frontiers | Frontiers in Agronomy

TYPE Review
PUBLISHED 22 August 2025
DOI 10.3389/fagro.2025.1508896

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OPEN ACCESS

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RECEIVED 10 October 2024
ACCEPTED 30 June 2025
PUBLISHED 22 August 2025

CITATION
Danso Ofori A, Titriku JK, Xiang X, Charlotte A, Ahmed MI and Zheng A (2025) Rice production in Ghana: a multi-dimensional sustainable approach. *Front. Agron.* 7:1508896. doi: 10.3389/fagro.2025.1508896

Rice production in Ghana: a multi-dimensional sustainable approach

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Rice is a vital crop in Ghana, contributing 15% to the country's Gross Domestic Product (GDP). However, rice production in the country faces significant challenges, including limited access to water, soil degradation, pest and disease pressures, inefficient pesticide use, and other factors that hinder industry growth. This study employs a multi-dimensional sustainable approach to evaluate rice production in Ghana, focusing on environmental, socioeconomic, and food security impacts. A systematic review of literature from 2000 to 2023 was conducted using databases such as PubMed, Web of Science, and Google Scholar. The study identifies key challenges and gaps in the current production system and emphasizes the urgent need for strategies that focus on sustainability, environmental protection, effective resource management, and socioeconomic advancement. These challenges not only affect the environment but also have serious implications for the country's socioeconomic development. This study aims to evaluate sustainable rice production in Ghana, considering its environmental, socioeconomic, and food security impacts. The research identifies key challenges and gaps in the current production system and emphasizes the urgent need for strategies that focus on sustainability, environmental protection, effective resource management, and socioeconomic advancement. The study highlights the importance of rice in ensuring food security in Ghana and advocates for yield-focused approaches to sustainably increase production. By promoting environmentally friendly practices, the research seeks to mitigate the negative impacts of rice farming, particularly concerning water usage and soil health. Furthermore, the study underscores the importance of sustainable agribusiness practices, providing valuable insights and recommendations for policymakers, stakeholders, and researchers. These strategies aim to secure a resilient and sustainable rice industry that can support both current and future generations. This review primarily focuses on national-level rice production practices in Ghana and their broader implications for environmental sustainability, socioeconomic development, and food security.

KEYWORDS

sustainable production, Ghana rice, resource management, environmentally friendly practice, rice production

1 Introduction

Rice is one of the most important staple crops worldwide, providing sustenance to more than half of the global population. In Ghana, rice holds a significant role as both a crucial food source and an important cash crop (Amfo et al., 2021). It is impossible to overstate rice's importance to the Ghanaian economy, where it accounts for approximately 15% of the country's GDP (I.S.S.E.R, 2011). Rice farming is of significant importance in response to the accelerating population expansion, rapid urbanization, and changes in consumer preferences. It significantly contributes to improving household food security in Ghana and across Africa, where it ranks as the second most consumed cereal staple after maize (Antwi and Aborisade, 2017). As shown in Table 1, paddy rice production in Ghana has increased substantially, from 302,000 metric tons (MT) in 2008 to 987,000 MT in 2020, according to the Ministry of Food and Agriculture (MoFA) (Agriculture, M.O.F.A, 2023). Over the past 50 years, Africa has produced 14.6 million tons of rice. Moving forward, the focus must shift to establishing sustainable production methods that prioritize environmental conservation, effective resource management, and socioeconomic development. Despite the expansion of agricultural land, there remains a growing demand for rice, which necessitates the adoption of sustainable farming practices for long-term production. By implementing ecologically friendly and resource-efficient methods, we can meet this rising demand while safeguarding natural resources and promoting socioeconomic development across the continent (Gupta and Seth, 2007). In line with this, the Ministry of Food and Agriculture has revised the National Rice Development Strategy (NRDS) with the goal of achieving self-sufficiency by 2024 (Agriculture, M.O.F.A, 2023).

Rice production in Ghana, like in many other African countries, faces several significant challenges. These challenges include limited access to water resources, soil degradation, pests and diseases, and the inefficient use of agrochemicals. Such factors impede the achievement of optimal rice yields and hinder the growth of the rice industry in both Ghana and across Africa. Unsustainable farming practices, such as excessive tilling, monocropping, deforestation, and the overuse of chemical fertilizers, not only contribute to environmental degradation but also reduce long-term productivity and undermine socioeconomic progress. These issues restrict farm productivity and profitability (Chidiebere-Mark et al., 2019). To address these challenges, a shift toward sustainable rice production practices is critical for the growth of Ghana's agricultural sector, especially within the rice industry. This shift is also essential for the preservation of the planet's finite natural resources, ensuring their availability for both current and future generations. In contrast to outdated, unsustainable practices (Figure 1), such as monoculture farming that heavily relies on chemical inputs and excessive water usage—resulting in environmental degradation and reduced agricultural productivity—contemporary sustainable practices allow farmers to increase yields even in the face of climate change.

This review examines the current state of sustainable rice production in Ghana, assessing its environmental, socioeconomic, and food security impacts. It also identifies key research gaps and outlines strategic directions for enhancing sustainable rice production in the country. The goal is to provide valuable insights and recommendations for policymakers, researchers, and stakeholders to facilitate the transition to sustainable rice production systems in Ghana. The following sections discuss integrated approaches to improving crop productivity, implementing sustainable pest management, adopting water-efficient irrigation techniques, and promoting soil conservation initiatives. Furthermore, the review critically analyzes the potential ramifications of utilizing genetically modified rice cultivars, while acknowledging the existing concerns surrounding their widespread adoption. Through a systematic examination of these areas, this article aims to provide a comprehensive understanding of the complexities of modern rice production.

2 Methodology

2.1 Search strategy

This review employs a systematic approach to identify, evaluate, and synthesize relevant literature on sustainable rice production in Ghana. A comprehensive search was conducted using electronic databases such as PubMed, Web of Science, Google Scholar, and Agricultural Research Databases. Keywords used in the search included "sustainable rice production," "Ghana rice farming," "rice resource management," "agroecology practices," and "environmentally friendly agriculture." Boolean operators (e.g., AND, OR) were applied to refine search queries and expand the scope of retrieved articles.

TABLE 1 Rice production trends in Ghana.

Year	Paddy rice production (1000 MT)	Milled rice production (1000 MT)	Rice consumption (1000 MT)	Rice self-sufficiency ratio (%)
2008	302	181	800	23
2019	963	665	1450	46
2020	987	622	–	43

Source: (Agriculture, M.O.F.A, 2023).

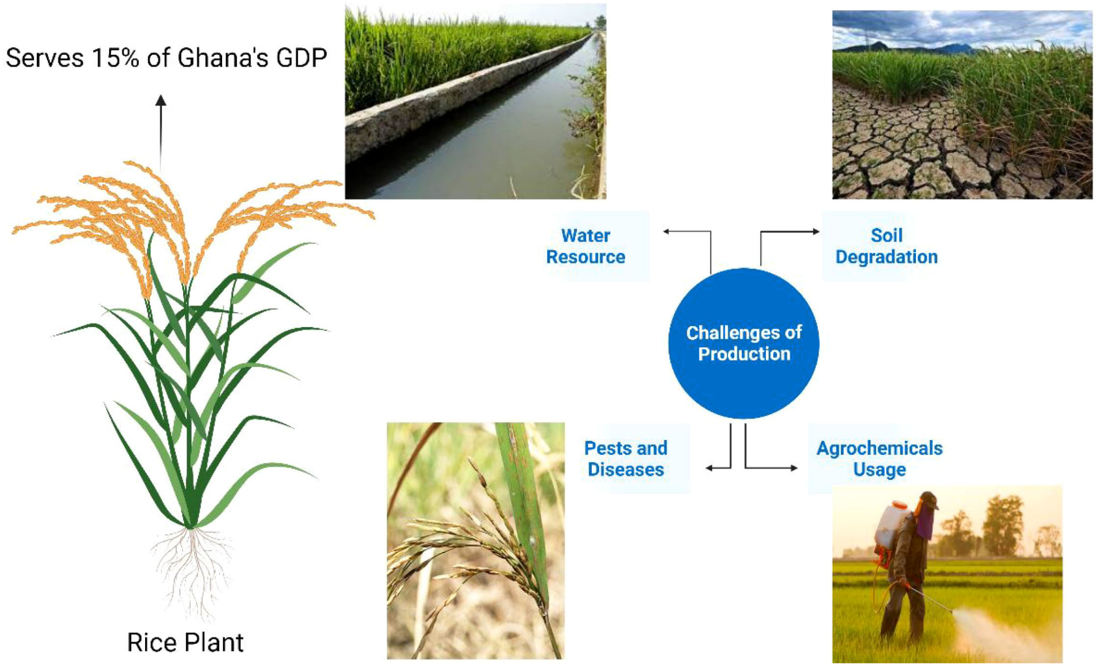

FIGURE 1
Overview of rice challenges and production trends in Ghana.

2.2 Inclusion and exclusion criteria

Inclusion Criteria:

1. Studies published between 2000 and 2023 to capture recent advancements in sustainable agriculture.
2. Peer-reviewed journal articles, government reports, and technical documents addressing rice farming in Ghana or comparable African contexts.
3. Studies focused on the environmental, socioeconomic, and food security aspects of rice production.
4. Articles discussing innovative agricultural technologies applicable to rice farming (e.g., AWD, precision irrigation, and biochar).

