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Sustainable Intensification Option for Sorghum-Based Cropping Systems in the West African Savanna: A Review of Soil and Crop Management Practices

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ABSTRACT

Sub-Saharan Africa faces rising demand for cereal production under conditions of soil degradation, erratic rainfall, and intensifying land use, making sustainable sorghum-based systems in the West African savanna a regional priority. We synthesized peer-reviewed and institutional literature published between 1990 and 2024, identified through systematic database searches, and screened for relevance to sorghum-based systems in the West African savanna. Key production constraints identified include declining soil fertility, inefficient and unbalanced fertilizer use, parasitic weeds, seasonal drought, and weak extension delivery. Promising pathways include integrated soil fertility management that combines organic inputs with judicious use of nitrogen and phosphorus, adoption of good agronomic practices, cereal–legume rotations and intercrops, and conservation-oriented residue and tillage practices tailored to smallholders. Evidence from long-term trials shows that integrated nutrient management and cereal–legume systems can raise sorghum yields by about 30%–80% compared with traditional farmer practice, while improving soil organic matter and nutrient balances. The range reflects aggregated findings across multiple experimental studies rather than results from a single meta-analysis. The review concludes that scaling context-specific ISFM, microdosing, and climate-resilient varieties, alongside strengthened extension and market support, is critical to closing sorghum yield gaps under increasing climate risk in the West African savanna.

1 | Introduction

Sub-Saharan Africa (SSA) is acknowledged as the world's most food-insecure region, with around 30% of its population experiencing regular food shortages, primarily due to persistently low agricultural yields [1]. In 2024, SSA recorded the highest prevalence of food insecurity globally (Figure 1). Despite contributing minimally to climate change, SSA faces significant risks from it, largely due to its reliance on rainfall for agriculture and limited technological adaptation to rising temperatures [2]. Crop productivity in the region remains substantially lower compared to other areas, which can be attributed to poor soil quality [3, 4] and inadequate crop management practices, both of which are

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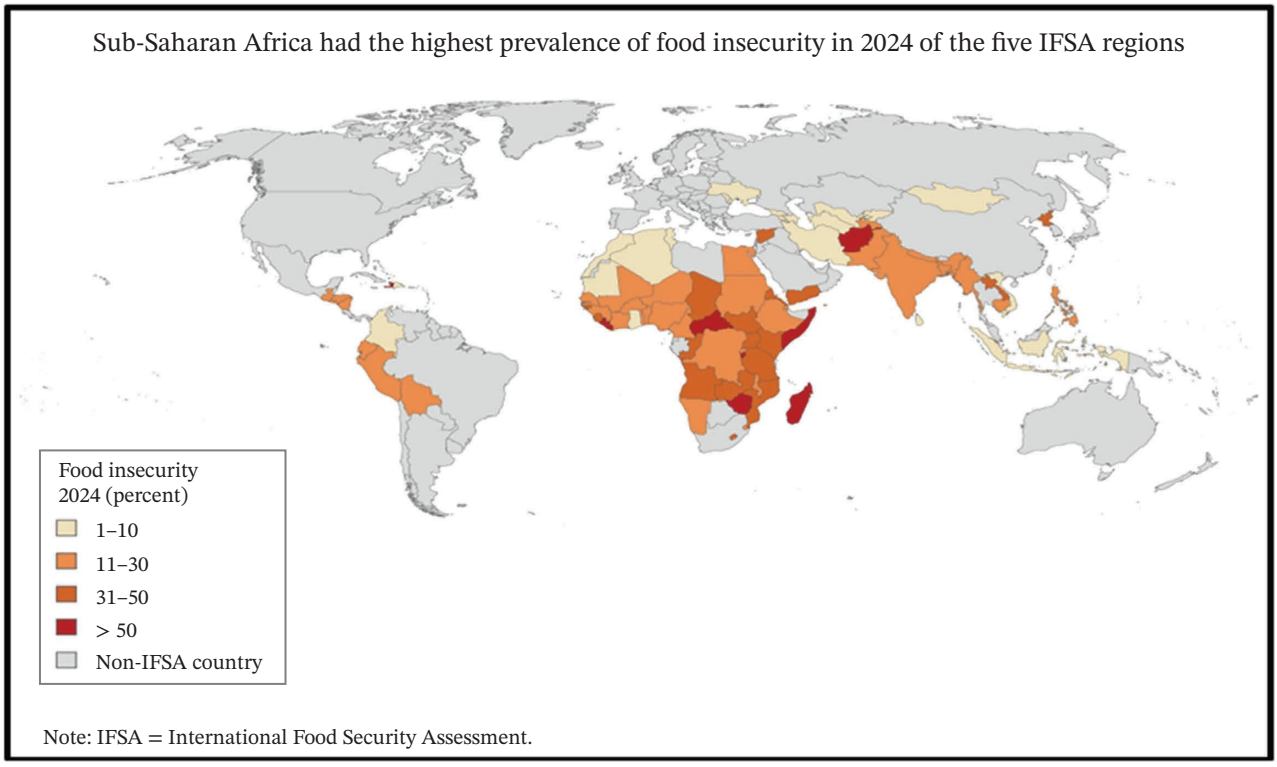


FIGURE 1 | Map of global food in security assessment in 2024. Source: USDA, Economic Research, International Food Security Assessment.

aggravated by the impacts of climate change [5]. Furthermore, there exists a considerable yield gap for key cereal crops, underscoring the disparity between potential and actual yields achieved by farmers [1, 6].

Agricultural production systems in the West African savanna are becoming intensified due to growing populations and market demands, particularly across various agroecological zones (AEZs) such as the Sahel and Sudan regions [7]. In Nigeria's dry savanna, which has a growing season of 4–6 months, cereal and legume crops dominate the agricultural landscape. However, in recent decades, newer crops such as maize (*Zea mays*) and soybean (*Glycine max*) have been incorporated into the cropping systems alongside the traditional crops like sorghum (*Sorghum bicolor*), pearl millet (*Pennisetum glaucum*), black pea (*Vigna unguiculata*), and peanut (*Arachis hypogaea*), which remain staples [8]. West Africa's savannah is a significant producer of sorghum, with Nigeria contributing 71% of the region's total production [9]. In 2020, Nigeria harvested over 6.4 million tons of sorghum, representing 23% of Africa's total output, making it the third most important cereal crop after maize and rice [10].

