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RESEARCH ARTICLE

Agrifood system carbon emissions and reduction policy: insights from China and Africa

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KEYWORDS

Agrifood systems, carbon emissions, China-Africa comparison, low-carbon transition

HIGHLIGHTS

- China and Africa contribute 32% of global agricultural emissions with distinct pathways.
- China's emissions have shifted to pre- and post-production, while Africa's remain production-based.
- Africa's emissions are driven by land-use changes and show significant regional disparities.
- China's low-carbon practices offer lessons for Africa's agricultural transformation.
- Sino-African cooperation can model sustainable agrifood systems globally.

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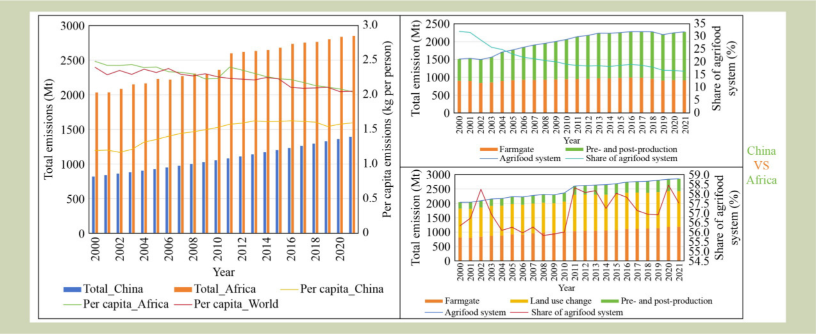
GRAPHICAL ABSTRACT



ABSTRACT

Amid climate change and food security challenges, transforming agricultural systems in middle- and low-income countries is crucial for carbon neutrality and sustainable development. China and Africa, responsible for 32% of global agricultural emissions, share agricultural similarities despite different development stages. China's modernization efforts offer valuable insights for Africa, highlighting opportunities for increased Sino-African cooperation. This study, analyzing FAO data from 2000 to 2021, compares emission trends, sources, inputs, and mitigation policies in China and Africa. It reveals that Africa's emissions remained consistently higher than China's, which grew faster compared to Africa's 40% increase. Notably, Africa shows regional disparities in emissions, with the highest increases in East and Central Africa (56% and 54%, respectively), while North and South Africa show slower growth. Structurally, China's emissions have transitioned from production to pre- and post-production stages. Conversely, Africa's emissions mainly stem from agricultural production (42%) and land-use changes (43%), emphasizing challenges in resource management and reliance on land expansion. The rapid growth of Africa's pre- and post-production emissions highlights the supply chain's growing role in emissions, with regional variations, such as livestock and rice cultivation driving emissions in East and West Africa, and land-use changes in Central Africa. China and Africa's agricultural policies differ significantly. China adopts multi-objective policies promoting green, low-carbon development, whereas Africa focuses on short-term yield increases with heavy reliance on fertilizers, conflicting with low-carbon objectives.

Learning from China could help Africa balance food security, income stability, and environmental sustainability, providing a pathway to achieve both food security and carbon reduction.

1 Introduction

As global climate change intensifies and food security issues become more pressing, the agrifood system, as one of the major sources of greenhouse gas emissions, plays a critical role in global carbon reduction strategies. According to the World Bank's 2024 report[1], middle- and low-income countries hold significant potential in advancing emission reduction in agrifood systems. China and Africa, as important representatives among developing countries, have contributed about 32% to global agrifood system carbon emissions due to rapid agricultural production growth and increasing food demand[2,3]. With the continued population growth and rising demand, China and Africa will remain key contributors to global agricultural carbon emissions in the future. Therefore, promoting the green and low-carbon transition of agrifood systems in developing countries is not only crucial for achieving global carbon neutrality but also has far-reaching implications for ensuring food security and promoting sustainable development.

Agrifood systems are widely recognized as a major source of global GHG emissions[4]. Recent research has focused on emission sources, driving factors and evaluations of mitigation policies and technologies. In China, studies have primarily emphasized accounting for carbon emissions, analyzing trends[5,6] and examining the impacts of agricultural modernization, such as the adoption of precision and circular agricultural practices[7]. In contrast, research in Africa has concentrated on the impact of land-use changes on carbon emissions. For example, Wang et al.[8] highlighted a positive correlation between agricultural growth and carbon emissions in Africa and demonstrated the potential of renewable energy deployment to mitigate emissions. Other studies have stressed the critical role of land-use changes, such as deforestation and farmland expansion, particularly in sub-Saharan Africa, where net carbon sinks are transitioning into net carbon sources. However, systematic comparative analyses of agrifood system emissions between China and Africa remain scarce.

China and Africa share notable similarities in agricultural development, especially in their reliance on agriculture for food security and the predominance of small-scale farming (Table 1). In both regions, the majority of farmers cultivate less than 2 ha (97.5% in China and 85.9% in Africa)[9–11]. Historically, China's reliance on a high-input, high-output agricultural model aligns with current practices in Africa, making China's emission reduction experience highly relevant. However, Africa faces unique challenges: it has a higher rural population share and a larger agricultural GDP share, yet lower economic levels (per capita GDP of 1965 USD) limit the promotion of agricultural modernization and low-carbon technologies[12–14].

In recent years, China has achieved remarkable progress in agricultural modernization and low-carbon transformation, particularly through policy guidance, technological innovation

Table 1 Overview of agricultural development in China and Africa (2021)

Indicator	China	Africa
Rural population (million)	536	777
Rural population (% of total)	38	56
GDP per capita (current USD)	12,498	1965
Smallholders (< 2 ha) (% of total)	97.5 (2006 est.)	85.9 (2006 est.)
Agricultural land (% of land area)	55	39
Fertilizer consumption (kg·ha^{-1} of arable land)	375	80.8
Agriculture, value added (% GDP)	7.7	16.0

Note: Data from FAO Database, World Bank Database.

and improved agricultural management. By enhancing production efficiency, reducing the use of chemical fertilizers and pesticides and promoting sustainable agricultural technologies, China has significantly lowered its agricultural carbon footprint. These efforts offer a viable pathway for Africa, especially in addressing challenges related to resource limitations and environmental vulnerability, helping the continent explore low-carbon transition strategies suited to its unique conditions[15]. Similarly, Africa has implemented smart subsidy policies to enhance food security and productivity. Examples include agricultural input subsidy programs in Nigeria and Kenya, as well as collaborative efforts with China to advance mechanization and digital agricultural technologies. Green ecological policies have also been adopted to reduce emissions, such as South Africa's low-emission development strategies and chicken manure-based biogas energy projects. integrated soil fertility management (ISFM) practices have improved soil health, while educational initiatives have raised farmer awareness of sustainable agricultural practices. Also, innovative tools, such as picture-based insurance and weather index insurance, have strengthened the financial resilience of farmers to extreme weather events. These policies and measures, which integrate productivity enhancement, ecological protection, and sustainable development objectives, underscore Africa's efforts and potential in addressing climate change and advancing low-carbon transitions in agriculture.

Despite differences in the stages of agricultural development and low-carbon transitions between China and Africa, China's experience in reducing emissions from its agrifood system offers valuable lessons for Africa. This study compares the similarities and differences between China and Africa in terms of trends in agrifood system carbon emissions, emission sources, agricultural inputs, and emission reduction policies. It further evaluates the applicability of China's experiences to Africa and other developing countries in facilitating low-carbon transitions in agrifood systems and provides targeted policy recommendations.

The structure of this paper is as follows: The first section introduces the study; The second section presents a comparative analysis of the total and intensity of carbon emissions in the agrifood systems of China and Africa; The third section explores the sources of carbon emissions in the agrifood systems of both regions; The fourth section examines differences in emission reduction policies and measures between China and Africa; Finally, the paper concludes with a summary of the main findings and policy recommendations.