Exclusion Criteria:

5. Articles outside the scope of sustainable practices (e.g., general agricultural economics or unrelated crops).
6. Publications lacking full-text availability or written in languages other than English.

2.3 Data extraction

Relevant studies were selected based on their abstracts and titles, followed by a full-text review. Data points extracted included:

- Key challenges in rice production.
- Existing practices and their limitations.
- Innovations and sustainable practices for resource management.
- Recommendations for policy and research.

2.4 Critical appraisal

To ensure the reliability and validity of included studies, a quality assessment was performed using the following criteria:

1. Methodological rigor of the study (e.g., use of robust data collection and analysis methods).
2. Relevance of findings to the Ghanaian context.
3. Consistency with existing literature on sustainable rice production.

2.5 Synthesis approach

Thematic analysis was used to categorize findings into key domains: water management, nutrient management, pest and disease control, seed improvement, and soil conservation. Comparative tables and visual illustrations were developed to highlight differences in methods and outcomes across studies.

This methodology ensures a transparent and comprehensive review of the current state of sustainable rice production in Ghana, offering actionable insights for researchers, policymakers, and stakeholders.

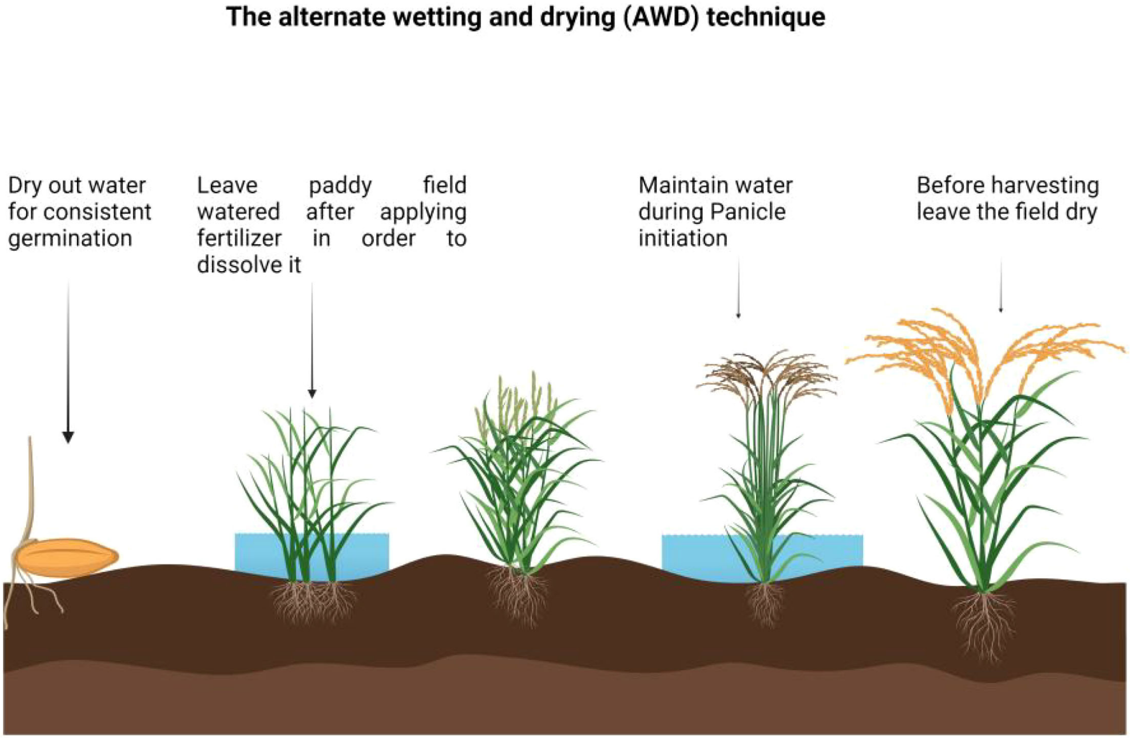

FIGURE 2
Illustration of alternate wetting and drying (AWD) technique in a rice field.

3 Sustainable rice production practices in Ghana

3.1 Water management

Irrigation continues to be a vital method for boosting agricultural production to meet the growing global demand for food. Given that rice cultivation is highly water-intensive, effective water management is a key component of sustainable rice production (Renault and Facon, 2004). In Ghana, where access to water resources is limited, managing water efficiently is crucial to sustaining rice production (Arouna et al., 2023). Various water and soil conservation techniques have been developed and implemented to improve water and soil management and establish efficient irrigation systems for rice farming (Arouna et al., 2023). Rice in Ghana is primarily grown in three different ecosystems: (i) irrigated rice fields, (ii) lowland or hydromorphic rice fields, and (iii) highland rice fields. The irrigated lowland rice system produces 75% of the world's rice, covering approximately 93 million acres. Furthermore, about 56% of the world's irrigated land is devoted to crops, with rice alone accounting for 40–46% of this area (Rao et al., 2017).

3.1.1 The alternate wetting and drying

The Alternate Wetting and Drying (AWD) technique is a promising method for reducing water consumption while maintaining or even increasing rice yields (Enriquez et al., 2021). The AWD technique involves a cyclical process, as illustrated in Figure 2, where rice fields alternate between wet and dry phases. During the wet phase, water is gradually supplied to the rice paddies, either through controlled irrigation or direct flooding, to ensure the field is adequately submerged. Following this, water is slowly removed or allowed to evaporate, initiating a controlled drying process. The duration of each wet and dry cycle can vary depending on factors such as temperature, soil type, and the stage of crop development, all of which must be considered when optimizing the AWD method (Ishfaq et al., 2020). By implementing a water control system, farmers can avoid overflooding their fields and maintain soil moisture at levels that align with the crop's water requirements.

In Ghana's Volta region, a study showed that AWD technique reduced water use by 20–30% compared to continuous flooding, without any significant difference in yield (Yovo et al., 2021). The implementation of AWD systems has also been shown to significantly reduce both water usage and global warming potential (GWP) (Gianluigi et al., 2016). However, there are conflicting reports on how managing irrigation to prevent flooding in rice fields affects rice yields. Some studies indicate an increase in yield with the AWD system compared to continuous flooding (CF), while others suggest a decrease. These discrepancies emphasize the importance of optimizing irrigation management, taking into account factors such as soil properties, drainage frequency, flooding duration, and crop adaptability (Gianluigi et al., 2016). Table 2 shows that AWD and Saturated Soil Culture (SSC) can produce yields comparable to or greater than those from

TABLE 2 Different irrigation systems and their water-use efficiencies and yields.

Irrigation system	Water-saving irrigation method	Water-conserving agronomic practice	Water use efficiency (WUE)	Yield (t/ha)
Irrigated lowland	Alternate wetting and drying (AWD)	Transplanting young seedlings at wider spacing	1.4 kg/m^3	5.7
Irrigated lowland	Saturated soil culture (SSC)	Transplanting young seedlings at wider spacing	1.3 kg/m^3	5.6
Irrigated lowland	Continuous flooding (CF)	Transplanting older seedlings at closer spacing	0.9 kg/m^3	5.2
Irrigated lowland	Aerobic rice (AR)	Direct seeding of aerobic rice varieties	1.8 kg/m^3	3.2

Source: (Yovo et al., 2022).

CF, while using less water. On the other hand, Aerobic Rice (AR) conserves more water but results in lower yields. This suggests that AWD and SSC are more water-efficient and productive than CF, while AR is more water-efficient but less productive. By integrating water-saving production and irrigation systems, it is possible to improve water productivity, enhance water efficiency, and achieve better economic returns, all while reducing environmental impacts, including global warming potential.

3.1.2 Precision irrigation

In addition to the Alternate Wetting and Drying (AWD) technique, other water-saving solutions are being explored for rice production in Ghana. One such approach is the use of precision irrigation systems, including drip and sprinkler irrigation. These technologies allow for precise water application, reducing water loss due to evaporation and ensuring that water is delivered directly to the crop root zone (Patle et al., 2019). Drip and sprinkler irrigation systems can enhance the efficiency of both water and fertilizer usage in rice cultivation.

The drip irrigation system, in particular, offers significant water conservation potential. By delivering water continuously to the plant roots and other parts of the plant, either on the soil surface or buried beneath it, the system reduces water wastage. The main objectives of drip irrigation are to deliver water to the root zone and minimize evaporation (Jarwar et al., 2019). According to Parthasarathi et al. (2018), drip irrigation increases water productivity, enhances root oxidizing power, improves canopy photosynthesis, and promotes better dry matter partitioning. It has been shown to boost aerobic rice yields by 29%, increase water-saving efficiency by 50%, and improve water productivity. This is

