ENGINEERING Agriculture

REVIEW

2026 / Volume 13 / Issue 5 / 26696

Current challenges and prospects of crop production in Ethiopia

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KEYWORDS

Agriculture, crop, Ethiopia, fertilizers, GHG, NUE

HIGHLIGHTS

- Agriculture is a major contributor to gross domestic product in Ethiopia.
- Agroecological diversity supports a wide range of crops.
- Crop productivity is low for several reasons including a shortage of nutrient input.
- Agriculture is a major greenhouse gas source requiring mitigation.
- Sustainable agricultural practices have been launched.

Received November 2, 2025;
Accepted February 22, 2026.

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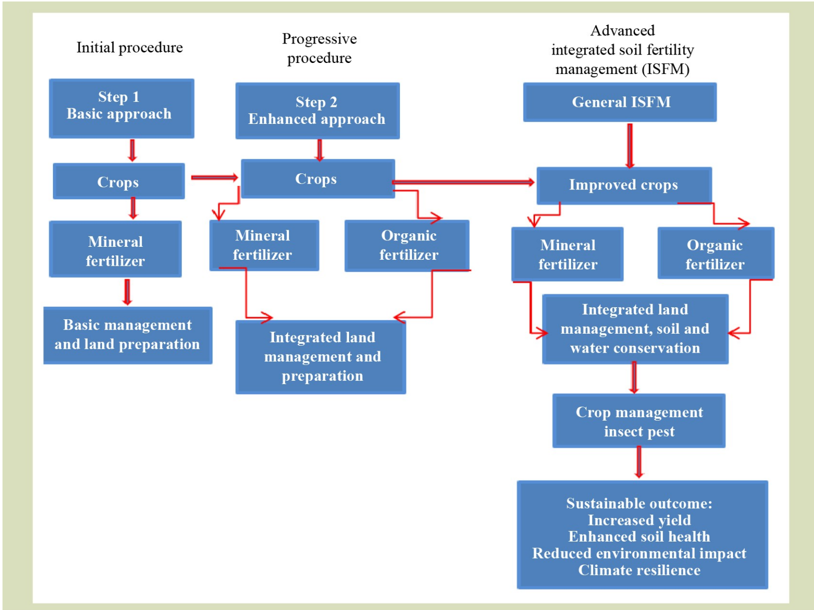
GRAPHICAL ABSTRACT



ABSTRACT

Agriculture is a major contributor to Ethiopia's economy, supporting the livelihoods of over 80% of the population and contributing about a third of the national gross domestic product. Despite this central role, crop productivity remains constrained by climate variability, soil degradation, suboptimal agronomic practices, emerging pests, and limited extension services. This overview examines key opportunities and challenges for sustainable intensification of Ethiopia's rainfed cropping systems, which cover about 60% of the country's land area but are only cultivated at 33% of its potential capacity. The main opportunities stem from several factors. First, agroecological diversity supports a wide variety of crops. Second, there is consensus on mitigating greenhouse gas emissions. Third, sustainable farming practices have been introduced. Before applying any fertilizer, a comprehensive soil test and analysis are crucial to determine site-specific nutrient requirements, which guide appropriate application according to the 4R (right amount, right product, right time, and right place) principles. Therefore, combining organic and mineral fertilizers in nutrient management is important for enhancing crop yield and quality, improving soil health, reducing fertilizer costs, and minimizing environmental pollution. Such measures are also key to improving nitrogen use efficiency. Further research should focus on both mineral and organic fertilizers in nutrient management to increase crop productivity, improve soil health, mitigate greenhouse gas emissions, and use water and nutrient resources sustainably.

1 Introduction

Agriculture is a major contributor of the global economy[1], serving as a primary driver of economic growth, livelihoods, and human welfare worldwide. It provides the main opportunities, engaging over 40% of the global labor force, especially in developing countries[2]. For instance, in sub-Saharan Africa, over 85% of the population depends on the sector for their livelihood, including over 1 billion smallholders and landless laborers[3]. Agriculture has a key role in Ethiopia's economy by generating employment (66%–70%), income, and food security[4], and by significantly boosting its gross domestic product (GDP)[5].

Small-scale farms are a substantive component of Ethiopian agriculture, accounting for about 95% of production and 85% of employment[6]. Crop and livestock production account for about 65% and 25% of the national agricultural GDP, respectively[7]. In 2024, the main agricultural season delivered a surge in major crop harvests, with production totaling 51 Mt, compared with 31.5 Mt during the same period in 2023. Similarly, horticulture production rose from 12.3 to 43.0 Mt in 2023 and 2024, respectively[8]. The growth rates of the three major economic sectors in Ethiopia[9] are shown in Fig. 1. Crop productivity is improving through better input supply and management techniques, as well as modern irrigation management[7]. Nevertheless, crop production and productivity are affected by multiple factors. The major factors are poor soil fertility, high costs of mineral fertilizers, and inadequate technology transfer and market linkages[10]. Crop production sustainability is also intertwined with climate change, newly introduced pests, and inadequate cropping systems. Due to rapid population growth[11,12], these challenges ultimately reduce productivity and adversely affect the environment and human health[5].

Global fertilizer market challenges are closely tied to local issues, such as war and high costs, that affect small-scale farms[13]. The Russia-Ukraine conflict has sharply raised mineral fertilizer prices by over 200% and reduced crop yields and food supplies[13]. In Ethiopia, this price surge caused a more than 10% reduction in mineral fertilizer supply in 2023 compared to 2022 (25% below target), while demand was 30% higher than supply[5]. In response to reduced supply, the agricultural trading corporation nearly doubled its spending to 1.1 billion USD (up from 0.6 billion USD in 2022) to offset the shortfall. As a result, yields dropped, mineral fertilizer use fell by 10%, and key impacts included a 20% reduction in productivity, reduced crop quality, and decreased export revenue[14]. Households produced less grain, driving Ethiopia to import an additional 1 Mt [7]. The objective of this overview is to assess the current challenges and prospects of crop production systems in Ethiopia.