2 Overview of carbon emissions from agrifood systems in China and Africa

From 2000 to 2021, total carbon emissions from agrifood systems in China and Africa had a steady upward trend. China's emissions rose from 819 Mt in 2000 to 1.39 Gt in 2021, an increase of about 70%[2]. This rise reflects the expansion of China's agricultural production scale and the growing demand for energy and resources associated with agricultural modernization. Meanwhile, Africa's total carbon emissions increased from 2.03 Gt in 2000 to 2.85 Gt in 2021, a growth of about 40%[16]. Although Africa's growth rate is lower than China's, its total emissions consistently exceed China's, primarily due to a larger scale of agricultural activity especially in East and Central Africa, where agricultural expansion and land-use changes have significantly driven up emissions[17]. Compared to China, Africa has more land resources available for conversion into arable land, yet this also brings heightened carbon emission pressures, particularly from deforestation and land-use changes, making land-use-related emissions a major contributor in Africa[18].

In terms of per capita emissions, China's per capita emissions increased from 1.2 kg in 2000 to 1.6 kg in 2021 (Fig. 1) with a steady upward trend. This indicates that as China advances its agricultural modernization, despite its large population, the carbon emission intensity of agricultural production has risen. Africa presents a different scenario. In 2000, Africa's per capita emissions were as high as 2.4 kg, far exceeding both China's and the global average, and while it decreased to 2.1 kg by 2021, it remains significantly higher than China's and the global

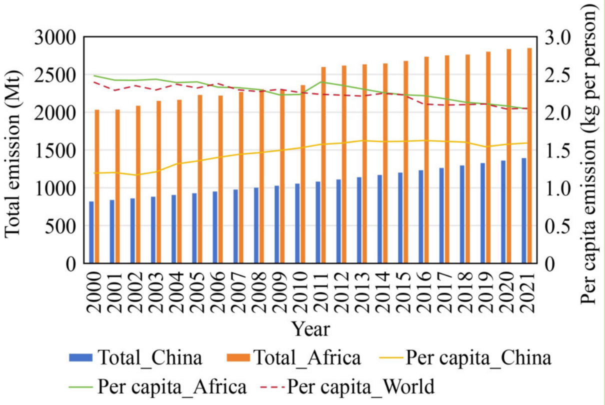


Fig. 1 Total carbon emissions and per capita emissions from the agrifood systems in China and Africa (2000–2021). Per capita carbon emissions correspond to the righthand side *y*-axis.

average. This reflects Africa's high agricultural carbon emission intensity, most likely due to its extensive agricultural activities, widespread use of traditional farming methods, and lower technological levels. Additionally, Africa's carbon emissions are heavily influenced by land-use changes, with large-scale deforestation for farmland conversion being one of the primary sources of emissions.

A comparison of these data reveals that while China's total emissions continue to increase, its per capita emissions are growing at a steadier rate and remain below those of Africa and the global average. This trend suggests that China is gradually controlling carbon emissions per unit of production through agricultural modernization and technological advancements. By promoting low-carbon technologies, such as precision and circular agriculture, China has effectively reduced agricultural emissions while increasing production efficiency. In contrast, Africa's total emissions are rising more slowly, but its per capita emissions remain high, reflecting a reliance on traditional farming methods and limited technological adoption. This also highlights the significant carbon emission pressures Africa faces from extensive land-use practices and related emissions[19].

From a global perspective, average per capita carbon emissions remained around 2.2 kg throughout this period[1]. The per capital emission of China is far below the global per capital while the per capita of Africa and the world are almost at the same level. This disparity underscores significant progress in China toward a low-carbon economy, whereas Africa faces greater challenges in reducing emissions due to extensive land use and agricultural expansion. To enhance agricultural productivity while reducing emissions, Africa must adopt proactive measures to support sustainable development and address climate change[18].

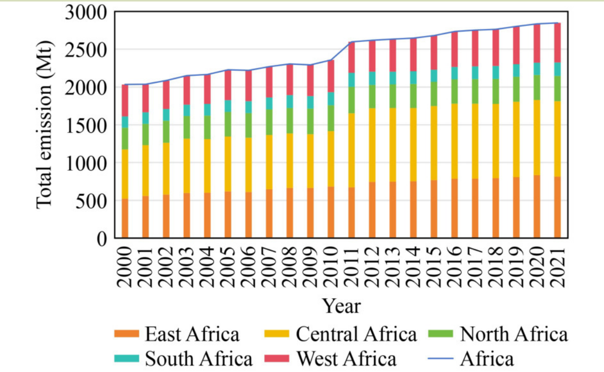


Fig. 2 Total carbon emissions from agrifood systems in different regions of Africa (2000–2021).

Although the overall carbon emissions in Africa have shown an upward trend, there are significant differences in the growth rate and contribution among various regions (Fig. 2). East and Central Africa are the main drivers of carbon emissions growth in Africa. East Africa's carbon emissions increased from 522 Mt in 2000 to 814 Mt in 2021, an increase of about 56%. Central Africa's emissions grew from 651 Mt in 2000 to 1 Gt in 2021, an increase of about 53.5%. The rapid growth of carbon emissions from agrifood systems in East and Central Africa is primarily driven by deforestation for agricultural expansion, livestock production, inefficient use of fertilizers and reliance on traditional farming practices such as slash-and-burn. Population growth and shifting dietary preferences further intensify the pressure on land and water resources, leading to increased emissions from land-use changes and livestock farming. Additionally, food waste, postharvest losses, and the use of fossil fuels in agricultural mechanization and transportation contribute to the region's rising carbon footprint. Addressing these challenges requires the adoption of sustainable farming techniques, better resource management and infrastructure improvements.

In contrast, North and South Africa have experienced slower growth in carbon emissions. North Africa's emissions grew from 288 Mt in 2000 to 333 Mt in 2021, an increase of about 16%, while South Africa's emissions rose from 150 to 179 Mt, or about 19%. This relatively slow growth most likely reflects higher levels of agricultural technology and industrialization in these regions, which reduce reliance on traditional agricultural expansion and effectively help control emissions. Additionally, advanced agricultural management and land-use policies in North and South Africa have further curbed rapid emission growth. West Africa's carbon emissions had a steady growth, increasing from 422 Mt in 2000 to 524 Mt in 2021, a rise of about 24%. Although the increase is less dramatic than in East and Central Africa, West Africa remains a significant contributor to Africa's overall carbon emissions. Dominated by smallholders, West Africa has varying levels of agricultural technology, resulting in relatively stable but uneven growth in carbon emissions. Regional differences in agricultural technology adoption and land management practices are likely to be key factors influencing emission patterns here.

Overall, these regional disparities in Africa's carbon emissions are substantial. East and Central Africa are the primary drivers of emissions growth, while North and South Africa benefit from more advanced agricultural technologies and effective land management policies, leading to slower emission increases. West Africa had steady growth, with significant internal disparities reflecting imbalances in agricultural technology and management practices. These differences underscore the need for region-specific emission reduction policies. Addressing each region’s unique challenges and development stage will be essential to crafting effective, targeted measures to manage and reduce carbon emissions in African agriculture.

3 Analysis of carbon emission sources and driving factors in agrifood systems in China and Africa

3.1 Analysis of carbon emission sources in China’s agrifood system

From an overall perspective, carbon emissions from China’s agrifood system increased by about 50% between 2000 and 2021, as shown in Fig. 3(a), reflecting the expansion of agricultural production and the extension of food system stages (e.g., production, transportation, processing and storage). However, despite this increase, the share of agrifood system emissions in China’s total national carbon emissions declined from 32% in 2000 to 16% in 2021, indicating that with the rapid growth of China’s industrial and energy sectors, agriculture’s relative contribution to national carbon emissions has decreased. Technological advancements and emission reduction measures have also contributed to stabilizing agricultural carbon emissions.