Sorghum is often intercropped with black peas and peanuts due to its drought tolerance compared to corn and upland rice. While pearl millet is more drought-tolerant and has higher yield potential, it is typically grown further north within West Africa, where rainfall is less abundant [11]. Between 1980 and 2020, sorghum production in West Africa surged from 51,000 tonnes to 13.6 million tonnes [10]; however, average yields have stagnated at around 873 kg ha^{-1} in 1980 to only 973 kg ha^{-1} in 2020. This stagnation is largely attributed to the continued reliance on traditional varieties characterized by heat tolerance but low yield potential [11].

Addressing food security and environmental sustainability is particularly critical in the West African Sudan Savanna, where smallholder sorghum-based systems underpin rural livelihoods and regional food supplies. Efforts to increase sorghum productivity and reduce poverty must therefore be aligned with the protection of key natural resources, including soil, water, and on-farm biodiversity, under increasingly variable climatic conditions [12]. This paper examines how strategic shifts in agricultural practices can enhance sorghum production and promote sustainability in sorghum-based systems of the West African savanna, with a focus on options suitable for smallholder, predominantly rainfed farming contexts. It highlights the importance of building on local ecological knowledge, farmer-managed seed systems, and regionally adapted genetic resources that reflect the strong ethnolinguistic structuring of sorghum diversity across the Sudan–Sahel belt [13].

The review emphasizes agronomic and soil management interventions tailored to intensified sorghum cropping, including improved and locally preferred varieties, balanced mineral fertilizer use, and cereal–legume associations and rotations that can improve soil fertility, water use efficiency, and climate resilience. Priority research needs include evaluating the economic viability and risk profiles of such practices for different household types, assessing the impacts of climate change and climate variability on sorghum yields and stability, and codesigning management options with local communities to strengthen adoption and long-term stewardship of land and genetic resources. This article provides a narrative review of peer-reviewed and gray literature (1990–2024) on sorghum-based systems in the West African savanna, synthesizing agronomic and soil management options for sustainable intensification and climate-resilient sorghum production in the West African Sudan Savanna AEZ. The study

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synthesizes context-specific insights that support improved sorghum productivity, soil health, and livelihood outcomes while contributing to regional progress toward food security and environmental sustainability targets.

2 | Methodological Approach

This review synthesizes evidence on sustainable intensification strategies for sorghum-based cropping systems in the West African savanna zone, with particular emphasis on the Sudan and Northern Guinea savanna AEZs. The review adopted a narrative synthesis approach to consolidate existing knowledge on integrated soil and crop management practices, focusing on interventions that address key production constraints, including soil fertility decline, climate variability, parasitic weeds, and socioeconomic barriers to technology adoption.

Literature sources were identified through systematic searches of multiple databases, including Google Scholar, Web of Science, Scopus, and institutional repositories—CAB Abstracts and AGRIS of major agricultural research organizations operating in West Africa, notably the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), International Institute of Tropical Agriculture (IITA), and national agricultural research systems. Search terms combined keywords related to "sorghum," "sustainable intensification," "soil fertility management," "West Africa," "Sudan savanna," "conservation agriculture," "integrated soil fertility management," "cereal–legume systems," "climate resilience," and "crop management practices." The search covered publications from 1990 to 2024 to capture both foundational research and recent developments in the field.

Inclusion criteria prioritized peer-reviewed journal articles, technical reports from reputable research institutions, conference proceedings, and government publications that presented empirical data or synthesized evidence on sorghum production systems in West African savanna zones. Studies were selected based on their relevance to soil management practices, crop productivity interventions, climate adaptation strategies, and farmer adoption of technologies. Attention was given to research conducted in Nigeria, Ghana, Mali, Burkina Faso, and Niger, which represent major sorghum-producing countries in the region. Both experimental research and on-farm participatory studies were included to ensure comprehensive coverage of controlled trials and real-world farmer conditions. The extracted information was organized thematically into major challenge areas and corresponding intervention strategies. Data on crop yields, nutrient application rates, agronomic efficiency (AE), economic returns, and adoption rates were systematically compiled from eligible studies. Where quantitative data were available from multiple studies addressing similar research questions, percentage yield responses were first normalized relative to the corresponding control or baseline and then summarized to obtain an aggregate yield improvement range. Studies reporting yield gains under broadly comparable semi-arid conditions for integrated soil fertility management (ISFM), fertilizer microdosing, cereal–legume rotations, and improved varieties were grouped, and their percentage yield effects were synthesized to derive an overall yield improvement range of approximately 30%–80%. This synthesis integrated findings across different spatial scales—from plot-level experiments to regional assessments—and temporal scales, including both short-term productivity gains and longer-term sustainability outcomes. Special consideration was given to context-specific factors such as soil type, rainfall patterns, farming systems, and socioeconomic conditions that condition both the magnitude of yield response and the adoptability of sustainable intensification practices in the West African savanna zone.

3 | Key Agronomic and Systemic Constraints Affecting Sorghum-Based Cropping Systems in the West African Savanna

Sustainable intensification in agriculture aims to increase productivity, enhance ecological resilience, and minimize environmental impacts by strategically managing agroecosystems—from field to landscape—using a combination of biological, chemical, cultural, and mechanical resources [14]. Agricultural production in the savannahs faces several key bottlenecks: declining soil fertility, inefficient fertilizer use, limited access to improved seeds, and significant losses due to pests, diseases, and weeds, particularly *Striga hermonthica* and *Striga gesneroides* infestations in cereal crops [7, 16]. Low adoption of mechanization [17] and declining genetic diversity further exacerbate these challenges. Erratic rainfall patterns, including prolonged droughts and floods, further exacerbate these issues, alongside bush burning, deforestation, and the destruction of farmland by small-scale mining operations. The limited adoption of improved technologies and practices is largely due to a combination of factors: lack of access to premium prices for agricultural products, financial constraints, labor shortages, high discount rates, and risk aversion among farmers [18]. Furthermore, unfriendly policies, inadequate seed systems, weak institutional support, poor infrastructure, and limited collaboration between farmers, extension agents, and researchers continue to hinder the adoption of improved technologies and practices.

3.1 | Unsustainable Soil Fertility Management

Soil fertility is closely linked to soil organic matter, which is influenced by biomass input, management practices, mineralization, leaching, and erosion [19]. Soil organic matter enhances structural stability and resistance to erosion from rainfall, as well as improving infiltration rates and supporting faunal activities [20]. The depletion of soil fertility is a significant factor contributing to the decline in per capita food production [19, 21]. This issue arises from unsustainable agricultural practices and continuous nutrient extraction without adequate replenishment, particularly in the savannah region, exacerbating poverty and food insecurity [21, 22]. The deterioration of soil's physical and chemical properties has led to a considerable decline in crop production [23]. Historically, farmers relied on long fallow periods to restore soil fertility and organic carbon; however, current fallow durations are insufficient for nutrient recovery, rendering these farming systems unsustainable [24, 25].