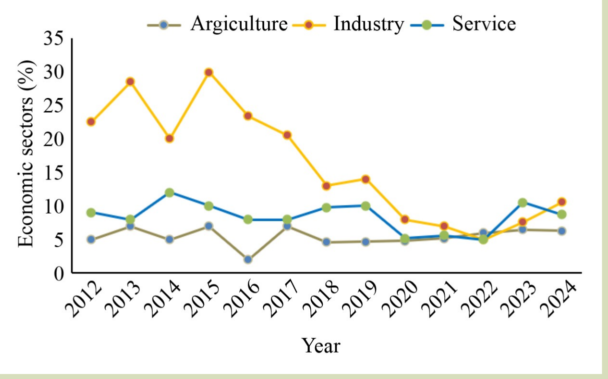


Fig. 1 Growth rate in economic sectors in Ethiopia.

2 Methodology

This review covers the current challenges and prospects of crop production in Ethiopia. Articles were collected from multiple academic databases (Scopus, ScienceDirect, ResearchGate, Google Scholar, and MDPI) and policy papers. Articles were found using keywords to capture a scope of relevant literature, with a focus on crop production challenges, prospects, and sustainable agricultural practices in the Ethiopian context. Inclusion criteria were: geographic focus on Ethiopia, sectoral focus, thematic scope, current challenges and prospects of crop production, including sustainable practices, and a time frame from 2001–2025. Exclusion criteria were: non-crop agricultural sectors, other countries, and purely economic studies. Two hundred papers were initially selected. Of these, 60 were duplicates, 40 were outside the scope, and 11 were in local languages. Finally, 90 were included for review: 50 journal articles, 24 reports, 12 policies, and four proceedings.

3 Challenges of crop production in Ethiopia

3.1 Climate change

Ethiopia lies within the lowlands of the Horn of Africa and the Great Rift Valley, making it vulnerable to climate hazards. Also, population growth, deforestation, overgrazing, and poor farming practices worsen this vulnerability[15]. From 1974 to 2016, the rural population almost tripled, putting greater pressure on land and depleting natural resources[16]. As a result, degrading land use and resource loss have occurred. In addition, most farmers work on plots smaller than 0.5 ha, limiting their ability to adapt. Many also depend on long-cycle crops that take several seasons to grow, keeping the system fragile[17].

Over 85% of the country relies on agriculture for its livelihood, making it highly vulnerable to environmental and agricultural crises[15]. Climate and rainfall variability primarily affect rural food security[18]. In 1984, a drought led to severe famine and the spread of various diseases[19]. Climate change increases pest prevalence and lowers crop yields[20]. High rainfall washes away 50% to 70% more soil in key areas, reducing arable land and shortening growing seasons[21].

In 2024, heavy rainfall in southern Ethiopia, particularly in Gofa and Wolayita, triggered landslides that killed over 270 people and displaced 15,300 others[22]. Similarly, projected rainfall declines for 2050 threaten to reduce agricultural output by over 6%. Additionally, ongoing climate problems and economic challenges have reduced usable farmland, increasing community reliance on food aid and heightening risks to food security and ecosystems[21]. Consequently, over 20 million people are currently affected by food shortages[22]. Climate change may be addressed through drought-tolerant cultivars, farmer-to-farmer training, improved forecasting, real-time rainfall and landslide monitoring for early warning, and soil and water conservation. This situation highlights the need for implementing enhanced land management, agroforestry, soil and water conservation, and forecast-based weather monitoring.

3.2 Deforestation

Ethiopia is undergoing significant land-use transformations driven by population growth, urbanization, livestock grazing, dam and reservoir construction, and habitat fragmentation. Additionally, most of the rural population relies on firewood due to limited access to electricity[23]. The main negative consequences of deforestation include biodiversity loss, climate change, soil degradation, and socioeconomic and environmental impacts[24]. Based on these factors, solutions need to be proposed that promote the green legacy initiative, reforestation, and public awareness of forest protection.

3.3 Nutrient depletion of agricultural soil

Soil nutrient depletion is a key factor in crop production in Ethiopia[25]. Soil depletion is exacerbated by population pressure, high erosion rates, the removal of biomass and manure from farms, overgrazing, deforestation, and insufficient nutrient replenishment[26]. Similarly, limited crop diversification and a lack of climate-smart agricultural practices are challenges[8,25,27,28]. Continuous cultivation of mountainous plots in the central and southern parts of Ethiopia results in severe losses of nitrogen, phosphorus, and potassium[26].

Multiple underlying mechanisms, including population growth, high crop offtake, insufficient nutrient replenishment, severe soil erosion, and the expansion of arable land for cultivation, drive soil depletion[29]. Natural resource degradation trends have also been observed in Ethiopia[30]. Fine clay and silt particles are highly erodible, significantly accelerating nutrient losses[31,32]. One study[33] on watersheds reported severe annual losses of primary nutrients, particularly nitrogen and phosphorus (Fig. 2). The rate of agricultural soil degradation is estimated at 40–130 $t \cdot ha^{-1} \cdot yr^{-1}$, greatly surpassing both the global average of 17 and the African average of 23 $t \cdot ha^{-1} \cdot yr^{-1}$[34,35].

Negative consequences of soil depletion include decreased grain yields, climate change, and desertification. These problems ultimately lead to socioeconomic crises, including biodiversity loss and increased poverty[36]. Nearly half of agricultural land is unsuitable for crop production due to various factors, such as acidity, heavy clay, infertile soils, coarse texture with poor water retention in semiarid areas, and high alkalinity in eastern and southern regions[37]. Poor soil quality reduces crop yields, resulting in annual grain losses exceeding 1 Mt[38]. These findings support the value of recommendations to promote integrated soil fertility management (ISFM), conservation agriculture, fertilizer subsidies, and adherence to 4R principles to restore soil fertility.