The production stage remains the primary source of carbon emissions in China’s agrifood system. According to Fig. 3(b), production emissions in 2000 were 904 Mt, rising slightly to 917 Mt in 2021. Despite this small increase, the production share in total agrifood emissions dropped significantly from 59.8% to 40.4%, indicating that improved agricultural technology and production efficiency have helped stabilize emissions at this stage. This stability reflects China’s efforts to enhance production efficiency through technologies like precision and circular agriculture[20]. In contrast, carbon emissions from land-use change in China’s agrifood system are extremely low, as depicted in Fig. 3(a), decreasing from 2 kt in

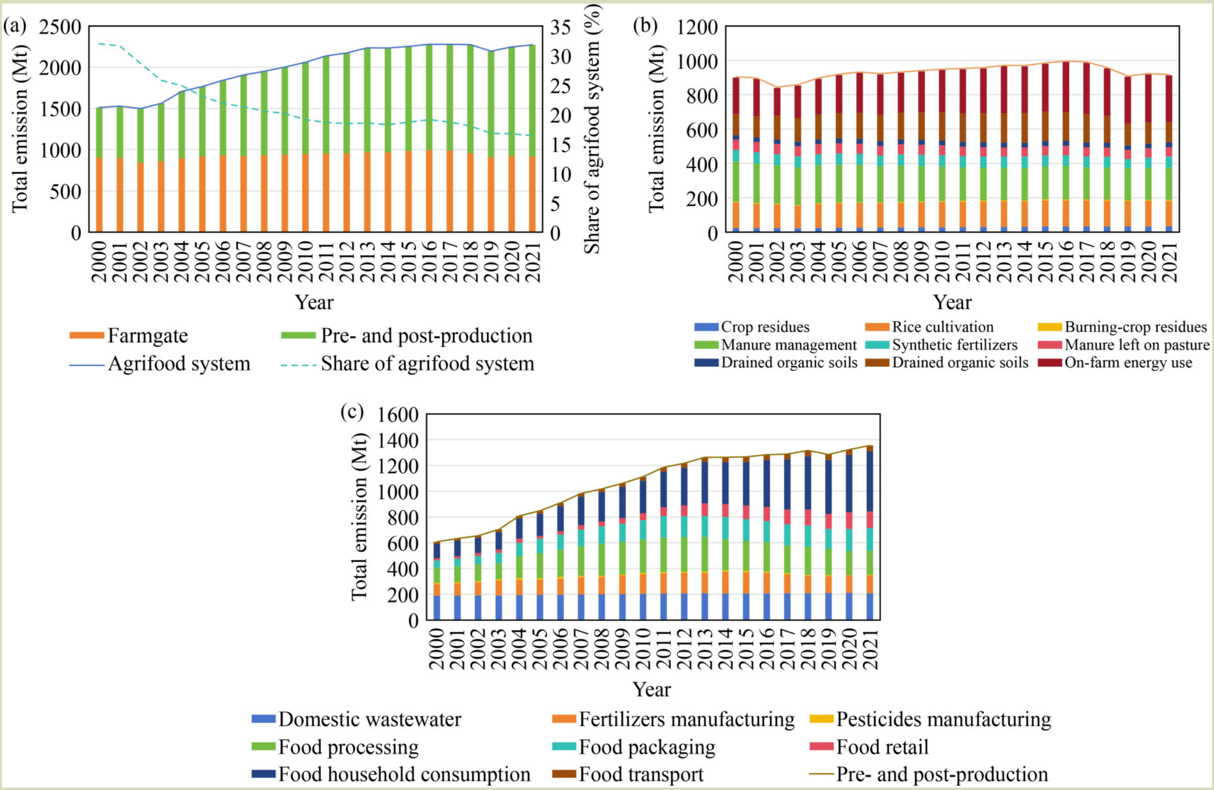


Fig. 3 Sources of carbon emissions in the agrifood system in China (2000–2021). (a) Structure of carbon emissions of agrifood system; (b) farmgate emission; (c) pre- and post-production emission.

2000 to 100 t in 2021. This nearly negligible contribution underscores China's achievements in controlling agricultural expansion and promoting sustainable land use[21]. Notably, carbon emissions from the pre- and post-production stages have increased significantly, as illustrated in Fig. 3(c). Emissions in these stages rose from 608 Mt in 2000 to 1.36 Gt in 2021, nearly doubling. This substantial growth is primarily driven by the increased production of fertilizers and pesticides, food processing, transportation and storage, as well as distribution activities. As shown in Fig. 3(c), emissions from household food consumption, food processing and food packaging have seen notable increases, reflecting the expansion of supply chains and the logistics network in China. The share of pre- and post-production activities in total agrifood emissions rose from 40.2% in 2000 to 59.6% in 2021, making these stages the dominant sources of emissions within the agrifood system.

In summary, China's agrifood system carbon emission structure has undergone significant changes over the last two decades. Emissions from the production stage have stabilized, as seen in Fig. 3(b), indicating enhanced agricultural efficiency, while emissions from pre- and post-production stages (Fig. 3(c)) have grown considerably, underscoring the increasing role of supply chains, logistics and consumer-related activities in overall carbon emissions. The near-zero emissions from land-use change (Fig. 3(a)) also highlight China's commitment to sustainable land-use practices. With production-stage emissions stabilizing, the main challenge for China's agriculture is shifting toward managing the supply chain and advancing the low-carbon transition of the entire food system.

According to Fig. 3(b), from 2000–2021, production carbon emissions in China's agrifood system remained stable, increasing only slightly from 904 to 917 Mt. Despite the growth in agricultural output, improvements in technology and resource management have effectively controlled production emissions. The production share in total agrifood emissions dropped from 18% in 2000 to 6% in 2021, as shown in Fig. 3(b)[22], reflecting a shift in emission sources toward other stages of the food system.

Within the production stage, enteric fermentation and agricultural energy use have consistently been primary carbon sources. Figure 3(b) illustrates a decline in emissions from enteric fermentation, dropping from 235 Mt in 2000 to 189 Mt in 2021, most likely due to improved livestock management and optimized feed. Agricultural energy use, another significant source, peaked at 291 Mt in 2016 before decreasing to 272 Mt by 2021, indicating that energy use efficiency has improved. Fertilizer use remains a major source of nitrous oxide emissions, as shown in Fig. 3(b). Despite the zero-growth policy for fertilizer use introduced in 2015, emissions from fertilizer use decreased only slightly, from 122 Mt in 2000 to 117 Mt in 2021. Emissions from rice paddies, another methane source, also saw a reduction, most likely due to enhanced water and paddy management practices such as intermittent irrigation[15]. Although crop residue burning contributed relatively low emissions, as Fig. 3(b) shows, it increased from 4.8 Mt in 2000 to 6.6 Mt in 2021, indicating a continued reliance on this practice in certain regions during the harvest season.

In summary, the production stage remains a significant source of carbon emissions, but its relative share has declined, as seen in Fig. 3(b). Through optimized management of primary sources, such as enteric fermentation, energy use, and fertilizer use, China has made progress in reducing production-stage emissions. However, with pre- and post-production emissions rising due to supply chain expansion, future strategies should prioritize supply chain management and low-carbon technology adoption, as depicted in Fig. 3(c).

Pre- and post-production emissions rose significantly from 2000 to 2021, with an increase of about 123%, as shown in Fig. 3(c). This growth underscores the complexity of China's agrifood supply chain, where emissions from fertilizer production, food processing, packaging and transportation have emerged as major carbon contributors. Although the pre- and post-production stage shares of total agricultural emissions decreased slightly from 13% in 2000 to 9.8% in 2021, the absolute increase in emissions highlights their expanding impact on the food system's carbon footprint. As indicated in Fig. 3(c), household food consumption, food processing, and food packaging are primary emission sources. Household food consumption emissions rose from 112 Mt in 2000 to 468 Mt in 2021, nearly quadrupling due to increased demand for consumer goods. Food processing emissions also rose from 119 to 187 Mt, driven by industrialization in food production. Food packaging, propelled by growing material demand, saw emissions increase from 54 to 175 Mt. Fertilizer production and waste management emissions have also risen, indicating that urbanization and consumer behavior changes are significant contributors.

In conclusion, the rise in pre- and post-production emissions indicates that future reduction efforts should focus on supply chain efficiency and low-carbon technology integration, as illustrated in Fig. 3(c). Reducing carbon emissions across

China's agrifood system will require comprehensive improvements in logistics, waste management and consumer practices[23].

