of agroforestry to increase soybean production while providing environmental benefits. Combining trees with crops can help improve degraded soils [16]. Appropriate species selection and management can also improve soil's biological, chemical, and physical properties. On-farm trees increase water infiltration and support hydrological functions. This occurs through litter fall and canopy protection [22]. Agroforestry also enhances soil microbial activity. This influence comes from trees, organic matter deposition, root exudates, and diverse litter. It can also retain rainfall, reduce soil erosion, and prevent nutrient loss. Moreover, agroforestry may also help mitigate the pollution caused by agricultural chemicals [23]. Such a case study demonstrated the prospects of agroforestry in enhancing soybean productivity, farmers' ecosystem services, and income diversification.

## 3 Organic Fertilizer from Local Waste

OverOver the past few years, there has been interest, there has been interest in local wastes, that havewhich have the potential to beto be organic fertilizers because of environmental and economic advantages. Such local waste sources can be used efficiently as organic fertilizers, including household organic waste, crop residues, and animal manure [24]. Due to their high content of essential nutrients and organic matter, such materials can be considered a valuable resource for sustainable agriculture. Research done by Guo et al. (2018) focused on the composting process that resulted in the generation of matured compost from large quantities of household food scraps. The compost was found to contain significant amounts of bioavailable N (3.38%), P (7.16%), and K (1.12%). Organic matter was also recorded at 54.45% [25]. High organic matter content is essential for soil health. The nutrient composition of organic fertilizers derived from local waste often surpasses chemical fertilizers regarding long-term soil health benefits.

Organic fertilizers have long been known to improve soil physical properties, such as lowering sodicity, reducing bulk density, increasing water infiltration rates, and improving porosity and aeration [26]. In addition, organic fertilizers also help leach salts in the soil and improve soil chemical properties, such as reducing acidity [27]. Furthermore, an increased application of organic matter such as compost generates an increase in the humic content of the soils, which also induces changes in biological soil properties, which, in turn, help to increase the growth and reproduction of useful macro- and microorganisms. According to Liu et al. (2024), these organic materials also enhance the soil's carbon and nitrogen levels, contributing to enhanced agricultural soil fertility and productivity. Also, the composting process of organic fertilizers can help mitigate unprocessed organic waste and aid in reducing pollution engendered in the ecosystem [28].

The application of organic fertilizers has had beneficial impacts on soybean yields in both the short term and the long term. In Liaoning, China, integrated technologies consisting of organic and inorganic fertilizers proved effective for both soybean cultivation and soil conservation. The results showed that the combination of organic and inorganic fertilizers resulted in higher soybean production compared to the use of inorganic fertilizers alone. Specifically, the application of 27 tons of organic fertilizer per hectare in combination with inorganic fertilizer resulted in an increase in yield of 12.8-32.5% compared to the application of inorganic fertilizer alone. Yields were improved by 35.2-49.8% for organic fertilizers used at twice the usual dose as opposed to inorganic fertilizers [29]. Organic fertilizers augment soil organic carbon and improve soil's water-holding capacity, which is necessary for soybean growth and development. The improved soil structure and water-holding capacity from organic fertilizer results in better root health and overall plant performance [30]. Research by Sajar (2022) proved that the application of organic fertilizers and eggshells gave a natural response to soil pH, available Ca, available P, and organic C. Organic fertilizer of 30 tons per hectare gave the best results on vegetative and generative growth of plants (plant height, number of productive branches, crown dry weight, root dry weight, seed dry weight per plant, 100 seed weight) [31].

Organic fertilizers play an important role in climate change mitigation by reducing greenhouse gas emissions compared to inorganic fertilizers. Emissions from organic fertilizers mainly come from production and storage, while emissions from chemical fertilizers mostly come from production. Urea production produces between 1.3 and 5.5 kg CO2-eq/kg N. In comparison, ammonium nitrate production produces between 3.5 and 10.3 kg CO2-eq/kg N. Emissions from compost vary between 0.25 and 170 kg CO2-eq/kg N, depending on process conditions [32]. The data suggest that fertilizer selection should consider the variability of emissions to reduce environmental impacts. This finding underscores the importance of organic fertilizers in improving the sustainability of

agriculture. Additionally, using local waste as organic fertilizer is economical and harmless to the environment and, therefore, promotes sustainable agriculture. Organic waste as fertilizer enables agriculturalists to cut down on chemical inputs and address waste management problems. Such measures reduce the impact of climate change and foster a circular agricultural economy that agrees with the world's sustainability targets.