3.4 Environmental pollution

Agricultural activities are the main contributors to environmental pollution. Population growth, expanding agricultural activities, and a lack of sustainable technologies drive this pollution. Meeting population food demands leads to the overuse of synthetic fertilizers and pesticides, as well as deforestation[39]. Agriculture remains the primary source of greenhouse gas (GHG) emissions, with crop farming, forestry, and energy as minor contributors[40,41].

Environmental pollution across the agriculture, mining, and rangeland sectors has led to higher GHG emissions[40,42]. The most significant sources of emissions are rumen fermentation, manure management, and savanna burning in Fig. 3[43]. Livestock contribute over half of agricultural emissions, mainly through enteric fermentation, manure management, and related soil emissions from decomposing excreta[44]. Also, only 0.1% of pesticides sprayed on crops reach the intended target pests; the vast majority, 99.9%, pollute the environment. Industrial wastewater releases chemicals and heavy metals into water bodies, harming aquatic ecosystems. It also reduces water usability, contributes to health issues, reduces labor productivity, and potentially reduces food security. Most people also use biomass fuels, such as wood and crop residues, which emit greenhouse gases, PM10, and CO_2, leading to respiratory health problems and environmental pollution[45].

Negative consequences of agriculture and land-use change account for 80% of domestic GHG emissions. These emissions drive erratic weather, including unpredictable rainfall, frequent flooding, and droughts, which, in turn, cause severe societal impacts[46]. Greenhouse gas emissions and agricultural activities also pollute the environment. Burning biomass emits harmful pollutants that degrade air and water quality and harm living organisms and ecosystems[47]. For example, smoke from biomass fuels causes indoor air pollution, leading to 60000 deaths annually and contributing to 5% of Ethiopia's disease burden[48]. This air pollution also causes an estimated

Fig. 2 Agricultural land degradation by soil erosion (Beyene SH, 11:30 A.M, September 20, 2025).

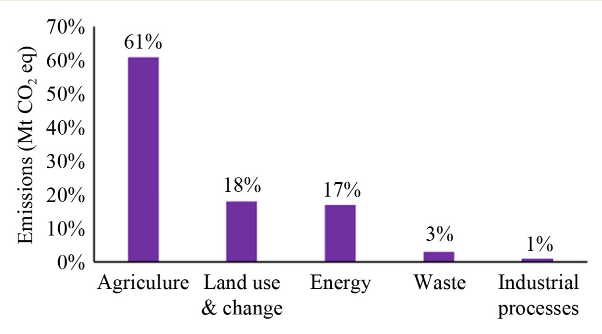


Fig. 3 Ethiopia's greenhouse gas emissions by sector and percent of total emissions.

economic loss of 8 billion USD·yr^{-1}[49]. In response, policymakers implement mitigation strategies, such as promoting waste recycling and providing awareness training, to protect the environment.

3.5 Poor crop management practices

The primary causes of low crop yields include improper land preparation, untimely sowing, limited fertilizer use, incorrect seed rates, pests, and inadequate irrigation[50]. Watershed degradation, limited funding, and limited extension services also reduce the effectiveness of small and medium-scale irrigation schemes. As a result, these schemes reach only about half of their intended beneficiaries[51]. Shapley values (Fig. 4) showed the yield was lower due to frequent tillage and late planting, particularly in waterlogged soil. For wheat, higher N application rates strongly increased predicted yield. The effects of other management practices were minimal[52].

Significant barriers to crop management strategies include farmland size, agroecological conditions, farmland location, and limited access to financial services[53]. Poor crop management leads to soil erosion, inadequate residue incorporation, reduced soil fertility and crop yields, and heightened food insecurity[54]. These findings suggest that policymakers should strengthen and promote improved crop management practices and subsidize farm inputs.

3.6 Occurrences of new pests

Crop diseases and insect pests are the main challenges to crop production in Ethiopia. Over 400 diseases and insect pests have been identified, and 20% of them cause significant economic losses. Although a substantial proportion of Ethiopian crop producers (< 70%) recognize pest problems and associated crop loss symptoms[55]. Insect and pest infestations during the dry period cause significant damage and yield loss in vegetable crop production. A lack of knowledge and integrated alternatives drives the excessive application of pesticides, which reduces their efficacy, diminishes crop yields, and causes environmental damage. Based on these findings, it is proposed that implement integrated pest management (IPM), use resistant cultivars, and conduct awareness training.

3.7 Limited knowledge, technology transfer and market access

The dissemination of new technologies, knowledge, and information from relevant offices to farmers and stakeholders remains limited nationwide. Although agricultural extension officers understand customized nutrient recommendations, they lack information about how they were developed and who is responsible. As a result, farmers often remain unaware of key issues due to ineffective dissemination of soil management information. Private companies and cooperative farmer unions involved in distributing new technologies face similar challenges. Another issue is the prevalence of informal local markets, where unequal information enables traders to capture more of the value, leaving producers with lower returns[56].

A barrier to technology dissemination is limited access to financial services. Low-income farmers often cannot secure loans because of strict requirements[57]. Weak infrastructure limits market access, and more than 85% have no year-round road access, raising transport costs and postharvest losses[58]. Policymakers should connect farmers with financial services and markets.