3.2 Analysis of carbon emission sources in Africa's agrifood system

From 2000 to 2021, carbon emissions from Africa's agrifood system increased from 2.03 to 2.85 Gt, a growth of about 40% (Fig. 4(a)). This increase is primarily driven by the expansion of agricultural activities, land-use changes, and an increasingly complex agricultural supply chain. Population growth and agricultural expansion, particularly in East and Central Africa, have intensified emissions, reflecting the substantial carbon footprint of Africa's agrarian expansion[24,25].

Land-use changes remain the largest source of carbon emissions in Africa, largely due to the conversion of forests to farmland, especially in tropical regions. As illustrated in Fig. 4(b), between 2000 and 2021, carbon emissions from net forest conversion fluctuated between 935 and 1140 Mt per year, highlighting the ongoing deforestation across the continent. These emissions are primarily driven by agricultural expansion and timber demand, with additional impacts from land management policies and natural climatic factors, such as shifts in rainfall patterns. Emissions from tropical forest fires, in particular, peaked at 123 Mt in 2011 before gradually decreasing to 94 Mt in 2021, reflecting improved fire management measures and the complex interplay between natural and human factors.

Agricultural production emissions also saw significant increases. Emissions from agricultural production activities rose from 751 Mt in 2000 to 1121 Mt in 2021, a growth of about 49% (Fig. 4(c)). This rise is associated with traditional extensive farming methods and livestock practices in Africa, which contribute to methane emissions through enteric fermentation and increased agricultural energy use. Enteric fermentation, primarily from ruminant livestock like cattle and sheep, remained the largest source of methane emissions in

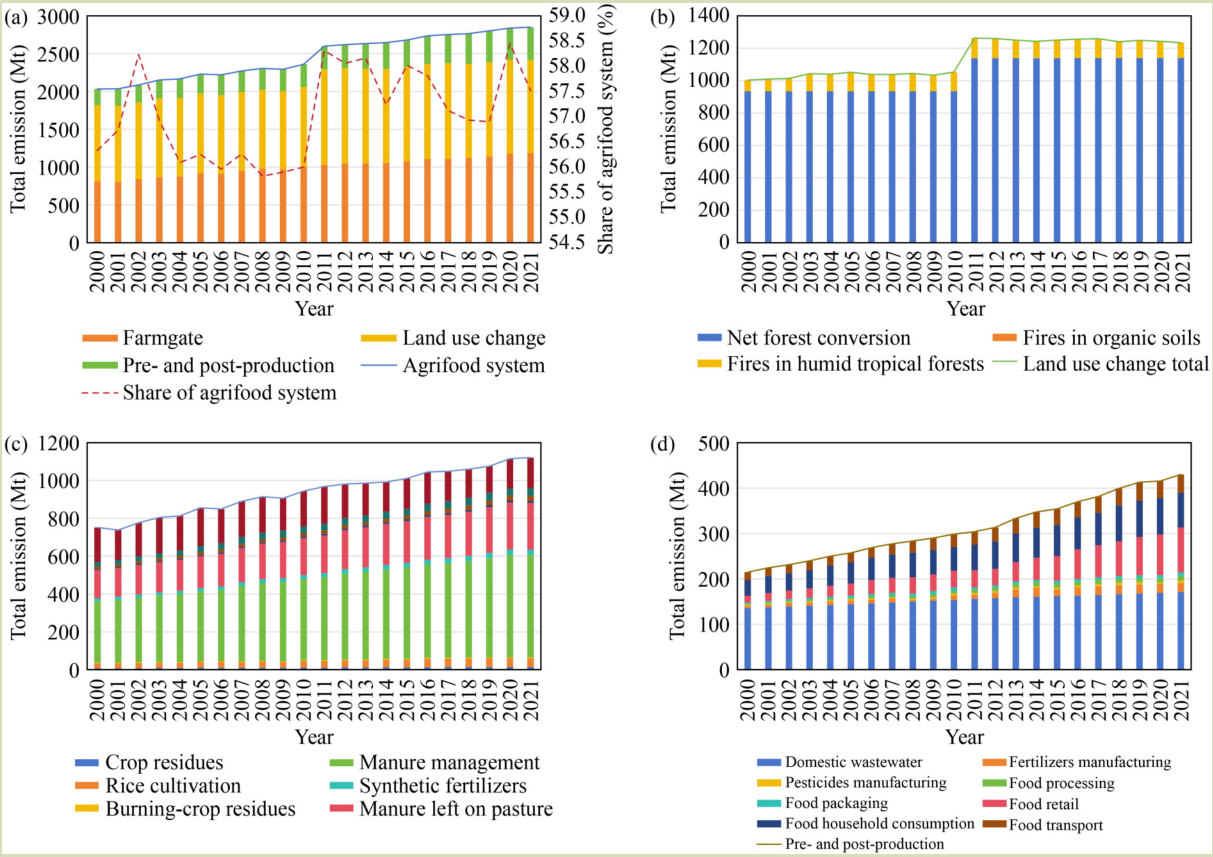


Fig. 4 Structure of carbon emissions in the agrifood system in Africa (2000–2021). (a) Structure of carbon emissions of agrifood system; (b) land use change emission; (c) farmgate emission; (d) pre- and post-production emission.

Africa's agrifood system, with emissions nearly doubling from 70 Mt in 2000 to 132 Mt in 2021. Additionally, emissions from tropical savanna fires, particularly in South Africa, decreased from 31 to 17 Mt, potentially due to improved fire management in recent years.

Emissions from pre- and post-production stages have also grown substantially, rising from 215 Mt in 2000 to 430 Mt in 2021 (Fig. 4(d)). Although smaller in scale compared to land-use and agricultural production emissions, these emissions reflect the modernization of activities such as fertilizer and pesticide production, food processing, and transportation. As the agricultural supply chain in Africa expands, the rising demand for processed and packaged foods has intensified emissions across these stages. This trend underscores the need for Africa to adopt low-carbon technologies, particularly in land management and supply chain optimization, to mitigate rising carbon emissions.

In summary, carbon emissions from Africa's agrifood system have risen significantly over the last two decades, with notable growth in land-use, agricultural production, and pre- and post-production stages (Fig. 4). While land-use change remains the predominant emission source, the rapid increase in pre- and post-production emissions suggests that as Africa's economy develops and agricultural sectors modernize, supply chain management and low-carbon technology integration will become increasingly critical for emissions control. Future emission reduction policies must consider the unique characteristics of each emission stage, including land management, agricultural technology improvements and supply chain optimization, to achieve sustainable carbon emissions control.

During this period, production emissions showed a continuous upward trend, increasing from 158 Mt in 2000 to 268 Mt in 2021, representing a growth of about 70% (Fig. 4(c)). This increase reflects the expansion of agriculture and livestock production, limited technological advancements, and reliance on traditional farming practices. While production emissions are still significant, they remain lower than in China, reflecting differences in modernization and resource input. Production emissions consistently accounted for between 21% and 30% of Africa's total agrifood system emissions, indicating their relatively stable significance in the overall emission profile.

Within the production stage, key sources of emissions include enteric fermentation and manure left on pastures. Methane emissions from enteric fermentation rose significantly due to the increasing ruminant population, underscoring the need for improved livestock management to mitigate emissions. Emissions from manure left on pastures increased from 33 Mt in 2000 to 64 Mt in 2021, highlighting inadequate waste management practices in livestock farming. Additionally, methane emissions from rice cultivation grew from 11 to 27 Mt, particularly in Central and West Africa, where expanded irrigation areas have led to higher emissions from rice paddies.