## 4 Mulching as a Land Management Technique

Mulching is a farming technique that covers the farm soils with nonbiological and biological materials for better soil conditions and increased plant growth. Biological (organic) mulches include straw, crop residues, and compost, while nonbiological (inorganic) mulches usually consist of plastic film, sacks, or gravel. The main mechanisms of mulching include maintaining soil moisture, reducing temperature fluctuations, and suppressing weed growth [33]. Research conducted at the Jiufeng National Forest Park Ecological Station's rain hall showed that applying organic mulch at a rate of 0.25-0.50 kg/m² was most effective in increasing soil water content and reducing water runoff. Mulch of this thickness can increase soil water retention by 51.7-81.6% and reduce runoff rate by 58-83%. The study showed that organic mulch could significantly improve water and soil conservation in areas that often experience heavy rainfall [34].

Mulch is essential in enhancing the growth stages of soybean plants in diverse climates and soil conditions. The importance of mulch is more pronounced in drought-stricken regions due to climate change while guarding soybean farming. A comprehensive study by Akhtar et al. (2019) revealed that the integrated use of straw mulch with nitrogen fertilizer increased the activity of soil enzymes such as urease, invertase, alkaline phosphatase, and catalase and improved soil nutrient availability (N, P, K) and organic carbon content. During the research period of 2015-2017, the treatment increased soil moisture content by 23% and decreased soil temperature by 8% at a depth of 0-0.2 m, which increased biomass and soybean seed yields by 67% and 75%, respectively, compared to the control [35]. Water efficiency is essential in water-scarce areas, where mulching helps retain moisture and prevent drought effects on soybean crops.

Research worldwide has consistently recognized Mulch practices as positively contributing to soybeans' yield and water use efficiency. The optimization of root and canopy structure can increase soybean seed yield if straw mulch and fertilizer are utilized in the process. The application of straw mulch improves the soil porosity by 2.75% to 4.97% and keeps the upper layer of soil at roughly 20°C, thereby stimulating the development of soybean roots. The combination of straw mulch and fertilizers improved the leaf area index (LAI) by 20.74% and increased the number of days in which net photosynthesis occurred to 106.94. The average soybean seed yield under straw mulch treatment was 4589.9 kg/ha, an increase of 15.2% compared to no mulch. These data indicate that no-till planting technology with straw mulch is highly significant in soil moisture conservation and soybean yield increase in the Huang-Huai-Hai region, especially in dryland farming areas [36].

The use of inorganic mulch or plastic mulch can also optimize soybean yield. Plastic mulch in ridge-furrow systems improved soil hydrothermal conditions, which positively impacted soybean growth and yield in drought-prone semi-humid areas of China. The plastic mulch increased surface soil moisture by 6.7% and soil temperature by 0.5-1.5°C. It increased leaf area index (LAI) by 9.0%, total chlorophyll content by 10.4%, and net photosynthetic rate by 1.6%. Soybean yield increased by 11.1%, water use efficiency by 10.7%, and net income by 8.6%. Dense planting with plastic mulch, along with nitrogen reduction, increased soybean yield with a range of 25.6-38.8% as well as water use efficiency in a range of 23.8-38.0%, with net income standing at 12,749.7 CNY ha-1 [37]. Such findings highlight

mulching practices as a practical, sustainable agricultural practice in increasing soybean production in the changing climate.

## 5 Interaction Between Agroforestry, Organic Fertilizer, and Mulching

Integrating agroforestry, organic fertilizer, and mulching works synergistically to enhance the productivity of soybeans and soil quality. This cutting-edge farming practice simultaneously takes care of several issues of sustainable agriculture. Agroforestry systems protect crops from intense sunlight, soil erosion, and nutrient leaching, and organic manures add nutrients and ameliorate soil quality. Mulching achieves this goal by conserving moisture in the soil, regulating soil temperature, and inhibiting weed growth [38]. Research in the Loess Plateau, China, examined the effects of mulching and irrigation on photosynthetic characteristics and soybean growth in an apple-soybean intercropping system. Two types of mulch (straw and plastic) and four irrigation levels (no irrigation, 55%, 70%, and 85% field capacity) were used as treatments. Results showed that plastic mulch and 70-85% field capacity irrigation increased photosynthesis, water use efficiency, and soybean yield. Research in 2017-2018 resulted in the highest average net photosynthesis (Pn) value for soybean was 17.59 µmol-m-2-s-1 under plastic mulch treatment with 70% field capacity irrigation, while in 2019, the highest value was 14.48 µmol-m-2-s-1 under plastic mulch treatment with 85% field capacity irrigation [39].