4 Prospects of crop production in Ethiopia

4.1 Agroecological diversity

Ethiopia's agroecology varies with altitude and from tropical to temperate climates, and is subject to typical seasonal and temperature variations. The Ethiopian Rift Valley, a plateau over 600 km long extending from Kenya to Oromia's East Showa zone, has unique agroecological, social, and cultural

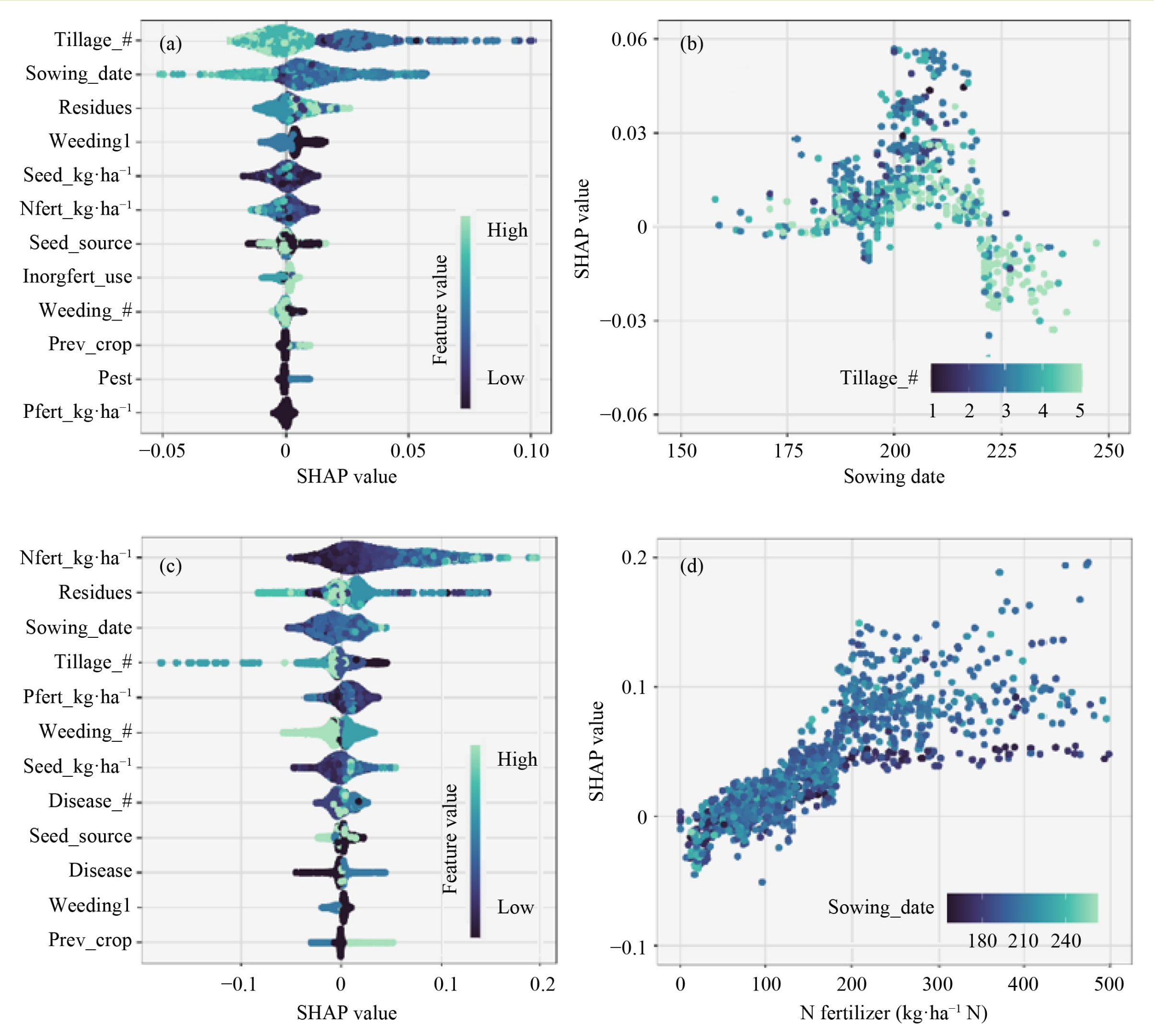


Fig. 4 Shapley additive explanation values for teff (*Eragrostis tef*) (a, b) and wheat (*Triticum aestivum* and *T. durum*) (c, d) in Ethiopia.

diversity. This diversity supports rich biodiversity and makes the area a center for crop domestication and genetic diversity.

Global agroecological zones are defined by growing-season length[59]. The Ethiopian Ministry of Agriculture divides the country into 33 agroecological zones, with about half the land classified as dry to sub-wet and the rest as wet to humid[60]. The three main agricultural agroecological zones are Kolla (lowlands), Woina-Dega (mid to highlands), and Dega (highlands). Kolla (< 1500 masl): the main crops are drought-tolerant, including sorghum, finger millet, sesame, cowpeas, and groundnuts. Where irrigation is available, farmers also grow cash crops, including cotton, sugarcane, and horticultural crops. Woina-Dega (1500–2300 masl): a wide variety of cereals and legume crops (maize, wheat, teff, pulses, and coffee). Dega (> 2300 masl): barley and wheat. Fertilizer recommendations vary based on local soil and environmental conditions. For example, in ISFM optimal ratio is a blend of equal parts organic and mineral fertilizers[61]. Crop production data for the country from 2019 to 2023 are shown in Fig. 5.

4.2 Conservation agriculture

Sustainable agricultural systems that integrate diverse

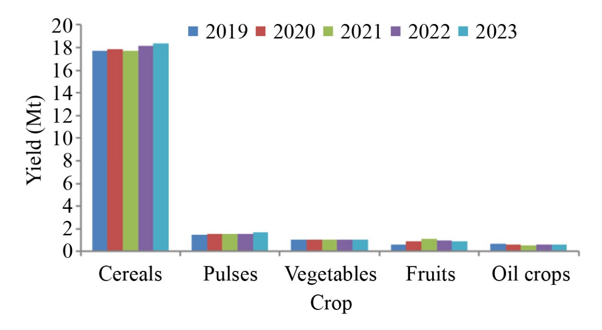


Fig. 5 Crop production data in Ethiopia from 2019 to 2023.

production practices are characterized by resource conservation, environmental friendliness, technical suitability, and socioeconomic feasibility[62]. These systems produce a variety of crops through diversification, combining pulses with cereal crops to create a varied diet for the soil microbiome. This, in turn, supports atmospheric nitrogen fixation and the conversion of unavailable nutrients into forms that plants can use[38] (Fig. 6). Sustainable farming also uses zero tillage, keeps soil covered, and rotates crops. These steps help protect natural resources and build up soil organic matter[63].