Additionally, the removal of crop residues from fields combined with low soil nutrient availability has resulted in negative nutrient balances in the region [26]. For instance, Bationo et al. [27] reported an annual loss of 4.4 million tons of nitrogen, while only 0.8 million tons were applied (Figure 2). Additionally, estimates for Nigeria's savannah zones indicate that nutrient mining resulted in a loss of 111,000 tonnes of P_2O_5 and 946,000 tonnes of

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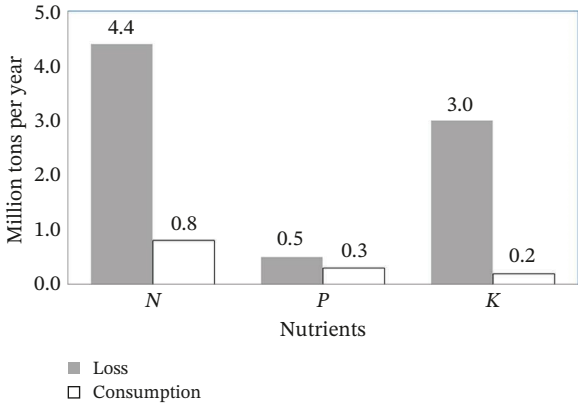


FIGURE 2 | Nutrient losses versus application rate in SSA (Sub-Saharan Africa) adapted from Bationo et al. [19].

K_2O from the 32.8 million hectares cultivated in 1983, equivalent to over US$800 million in NPK fertilizer [26]. This highlights the detrimental effects of nutrient mining on agricultural productivity and underscores the necessity for effective management strategies for nutrient inputs and outputs to conserve soil fertility. Studies suggest that expanding new farms cannot increase output by more than 1% without exacerbating environmental degradation [28]; thus, intensification emerges as the most viable option.

Soil degradation is now recognized as a critical environmental issue in SSA [29]. Research by Mapanda et al. [30] revealed that converting woodlands to croplands diminishes soil nutrients and cation exchange capacity (ranging from 9.6 to 21.0 cmol·kg^{-1} in clay to 7.0–15.5 cmol kg^{-1} in loamy sand) and microbial carbon (ranging from 0.06% to 0.54% in clay to 0.02%–0.37% in loamy sand). The extent of these changes varies based on soil type and depth. Effective management of soil resources for optimal goods and services requires careful handling of organic resources, mineral inputs, and the soil organic carbon (SOC) pool [31]. The significance of SOC has spurred interest and research into its accumulation within the soil–plant system, particularly through conservation tillage practices. Maintaining SOC is crucial for combating land degradation and enhancing future food production [19]. Higher levels of soil organic matter can improve the efficiency of mineral fertilizer use in agriculture.

Recent studies by Lavanya et al. [32] indicate that yield variability correlates with SOC variability; however, soil organic matter levels are typically low in most savannah soils, often ranging between 1 and 10 g/kg [33]. High tropical temperatures accelerate the decomposition of organic matter, leading to faster decay rates compared to other regions [34, 35]. Therefore, increasing soil organic matter levels is essential for enhancing crop production in the savannah region. Improved management practices can be achieved through cultivating crop varieties that produce substantial above- and below-ground biomass, implementing in situ residue management techniques, utilizing off-site plant residues [36], and producing high-quality manure along with organic fertilizers.

Preliminary observations in the Northern Guinea savannah bordering the Sudan savannah indicate that legumes require approximately 30 kg ha^{-1} of P_2O_5, while cereals like maize need at least 60 kg ha^{-1} of P_2O_5—levels rarely met by most farmers [37]. Additionally, the removal of crop harvests and residues can lead to increased acidity due to leaching, resulting in losses of calcium, magnesium, and potassium and elevated levels of soluble manganese and aluminum toxicity. Although mineral fertilizers could replace these nutrient losses, socioeconomic constraints often limit their use; many farmers apply insufficient quantities due to financial limitations or the unavailability of fertilizers. Consequently, optimal crop production remains elusive despite the region's potential for sustainable agricultural practices.

Currently, efforts to mitigate nutrient depletion focus on applying fertilizers primarily containing NPK nutrients but often in inadequate amounts. Increased NPK usage can enhance yields [38, 39], but it may also accelerate the depletion of other essential nutrients such as sulfur and zinc. Continuous potassium addition can disrupt cation balance within soils, inhibiting plant uptake of vital cations like calcium and ultimately reducing crop productivity [40]. Both mineral and organic fertilizer inputs are necessary for improving soil fertility in the subregion [41]. Various studies have concluded that soil fertility poses a greater limitation on agricultural production than rainfall does [42].

3.2 | Climate Variability and Seasonal Effects on Crop Productivity

The Savannah climate is characterized by high temperatures year-round, with distinct wet and dry seasons. This AEZ experiences a single rainy season from May to September, with the mean annual rainfall ranging from 600 to 800 mm. Maximum rainfall typically occurs in August [43]. The length of the rainy season varies between 4 and 5 months, with rainfall decreasing from south to north [44]. The alternation between months of rainfall and dry spells in West Africa is significantly influenced by large-scale atmospheric circulation patterns, which shape the region's rainfall variability and climate [45, 46]. These influences are primarily linked to the dynamics of the West African Monsoon (WAM), the Intertropical Convergence Zone (ITCZ) shifts, and global ocean–atmosphere interactions. These interactions determine not only seasonal rainfall distribution, which plays a crucial role in determining the onset and intensity of thunderstorms and squall lines that contribute over 80% of the annual rainfall across the West African subregion [44, 47], but also interannual variability influenced by global climatic phenomena [46].

Recent evidence indicates a troubling trend of decreasing rainfall and rising temperatures in the Savanna zone. Both empirical studies and process-based crop models suggest significant negative impacts on cereal crop production. Yield changes vary widely, with estimates ranging from −50% to +90%, while the median yield loss is approximately −11% [48]. A recent review highlights potential yield changes between −57% and +15%, with a median loss of −9% [49]. Furthermore, projections for sorghum yields across the West African savannah indicate declines of about 2%–5% in the near term, rising to 10%–20% by mid- to late century under current climate scenarios, with particularly strong losses in Senegal, south-west Mali, and northern Nigeria ([50, 51]; [51]). These impacts arise from more frequent heat extremes, shortened growing periods and shifts in monsoon onset, and cessation that amplify year-to-year yield variability and production risk for smallholders in countries such as

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Burkina Faso, Niger, and Mali [51–53]. Projections also suggest that increased atmospheric CO_2 could coincide with regional temperature rises of about 1.5°C–2.8°C and rainfall reductions or seasonal redistributions of 100–400 mm/year by mid-century, partially offsetting but not eliminating net yield losses for sorghum systems in the Sudanian and Sahelian zones [51, 54].