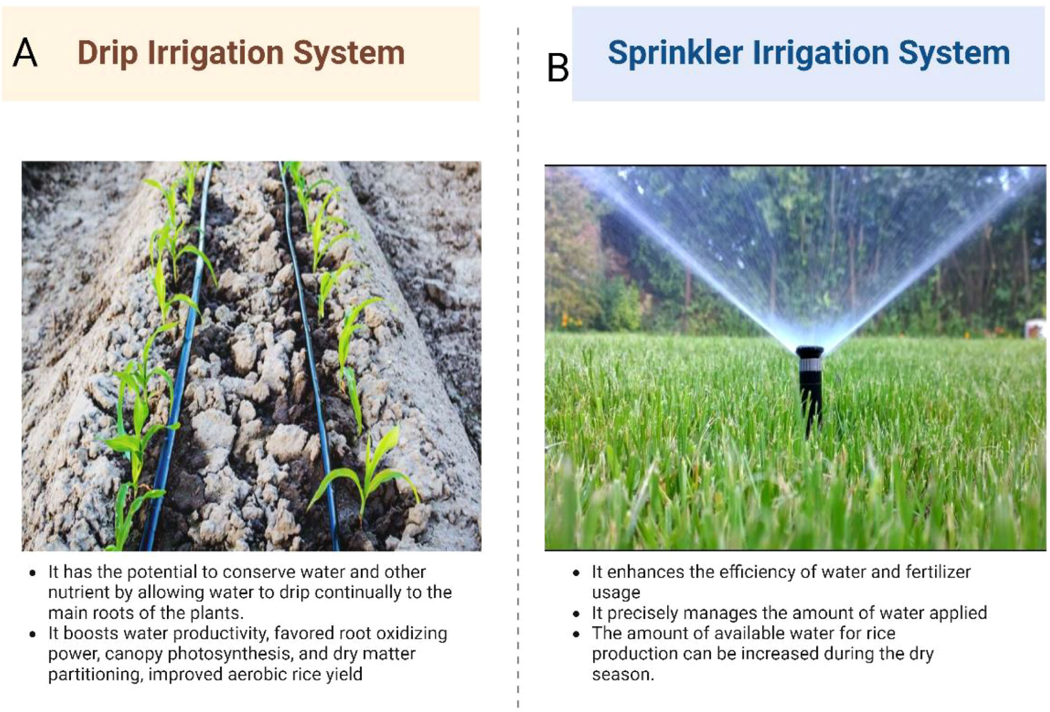

FIGURE 3
Overview of rice farms using drip and sprinkler irrigation systems. **(A)** Drip irrigation system: Water lines run along the rows of rice plants, delivering water directly to the root zones to conserve water and enhance productivity. **(B)** Sprinkler irrigation system: Sprinklers distribute water over a grassy area, improving irrigation efficiency and water management across the field.

TABLE 3 Alternate wetting and drying (AWD) production systems affect rice grain quality in various countries.

Countries	Effect of AWD on rice grain	Reference
China	Severe AWD decreased grain quality while moderate AWD increased it.	(Ye et al., 2013)
	Increased grain pulpiness, decreased chalkiness, and improved head rice recovery, with no changes to amylose, protein, or gel consistency.	(Yang et al., 2007)
Japan	Better grains and increased grain ripening ratio and protein concentrations were the result of prolonged moderate AWD.	(Itoh et al., 2011; Darzi-Naftchali et al., 2017)
Iran	Increase in grain protein content and milling recovery under mild AWD.	(Darzi-Naftchali et al., 2017)
Bangladesh	Decrease in the concentration of grain sulfur, calcium, iron, and arsenic and increase in the concentration of grain Mn, Cu, and Cd.	(Norton et al., 2017)
Philippines, India, Nepal, Bangladesh, and Cambodia	Intermediate amylose contents, decrease in chalkiness, and increase in head rice recovery.	(Sandhu et al., 2017)

particularly important because traditional flooding methods in rice cultivation are significantly more water-intensive compared to those used for other agricultural crops (Samoy-Pascual et al., 2022). In addition, water collection methods can help increase water availability during the dry season. These methods involve collecting and storing rainwater runoff from roofs and fields or creating small ponds or reservoirs to store water for irrigation. This can be particularly valuable in regions with variable rainfall, providing a sustainable water supply for rice cultivation. As global populations continue to grow, water scarcity will become an increasingly urgent concern. Traditional flooding methods waste substantial amounts of water, contribute to greenhouse gas emissions, release methane, and pollute aquifers (Jarwar et al., 2019). Figure 3 provides a visual representation of a rice farm incorporating both sprinkler and drip irrigation systems. This advanced farming setup integrates modern water-saving technologies to optimize water distribution and improve overall rice yields.

Sprinkler irrigation, which sprays water from above the plants, is another alternative. While these systems are more accessible and less costly, they tend to result in greater water runoff and evaporation due to their broader coverage area. Arouna et al. (2023), reviewed various methods used to estimate irrigation water requirements for rice production and found that drip irrigation systems, compared to surface flooding, increased irrigation water productivity to 1.03 kg/m^3, reduced irrigation water use by 42%, and improved irrigation efficiency.

However, drip irrigation systems require specialized setup and maintenance, such as checking for emitter leaks or clogs, adjusting the water flow rate, and monitoring soil moisture levels. These tasks may require additional labor input. Despite this, these water management techniques can increase water productivity in rice production systems, contributing to overall water conservation. The concept of "water productivity" refers to the amount of grain produced per unit of water used. By implementing water-efficient strategies, rice farmers can ensure that limited water resources are used effectively to maximize yields (Pourgholam-Amiji et al., 2020).

The impact of AWD production systems on rice grain quality in various nations is summarized in Table 3 based on previous research. AWD can have different effects on rice grain quality in different geographic areas, emphasizing the necessity of region-specific measures for water management in rice agriculture.

3.2 Nutrient management

Nutrient management is a critical component of sustainable rice cultivation in Ghana, as it directly influences crop development, yield, and environmental sustainability (Tsujimoto et al., 2019). The goal of effective nutrient management is to provide rice plants with a balanced and adequate supply of nutrients while minimizing nutrient loss and reducing environmental pollution (Mangaraj et al., 2022). Following the Green Revolution, farmers increasingly relied on chemical fertilizers to boost rice production. However, the excessive use of fertilizers has led to soil degradation and has had adverse effects on ecosystems and biodiversity. The overuse of chemical fertilizers, in particular, has caused significant deterioration in the physicochemical properties of the soil (Pereira et al., 2023). Long-term fertilizer application across various crops has been linked to changes in soil organic carbon (SOC), pH levels, nitrogen (N) content, and moisture, all of which affect nutrient availability to soil microbes (Shen et al., 2022; Thakur et al., 2023). Despite these challenges, chemical fertilizers remain a primary input in high-yielding rice farming systems worldwide.

3.2.1 Essential nutrients for successful rice cultivation

The three most essential nutrients for rice cultivation are nitrogen (N), phosphorus (P), and potassium (K). To produce one ton of raw rice, approximately 15–20 kg of mineral nitrogen (N), 11 kg of phosphorus pentoxide (P_2O_5), 30 kg of potassium oxide (K_2O), 3 kg of sulfur (S), 7 kg of calcium (Ca), 3 kg of magnesium (Mg), 675 g of manganese (Mn), 150 g of iron (Fe), 40 g of zinc (Zn), 18 g of copper (Cu), 15 g of boron (B), 2 g of

TABLE 4 Some recommended rice fertilizer dosages for selected West African countries.

Country	Rice Ecology	Dosage	Reference
Ghana	Lowland	90 N–26 P–50 K	(Buri et al., 2012)
	Rainfed upland	90 N–20 P–30 K	(Nyalemegbe et al., 2012)
Nigeria	Lowland	60 N–13 P–25 K	(Ekeleme et al., 2008)
	Rainfed upland	50 N–30 P–30 K	(Oikeh et al., 2008)
Cote d'Ivoire	Irrigated lowland	71 N–20 P–38 K	(Kouakou et al., 2022)
	Rainfed upland	70 N–21 P–30 K	(Chivenge et al., 2020)
Togo	Lowland	122 N–13 P–25 K	(Meertens, 2001)
	Rainfed upland	45 N–10 P–19 K	(Aboa et al., 2008)

molybdenum (Mo), and 52 kg of silicon (Si) are required (Moro et al., 2008). Among these, phosphorus is a particularly important nutrient for rice formation, as it plays a key role in energy transfer and plant metabolism. Several soil factors, such as pH, phosphorus adsorption capacity, temperature, rice variety, and management practices, affect the availability and effectiveness of phosphorus in rice farming. Phosphorus is less mobile in the soil compared to nitrogen (N) and potassium (K), leading to a significant accumulation of applied phosphorus in agricultural soils (Tovohery et al., 2022). In acidic soils, phosphorus forms complexes with iron (Fe) and aluminum (Al), while in high-pH soils, it binds with calcium (Ca), causing 75% to 90% of applied phosphorus to precipitate and become unavailable for plant uptake (Etesami, 2020). To optimize nutrient availability and minimize waste, it is crucial to apply the correct fertilizer dosages. Table 4 outlines the recommended fertilizer dosages for different rice ecologies in various African countries, including lowland, rainfed upland, and irrigated lowland rice systems. Following these dosage guidelines ensures that rice crops receive the necessary nutrients for optimal growth while preventing over-fertilization, which could lead to environmental contamination.

3.2.2 Optimized fertilization techniques

Nine commonly used optimized fertilization techniques for sustainable rice cultivation include straw inclusion, delayed nitrogen (N) application, formula-based fertilization, reduced fertilization rates, deep fertilization, slow/controlled-release fertilizers, combined application of organic and inorganic fertilizers, biochar addition, and green manuring. These methods contribute to sustainable rice production by promoting balanced fertilization. Balanced fertilization involves applying fertilizers at the right times, in the correct amounts, and in the appropriate ratios to meet the crop's nutritional needs while minimizing environmental impact (Umme Aminun et al., 2019). Soil testing is a critical technique for detecting nutrient imbalances or deficiencies and for guiding accurate fertilizer recommendations.