Land-use changes continue to account for the largest share of agricultural carbon emissions in Africa, particularly from deforestation and tropical forest fires. Between 2000 and 2021, emissions from net forest conversion ranged from 934 Mt to 1.14 Gt annually (Fig. 4(b)). These activities are largely driven by agricultural expansion and timber demand, which place significant pressure on forest ecosystems in tropical regions. Factors like fire management, land-use policies, and climate-related factors, such as changing rainfall patterns, have also influenced emissions from tropical forest fires, which, despite a peak in 2011, have gradually declined, indicating some success in fire management. Pre- and post-production emissions have grown rapidly, particularly in waste management, food processing, and transportation (Fig. 4(d)). Emissions from waste management increased from 45 to 56 Mt, closely linked to Africa's rapid urbanization and limited waste management infrastructure. Household food consumption emissions surged from 1 Mt in 2000 to 53 Mt in 2021, reflecting the rise of a middle class and changing consumption patterns. Additionally, food packaging emissions grew from 80 to 180 kt, driven by increased demand for packaged foods. Emissions from food processing increased 8-fold, from 200 kt to 1.6 Mt, while food transportation emissions rose threefold, from 3.4 to 10.2 Mt, reflecting the impact of regional economic integration and expanded trade networks.

In conclusion, as Africa's economy and consumption patterns evolve, carbon emissions from the pre- and post-production stages are expected to continue increasing. Future emission reduction strategies should focus on enhancing energy efficiency, optimizing supply chain logistics, and improving waste management systems to better control carbon emissions across all stages of the agrifood system.

3.3 Comparative analysis of carbon emission sources in agrifood systems across African regions

The African continent, with its vast expanse and significant variations in climate conditions and natural resource distribution, has a diverse range of agricultural development across regions. Consequently, it is essential to analyze the regional differences in the carbon emission structures of agrifood systems. Based on FAO carbon emission data from 2000 to 2021, this study examines the carbon emission structures of agrifood systems in Africa[1].

In North Africa (Fig. 5(a)), carbon emissions from the agrifood system increased modestly from 288 to 333 Mt (a growth rate of 16%). Emissions from the agricultural production stage showed a fluctuating downward trend, decreasing from 186 to 155 Mt, potentially due to advancements in agricultural technology and improved resource management. Land-use change emissions remained relatively stable, decreasing from 25 to 22 Mt. However, emissions from pre- and post-production activities more than doubled, rising from 77 to 156 Mt, highlighting the increasing carbon burden of processing, transportation, and retail. Per capita emissions declined from 1.6 to 1.3 t, while emissions per unit of output fell from 0.9 to 0.4 t per 100 USD, reflecting improvements in carbon efficiency.

In East Africa (Fig. 5(b)), carbon emissions rose significantly from 522 to 814 Mt (a growth rate of 56%). Emissions from agricultural production and land-use change increased to 496 and 244 Mt, respectively, while emissions from pre- and post-production activities saw the highest growth, from 41 to 75 Mt (a growth rate of 84%). In South Africa (Fig. 5(c)), total emissions increased from 151 to 179 Mt (a growth rate of 19%). Emissions from agricultural production and pre- and post-production activities grew to 73 and 48 Mt (a growth rate of 65%), while emissions from land-use change remained relatively stable.

In West Africa (Fig. 5(d)), emissions rose from 422 to 524 Mt (a growth rate of 24%). Agricultural production and land-use change emissions increased to 271 and ~125 Mt, respectively. Notably, emissions from pre- and post-production activities surged from 54 to 127 Mt (a growth rate of 137%), underscoring the growing importance of non-production activities in overall emissions, even as per capita emissions remained below the global average.

In Central Africa (Fig. 5(e)), total emissions increased from 651 Mt to 1 Gt (a growth rate of 54%). Land-use change was the dominant source of emissions, rising from 514 to 786 Mt, reflecting the significant impact of large-scale land development. Emissions from agricultural production increased steadily from 123 to 189 Mt, while emissions from pre- and post-production activities, although smaller in scale, rose from 14 to 25 Mt (a growth rate of 77%). Central Africa had higher per capita and per unit of output emissions compared to other regions, though both metrics had a declining trend: per capita emissions fell from 7 to 5 t, and emissions per unit of output dropped from 24 to 4 t per 100 USD. Overall, the increase in emissions, particularly from land-use change, underscores the need for targeted policies and measures to manage and reduce carbon emissions, advancing sustainable development in the region.

3.4 Driving factors of carbon emissions in the agrifood systems in China and Africa

3.4.1 Fertilizer use and policy impact

Between 2000 and 2021, China's fertilizer use and application intensity had notable shifts, with usage initially increasing and then declining after the implementation of the zero-growth policy in 2015[20]. This policy aimed to curb fertilizer consumption, improve agricultural productivity, and promote sustainable practices (Fig. 6(a)). Specifically, nitrogen fertilizer use rose from 221 kt in 2000 to a peak of 310 kt in 2014, before falling to 213 kt by 2021. Phosphate and potash fertilizers followed similar trends, reflecting effective management measures such as soil testing and formula-based fertilizer application techniques, which contributed to reduced application intensity and enhanced efficiency. As shown in Fig. 6(a), nitrogen application intensity dropped from 233 $kg \cdot ha^{-1}$ in 2013 to 166 $kg \cdot ha^{-1}$ by 2021, demonstrating the success of China's policy in promoting efficient fertilizer use and supporting a low-carbon agricultural transition.

In contrast, Africa's fertilizer use had a steady upward trend between 2000 and 2021(Fig. 6(b)), driven primarily by the need to increase crop yields. During this period, nitrogen, phosphate and potash application volumes rose by 94.3%, 91.9% and 123%, respectively, while application intensity increased by 54.6%, 52.0% and 76.1%. These increases reflect a growing reliance on fertilizers to meet yield demands. However, application intensity and efficiency remain uneven across

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[1] These regional classifications follow the FAO database: North Africa includes Algeria, Egypt, Libya, Morocco, Sudan, Tunisia, and Western Sahara; South Africa comprises Botswana, Lesotho, Namibia, South Africa, Eswatini, and Zimbabwe; Central Africa covers Angola, Cameroon, the Central African Republic, Chad, the Republic of Congo, the Democratic Republic of Congo, Equatorial Guinea, Gabon, and São Tomé and Príncipe; East Africa includes Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Seychelles, Somalia, South Sudan, Tanzania, Uganda, Zambia, and Zimbabwe; and West Africa encompasses Benin, Burkina Faso, Cabo Verde, Côte d'Ivoire, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, and Togo.