However, analysis of rainfall and crop yield data reveals that approximately 50% of maize areas in West, Central, and East Africa have experienced yield declines due to insufficient rainfall during average years [55]. Farmers typically sow seeds with the first rains; however, if subsequent rains are delayed, they face the risk of reseeding due to prolonged drought conditions. In Nigeria's Sudan Savannah zone, drought probabilities peak at both the beginning and end of the growing season [56]. Drought stress early in the season can severely hinder plant establishment. Unfortunately, many smallholder farmers lack the resources for resowing. As a result, drought during critical growth stages, such as seedling emergence or grain filling, can lead to poor establishment or complete crop failure. Even when total seasonal rainfall appears adequate, its distribution remains uncertain. This variability means that neither genotype maturity nor planting dates can fully mitigate drought impacts. Strategies aimed at reducing crop susceptibility to drought while maintaining or boosting yields during favorable years are essential for stabilizing rural incomes and alleviating chronic food shortages before harvest.

3.3 | Parasitic Weeds

Parasitic weeds, particularly Striga and Alectra species, pose a significant threat to cereal and legume crops, especially in the savanna regions [57]; [58]; [59]. Striga *hermonthica* is a major constraint on cereal production in West Africa's dry savannas [60]. Striga infestations affect approximately 40 million hectares of cereal crops, mainly sorghum and millet, with nearly 70 million hectares experiencing moderate infestation levels, impacting the livelihoods of over 100 million farmers [58].

Striga spp. remain a major constraint to cereal and legume production in the northern Guinea and Sudan savannas of Nigeria, severely affecting millet, sorghum, maize, upland rice, and cowpea [59, 61]. In the Sudan savanna, more than 80% of maize and sorghum fields are infested, with yield losses ranging from partial reductions to complete crop failure, depending on infestation intensity [57, 62]. Similar patterns are reported across West Africa, where *Striga hermonthica and S. gesnerioides* infest an estimated 17 million hectares (about 64% of cereal land) in countries such as Benin, Niger, Mali, Burkina Faso, Togo, and Senegal, causing severe economic losses [63–65]. Yield losses of 30%–60% in susceptible cowpea cultivars have been documented in Burkina Faso and northern Ghana, with total crop failure under heavy infestation [66, 67]. Key drivers of Striga proliferation include declining soil fertility, shortened fallows, continuous cereal monocropping, and the use of susceptible germplasm [65, 68]. In response, regional breeding programs and integrated management initiatives are developing and promoting Striga-resistant or tolerant maize, sorghum, rice, and cowpea varieties, alongside complementary control options [59, 62].

Management practices, such as crop rotation, intercropping with legumes like soybean, and the use of resistant varieties, are popular control measures to reduce Striga infestations [57, 59]. Intercropping maize with soybeans can provide a cost-effective way to control Striga *hermonthica*, as legumes can act as trap crops, stimulating Striga seed germination but preventing the parasite from attaching to their roots.

3.4 | Socioeconomic Constraints and Weak Extension Services

Significant advancements have been made in developing and testing innovative technologies aimed at enhancing agricultural intensification [69]. However, the efforts to disseminate these technologies among smallholder farmers have had minimal impact, resulting in limited adoption across various farming communities [69, 70]. Multiple factors—including technical, socioeconomic, institutional, and policy-related barriers—have been identified as obstacles to technology adoption. In many West African nations, extension services often provide recommendations that are either inappropriate or ineffective. Furthermore, the indiscriminate promotion of mineral fertilizers without considering soil and climatic variations poses a challenge to their effective utilization [71].

Technologies that perform well under controlled conditions may not translate effectively to farmers' real-world contexts due to differences in management practices, input availability, and soil types [72]. Economic incentives are widely recognized as critical drivers for technology adoption [72]. Poor communication among farmers, extension agents, and researchers has frequently contributed to the inadequate uptake of promising technologies developed through research efforts. Consequently, the benefits of investments in agricultural research remain largely unrealized.

For instance, in Nigeria, the Participatory Research and Extension Approach (PREA) is a popular model for disseminating improved agricultural technologies. However, this model faces sustainability challenges due to underfunding and a lack of adequately trained personnel. Extension workers are expected to guide various topics—including production, postharvest handling, and livestock management—despite often lacking comprehensive knowledge across these areas. Ajeigbe and Dashiell [73] highlighted that PREA effectively bridges gaps by making agricultural technologies readily available and accessible within farming communities while enabling participating organizations to gain valuable experience in fostering researcher–farmer extension partnerships. Thus, addressing the socioeconomic constraints and enhancing the effectiveness of extension services are crucial for improving technology adoption among smallholder farmers in West Africa. This requires a concerted effort to align extension recommendations with local conditions and improve communication channels among all stakeholders involved in agricultural development.

4 | Priority Interventions for Sustainable Soil Crop Management Strategies

4.1 | Role of Mineral Fertilizer in Enhancing Sorghum Productivity

Nitrogen (N), phosphorus (P), and potassium (K) are key elements targeted in inorganic fertilizers, with nitrogen often being the most limiting nutrient in savannah soils. In the Sudan and Sahelian zones, a flush of N occurs at the start of the wet season,

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its magnitude related to the length of the preceding dry season. This N release, which can range from 13 to 183 kg N/ha, may not fully benefit crops depending on rainfall patterns early in the season [74]. To replenish soil fertility, farmers use both chemical fertilizers and organic manure, although adoption rates can be limited. The most common chemical fertilizers used on sorghum and millet in Nigeria are compound NPK fertilizers (20:10:10 and 15:15:15), but application rates are often low. Research has demonstrated that applying mineral nitrogen (N) fertilizer substantially boosts sorghum grain yields in the Sudan savannah. For instance, yield gains of 35%–64% at BUK and 23%–78% at Minjibir confirm the strong sorghum response to nitrogen in the Sudan Savanna of Nigeria, with 80 kg N ha^{-1} identified as the economically optimal rate compared with the common 60 kg N ha^{-1} recommendation [38]. Similar studies across the Sudano–Sahelian and Sudanian zones of West Africa report yield increases of 19%–90% and often identify optimal rates between 40 and 80 kg N ha^{-1}, depending on agroecology and management intensity [75]. Agronomic nitrogen use efficiency varies widely among sorghum cultivars, highlighting exploitable genetic diversity that could help sustain productivity while reducing dependence on mineral N inputs [76, 77].