3.2.2.1 Straw inclusion

Incorporating rice straw into the soil can reduce the need for additional fertilizers, particularly potassium (K), nitrogen (N), and phosphorus (P), as rice straw contains approximately 80%, 40%, and 30% of the K, N, and P required for rice growth, respectively. However, due to the slow decomposition of rice straw, the timing of its incorporation, combined with effective water management, is critical for maximizing its benefits (Chivenge et al., 2020). Studies have shown that integrating rice straw *in situ* can enhance soil organic carbon (C), promote nutrient recycling, and improve crop yields in subsequent seasons (Kumar et al., 2023). Schmidt et al. (2015) highlighted that rice straw serves as a substrate for fostering biodiversity by supporting the growth of invertebrates that decompose the straw, thereby enhancing nutrient cycling in paddy soils. A study conducted in Vietnam demonstrated that adding rice straw to the soil increased soil organic carbon, improved soil pH, and enhanced nutrient content compared to the initial soil conditions (Thanh et al., 2016). Regular incorporation of crop residues, such as rice straw, into the soil after each harvest can significantly improve the nitrogen-supplying capacity of the soil over time. In Ghana, crop straw is an abundant and underutilized biomass resource. As shown in Figure 4, a visual example of straw inclusion in newly prepared rice beds illustrates how this technique can contribute to sustainable nutrient management in rice farming. However, despite its potential, the traditional methods of straw utilization in Ghana have led to its underuse (Seglah et al., 2019).

3.2.2.2 Delaying N application

Reducing nitrogen (N) fertilizer application while maintaining crop output has become a key strategy for sustainable agriculture, driven by increased consumer awareness of food safety and environmental protection (Ren et al., 2022). One effective approach to improving nitrogen use efficiency (NUE) in rice farming is adjusting the timing and rate of nitrogen application (Govindasamy et al., 2023). By delaying nitrogen application during the basal stage, farmers can reduce the total amount of nitrogen required. Instead, higher quantities of fertilizer can be applied during the tillering and booting stages, as rice plants are more responsive to nitrogen uptake at these growth stages. This strategy not only has the potential to increase rice yields but also helps to reduce nitrogen losses and improve NUE. Furthermore, optimizing nitrogen application can reduce labor input, thereby speeding up the cultivation process (Zhuang et al., 2022).

3.2.2.3 Formula fertilization

Formula fertilization, which involves calculating the optimal rates and ratios of nitrogen (N), phosphorus (P), and potassium (K) fertilizers based on comprehensive soil testing, is essential for maximizing fertilizer application in rice farming (Dash and Kuila, 2023). By conducting thorough soil analyses, farmers can gain

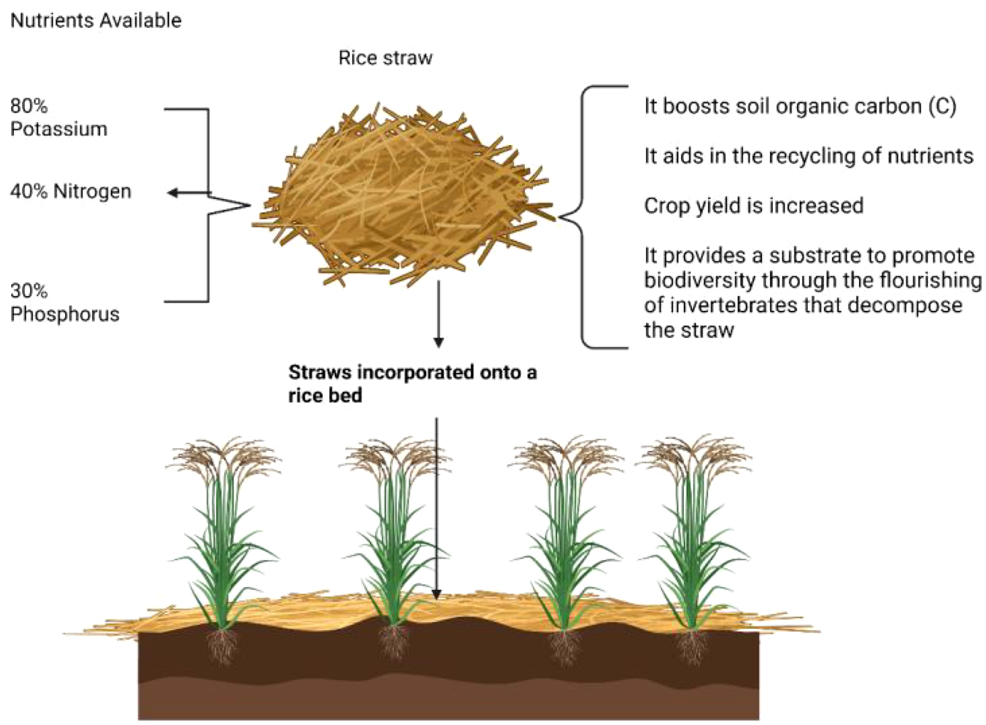

FIGURE 4
Straws incorporated into newly constructed rice bed.

valuable insights into the nutrient content and pH levels of the soil, allowing them to tailor their fertilization strategies accordingly (Vidyashree and Murali Arthanari, 2021). This method not only has the potential to increase rice yield but also improves nitrogen use efficiency (NUE). Moreover, by accurately estimating the soil's nutrient requirements, fertilizer applications can be optimized, reducing both costs and the environmental impact associated with excessive fertilizer use. Effective nutrient management is critical in rice farming, as it ensures high production levels while minimizing nutrient runoff and leaching into the environment (Paramesh et al., 2023).

3.2.2.4 Lowering fertilization

Reducing nitrogen (N) fertilizer application rates by 10–30%, based on current application practices and the specific needs of the crop, is a practical approach for minimizing the environmental impact of excessive fertilizer use in agriculture (Laporte et al., 2021). This strategy allows farmers to meet the nutrient demands of their crops while significantly reducing their reliance on chemical fertilizers (Wang et al., 2018). To maintain grain yield, enhance nitrogen use efficiency (NUE), and minimize environmental harm, nitrogen fertilizer use must be reduced (Hu et al., 2023; Zhu et al., 2023). This reduction not only supports more environmentally sustainable farming practices but also reduces nitrogen losses, contributing to improved soil health and water quality (Liu et al., 2016). By adopting precise nutrient management strategies, farmers can effectively balance crop yield with minimizing the adverse effects of over-fertilization (Sapkota et al., 2021).

3.2.2.5 Deep fertilization

Applying chemical fertilizer below the soil's surface, often at a depth of between 6 and 10 cm, is known as "deep fertilization." This method offers several potential benefits for rice cultivation. By placing fertilizers closer to the root zone, where nutrients are more readily absorbed by the plants, nitrogen use efficiency (NUE) can be significantly increased (Govindasamy et al., 2023). This targeted approach enhances nutrient uptake while reducing losses, thereby improving the overall efficiency of fertilizer use (Mejias et al., 2021). The side-deep fertilization method has become essential for the sustainable growth of rice crops (Wang et al., 2022a), as it helps overcome productivity limitations and supports widespread adoption (Khalofah et al., 2021).

Deep fertilization, as shown in Figure 5, involves the precise and meticulous application of fertilizer below the soil surface to maximize the availability of nutrients to rice plants. Farmers use specialized equipment to distribute chemical fertilizers accurately at the desired depth, which is typically between 6 and 10 cm. This practice not only ensures that plants receive a consistent supply of nutrients but also helps in reducing nutrient wastage by minimizing surface runoff or volatilization.

Moreover, deep fertilization can contribute to increased rice yields by improving the consistency of nutrient supply throughout the growing season (Wu et al., 2022). Hong et al. (2023) reported that under standard rice and soybean cultivation conditions, deep fertilization is an efficient fertilizer application technique to boost rice and soybean yields. It also encourages the development of deeper root systems, which enhances the plants' ability to access

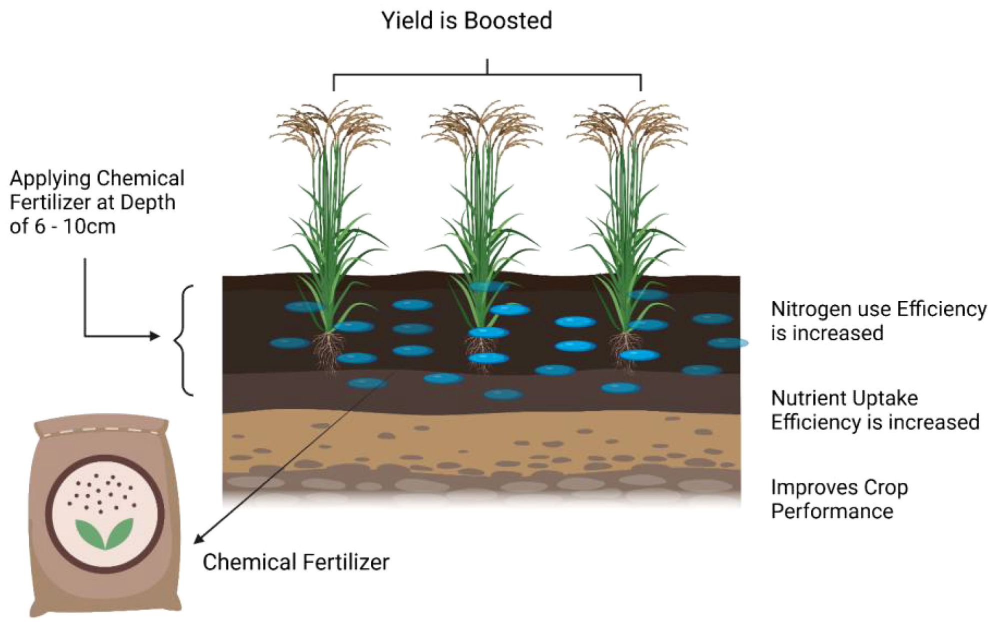

FIGURE 5
Deep fertilization in rice farm.

water and nutrients from lower soil layers. Studies have shown that deep fertilization boosts tiller and panicle rates, increases yields, and reduces labor costs. Additionally, this method helps prevent premature senescence, controls pests and diseases, and increases fertilizer utilization by up to 25% (Zhang, 2007). Deep fertilization ultimately supports plant growth and development by making more nitrogen available in the root zone (Rychel et al., 2023). By adopting deep fertilization, farmers can improve nutrient management, optimize crop performance, and contribute to the sustainability of rice production.