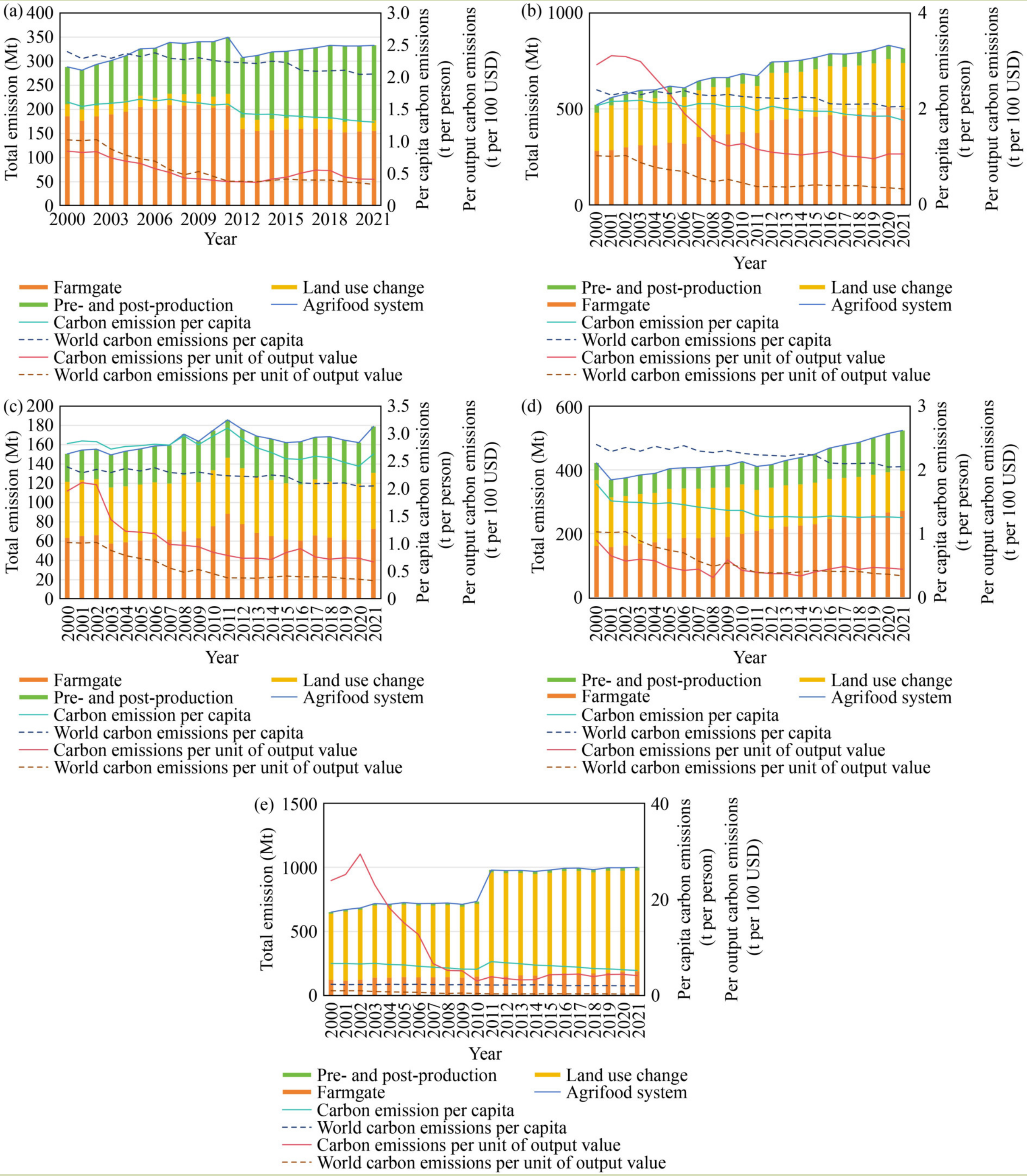

Fig. 5 Carbon emission structures in regional agrifood systems in Africa (2000–2021). (a) North Africa; (b) East Africa; (c) South Africa; (d) West Africa; (e) Central Africa.

regions, due to disparities in technology levels and management capacity. Most African agricultural practices still rely on traditional methods, with limited access to advanced fertilizer management technologies, resulting in low modernization.

3.4.2 Pesticide use

Between 2000 and 2021, China's pesticide usage and application intensity initially rose, peaking in 2014, before declining as a result of the Zero Growth Action for Pesticide Use policy implemented in 2015. This policy encouraged

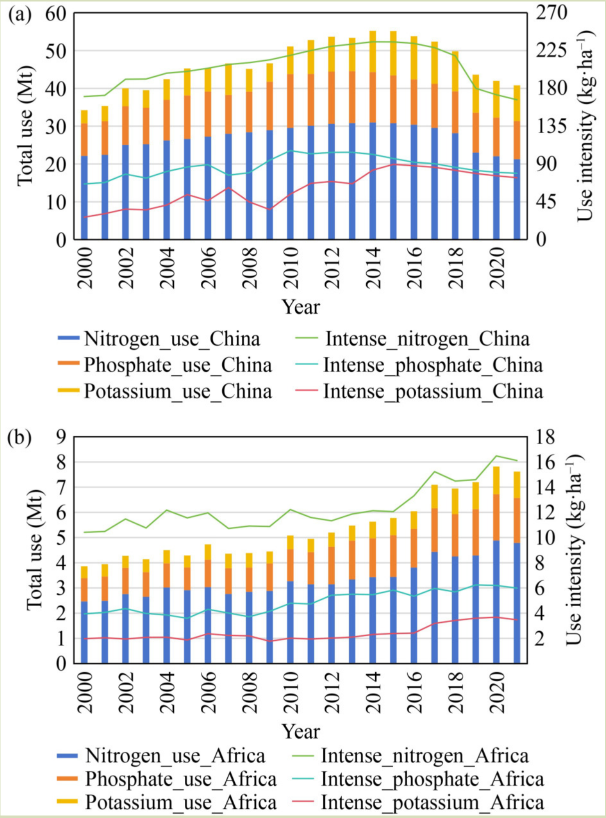

Fig. 6 Fertilizer input and application intensity (2000–2021) in China (a) and Africa (b).

efficient pesticide use and environmental awareness, resulting in a reduction in usage from 0.3 Mt in 2014 to 0.2 Mt by 2021 (Fig. 7). Despite the reduction, however, the yield response to pesticide use decreased, indicating a need for further optimization of application strategies to maintain crop yields sustainably. This decline in usage and intensity underscores the impact of regulatory measures on reducing agricultural inputs and supporting sustainable development goals.

In contrast, Africa's pesticide usage and application intensity have continued to rise. Pesticide use increased from 74 to 204 kt, with application intensity reaching 0.7 kg·ha^{-1} by 2021, as shown in Fig. 6. Although efficiency has improved, the continued rise in usage raises environmental and sustainability concerns, particularly in areas with limited regulatory oversight. African countries may benefit from adopting similar policies to China's, focusing on regulated pesticide use and the development of integrated pest management practices.

3.4.3 Agricultural energy use and efficiency

From 2000 to 2021, China's total agricultural energy use increased significantly, peaking in 2016 before declining (Fig. 8). This trend reflects both the modernization of agricultural practices, such as increased mechanization, and the government's efforts to promote energy efficiency. Energy use initially rose with the expansion of agricultural production but has been partially mitigated by policies encouraging low-carbon development and energy-saving technologies. The decline after 2016 highlights China's success in balancing productivity with reduced energy consumption in agriculture.

Africa's agricultural energy use, in contrast, remained significantly lower, increasing slowly from 2.4 × 10^5 TJ in 2000 to 3.8 × 10^5 TJ in 2021. The slower growth reflects lower mechanization rates and limited technological advancement across many regions, which constrains productivity improvements. As agricultural modernization progresses, Africa will need to invest in mechanization and energy efficiency to enhance productivity and reduce emissions.

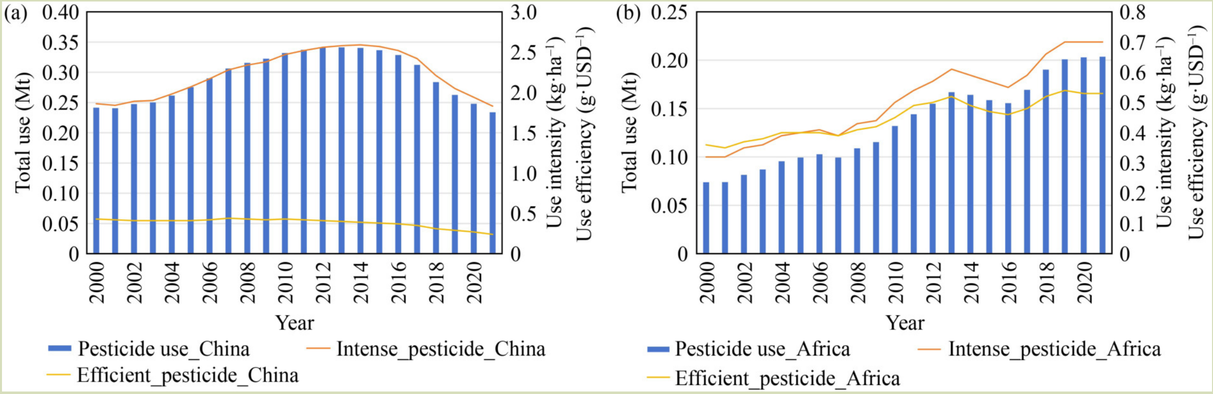

Fig. 7 Pesticide input, application intensity and efficiency of use (2000–2021) in China (a) and Africa (b).