Similarly, MacCarthy et al. [78] found economically optimal rates of 40 and 80 kg N/ha for intensively managed homestead fields and less intensively managed bush fields, respectively, in Ghana's savannah zones. Agronomic NUE ranged from 21 to 37 kg grain/kg N for homestead fields and 15 to 49 kg grain/kg N for bush fields. Bationo [79] also found an optimum rate of 50 kg N/ha for sorghum across the Sudano-Sahelian zone of West Africa. To maximize nitrogen efficiency, applying nitrogen fertilizer in two equal doses is generally recommended. Early-season N uptake can be low due to losses from erosion or leaching, making later application (e.g., 42 days after sowing) more effective as root systems develop. Higher planting densities can further enhance nutrient utilization. N losses in the Sudano-Sahelian zone average 40% [79], contributing to low yields. Therefore, improved crop management, plant densities, and field geometry are crucial for increasing N recovery.

Phosphorus (P) is another key limiting nutrient in the Sudan Savannah zone. Research has long focused on assessing soil P deficiency and evaluating the potential of local phosphate rocks (PRs) [80]. Bationo [79] estimates that 80% of SSA soils are P-deficient, limiting the effectiveness of other inputs. Sandy Sudano-Sahelian soils are particularly low in available and total P compared to other West African soils, with total P as low as 40 mg P/kg and available P below 2 mg P/kg. Bationo [79] found total P ranging from 25 to 340 mg/kg (mean of 109 mg/kg) in pearl millet–producing soils of West Africa. West Africa possesses substantial PR deposits that can replenish soil phosphorus and enhance cereal yields when appropriately managed. In the Sudan savannah of Nigeria (Table 1), P fertilization increased the sorghum grain yield by 20%–40% over unfertilized control, with an optimum rate of around 45 kg P ha^{-1}[16, 81]. Locally processed PR-based fertilizers, such as partially acidulated or calcinated products, have shown promising yield responses for sorghum in Burkina Faso under rainfed conditions. PR-enriched composts similarly improved sorghum performance on degraded soils in the Central Plateau of Burkina Faso. Across Niger and neighboring countries, trials indicate that natural phosphates can match conventional mineral P in millet and cowpea systems when used on acidic to moderately acidic soils and combined with organic resources [27, 82]. However, low PR solubility, transport constraints, and limited effectiveness on nonacidic soils remain important barriers. Integrating PR with organic amendments and broader agroecological practices is therefore critical to sustain soil fertility, support continuous cultivation, and raise farmer incomes while reducing environmental degradation in West African production systems [83, 83].

4.2 | ISFM

ISFM is recognized as a valuable strategy for resource-constrained farmers, as it addresses challenges related to poverty and food insecurity and enhances food quantity, quality, income, and soil productivity. Increased use of organic and inorganic fertilizers and improved crop diversification, including legumes, are important for restoring or maintaining soil fertility in intensive cropping systems in the dry savannahs of West Africa [85]. However, the high cost of fertilizers results in low usage by farmers, with the average fertilizer application in Nigeria around 11.4 kg ha^{-1}, and even lower in other West African countries [86, 87].

To address these challenges, various concepts have been proposed for long-term crop production in the dry grasslands of West Africa. Balanced nutrient management, promoted in the late 1990s, targeted nitrogen and phosphorus deficiencies in Nigeria, Benin, and Togo [8]. A key feature of balanced nutrient management is the combination of organic and inorganic nutrient sources, which can reduce nitrogen fertilizer costs by approximately 50%. Furthermore, cereals or herbaceous legumes utilizing less available phosphorus or rock phosphorus appear to have more efficient mechanisms for phosphorus acquisition than other soil crops [88]. The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has developed drought-tolerant and phosphorus-efficient sorghum varieties and hybrids [89]. These varieties are promoted in the West African savannah, particularly in Mali and Nigeria, and are combined with balanced nutrient management using microdosing technology.

TABLE 1 | Examples of PR use in West Africa.

Country/zone	PR or P source	Crop/system	Key outcome
Nigeria, Sudan savannah	Mineral P fertilizer	Sorghum	20%–40% grain yield increase at ≈45 kg P ha^{-1} [16, 81]
Burkina Faso, Kodjari PR	Calcinated and partially acidulated PR	Sorghum (rainfed)	Local PR fertilizers increased sorghum yield vs. the unfertilized control [27, 82]
Burkina Faso, Central Plateau	PR-enriched compost	Sorghum on degraded soils	PR–compost mixtures improved sorghum yield and P uptake [83, 83]

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ISFM aims to maximize the AE of applied nutrient inputs [90] and includes proper fertilizer management, use of improved varieties, combined application of organic inputs and fertilizer, and adaptation of input application rates to within-farm soil fertility gradients [88]. Studies in Mali, Burkina Faso, and Niger [91] showed that manure application alone produced 34–58 kg of cereal grain dry matter per ton of manure and 106–178 kg of stover dry matter per ton of manure. Combining manure with inorganic fertilizer increased yields to 80–90 kg of grain per ton of manure and 84–192 kg of stover per ton of manure, with continuous increases in sorghum yields observed over time (Figure 3). Manure can also serve as a source of phosphorus [92]. Agegnehu and Amede [93] found that 5 t/ha of high-quality manure can meet the nitrogen requirement for a modest maize yield of 2 t/ha but not the phosphorus requirement in P-deficient areas. Akinseye et al. [94] showed that poultry manure, combined with a microdose of NPK (3 g/hill), resulted in a 50% yield increase for sorghum and pearl millet compared to the control, demonstrating the effectiveness of combining smaller amounts of NPK with manure.

4.3 | Climate-Resilient Sorghum Cultivars

The adoption of climate-smart agricultural technologies involves integrating sustainable cropping systems that boost productivity and protect the environment. This is achieved through developing new sorghum cultivars with enhanced resilience to biotic and abiotic stresses, high yields, and desirable market traits. Because seeds are a cost-effective and vital input, a variety's capacity to yield well under challenging conditions is crucial for overall farming system productivity.