3.2.2.6 Slow/controlled-release fertilizers

Slow/controlled-release fertilizers are specialized fertilizers created by encapsulating mineral nutrients in a synthetic polymer matrix or coating them with a polymer film (Negi et al., 2022; Liang et al., 2023a). This innovative approach has numerous advantages in agriculture, particularly in enhancing crop and grain yields (Yu et al., 2006). Slow/controlled-release fertilizers promote sustainable crop production by providing a steady supply of nutrients while preserving soil health over time (Dhanushkodi et al., 2022). These fertilizers work by controlling the release of nitrogen, ensuring a continuous nutrient supply to plants over an extended period (Sarkis et al., 2021). The regulated release of nutrients optimizes plant nutrient uptake, reduces the risk of nutrient runoff or leaching, and lowers the need for frequent fertilizer applications (Purnomo and Saputra, 2021). As a result, slow/controlled-release fertilizers not only improve nutrient efficiency but also reduce the environmental impact associated with excessive fertilizer use. Additionally, the use of these fertilizers reduces labor costs by minimizing the frequency of fertilizer applications, saving time and effort for farmers. By fertilizing less often, they also help reduce the overall cost of agriculture while contributing to more sustainable farming practices (Sapkota et al., 2021).

3.2.2.7 Combined application of organic and inorganic fertilizers

It is essential to partially replace chemical fertilizers with organic resources, such as manure, when using both organic and inorganic fertilizers together (Wang et al., 2018). This integrated approach offers several advantages for agricultural systems. First, the addition of organic materials enhances soil fertility by providing a diverse range of nutrients and organic matter (Zhao and Zhou, 2011; Urra et al., 2019). Organic inputs improve soil structure, increase nutrient-holding capacity, and stimulate microbial activity, all of which contribute to overall soil health (Urra et al., 2019). Studies have shown that combining organic and inorganic fertilizers can significantly boost rice yields. For examples, Nyalemegbe et al. (2010), found that the combined use of cow dung and urea resulted in a paddy yield of 4.7 t ha^{-1}. Similarly, Zhao and Zhou (2011) demonstrated that the combined application of large amounts of organic manure and inorganic fertilizers (A1B5) improved soil moisture capacity and organic matter content more rapidly than individual fertilizer types. Organic matter increased by 3.33 g kg^{-1}, and field moisture capacity increased by 11.25% from the beginning of the trial. The combined approach also led to higher yield increases, ranging from 0.8% to 9.4%, compared to the use of inorganic fertilizers alone. This suggests that integrating organic and inorganic fertilizers optimizes productivity and soil fertility. Additionally, in intensive agricultural systems, soil acidity can be managed effectively by applying both organic and inorganic

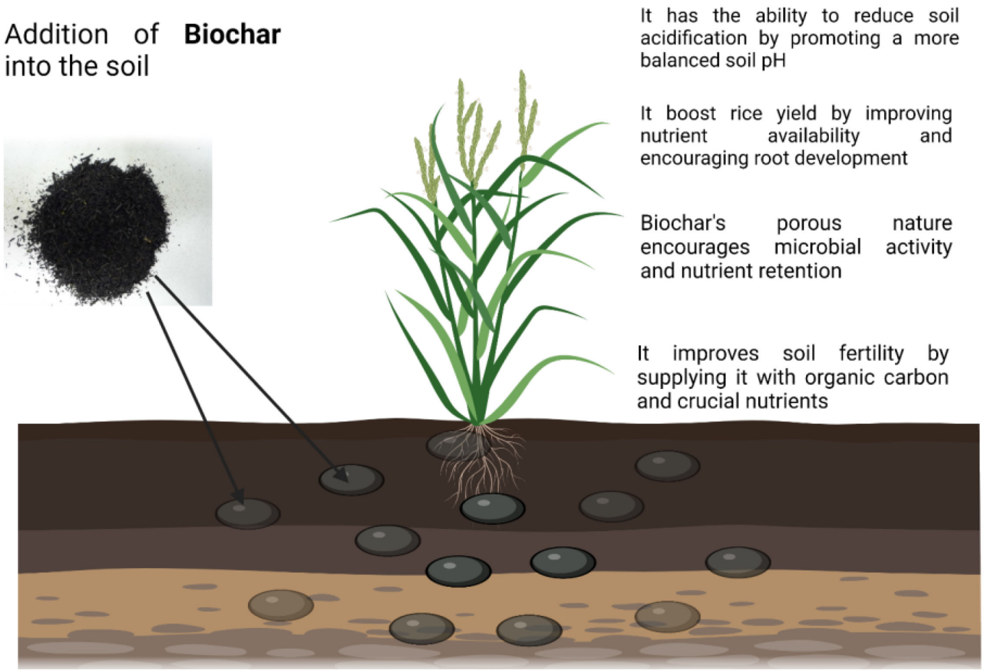

FIGURE 6
Illustration of adding biochar to soil.

fertilizers simultaneously. The organic materials help balance the soil's pH, creating a more favorable environment for plant growth (Bisht and Chauhan, 2020).

3.2.2.8 Biochar incorporation

Biochar is a solid byproduct produced when organic biological materials are pyrolyzed in low-oxygen (anaerobic) or limited-oxygen (hypoxic) conditions (Li et al., 2020). It is commonly added to agricultural fields to enhance soil fertility, and rice cultivation stands to benefit significantly from this practice. First, biochar improves soil fertility by providing organic carbon and essential nutrients to the soil. Its porous structure enhances microbial activity and boosts nutrient retention, which contributes to improved soil health and fertility (Alkharabsheh et al., 2021). Research has shown that biochar can increase rice yield by improving nutrient availability and promoting better root development (Liu et al., 2021). Abukari (2019) observed that increasing the rate of biochar application, combined with four water-absorbing polymers (WAP), led to enhanced soil moisture content. Field trials also revealed that adding biochar to upland rice paddies improved both soil water permeability and water retention capacity, which are crucial for managing water stress in rice cultivation (Abukari, 2019). Maccarthy et al. (2020), conducted experiments in Ghana and found that biochar improved the soil's ability to store soil organic carbon in the topsoil. Furthermore, the combination of biochar and nitrogen fertilizer led to considerable improvements in rice yield parameters, including root volume and nutrient uptake (N, P, and K). In 14 out of 16 trials, grain yields were significantly higher in plots treated with biochar compared to those treated with fertilizer alone, with grain production increasing by 12% to 29% across all nitrogen application rates. Biochar also enhances the physical and chemical properties of the soil, including its ability to retain more water, which helps maintain soil moisture during periods of drought or water stress (Zhang et al., 2021). According to Atkinson et al. (2010), significant increases in plant productivity were observed depending on the amount of biochar added, especially in tropical regions. Additionally, biochar helps reduce soil acidification by balancing the soil's pH, thereby creating a more favorable environment for plant growth (Shetty and Prakash, 2020). Incorporating biochar into rice farming practices as shown in Figure 6, not only improves soil quality but also supports sustainable crop production. By enhancing nutrient availability, water retention, and soil health, biochar is a valuable tool for promoting sustainable rice cultivation.

3.2.2.9 Green manuring

Green manuring is a technique in which green plant matter, also known as green manure, is integrated into the soil via plowing (Das et al., 2020), as shown in Figure 7. This technique offers several benefits for rice cultivation, enhancing soil fertility and supporting sustainable farming practices. One of the primary benefits of green manuring is the increase in soil fertility. By adding organic matter, green manure provides essential nutrients for plants. Research by Latt et al. (2009), demonstrated that the application of *Sesbania rostrata* as green manure significantly improved rice yield and growth. In their study, treatments using urea (40 and 80 kg N ha^{-1}) and a no-application control were compared with green manure treatments (2 and 4 plants per pot). Results showed that the green manure treatments led to substantial increases in both dry matter weight and grain weight, outperforming the urea and control