Integrating these agricultural technologies has remarkably improved crop yields and soil health. Similar research was also conducted to evaluate organic fertilizers on soybean yield in acidic soils. The results showed that oil palm empty fruit bunch fertilizer increased soybean vegetative growth by almost 50%, including plant height, number of leaves, and root length. Vermicompost fertilizer increased reproductive growth, such as pod number (from about 0-4 units to 42-51 units), seed number (from about 0-5 units to 88-90 units), and seed weight (from about 0-0.37 g to 12-25 g). Organic fertilizers are proven to regulate soil pH and increase soybean yields in acidic soil conditions [40]. When combined with agroforestry systems, these agricultural technologies will increase the benefits.

The environmental and economic benefits of integrated farming systems between agroforestry, organic fertilizer, and mulching systems are enormous. Natural resources such as water and nutrients that are utilized efficiently can contribute to sustainable agriculture and increased farmer income. Enhanced water-use efficiency and nutrient cycling lessen the requirement for outside inputs, and as a consequence, production costs are also reduced. Integrating several technologies from an economic outlook can have long-term advantages. Research conducted in a 10-15-year-old coconut plantation of Bumi Restu Village, East Wasile District, East Halmahera Regency, tested the effectiveness of agroforestry systems on farmers' income. The study results explained that soybean cultivation with coconut agroforestry systems is feasible because coconut farmers get an additional profit of Rp. 4,402,000 / soybean harvest with an R / C value of 1.55 [41]. Such integrated systems have the potential to provide long-term positive impacts that support global sustainability and food security. Food production systems can become more stable and sustainable by improving soil health and crop resilience to climate change.

## 6 Impact on Mitigation and Adaptation to Climate Change

Agroforestry systems and organic fertilizers are essential for climate change mitigation practices since they reduce emissions and increase carbon sinks. A study conducted by Walden et al. (2020) on agroforestry systems in Ethiopia revealed that agroforestry has higher

carbon sequestration potential, with above-ground carbon sequestration levels ranging from 0.29 to 15.21 Mg C $ha^{-1}$ $year^{-1}$ and below-ground between 0.3 to 2 Mg C $ha^{-1}$ $year^{-1}$ [42]. Similar research was also conducted in Balung River Plantation, Sabah, Malaysia. The results showed that the agroforestry system (oil palm and agarwood) had higher total aboveground carbon (79.13 to 85.40 Mg C $ha^{-1}$) compared to oil palm monoculture (60.30 to 76.44 Mg C $ha^{-1}$) [43]. This increased carbon storage capacity contributes to global climate change mitigation efforts and increases agricultural systems' resilience to climate variability. In addition, applying organic fertilizers has shown promising results in reducing greenhouse gas emissions compared to chemical fertilizers. Organic farming systems showed a 40.2% reduction in N2O emissions per hectare compared to non-organic systems [44].

Mulching and agroforestry have been resourceful in enhancing soybean's resilience towards extreme weather conditions due to increased temperatures or droughts. A comprehensive study by Li et al. (2022) in a semi-arid area of soybean fields in Hesheng Town, Qingyang City, Gansu Province, China, revealed that the use of polyethylene plastic mulch increased soybean grain yield by 38.6-44.2%, while the use of corn straw mulch increased yield by 21.8-25.4% compared to no mulch [45]. The advancement in the efficiency of water use is significant in water-scarce areas, where it is necessary to use mulches as an effective method of conserving soil moisture and mitigating the effects of drought on soybeans. Furthermore, agroforestry systems also offer more benefits concerning climate adaptation. Research at the University of Guelph Agroforestry Research Station revealed that soybean yields in tree-competitive zones were lower compared to monocultures. However, soybean yields remained stable in agroforestry despite reduced rainfall, while in monoculture, there was a significant reduction in yield [46].