In the dry regions of Ethiopia, reduced tillage and crop residue retention can improve soil water storage, thereby increasing grain and straw yields. For example, in one dry area of Ethiopia, incorporating 3 $t \cdot ha^{-1}$ of teff straw resulted in more than a 60% increase in sorghum grain yield under tillage used by oxen and a 46% increase under no-till farming[64]. Similarly, reduced plasticulture improves maize yield[65]; shallow straw incorporation enhances soil hydrothermal conditions and increases maize yield[66]; and optimized ridge-furrow size/ratio increases rainfed wheat yield[67]. The main barriers to the adoption of conservation agriculture are a lack of education, limited credit, a lack of market access, and policy implementation. These findings indicate that policymakers link and provide financing and incentives for farmers.

Fig. 6 Sustainable techniques, intercropping, and improved soil (CIMMYT).

4.3 Integrated soil fertility management

Integrated soil fertility management (ISFM) is a holistic soil fertility management approach that integrates locally adopted technologies to enhance soil fertility and increase grain yield[68]. The core elements of ISFM include combinations of organic and mineral fertilizers, and newly released crop cultivars[69]. This combination must be customized to local contexts and enhanced agronomic techniques[68]. ISFM is essential in sustainable crop production by improving water retention, soil cover, and GHG mitigation[70]. The adoption of ISFM strategies is influenced by several factors, including socioeconomic, institutional, farm-specific, education level, family member, farming experience, training, extension, and financial services, all of which significantly encourage ISFM adoption[71]. In contrast, adoption rates are negatively associated with older household heads, far field distances, and steeper farmland slopes[72].

Using mineral and locally sourced organic materials and leaving crop residue in fields helps plants use nutrients more effectively and keeps soil healthy[73,74]. Also, organic fertilizers are less costly and last longer than mineral fertilizers[2,75]. Given these benefits, more farmers are adopting eco-friendly, regenerative farming methods[76] (Fig. 7). ISFM is matched to

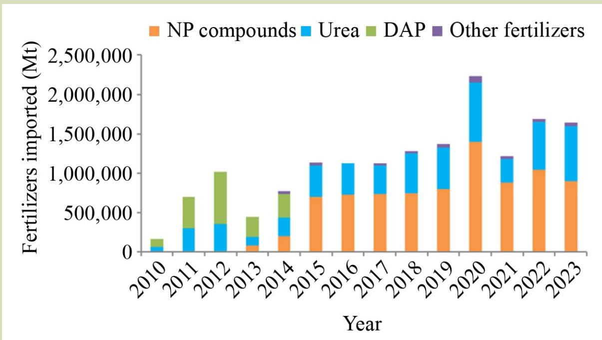


Fig. 7 Composition of Ethiopian fertilizers imported from 2010 to 2023.

local climate, soil, resources, and community knowledge to help farmers use it well. For example, in wetter areas, ISFM can boost family incomes, improve food before harvest, and help keep children in school. In drier areas, gains are smaller, and families may have less time for other work because farming takes longer[68]. ISFM refers to gradually mixing organic and mineral fertilizers with new crops, which helps farmers learn and improve[77] (Fig. 8). For example, in the central area of Ethiopia, using N+P and organic fertilizers raised SOC by about 0.5%[78] and gave higher maize yields than N + P alone[79].

4.4 4R nutrient management

The 4R nutrient management framework promotes sustainable crop intensification. It is guided by four principles: the right nutrient source, rate, place, and time. The 4R principles are critical where nutrient use is low or unbalanced, or where soils are deficient. Ethiopia is still adopting 4R nutrient management, but government-led programs are now actively promoting it. For example, a national initiative collected and analyzed over 100,000 soil samples from all agricultural kebeles (the smallest administrative unit of Ethiopia), generating detailed soil fertility maps and regional fertilizer guidelines. These data now guide national policy and actions on fertilizer use, land management, and crop selection, with specific recommendations[80].

4.5 Mitigation of climate change

Ethiopia's 10-year economic plan (2021–2030) targets agriculture and 6.2% annual growth. The plan aims to protect