The large-scale demonstrations summarized in Table 2 were conducted in the Sudan Savanna AEZ, Nigeria, where extensive and reliable trial data were available to support a comprehensive evaluation. This focus not only reflects the country's advanced research infrastructure but also justifies the scale of demonstration required to validate the performance of improved sorghum technologies under diverse field conditions. As reported by Ajeigbe et al. [95], improved sorghum varieties and associated technologies were evaluated and demonstrated by smallholder farmers across several states within Nigeria's Sudan savannah AEZ. The adoption and promotion of sorghum varieties resistant to major diseases and pests substantially boosted production across different technological interventions. In the Kano–Jigawa and Sokoto–Kebbi staple crop processing zones (SCPZs), improved varieties achieved grain yield increases of 53% and 64%, respectively, compared to local varieties (Table 2). Seed dressing improved yields by 27% and 30%, while tillage practices contributed yield gains of 18% and 13% in the same SCPZs. The integration of early maturing, low-phosphorus-tolerant sorghum varieties with stay-green traits [96], along with the development of downy mildew and Striga-resistant millet varieties [97], further strengthens the sustainability and resilience of sorghum-based production systems.

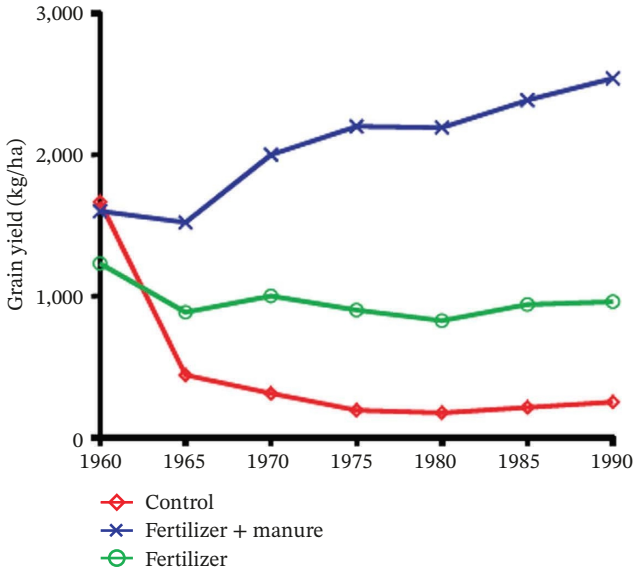


FIGURE 3 | Sorghum grain yield as affected by mineral and organic fertilizers over time adapted from Bationo et al. [91].

4.4 | Cereal–Legume Rotation/Association

In the Sudan savanna of Nigeria, cereal–legume intercropping is a common traditional farming practice employed to mitigate climate risk, address low seedling emergence, and enhance food crop diversity [98]. Research indicates that integrating organic and inorganic fertilizers can further improve these intercropping systems for smallholder farmers in the region. For instance, Ajeigbe et al. [98] found that a 2-row sorghum to 4-row cowpea (2S:4C) system, utilizing improved cowpea varieties and insecticide application, proved particularly effective for resource-poor farmers.

An extensive evaluation of improved cowpea–cereal cropping systems (Table 3) was conducted between 2003 and 2005, involving over 1600 farmers across multiple locations [99]. This large-scale demonstration was undertaken to validate the robustness and adaptability of the improved systems under diverse farmer-managed conditions, ensuring their practical relevance and scalability. Results demonstrated the superiority of these improved systems, with grain yields exceeding those of traditional systems by 160%–680%. This translates to gross returns 160%–571% higher than traditional controls. Furthermore, the improved systems yielded better quality crop residues, with an increased proportion of leguminous material, thereby benefiting livestock productivity. Farmer group formations and networking with stakeholders such as extension agents, input dealers, and government officials were crucial for effective technology dissemination and capacity building.

Beyond traditional intercropping, relay and sequential cropping systems have gained attention as alternative approaches [79]. Studies suggest that rotating cereals with legumes can enhance nitrogen use efficiency. For example, Bationo and Ntare [92] observed an increase in nitrogen use efficiency from 20% in continuous pearl millet cultivation to 28% when pearl millet was rotated with cowpea. Similarly, Roder [100] reported that rotating sorghum with another crop improved soil conditions and reduced weed and insect populations, leading to sorghum yield increases of 17%–60% under unfertilized conditions.

4.5 | Low-Cost Technologies for Smallholder Farmers

4.5.1 | Microdosing Fertilization Strategy

Microdosing fertilization involves applying small, targeted doses of fertilizer directly in the planting hole at sowing or near the

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TABLE 2 | Crop yield benefits from large-scale technology demonstrations in the Sudan savanna region, Nigeria.

SCPZ	LGA	Variety technology		Seed dressing techniques		Tillage technique	
		OPV/Hybrid	Local	Dressed	Undressed	Conventional	Minimum
Kano-Jigawa	Rano	1438	1080	1190	1078	1152	966
	Bebeji	1521	1247	1537	1136	2399	1905
	Kura	3680	1800	5700	5400	7200	6200
	Bunkure	1771	910	2394	1360	2443	2456
	G/Mallam	1216	902	2460	1683	1785	1170
	Dawakin Kudu	1508	1391	1438	1006	1895	1640
	Gwaram	890	250	2304	1368	2076	1272
	M/Madori	1124	903	1350	927	1327	837
	Auyo	2227	1300	3200	3150	3500	3100
	K/Hausa	1289	1020	1633	933	1167	733
	Hadejia	861	700	2288	2000	1988	2600
	Mean yield	1593	1046	2318	1822	2448	2080
	% yield gained	52.4		27.2		17.7	
Sokoto-Kebbi	Dandi	687	456	1800	1584	1060	484
	Ngaski	964	576	2564	2240		
	Bagudo			780	560	735	860
	Shanga	760	640	1600	1300		
	Suru	1360	1000	1200	800	1040	840
	Kware	1840	760	3700	2500	2000	2110
	Mean yield	1122	686	1941	1497	1209	1074
	%Yield gained	63.5		29.6		12.6	

Note: N.B: confidence intervals were not available for the included studies; the number of demonstration plots and participating farmers across the three technologies ($n = 200$) (adapted from [38]).

plant 2–3 weeks after emergence [101]. This technique enhances fertilizer use efficiency, boosts yields, and minimizes input costs. Its adaptability and profitability are key advantages. While high fertilizer rates have historically been recommended, their cost has often prohibited farmer adoption. Microdosing overcomes this barrier by using lower, more efficient fertilizer applications that deliver economically optimal returns, making it a more accessible and attractive option. Successful adoption of microdosing can encourage farmers to increase their investments in inputs for sustained productivity gains. Beyond its immediate benefits, microdosing serves as an initial step toward sustainable agricultural development. Trials in Burkina Faso, Mali, and Niger have demonstrated promising outcomes (Figure 4), with sorghum and millet yields increasing by 45%–120% compared to traditional practices, and farmer incomes rising by 50%–130% [101].