Enhanced integration of the approaches has the promise of improving food security worldwide. An integrated agroforestry system, organic manuring, and mulching are climate-smart and ecologically improving farming systems that can fit varying climatic and geographical environments. The results show that such practices are critical in increasing food security on a broader scale. Furthermore, using these practices may assist smallholder growers in overcoming poverty because income will be more dependable and efficient than for those dependent on 'worn-out' farming practices. The pressures of the climate crisis mean that an integrated strategy shows much promise in achieving sustainable and resilient food systems globally.

## 7 Implementation Challenges and Opportunities

Implementing agroforestry, organic fertilizer, and mulching on a large farm scale faces several technical, social, and economic constraints. The study by Rayamajhi and Acharya (2023) identified critical constraints, including lack of human resources, lengthy certification processes, poor productivity, and problems with soil management. They often arise due to the lack of the farmers' knowledge of the most suitable agroecological practices and the difficulty of implementing several sustainable technologies simultaneously. Social ones include an unwillingness to abandon long-standing methods of farming practice and the view that it is labor-intensive. From an economic point of view, high initial investment costs, especially for agroforestry systems, can be prohibitive for smallholders [47]. Research by Do et al. (2020) found that farmers prefer monoculture due to the initial income earned and the quick return on investment. The research has demonstrated that farmers opt for monoculture because of the income earned and the quick returns on investment. It has also been noted that annual returns from monoculture are likely to decrease gradually due to land degradation. The gladdening aspect of agroforestry systems is that they have become very profitable. On the other hand, they demand enormous initial and recurrent overhead costs, which could lead to a loss year in the initial years. Offering initial financial reimbursements to cover such

losses can stimulate the uptake of agroforestry in the area [48]. These constraints are also, however, best resolved through policy and Government intervention.

Some countries are implementing supportive policies for agroecology and organic farming. Governments in different countries show diverse commitments to organic and sustainable agriculture. The Tanzanian Government has launched the National Ecological Organic Agriculture Strategy to promote sustainable agriculture and integrate organic agriculture into the national biodiversity policy. Vietnam has established the Vietnam National Action Plan on Food System Transformation, focusing on sustainable agriculture until 2030. The Cambodian Government has established C.A.S.I.C. to promote agroecology and conservation agriculture as part of its agricultural modernization efforts. Japan's Ministry of Agriculture, Forestry and Fisheries is supporting the establishment of "Organic Villages" to strengthen the organic farming sector. Taiwan has upgraded the status of the Board of Agriculture to the Ministry of Agriculture with the establishment of the Department of Resource Sustainability and other agencies focused on sustainability, conservation, and rural development. Taiwan has also established three Organic Agriculture Promotion Zones and an Organic Agriculture Research Center to support organic agriculture research, certification, and education to achieve net-zero emissions in the agricultural sector by 2040. Kerala, India, has initiated an Organic Farming Mission to promote adopting sustainable, organic, and climate-smart farming practices across 5,000 hectares over the next five years. The mission aims at transforming the entire state into an organic farming hub. Kerala also focuses on developing export markets for organic products, especially the Jeerakasala and Gandhakasala rice varieties [49].

The latest regulatory data from I.F.O.A.M. - Organics International in 2022 shows that 75 countries have implemented comprehensive organic farming regulations. In addition, 19 countries have implemented organic regulations, but they still need to be fully enforced. Meanwhile, 14 other countries are in the process of drafting legislation. Such countries illustrate that the barriers to implementing sustainable agricultural practices can be improved through a comprehensive policy framework integrating assistance, education, and regulation [49].

# 8 Conclusion

Integrating agroforestry, organic fertilizer derived from local waste and mulching is a promising approach to increasing soybean productivity while addressing the challenges of climate change. Agroforestry reduces soil erosion by 50% and increases soil carbon stocks by 26-34% at varying depths. Organic fertilizers improved soil health, water retention and microbial activity, while their combination with inorganic fertilizers increased yields by 12.8-32.5%. Mulching also contributed by increasing soybean seed yield by 38.6-44.2%, depending on the type of mulch used.

These practices provide synergistic benefits, increasing agricultural productivity, reducing greenhouse gas emissions and increasing resilience to climate extremes. These practices are essential in ensuring food security, particularly in semi-arid regions, while supporting sustainable agricultural systems. Future research should prioritize identifying agroecological zones where these practices can be most effective and exploring strategies to reduce implementation costs for smallholder farmers. Policymakers and stakeholders should also focus on creating an enabling environment through financial incentives, education, and infrastructure development to facilitate adoption. These efforts are essential to scaling sustainable practices and achieving global agricultural sustainability.

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