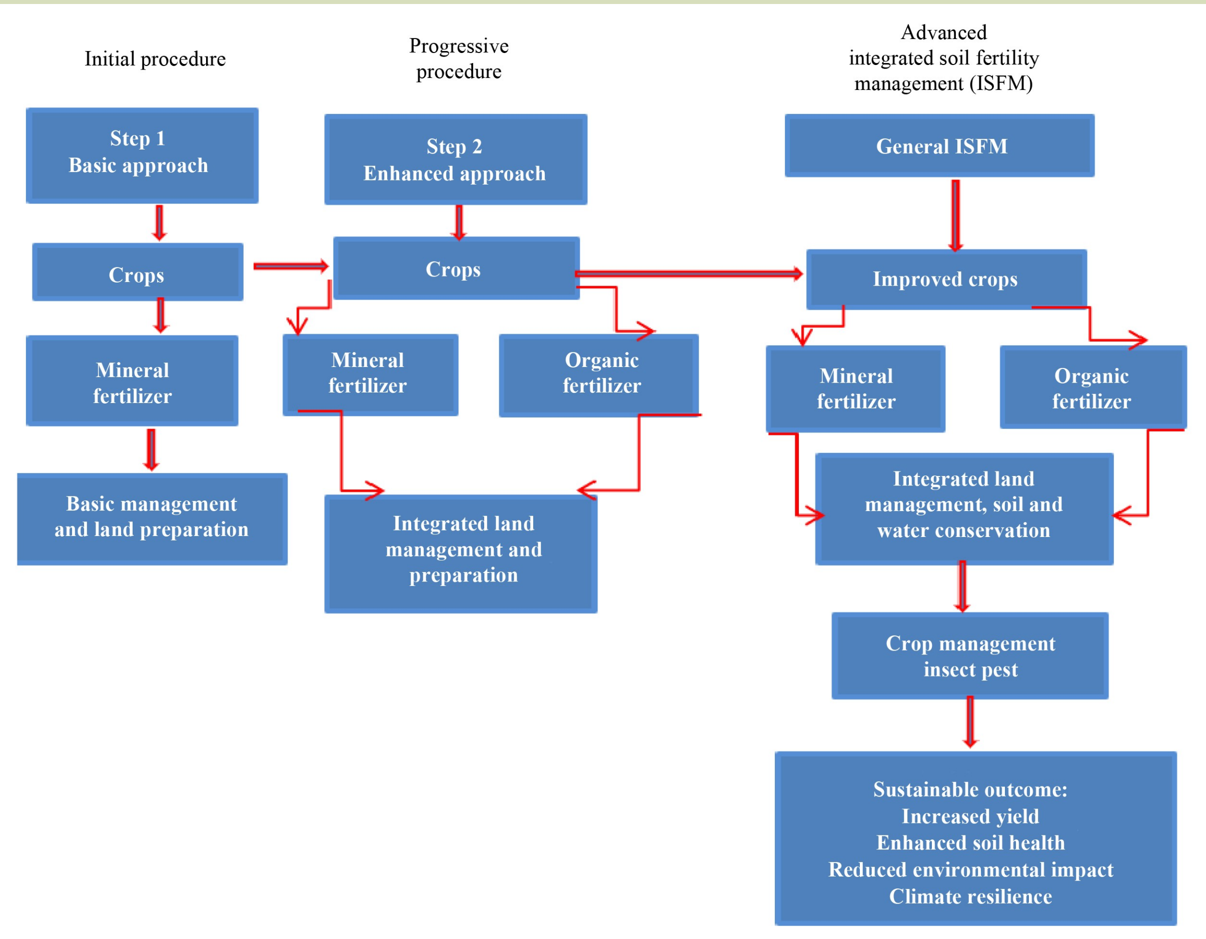


Fig. 8 Integrated soil fertility management procedures.

soil, cut greenhouse gas emissions, and conserve forests[81]. In 2010, emissions were 247 Mt CO_2 eq (Fig. 9). If current practices continue, levels could rise to 404 Mt CO_2 eq. An unconditional approach would reduce emissions to 347 Mt CO_2 eq by 2030, a 14% drop. With additional measures, emissions could fall to 126 Mt CO_2 eq[82]. The intended nationally determined contributions for Ethiopia commit to keeping GHG emissions at 145 Mt CO_2 eq over 5 years, a 64% cut from projected levels. Figure 10 shows proposed sectoral cuts: 90 Mt CO_2 eq. for agriculture, 130 for forestry, 20 for industries, 10 for transport, and 5 for construction.

The country adapts to climate change through a climate-resilient green economy strategy[27]. These actions protect people, the environment, and the economy from climate risks. Climate-smart farming methods include conservation agriculture (crop rotation and cereal-legume intercropping), integrated soil fertility management, agroforestry, and water

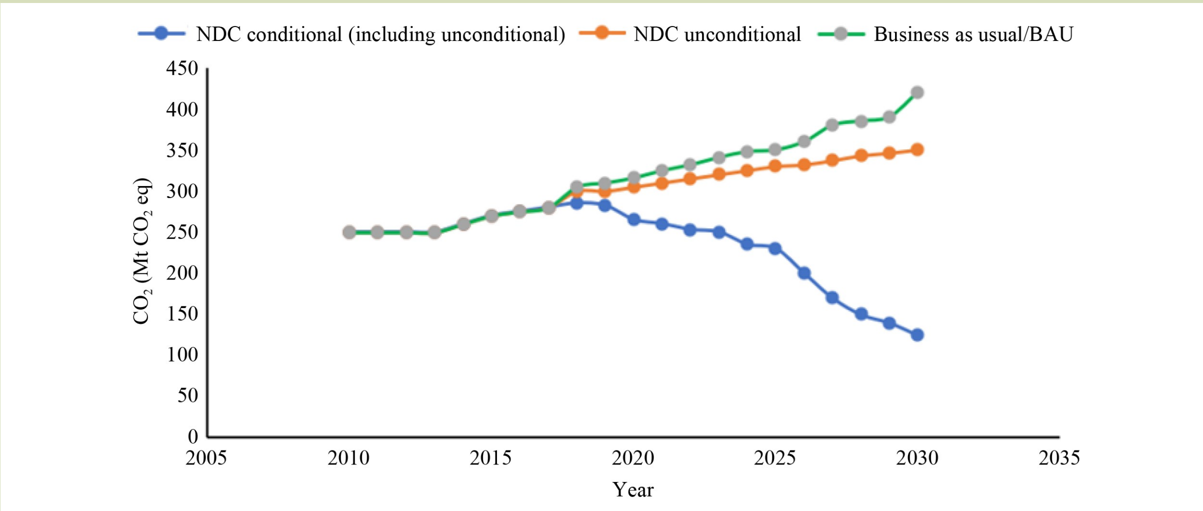


Fig. 9 Ethiopia's nationally determined contributions (NDC) for carbon emissions in three pathways: business-as-usual, unconditional NDC and conditional NDC.