4.5.2 | Seed Dressing

In the absence of durable resistance, an integrated approach using resistant or moderately resistant varieties, seed dressing fungicides, and herbicides can effectively manage diseases and Striga. Gray leaf spot significantly reduces sorghum production in the Sudan savanna of Nigeria. Studies [102] showed that metalaxyl seed treatment reduced the mean plant smut incidence to 4.8% (severity 0.9%) compared to 11.3% (severity 5.2%) in untreated seeds, representing disease reductions of 57% and 83%, respectively. Similarly, Richard et al. [103] reported positive returns from seed dressing, with treated plants yielding 28.9% more than untreated plants due to reduced disease infection, resulting in a net profit of US$372.55 per hectare. Seed dressing with fungicides and/or fertilizer is a viable strategy for increasing sorghum productivity and promoting sustainable intensification for smallholder farmers in the Savanna region of Nigeria.

4.5.3 | Conservation Agriculture (CA)

Interest in conservation tillage has increased in the last decade, particularly in semi-arid developed countries like Australia and the USA. Adoption has been slower in West African semi-arid regions [104] due to competing uses for crop residues, labor demands, lack of suitable mechanization tools, and high input costs, including herbicides. Economic pressures, such as rising fuel, labor, and variable costs, coupled with volatile market prices, further compel producers to minimize input costs and maximize profits [105]. CA is a management system focused on minimal soil disturbance, maintaining permanent or semi-permanent organic cover (e.g., crop residues), and implementing spatial/temporal crop rotations [106]. In mechanized systems, CA can reduce labor, fuel, and machinery expenses [105]. The core principles of CA are (i) maintaining soil cover, (ii) minimizing soil disturbance, and (iii) employing regular crop rotations [63].

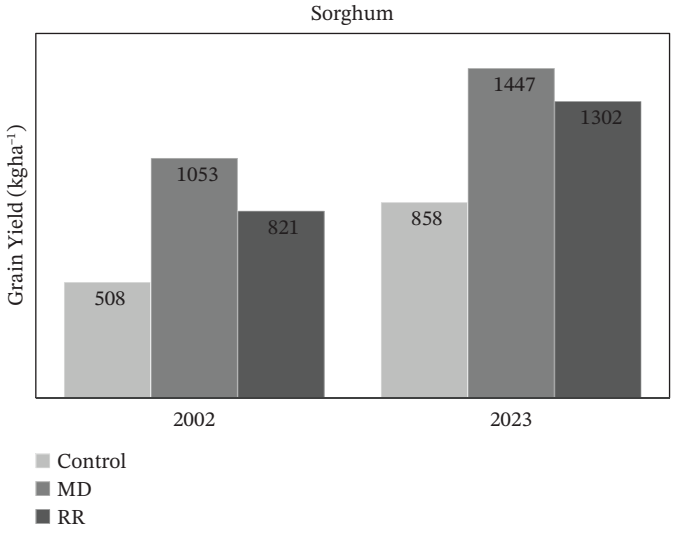
Despite being a dominant paradigm in discussions about sustainable intensification of food production in SSA, the yield benefits of CA in African smallholder systems remain debated [107]. A meta-analysis indicated that grain yield under CA was positive in areas with rainfall below 600 mm per annum but negative with higher rainfall, likely due to water conservation in drier areas and waterlogging in wetter areas [103]. Similarly, Corbeels et al. [107] found average yields under CA to be only

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TABLE 3 | An extensive evaluation of crop productivity (kg ha^{-1}) and economic value (ha^{-1}) of farm outputs under improved cropping systems in the Nigeria Sudan savanna zone, 2003–2005 cropping seasons.

No of farmers	Legumes		Cereals		Economic value	
	Grain	Fodder	Grain	Fodder	Grains	Total
Improved Intercropping Systems						
			2003			
Sg:-C (367)	1137	1942	688	2429	73,362	107,350
			2004			
SC (279)**	1456	2051	—	—	72780	113,809
Sg:-C (418)	987	1778	1073	4061	76,157	119,831
			2005			
SC (523)**	1388	1619	—	—	83,254	107,544
Sg:-C (644)	933	1938	1238	4139	93,096	142,860
Traditional systems						
			2003			
*G:Ml	413	1227	115	2017	44,780	67,215
C:G:Sg:Ml	519	1621	548	1002	34,834	61,151
C:Sg:Ml	397	1109	732	1541	37,842	57,557
Sg			1625	2205	39,540	43,949
Ml			1410	1598	36,660	39,856
			2004			
Sg:C	148	557	901	3695	29,940	48,474
Mi:C	93	374	350	2166	13,384	25,190
Mz:C	267	437	652	1533	29,664	41,470
			2005			
Sg:Mz:C	264	978	1251	4020	53,400	88,167
Mi:Mz:C	170	756	911	1933	37,556	58,556
Sg:C	204	415	546	2366	28,630	46,687
Mi:C	126	271	204	1454	13,690	25,018

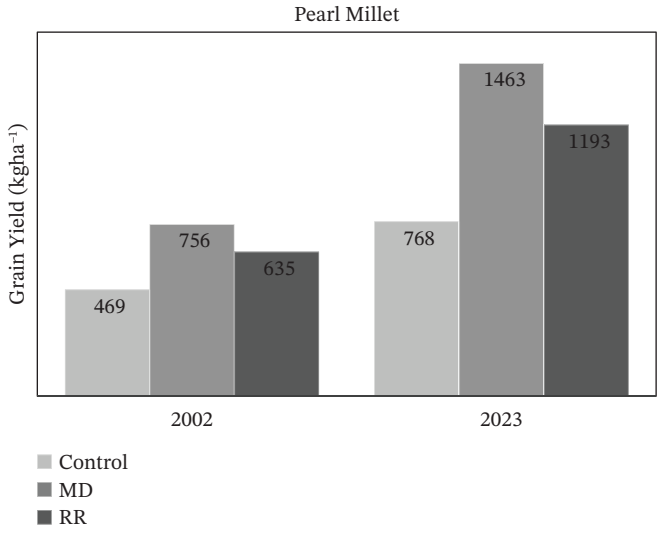
*C = cowpea, Ma = maize, Sg = sorghum, Mi = millet.
**Sole cowpea cropping; exchange rate: Naira to a dollar @ 2010 (122 = $1) (adapted from Ajeigbe et al. [99]).