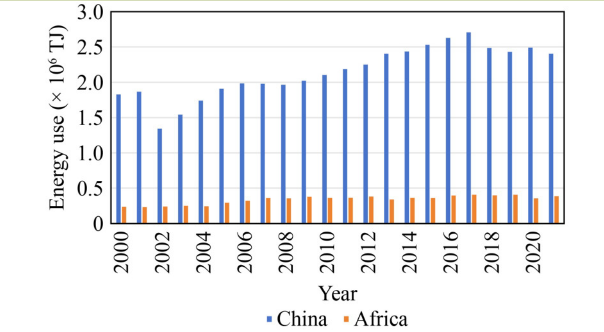

Fig. 8 Agricultural energy use in China and Africa (2000–2021).

In summary, the differences in agricultural energy use between China and Africa highlight the asynchronous development of agriculture in the two regions. China leads in agricultural modernization and energy use efficiency, thanks to continuous policy support and technological innovation. Despite high energy usage, China has shown a downward trend in energy consumption. In contrast, Africa's total agricultural energy use remains low, but its upward trend reflects efforts toward modernization. To improve productivity and sustainability in the future, African agriculture will need to increase mechanization, enhance energy use efficiency, and draw on China's experiences in emission reduction and energy savings.

4 Emission reduction policies and measures in the agrifood systems in China and Africa

4.1 Emission reduction policies and measures in China's agrifood system

China's agricultural emission reduction policies have evolved from an early focus on production efficiency to a comprehensive strategy emphasizing green development, incorporating key elements of agricultural support and subsidy frameworks. By integrating technological innovation with targeted agricultural subsidies, China has effectively promoted low-carbon agricultural practices that reduce greenhouse gas (GHG) emissions and enhance resource use efficiency.

China's technological measures in this area include precision agriculture, circular agriculture, biomass energy applications, integrated water-fertilizer management and comprehensive soil-crop system management. Precision agriculture leverages advanced technologies such as remote sensing and the Internet of Things to monitor crop health, optimize pest control and assess soil quality in real time, improving resource efficiency and minimizing environmental impact[26]. Circular agriculture focuses on recycling agricultural byproducts like manure and crop residues, enriching soil organic content and enhancing carbon sequestration capacity[2,18]. Biomass energy with carbon capture and storage is applied to produce renewable energy while capturing emissions, supporting China's carbon neutrality goals[18].

These technological advancements are supported by a robust policy framework that aligns with multi-objective goals. Under the OECD classification of agricultural support policies, China has implemented commodity production support, input use support, entitlement-based support, non-commodity standards support and general service support. Examples include minimum procurement price policies, subsidies for machinery and improved seeds, farmland fertility protection programs and incentives for adopting environmentally friendly practices such as converting farmland to forests and promoting conservation tillage.

Notably, reforms in China's agricultural subsidy system emphasize green objectives (Table 2). Subsidies for chemical fertilizers, agricultural inputs and seeds have been redirected toward supporting organic fertilizers, energy-efficient machinery and farmland fertility protection. Investments in high-standard farmland construction have enhanced productivity while reducing the reliance on chemical inputs like fertilizers and pesticides, further lowering carbon emissions. Additionally, cold storage and preservation facilities have reduced food loss and waste, contributing to the reduction of supply chain emissions.

China's strategic initiatives, such as the 14th Five-Year Plan, focus on high-standard farmland construction, seed industry revitalization, and agricultural mechanization, reinforcing the broader goals of food security, farmer income stability and environmental sustainability. These initiatives are complemented by green subsidy systems that incentivize the adoption of technologies to optimize resource use and improve resilience against climate challenges[10,11]. Collectively, these policies and technologies not only enhance productivity and support the low-carbon transition of the agricultural sector but also align with China's broader carbon neutrality commitments and global climate goals.

To ensure long-term progress, further optimization of the policy framework is necessary to strengthen synergies between food security, farmer incomes and environmental sustainability, ensuring a balanced approach to agricultural

Table 2 Emission reduction technologies and measures in agrifood system in China

Policy type	Policy	Specific measures	Emission reduction mechanism
Technology promotion	Fertilizer reduction	Soil testing and formula fertilizer application	Precision fertilization reduces fertilizer usage, lowering nitrogen fertilizer's contribution to GHG emissions
	Pesticide reduction	Biological and physical pest control	Reduces the use of chemical pesticides, lowering carbon emissions from production and use
	Recycling	Resourceful utilization of manure and straw	Converts waste into fertilizer, reducing GHG emissions and increasing soil carbon sinks
	Conservation tillage	Reduced/no tillage, permanent cover	Reduces soil disturbance, increases organic matter content, and enhances soil carbon storage
	Biochar application	Biochar additives	Improves soil structure, enhances carbon sequestration, and reduces GHG emissions
	Biomass energy	Biogas production and power generation	Uses agricultural waste to produce renewable energy, reducing fossil fuel use and emissions
	Integrated water-fertilizer	Combined irrigation and fertilization	Improves water and fertilizer use efficiency, reducing waste and GHG emissions
	Soil-crop system management	Integrated nutrient management	Optimizes soil nutrient management, enhances crop growth efficiency, and reduces fertilizer use and related emissions
Agricultural subsidies	Green subsidy system	Organic fertilizer subsidy	Encourages farmers to use organic fertilizers, reducing reliance on chemical fertilizers
	Comprehensive material subsidies	Subsidies for agricultural inputs	Lowers costs, encourages proper fertilizer and pesticide use, and reduces environmental pollution and GHG emissions
	High-quality seed subsidies	Support for high-quality seed use	Increases yields and quality, potentially reducing carbon emissions by enhancing photosynthesis or reducing land use
	Agricultural equipment subsidies	Promotes mechanization	Improves production efficiency, reduces reliance on manual and animal labor, and lowers energy consumption and emissions
	Target price policy	Price subsidies for specific crops	Stabilizes market prices, encourages crop cultivation with higher carbon sequestration or lower carbon intensity
	Agricultural insurance premium subsidy	Insurance for crop and livestock producers	Reduces risk from natural disasters, encourages environmentally friendly and disaster-resilient agricultural practices
Infrastructure development	Cold storage facilities for agricultural products	Construction of cold storage and preservation facilities	Reduces post-harvest losses, lowering carbon emissions from food waste
	High-standard farmland construction	High-standard farmland construction	Enhancing agricultural productivity and promoting low-carbon farming

development that meets economic, social and environmental objectives.

4.2 Emission reduction policies and measures in Africa's agrifood system

Africa faces unique challenges in addressing climate change, requiring a balanced approach that supports agricultural productivity and environmental sustainability. African governments, often with support from international partners, have developed two primary policy categories: agricultural subsidy policies aimed at improving productivity and green ecological policies focused on promoting sustainable farming and ecosystem restoration. These policies are crucial for reducing GHG emissions, enhancing food security and boosting rural incomes across the continent[27,28].

In terms of agricultural subsidy policies, 12 sub-Saharan African countries have implemented smart subsidy programs aimed at improving food security, input adoption and producer welfare[29]. Nigeria initiated its program in 1992, followed by Zambia in 2002 and then Malawi in 2005, whose program inspired broader regional adoption. By 2008, Burkina Faso, Ghana, Kenya, Mali, Rwanda, Senegal and Tanzania had implemented similar initiatives, with Burundi following in 2012. Mozambique piloted a program from 2009 to 2011, while Ethiopia's policy of selling fertilizer below cost is sometimes considered a subsidy. These programs vary, with some offering universal price subsidies and others using vouchers to target specific farmers and food crops, sometimes developing the private sector for input supply. Only three programs acknowledged potential benefits for poor consumers, and only Tanzania's program focused explicitly on input use efficiency and soil fertility[16]. Recently, Kenya's national fertilizer subsidy program, introduced in 2022, provided subsidies of up to 72.7% on commercial fertilizer alternatives to mitigate the global fertilizer crisis. Also, China's cooperation with African countries in agriculture has driven agricultural modernization, including rice variety improvement in Burundi, mechanization loan support in Kenya, and the launch of digital agriculture service platforms, significantly improving agricultural productivity and efficiency[28]. At the same time, through the Global Development Initiative, the Chinese government has aligned with Africa's development strategies, focusing on fostering endogenous growth in Africa, particularly in agricultural technology cooperation and agricultural trade facilitation, to ensure food security in Africa[30].