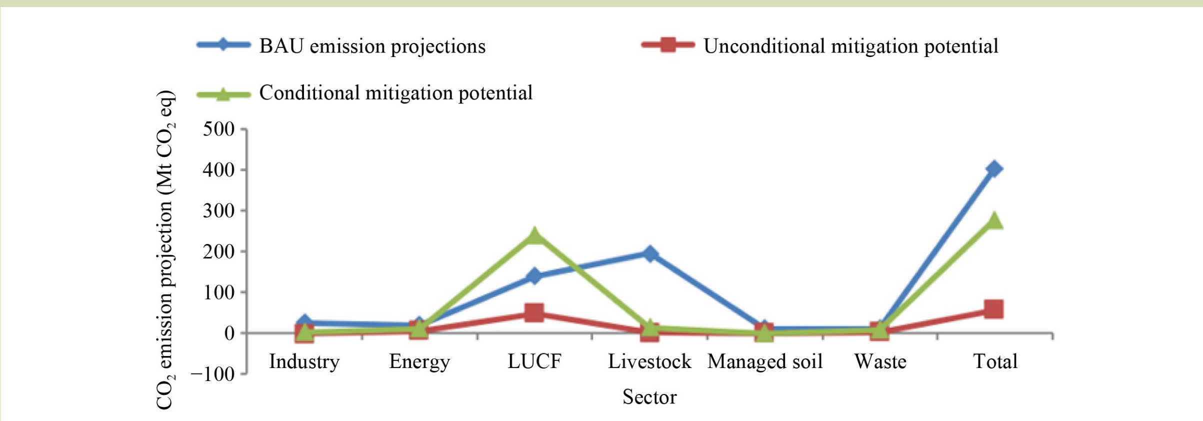


Fig. 10 Sectoral emission: land-use change and forestry (LUCF) and mitigation by sector for 2030 for in three pathways: business-as-usual (BAU), unconditional nationally determined contributions (NDC) and conditional NDC.

harvesting[83] (Table 1). The strategy boosts climate resilience, lowers emissions, increases grain and livestock production using accessible technologies, improves food security, strengthens farmer livelihoods, and reduces emissions. The green legacy initiative of Ethiopia intends to plant over 7.5 billion trees by 2025 to capture carbon and enhance the environment[43].

4.6 Green legacy initiatives

The Ethiopian Government launched its green legacy initiative in 2019 to address several environmental challenges. This program aims to plant one million tree seedlings each year. Its main goals are to increase green spaces, restore degraded land, and engage the public in reforestation. This initiative has improved Ethiopia's environmental reputation[9,84]. Now, both the government and communities focus on sustainable land management, introducing terracing, agroforestry, and soil restoration to help secure food for the growing population[20]. This initiative also supports biodiversity by planting a variety of native and fruit trees[85]. Over 32 billion seedlings have been planted so far, with a target of 50 billion by 2030. It has created over 700,000 jobs in nursery management, seedling preparation, agroforestry, and sustainable land management across Ethiopia[86].

4.7 Leveraging large labor

In sub-Saharan Africa, 75% of people work in agriculture, directly or indirectly[87]. Similarly, in Ethiopia, which has the largest share of agricultural laborers, estimated at 80%[87,88]. Sixty percent of Ethiopians are under 30, creating a young, growing workforce. The government taps this workforce by building industrial parks. These parks attract foreign investors and focus on employment, foreign exchange, and sustainable production[89].

4.8 Policy and institutional support

National policies and institutional mechanisms support Ethiopia's crop production system through an integrated framework that aims to achieve food security, economic growth, and environmental sustainability. The major agricultural policy frameworks are agricultural development-led industrialization (ADLI), growth and transformation plan (GTP-I and II), and homegrown economic reform agenda (HGERA).

Agricultural development-led industrialization (ADLI) emphasizes increasing crop productivity, promoting crop diversification, shifting to a market-based system, and ensuring food security. GTP- I and II focused on smallholder production and productivity, thereby increasing the contribution of the sector to the economy and stabilizing the macro-economy. HGERA emphasizes modernizing agriculture by adopting new technologies, improving irrigation systems, expanding market access for farmers, and attracting large-scale agribusiness investors. To ensure increased productivity and build resilience to climate shocks and other challenges[90].

The institutional support framework supports crop production, including research and extension, crop insurance, the

Table 1 Climate-smart agricultural (CSA) practices adopted in Ethiopia

Climate smart agriculture practice	Component	Climate-smart agricultural practice
Integrated soil fertility management	• Combination of organic and mineral fertilizers, and new cultivars • Reduced/zero tillage • Crop diversification • Cover crops	• Enhanced soil health • Improved yield • Minimize greenhouse gas emissions • Climate resilience
Small-scale irrigation	• Efficient irrigation techniques • Affordable	• Improved crop yield
Agroforestry	• Tree-based conservation practices • Farmer plants and manages indigenous and fruit trees	• Enhance soil fertility • Stores a huge amount of CO_2 • Increased yield • Climate resilience
Crop diversification	• Give high yield, • Minimize insect pest pressure • Escape harsh conditions	• Enhanced soil health • Improve livelihood and income • Climate resilience

agriculture growth programme, and integrated industrial parks. Research and extension play a vital role in developing improved technologies and demonstrate on farmer fields. Crop insurance is a subsidy on risk management for farmers, protecting them from natural disasters and crop failure. Agriculture growth programme: It helps farmers and their service providers expand best practices and use improved technologies. Also, supporting small-scale rural infrastructure development and management, such as building and maintaining facilities. Integrated industrial parks are linking farmers to industry in order to enhance farmer income, reduce post-harvest losses, create job opportunities, and improve market access for rural communities. These actions aim to increase key value chain productivity and efficiency by improving market access (Fig. 11).