(a)

FIGURE 4 | (Continued)

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(b)

FIGURE 4 | Cereal response to low-cost technologies in the Sudan Savanna zone of Mali. (a) Sorghum grain yield [control, microdose (MD), recommended rates (RRs), and Zai]; (b) pearl millet grain yield (kgha^{-1}) [control, microdose (MD), recommended rates (RRs), and Zai]. Adapted from Tabo et al. [101].

slightly higher than conventional tillage (3.7% for six major crops and 4.0% for maize), with the greatest benefits in low-rainfall conditions. In semi-arid Zimbabwe, Nyamangara et al. [105] found that CA's yield benefits are realized only with mineral fertilizer application. The maize grain yield increased by 20%–33%, 7%–9%, and 58%–69% when CA (mulching, crop rotation, and mulching + crop rotation, respectively) was combined with mineral fertilization. Without fertilizer, these CA practices depressed the maize grain yield by 48%, 28%, and 36%, respectively.

4.5.4 | Minimum Tillage vs. Conventional Tillage: Impacts on Soil and Crop Production

Minimum tillage practices offer several advantages over conventional tillage, including improved soil structure, enhanced water conservation, and reduced soil erosion from wind and water [108]. Conversely, conventional tillage can mix soil organic matter in surface layers, potentially accelerating its decomposition and increasing emissions of CO_2 and NO_2 [109]. Soil tillage practices significantly influence agricultural sustainability

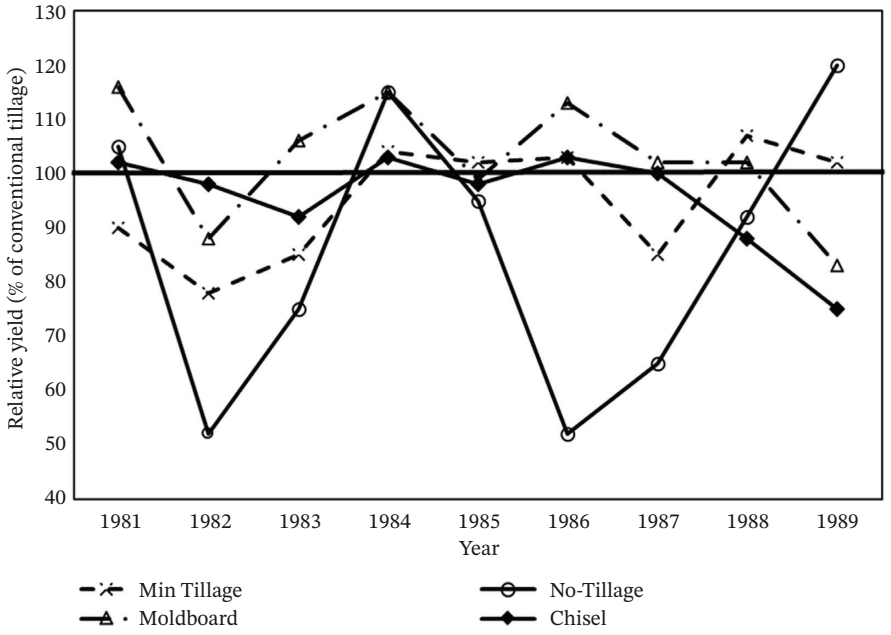


FIGURE 5 | Relative yield of grain sorghum grown under conservation tillage and two forms of primary tillage (1981–89). Adapted from Matocha and Sorenson [104].

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by affecting soil processes, properties, and crop growth [110]. Minimum tillage has demonstrated positive effects on soil compaction, moisture retention, and temperature regulation, which can benefit the production of crops like sorghum, maize, and soybean [111].

The environmental impact of soil tillage is a critical consideration for sustainability, influencing factors such as soil degradation, water quality, and greenhouse gas emissions from soil-related processes. Tillage serves several agronomic purposes, including soil conditioning (modifying soil structure to improve seed–soil contact, root development, water infiltration, and temperature control), weed and pest suppression (through direct termination or disruption of life cycles), residue management (altering residue placement and size to minimize negative and maximize beneficial effects), incorporation/mixing (distributing substances like fertilizers and seeds), segregation (consolidating rocks or soil aggregates), and land forming (modifying the soil surface through ridging or furrowing).

However, excessive or improper tillage can negatively impact soil and crop production, leading to land degradation, subsoil compaction, increased vulnerability to erosion [112], accelerated decomposition of soil organic matter, high energy consumption, and increased labor demands. Long-term studies indicate that grain sorghum yields in minimum tillage systems can equal or surpass those in conventional tillage systems [104]. Based on 9-year average relative yields, minimum tillage can achieve 95% of the productivity of conventional tillage. Moreover, seasonal yield responses have demonstrated an approximate 9% increase in sorghum grain yield with minimum tillage (Figure 5).

5 | Conclusion, Future Research Directions, and Policy Recommendations

This review reinforces the critical importance of sustainably intensifying sorghum-based cropping systems across the West African Sudan Savanna to restore soil health, boost productivity, and ensure long-term livelihood security. The synthesis demonstrates that sustainable intensification demands a holistic and regionally adaptive approach, integrating soil fertility enhancement, climate-smart crop management, and inclusive technology dissemination. Sustainable outcomes hinge on closing the yield gap through site-specific nutrient management attuned to local soil conditions, rainfall variability, and production potential. ISFM—which combines the judicious use of organic and inorganic resources with sorghum–legume rotations and intercropping systems—emerges as a cornerstone for building resilient farming systems. Affordable innovations such as fertilizer microdosing, seed dressing, and small-scale mechanization can further empower smallholders to adopt proven practices that sustain productivity while conserving resources. Equally, CA—through minimum tillage, residue retention, and crop diversification—can reduce soil degradation and improve water use efficiency in the semi-arid landscapes of the Sudan and Northern Guinea Savannas.

Moving forward, research should focus on long-term assessments of intensification pathways, quantifying their cumulative impacts on soil organic matter, nutrient cycling, and ecosystem services. Priority should also be placed on studying soil microbial dynamics, exploring symbiotic interactions that enhance nutrient availability, and breeding climate-resilient sorghum varieties suited to evolving rainfall and temperature regimes. Collaborative, farmer-participatory research platforms are essential to ensure new technologies align with local knowledge and cultural practices. To catalyze widespread adoption, enabling policy frameworks must create an environment favorable to innovation at the farm level. Governments and development partners should promote targeted fertilizer subsidies, efficient seed certification systems, and strengthened extension networks that deliver practical, regionally tailored advice. Secure land tenure arrangements will further encourage long-term soil investment. Finally, establishing a climate information network—integrating local weather stations and digital advisory tools—will support adaptive decision-making across the region. Therefore, by combining participatory science, supportive policy, and integrated soil–crop management, the West African Sudan Savanna can unlock the potential of sorghum-based systems to achieve sustainable intensification that is both ecologically sound and socioeconomically inclusive.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

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