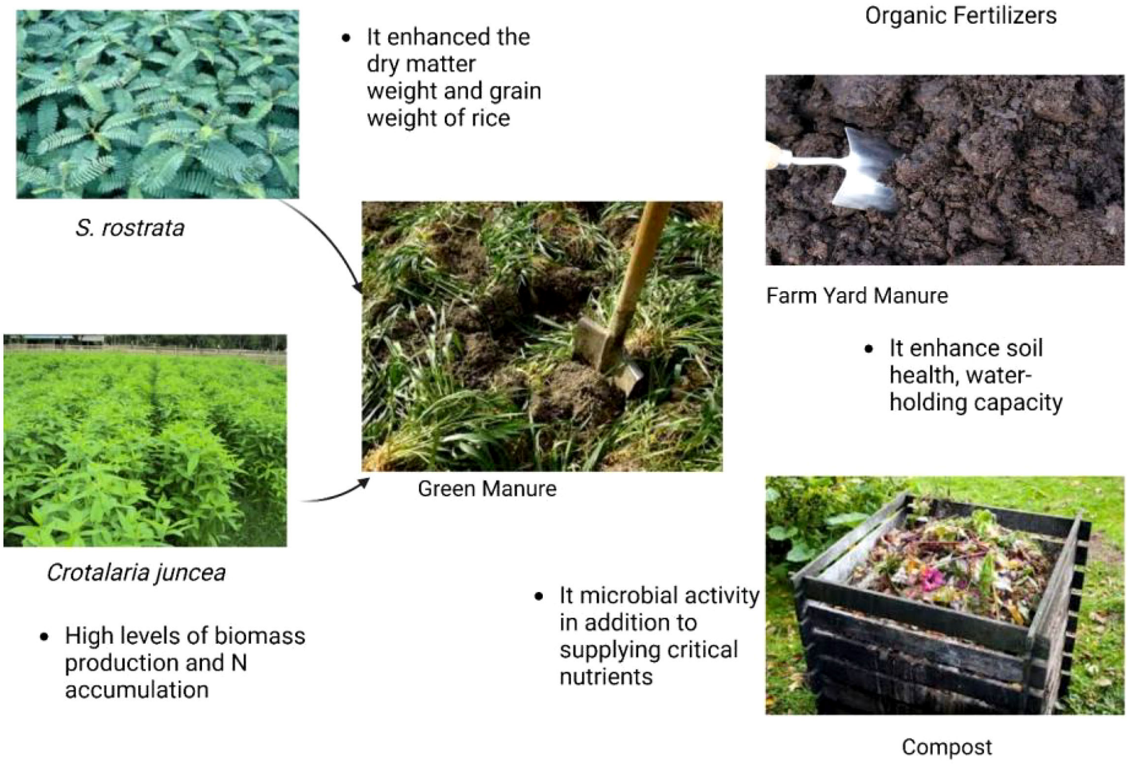

FIGURE 7
Picture of green manuring in rice field.

treatments. Additionally, nitrogen intake by the rice plants increased with each green manure application. This suggests that incorporating green manure legumes can significantly enhance the biologically fixed nitrogen (N) content in rice soils. As green manure decomposes, it releases vital nutrients back into the soil, further improving soil fertility (Naz et al., 2023). Studies have consistently shown that green manuring boosts rice output. For example, Zhou et al. (2020) found that green manure application increased rice yield by 4.1%. In addition to boosting nutrient content, green manuring improves the physical characteristics of the soil. It enhances soil aggregation, moisture retention, and nutrient-holding capacity, all of which are essential for healthy crop growth. Green manure can also help modify soil pH levels, as certain green manure crops can reduce soil acidity (Rayne and Aula, 2020).

Another important advantage of green manuring is that it reduces the need for chemical fertilizers. Since the organic matter in green manure provides a natural source of nutrients, farmers can rely less on synthetic fertilizers, promoting more sustainable agricultural practices (Li et al., 2021). Overall, green manuring is an effective strategy for improving soil fertility, increasing crop yield, reducing chemical inputs, and enhancing overall soil health in rice farming.

The positive impacts of green manuring on rice production—such as increased rice yield, improved dry matter weight, enhanced microbial activity, and better soil health—are well-documented and visually illustrated in Figure 7. This technique demonstrates the potential of green manure to sustainably improve rice farming practices.

The increasing demand for higher agricultural yields has highlighted the importance of environmental protection in promoting optimal fertilization practices. Many advanced fertilization techniques have been shown to boost crop yields by over 5% while reducing total nitrogen (TN) losses by more than 15% (Zhuang et al., 2022).

By tailoring fertilizer applications to match the specific nutrient needs of soil and crops, farmers can significantly enhance nutrient use efficiency while minimizing the risk of nutrient runoff into water bodies (Adi et al., 2021). Beyond chemical fertilizers, composting and organic fertilizers are gaining popularity as sustainable methods for rice production. Examples of effective organic fertilizers include compost, green manure, and farmyard manure, which not only improve soil fertility and structure but also promote nutrient cycling (Goldan et al., 2023). These organic additions contribute to healthier soils by enhancing water-holding capacity, stimulating microbial activity, and supplying essential nutrients (Liang et al., 2023b).

Site-specific nutrient management (SSNM) is another increasingly adopted strategy for sustainable rice farming. SSNM involves determining the nutrient requirements of rice plants at various growth stages and applying targeted nutrient treatments accordingly. This approach has been shown to reduce nutrient losses, improve fertilizer efficiency, and mitigate environmental impacts (Rodriguez, 2020).

Soil amendments, such as lime and gypsum, also play a critical role in balancing nutrient deficiencies and restoring soil pH. Fageria and Knupp (2014) reported that these treatments optimize nutrient uptake efficiency and enhance nutrient availability for rice plants. Moreover, precision nutrient management techniques, such as fertigation (the delivery of fertilizers through irrigation systems) and foliar nutrient sprays, offer additional benefits by improving nutrient uptake and reducing losses (Niu et al., 2021).

3.3 Current practices in rice cultivation in Ghana

Rice cultivation in Ghana has become increasingly important as the country seeks to reduce its reliance on rice imports and boost domestic production. Rice is a staple food in Ghana, and its demand has risen significantly due to population growth and changing dietary patterns (Abankwah and Tutu, 2021). Rice farming in Ghana is predominantly concentrated in the Volta, Northern, and Upper West regions, where unfavorable climatic conditions and limited access to water resources constrain cultivation (Nyamekye et al., 2018). These challenges are further compounded by several systemic issues that hinder the sector's growth. Low productivity remains a critical concern, driven by inadequate irrigation infrastructure that limits farmers' ability to manage water effectively, particularly during dry season. Additionally, the use of poor-quality seeds and limited access to modern farming techniques further exacerbate the problem, resulting in suboptimal yields (Boadjo and Culas, 2021).

Traditional rice farming practices in Ghana are largely rain-fed, which makes the crop highly susceptible to fluctuations in rainfall patterns, resulting in inconsistent yields (Naazie et al., 2023). Smallholder farmers, who dominate the rice sector, typically use rudimentary methods such as manual planting and harvesting. The use of improved rice varieties, which have higher yields and resistance to pests and diseases, is still limited due to the high cost of seeds and lack of access to agricultural extension services (Azumah et al., 2022; Naazie et al., 2023). Furthermore, the quality of rice produced is often lower than that of imported rice, which discourages local consumption and keeps the sector heavily dependent on imports (Abankwah and Tutu, 2021).

In recent years, the government of Ghana, along with various development partners, has initiated several programs aimed at increasing rice productivity and reducing imports (Pauw, 2022). These include the introduction of improved seed varieties, support for smallholder farmers through subsidies, and the construction of irrigation systems. Additionally, efforts to improve post-harvest handling, processing, and storage are gaining traction, with the aim of adding value to local rice production (Lamptey et al., 2022). Despite these initiatives, challenges such as inadequate mechanization, poor infrastructure, and limited market access continue to hinder the full potential of the rice sector.

4 Integrated pest management

Integrated pest and disease management (IPDM), which aims to reduce dependence on chemical pesticides while effectively managing pests and diseases, is vital for achieving sustainable rice production (Deguine et al., 2021; Dara et al., 2023). Overuse of chemical pesticides can lead to the destruction of beneficial insects and trigger pest outbreaks (Hill et al., 2017; Hong-Xing et al., 2017). Additionally, herbicide resistance has emerged as a significant challenge for rice production in many regions worldwide. Numerous weed species have developed resistance to major herbicide classes, with several species showing resistance to multiple classes (Heap, 2014). Utilizing a combination of cultural, biological, and chemical control measures as part of integrated pest management (IPM) strategies results in a strategy that is ecologically and economically sustainable.

4.1 Crop rotation

Integrated Pest Management (IPM) in rice production is deeply rooted in traditional farming practices. One key strategy is crop rotation, which involves alternating rice with other crops to disrupt the pest life cycles and reduce their populations (Fahad et al., 2021). Other preventive measures include minimizing fertilizer use, planting multiple rice varieties or lines within the same field, rotating nursery locations, and implementing phytosanitary practices to prevent the spread of virulent virus strains to other rice-growing regions (Wang et al., 2022b). Additionally, effective soil management techniques, such as field leveling and removing weed hosts, help to hinder the development and spread of diseases and pests (Aamir et al., 2020).

4.2 Biological control techniques

Chemical pesticides can be substituted with sustainable biological control methods. Biological control reduces pest populations by using the natural enemies of pests, such as parasitoids and predators (Shavanov et al., 2022). For instance, introducing predatory insects like spiders and beetles into rice fields can effectively decrease pest populations (Ndakidemi et al., 2021). This biological approach also encompasses the use of pheromones for pest monitoring and preventing breeding, sterilizing insects before releasing them, and employing bio-pesticides, which are derived from living organisms or their byproducts (Baker et al., 2020). Biological pesticides, such as neem seed kernel extract (*Azadirachta indica A. Juss*), *Vitex negundo L.* leaf extract, and *Bacillus thuringiensis*, have been shown to impact the growth, feeding, and productivity of rice leaf folder larvae (Nathan et al., 2005). These natural plant products, which contain bacterial toxins, can inhibit growth, act as antifeedants, and even have toxic effects on harmful insects.