5 Conclusions, future directions, and recommendations

Agriculture has been the backbone of the national economy, supporting most people and contributing significantly to GDP. There are many opportunities for crop production, including

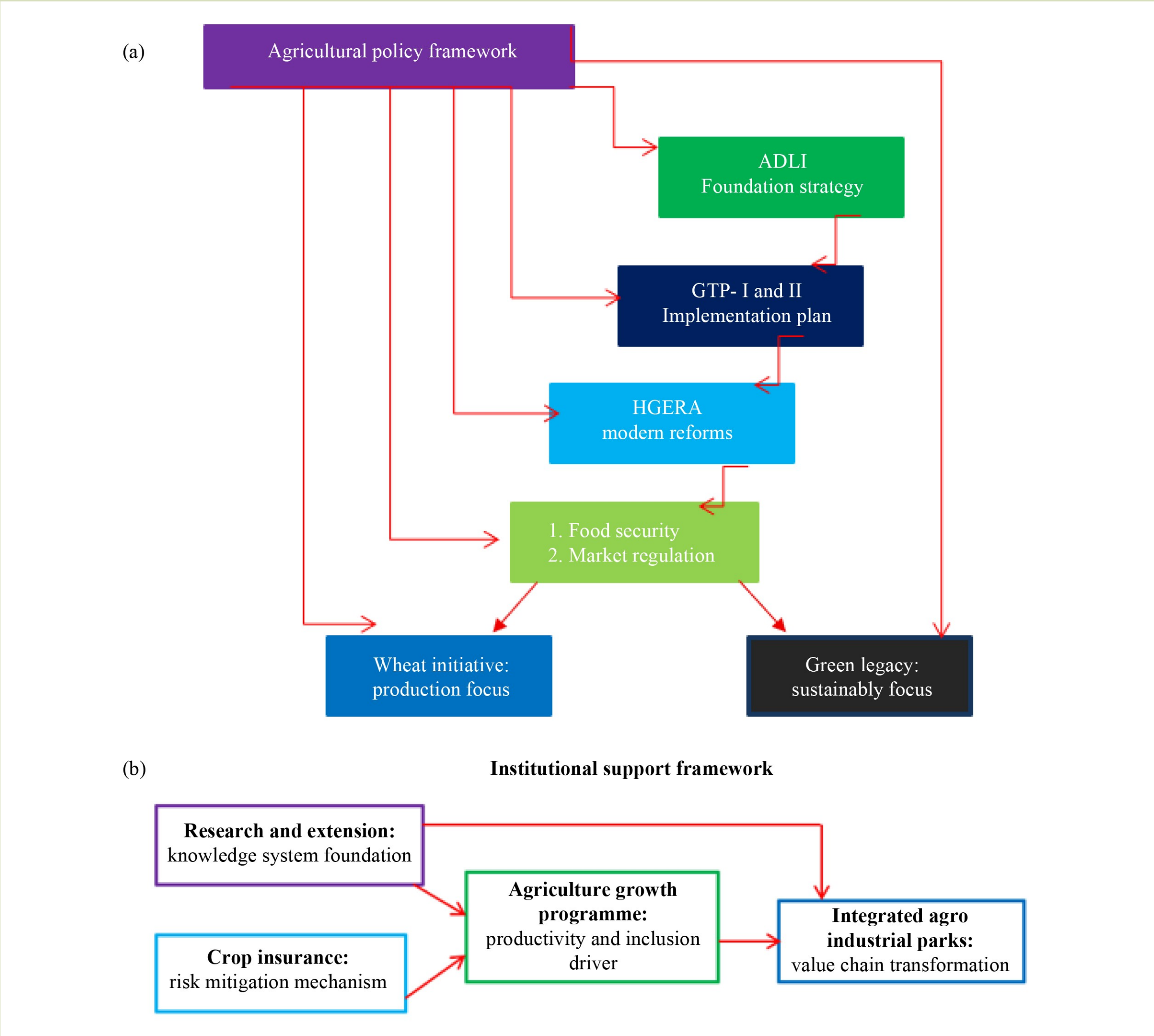


Fig. 11 Agricultural policy framework (a) and institutional support framework (b) for crops production.

diverse growing conditions, improved soil management, a young workforce, and national programs such as the green legacy initiatives and climate-resilient strategies. However, crop productivity remains low, constrained by several challenges, including population growth pressure, soil depletion, climate change, environmental pollution, deforestation, poor agricultural practices, the emergence of new pests, and limited technology transfer and market access. These constraints are the main barriers to future crop production needed to feed the country's growing population.

Future directions should focus on ISFM, guided by robust soil testing and digital mapping, and on applying the 4R nutrient principles. Before applying any fertilizer, a comprehensive soil test and analysis are crucial to determine site-specific nutrient requirements. Integrating organic and mineral fertilizer management is essential for enhancing soil fertility, improving productivity, reducing fertilizer costs, and minimizing pollution. Also, strengthen climate-smart agriculture by using drought-resistant crops, conservation agriculture, and efficient irrigation. Promote sustainable pest management, and use digital tools to strengthen extension services and link smallholders to markets. These measures are also key to improving nitrogen use efficiency and crop productivity, as well as mitigating greenhouse gas emissions.

This study underpins three important recommendations.
(1) Government and development stakeholders should collect soil data through digital mapping and deliver soil information to farmers through digital advisory services.
(2) Policymakers should strengthen the implementation of ISFM and adhere to 4R principles.
(3) They should be a strengthening of initiatives such as the green legacy initiatives, climate-smart resilience, and conservation agriculture, as these are crucial for boosting productivity and sustainability.

Acknowledgements

This paper was funded by the China Scholarship Council and the National Key Research and Development Program of China (2023YFD1900600).

Compliance with ethics guidelines

Melkamu Hinsermu and Xuejun Liu declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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