Integrated Pest Management (IPM) also includes the judicious use of chemical pesticides when other control methods fail. To

TABLE 5 Effects of cropping systems on the yield and socioeconomic benefits of rice production.

Cropping system	Yield t/ha	Harvest index %	Profit in USD/ha	Profit margin %
RR	5.2 b	42.2 a	162 c	8.5 c
FR	6.1 ab	45.1 a	465 b	24.4 b
PR	7.1 a	42.8 a	826 a	43.4 a
WR	5.9 b	45.8 a	385 b	20.2 b

Different letters following the values in a column indicate significant differences ($p < 0.05$). The same letter means it is not significantly different. RR, Successive cropping of rice; FR, fallow followed by rice; PR, potato rice rotation; WR, watermelon rice rotation [120].

ensure selective pesticide use, it is crucial to evaluate their effectiveness, environmental impact, and potential risks to non-target organisms (Nawaz et al., 2019). Farmers must benefit from ecosystem diversity, and pesticide use should be aligned with ecological principles. Maximizing long-term productivity in rice fields requires an understanding of how to utilize the ecosystem effectively. Pesticide use can be optimized by minimizing pesticide residues and environmental impacts, adhering to the recommended application time and dosage based on pest monitoring and forecasting systems (Zhao et al., 2022). Regular scouting and monitoring of rice fields are essential for early pest and disease detection. Timely intervention allows farmers to avoid infestations and potential crop losses (Patil et al., 2022).

5 Improved rice seed

The cultivation of disease-resistant rice varieties plays a significant role in long-term pest and disease management (Tudi et al., 2021). To reduce the reliance on chemical pesticides, breeding programs in Ghana have focused on developing rice varieties resistant to major diseases such as blast and sheath blight. As a result, the adoption of resistant varieties offers a safer and more environmentally friendly alternative to excessive pesticide use in rice production. Various techniques have been used to develop insect-resistant rice varieties. These include mutagenesis, which induces genetic mutations in plants, and the introduction of foreign genes through methods like single-gene insertion or gene pyramiding. Other advanced techniques such as transplastomic methods, genetically engineered Bt toxins, oligonucleotide-directed mutagenesis, engineered nucleases, plant membrane transporters, and antisense technologies have also been employed (Dhakal and Poudel, 2020). The use of improved rice seeds offers several benefits, including higher grain yields, better crop growth, and reduced damage from weeds, insects, and diseases (Murielle et al., 2023).

However, there are several concerns related to the cultivation of genetically modified (GM) rice in rice production. Despite the potential benefits of GMO rice, such as higher yields, enhanced pest resistance, and improved nutritional value, there are valid reservations (Murielle et al., 2023). One major concern is the safety of consuming genetically modified rice, with many stakeholders worried about the potential long-term health effects of GM crops. This has led to calls for rigorous safety evaluations to ensure consumer safety. Another significant issue is the environmental impact of GMO rice cultivation. Critics argue that GMO rice could have unintended consequences, such as the emergence of herbicide-resistant weeds or gene flow to wild relatives, which could disrupt local ecosystems and biodiversity (Dhakal and Poudel, 2020).

6 Soil health

Soil conservation techniques are essential for promoting sustainable rice production in Ghana. As the population grows and the need for food security becomes more pressing, it is crucial to adopt practices that not only increase rice yields but also protect the long-term health and fertility of the soil. By implementing effective soil conservation methods, Ghana can achieve sustainable rice production while safeguarding the environment and the well-being of its people. According to Sánchez (2010), with proper soil management, efficient fertilizer use, and appropriate crop varieties, crop yields in Africa could potentially triple. One key technique for sustainable rice cultivation is conservation tillage. This method reduces or completely eliminates the need for ploughing and tilling, which can lead to soil erosion and degradation. Instead, no-till or minimal-tillage farming practices are used to preserve organic matter and prevent soil compaction. Conservation tillage improves soil structure, enhances water infiltration, and boosts nutrient retention, which ultimately benefits soil health (Kumar et al., 2020). Additionally, zero-tillage transplanting and zero-tillage direct seeding are conservation tillage techniques that have been shown to improve crop water use efficiency and soil hydrology (Cooper et al., 2023).

6.1 Soil conservation

In Ghana, crop rotation is a cornerstone of sustainable farming, particularly for rice growers. Alternating rice with legumes or vegetables not only disrupts pest and disease cycles but also improves soil fertility and reduces long-term degradation. This practice supports both soil health and environmentally responsible agriculture. Research underscores the benefits of this method. Li et al. (2023) found that crop rotation enhances soil quality by addressing challenges such as soil-borne pests and weeds that pesticides often fail to control. Hameed et al. (2023) observed that integrating maize into a rice-based rotation increases rice

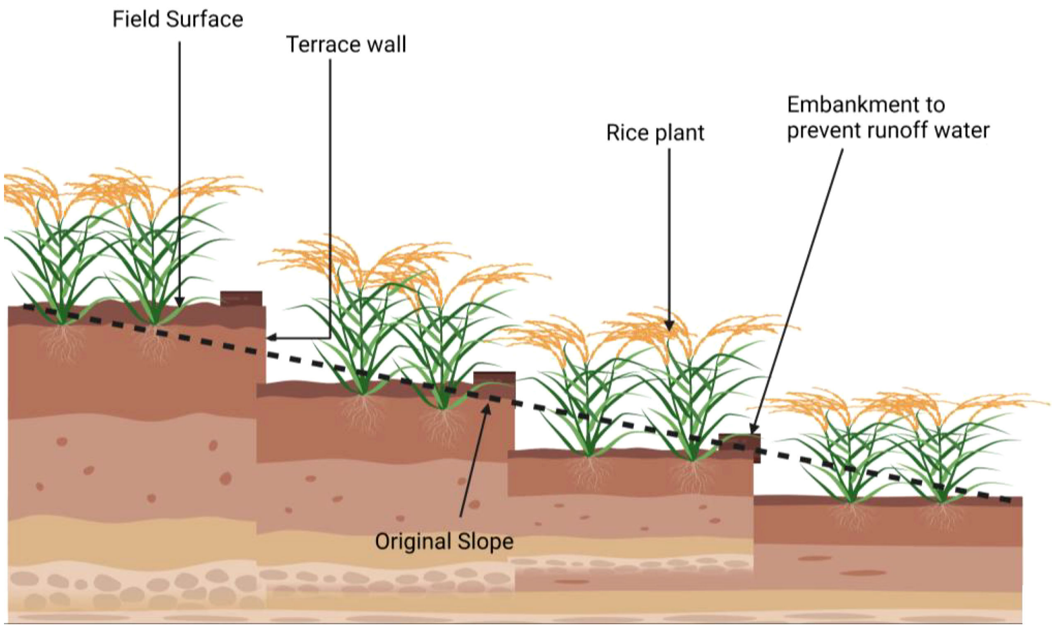

FIGURE 8
Sectional drawing of the terrace.

productivity by 10.5% and maize yield by 11.3%, while raising net revenue by 16.7%. Such results demonstrate the dual agronomic and economic benefits of diversifying cropping systems. He et al. (2021) further compared various rotational systems and found that potato–rice (PR), fallow–rice (FR), and watermelon–rice (WR) rotations consistently outperformed continuous rice cropping (RR). PR systems delivered the highest yields and profits, while FR systems were the second most effective. The data (Table 5) show that PR systems significantly improved rice yields ($p < 0.05$) compared to WR and RR, confirming their efficacy for maximizing agricultural returns.

6.2 Integration of agroforestry and terracing

Agroforestry systems are gaining prominence among rice farmers in Ghana as a method to enhance soil health and farm productivity in inland valleys. Combining trees with rice fields brings several benefits, including improved soil fertility, biodiversity, and crop yields (Pantera et al., 2021). Trees contribute organic matter through their leaf litter, which enriches soil nutrients, reduces evaporation, and moderates soil temperature. This results in better water retention and enhanced soil structure (Asase and Tetteh, 2010). Agroforestry also supports broader environmental goals, promoting biodiversity and the sustainability of agricultural landscapes (Sauer et al., 2021). Such systems are especially effective in regions suffering from soil degradation due to resource constraints and traditional farming practices.

For sloped terrains, terracing is a widely used technique to combat soil erosion and conserve rainwater. By creating step-like structures, terraces slow water runoff, enabling it to infiltrate the soil and preventing the loss of valuable topsoil. Terracing is a practical solution in Ghana's hilly areas, ensuring soil quality, reducing erosion, and supporting sustainable rice production. Several terracing techniques have been developed to optimize erosion control. For example, terraces often incorporate features like contour hedgerows, vegetative filter strips, and grass barriers (Deng et al., 2021). Sukristiyonubowo (2007) recommends applying urea and KCl fertilizers, along with 33% of the previous season's rice straw, for sustainable rice cultivation on terraced fields. This practice enriches soil carbon and nitrogen stocks, crucial for long-term fertility (Liu et al., 2015). Figure 8 illustrates the design of terraced systems, which involve cut-and-fill techniques to create level fields. These terraces expand arable land on steep slopes, supporting large-scale rice farming. Ridges and embankments are vital for controlling runoff and preventing water loss, ensuring the productivity and sustainability of terraced rice fields.

6.3 Use of cover crops

An essential technique for soil conservation in sustainable rice production is the use of cover crops (Silva et al., 2023). Farmers grow cover crops, such as legumes or grasses, during fallow periods or between rice harvests. These crops play a vital role in improving soil structure, increasing organic matter, suppressing weeds naturally, and protecting soil from erosion and nutrient leaching (Ma et al., 2023). By reducing the reliance on herbicides, cover crops contribute to environmentally friendly farming practices while enhancing soil health and fertility.

Implementing soil conservation techniques like cover cropping can advance sustainable rice cultivation in Ghana, yielding multiple benefits. These methods not only enhance crop productivity, soil fertility, and water management but also minimize the environmental impacts of farming (Nascente and Stone, 2018). Sustainable rice production ensures food security for Ghana's population while safeguarding the environment for future generations.

7 Conservation of beneficial insects and pollinators

Compared to other crops, rice fields function as transitory wetlands, undergoing rapid physical, chemical, and biological changes. These ecosystems harbor a high diversity of organisms, particularly arthropods, which occupy intermediate positions in the food chain. Arthropods include herbivores, saprophytes, parasites, and predators, all of which play critical roles in maintaining ecological balance, enhancing crop pollination, and providing natural pest control (Ali et al., 2022; Yunus et al., 2022; Elmquist et al., 2023). Protecting beneficial insects and pollinators is essential to preserving biodiversity, boosting crop yields, and minimizing the use of chemical pesticides (Ballal et al., 2022). Although studies have explored the biodiversity of rice ecosystems, relatively few have detailed how natural enemies, such as parasitoids and predators, contribute to arthropod pest management during different stages of rice crop development (Dominik et al., 2018; Romeis et al., 2019). Evidence suggests a positive correlation between agricultural productivity and biodiversity within agroecosystems. Increased biodiversity is associated with enhanced crop yields, likely due to the effective control of pest populations by natural enemies (Engbersen et al., 2022; Niggli et al., 2023). Conversely, a decrease in biodiversity corresponded to a decrease in agricultural productivity. One of the primary justifications is their ability to effectively diminish insect pest populations (Jankielsohn, 2023).

In contrast, reduced biodiversity often leads to declines in productivity. For example, lower biodiversity in agroecosystems has been linked to an 18% increase in plant pest populations and a 53% decline in their natural enemies (Luo et al., 2014). Table 6 provides a summary of various insect species that damage rice crops and the parasitoids that attack them. These natural enemies significantly reduce pest populations, demonstrating the importance of preserving ecological harmony in rice fields. Additionally, arable weeds within these habitats support herbivores and their natural enemies, as well as various crop pollinators, further contributing to biodiversity and ecological stability (Primoli et al., 2020).

8 Future prospect

The future of sustainable rice production in Ghana heavily depends on the adoption of best practices that address environmental, socioeconomic, and food security concerns. These practices will help mitigate challenges and improve the long-term viability of rice farming in the country.

8.1 Environmental sustainability

To address environmental challenges, priority should be given to precision irrigation techniques. Methods like Alternate Wetting and Drying (AWD) and drip irrigation have been shown to reduce water consumption by 20–30%, while maintaining or even enhancing rice yields (Yovo et al., 2021). Additionally, the implementation of Integrated Pest Management (IPM) strategies, such as biological control and crop rotation, can help minimize the use of chemical pesticides. This not only reduces environmental pollution but also promotes ecological balance (Deguine et al., 2021). Moreover, soil conservation practices, such as conservation tillage, agroforestry, and the use of cover crops, improve soil health, reduce erosion, and enhance water retention (Kumar et al., 2020). These strategies not only combat environmental degradation but also contribute to long-term agricultural productivity.

TABLE 6 Various rice insect pests and their parasitoids.

Insect order	Insects	Parasitoids	Reference
Araneae	Leaf- and planthoppers	Hunting spiders (Lycosa)	(Tahir and Butt, 2009)
Coleoptera	Blister beetles	Coccinellidae (predatory beetles)	(Liu et al., 2018)
Coleoptera	Leaf beetles	Coccinellidae (predatory beetles)	(Samik et al., 2015)
Coleoptera	Stem borers	Tiger beetles (Cicindellidae), ground beetles (Carabidae), and Hydrophilidae (*Hydrophilus acuminatus* larvae)	(Yamazaki et al., 2003; Ghahari et al., 2009)
Diptera	Stalk-eyed flies	*Tomosvaryella* spp., tachinid flies	(Litsinger et al., 1986)
Hemiptera	Green leafhoppers	Mirid bugs (*Cyrtorhinus lividipennis*)	(Han et al., 2014)
Hymenoptera	Brown planthopper eggs	Mymarids, trichogrammatids, and eulophids	(Gurr et al., 2011)
Hymenoptera	Stem borer larvae and pupae	Braconids and elasmids	(Schoenly et al., 2003)
Neuroptera	Green lacewing	Aphid lions (larval form)	(Elango and Sridharan, 2017)

8.2 Socioeconomic considerations

From an economic perspective, the adoption of sustainable rice production practices must be economically viable for smallholder farmers, who constitute the majority of Ghana's rice sector. Farmer training programs and capacity-building initiatives are essential to ensure the effective implementation of these practices. For example, using slow/controlled-release fertilizers in combination with organic-inorganic fertilization can reduce input costs while improving nutrient use efficiency (Govindasamy et al., 2023). Additionally, farmer cooperatives and community-based organizations can play a vital role in sharing knowledge, providing access to resources, and fostering collective action. Policymakers should consider offering financial incentives, such as subsidies for eco-friendly inputs and grants for irrigation infrastructure, to encourage the widespread adoption of sustainable practices.

8.3 Enhancing food security

With regard to food security, the focus should be on increasing rice production through yield-enhancing methods that are both sustainable and scalable. The adoption of improved rice varieties, resistant to pests, diseases, and climate-related stressors, can significantly boost productivity (Tudi et al., 2021). Furthermore, techniques such as site-specific nutrient management (SSNM) and the use of precision agriculture technologies can optimize resource use and maximize yields (Rodriguez, 2020). These strategies will help Ghana reduce its dependence on rice imports and move towards achieving rice self-sufficiency, as outlined in the National Rice Development Strategy (NRDS).

8.4 Policy frameworks and research investment

Robust policy frameworks and sustained investment in research and development (R&D) are crucial to supporting these efforts. Policymakers should establish regulatory frameworks that incentivize sustainable practices and discourage unsustainable methods. Public-private partnerships can facilitate the introduction of innovative technologies, such as precision irrigation systems and pest-resistant rice varieties, to local farming communities. Additionally, research institutions should focus on addressing Ghana's unique challenges, such as soil degradation, water scarcity, and the impacts of climate change, through targeted studies and pilot projects. Collaborative efforts between researchers, policymakers, and farmers will be essential to translating scientific research into practical, actionable strategies.

By emphasizing best practices in environmental sustainability, socioeconomic viability, and food security, Ghana can foster a resilient and sustainable rice industry. The integration of precision irrigation, IPM, soil conservation, and improved seed varieties—supported by robust policy frameworks and farmer-focused extension services—will be central to achieving this goal. Future research should also explore advanced technologies, such as climate-resilient rice varieties and digital agriculture tools, to further enhance sustainability. Through collaboration, innovation, and a strong commitment to sustainability, Ghana can ensure the long-term security of its rice production, safeguard the environment, and improve the livelihoods of its farmers.

9 Conclusion

This study underscores the importance of adopting sustainable rice production practices in Ghana to address critical challenges in the agricultural sector and secure long-term environmental, socioeconomic, and food security benefits. Through a Dimensional Sustainable Approach, the research highlights key findings across environmental, economic, and social dimensions, emphasizing the need for efficient water management, nutrient optimization, integrated pest control, seed improvement, and soil conservation. These practices are essential for mitigating environmental degradation, improving farmer livelihoods, reducing poverty, and enhancing food security. The analysis identifies precision irrigation, biological pest control, and conservation tillage as key strategies for future adoption. However, significant gaps remain in current practices, particularly in policy implementation, knowledge dissemination, and farmer adoption of innovative strategies. Addressing these gaps requires collaborative efforts among policymakers, researchers, and farmers to implement targeted interventions that enhance sustainability and productivity. Strong policy frameworks, investment in agricultural research, and extension services are critical to facilitating this transition. Future studies should explore advanced technological innovations, precision agriculture, and climate-resilient practices to further strengthen sustainability in Ghana's rice industry. By linking key findings to practical applications, this study provides actionable recommendations that can drive sustainable agricultural development. Ensuring that sustainability strategies are well-integrated into national agricultural policies will be crucial for achieving long-term food security, economic stability, and a resilient rice industry that supports both current and future generations.

Author contributions

AD: Conceptualization, Writing – original draft, Writing – review & editing. JT: Conceptualization, Writing – review & editing. XX: Conceptualization, Writing – review & editing. AC: Conceptualization, Writing – review & editing. MA: Writing – review & editing. AZ: Funding acquisition, Writing – original draft.

Funding

The author(s) declare that financial support was received for the research and/or publication of this article. This work was supported by the Project of Science and Technology Department of Sichuan Province (No. 2019YFN0010, 2020YFH0161, and 22GJHZ0024) and the Chengdu Science and Technology Bureau (2021-YF05-02326-SN).Funding: This work was supported by the Project of Science and Technology Department of Sichuan Province (No. 2019YFN0010, 2020YFH0161, and 22GJHZ0024) and the Chengdu Science and Technology Bureau (2021-YF05-02326-SN).

Acknowledgments

I want to acknowledge Osmond Datsomor of Yangzhou University and Mark Owusu Adjei of Sichuan Agricultural University for their time, efforts, and suggestions in this review article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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