African nations have also implemented green ecological policies that address both climate adaptation and emission reduction (Table 3). Many African countries have been actively participating in international climate agreements, including the UN Framework Convention on Climate Change and the Paris Agreement[27,29]. For example, South Africa has introduced a low emission development strategy and enacted a carbon tax law to curb domestic emissions. Also, African countries are making strides in green energy transitions, as exemplified by South Africa's biogas power generation initiative, which uses chicken manure as a renewable energy source[16].To address soil degradation and productivity issues, many African countries have adopted ISFM practices, which help to improve soil quality and increase crop yields. Education and training programs are also widely implemented to raise farmer awareness of sustainable agricultural practices, encouraging the adoption of efficient and environmentally-friendly pesticide strategies. Additionally, innovative agricultural insurance mechanisms, such as picture-based and weather index insurance, provide African farmers with financial resilience against extreme weather events, reducing the economic risks associated with climate change[27].

Overall, African countries lag in environmental protection and climate action despite unified support for the Paris Agreement. Effective climate policies require not just financial and technical resources but strong governance, targeting corruption and clear communication of goals. South Africa demonstrates progress, with significant civil society involvement, yet it faces challenges in transitioning from coal to renewables. Without proper governance, increased climate funding might worsen environmental outcomes. To support African climate efforts, international goals should align with African priorities in infrastructure, energy and economic growth, addressing long-standing land and resource issues. Africa's agricultural emission reduction policies combine objectives of enhancing agricultural productivity and environmental protection, particularly through financial incentives to improve production efficiency while actively promoting ecological restoration and sustainable development policies. This system reflects Africa's multilevel efforts to address climate change, improve food security, and achieve sustainable agricultural development.

Table 3 Agricultural emission reduction policies in Africa

Policy type	Policy/Measure	Country/Region	Specific content and objectives
Agricultural subsidy	Large Input Subsidy Program	12 countries including Malawi	Reduces farmers' financial risks through fertilizer subsidies, enhancing maize productivity
	National Fertilizer Subsidy Program	Kenya	Provides up to 72.7% subsidy on commercial fertilizer alternatives to mitigate the impact of the fertilizer crisis
	Agricultural Mechanization Loan Support		Provides loan support for agricultural mechanization, improving agricultural productivity
	Digital Agriculture Service Platform		Launches a digital agriculture service platform to enhance agricultural production and management efficiency
	Rice Variety Improvement	Burundi	Improves rice varieties to increase yields
Green ecological	National climate change policies and action plans	South Africa, Nigeria, Kenya	Introduces policies and plans to commit to a 32% emission reduction by 2030
	Low emission development strategy	South Africa	Implements a low-emission development strategy and controls GHG emissions through a carbon tax law
	Green energy transition	South Africa (RCL Foods)	Uses chicken manure for biogas power generation, saving energy costs
	Integrated Soil Fertility Management	Multiple African countries	Promotes soil fertility management techniques to improve soil health and crop yields
	Education and Training Programs	Multiple African countries	Increases farmers' awareness of sustainable agricultural practices and skills
	Agricultural insurance	Multiple African Regions	Uses insurance to reduce farmers' reluctance to invest in agriculture due to weather risks

4.3 Comparative analysis of emission reduction policies in agrifood systems in China and Africa

Under the dual pressures of food security and climate change, China and Africa have significant differences in their agrifood system emission reduction policies, while also offering opportunities for mutual learning. China’s policies emphasize a combination of technology-driven solutions and integrated management to reduce GHG emissions during production. Key approaches include precision agriculture, circular agriculture and biomass energy applications. Precision agriculture uses technologies such as remote sensing and the Internet of Things to optimize fertilizer application and pest control, enhancing resource use efficiency and reducing emissions. Circular agriculture focuses on recycling agricultural byproducts, such as crop residues and livestock manure, to enrich soil organic content and boost carbon sequestration capacity.

Policy support is a critical element in China’s approach, with green subsidy programs such as organic fertilizer subsidies and mechanization incentives encouraging the adoption of low-carbon technologies by farmers. Also, agricultural insurance and the development of cold storage facilities are integrated into emission reduction frameworks to minimize carbon emissions associated with food loss and waste. Overall, China’s policies are characterized by a systematic integration of technological innovation and policy guidance, balancing agricultural productivity with environmental sustainability.

In contrast, Africa’s emission reduction policies prioritize balancing agricultural productivity and climate adaptation, often leveraging international cooperation to drive green transitions in resource-constrained settings. Agricultural subsidy programs, such as input subsidy programs, reduce input costs and improve food productivity but show limited environmental benefits. Green ecological policies play a more prominent role, with South Africa implementing carbon taxation and low-emission development strategies while promoting biomass energy initiatives such as biogas production from chicken manure to reduce fossil fuel reliance. Additionally, many African nations adopt ISFM practices and innovative agricultural insurance mechanisms, such as weather index insurance, to improve soil quality and enhance resilience against climate-related risks. While these measures have shown success in climate adaptation, their effectiveness in emission reduction is constrained by limited technological adoption and inconsistent policy implementation.

In summary, China’s emission reduction policies are centered on technological innovation and robust policy frameworks, reflecting systematic and efficient implementation. Africa, conversely, relies more heavily on international cooperation and region-specific strategies to address the dual goals of agricultural production and climate adaptation. The differences in their approaches highlight the influence of varying developmental stages and resource endowments on policy design. Moving forward, China’s experience in low-carbon technologies and Africa’s strategies for ecological adaptation can serve as complementary pathways, offering diverse solutions for global agricultural emission reduction and sustainable development.

5 Conclusions and policy implications

Under the combined pressures of global climate change and food security, transforming agrifood systems in developing countries is essential for achieving the global dual-carbon targets and promoting sustainable development. China and Africa, as representative developing regions, together contribute about 80% of global agricultural carbon emissions. Despite both regions being reliant on smallholders, China has made significant strides in reducing emissions through modernization and technological innovation, while Africa remains in a critical phase of transitioning from traditional to modern agriculture. This comparative analysis of China and Africa’s agrifood systems provides valuable insights for other developing countries seeking to reduce carbon emissions.

5.1 Conclusions

This study analyzed differences in agrifood system carbon emissions between China and Africa, with key findings as follows.

Firstly, carbon emissions in both China and Africa have risen, with China showing a higher growth rate but lower carbon intensity. China’s emissions increased from 819 Mt in 2000 to 1.39 Gt in 2021 (70% increase) whereas Africa’s emissions grew from 2.03 to 2.85 Gt (40% increase). Africa’s total emissions remain higher, largely due to extensive agricultural activities, especially in East and Central Africa where land-use changes are a major contributor. Per capita emissions reveal a stark contrast: China’s per capita emissions grew modestly from 403 to 489 kg, while Africa’s rose from 5.05 to 5.82 t, reflecting the carbon intensity associated with traditional agricultural practices and limited technological advancement in Africa.

Secondly, emission sources differ significantly. In China, emissions are shifting from the production phase to pre- and post-production stages, with a notable increase in emissions from food processing and packaging. In contrast, emissions in Africa are concentrated in land-use changes and traditional livestock farming, highlighting a reliance on extensive agricultural practices due to limited modernization.

Thirdly, China has achieved greater efficiency in fertilizer, pesticide and energy use through its zero-growth policy, which has reduced nitrogen application intensity by 28.5% and pesticide use by 32.4% since 2015. Africa, however, has seen substantial increases in fertilizer use, up by 94.3%, 91.9% and 123% for nitrogen, phosphate and potassium, respectively, with application intensity rising over 50% across the board. These increases reflect yield demands but are hampered by regional disparities in efficiency due to varying levels of technology and management capacity. Pesticide use also continues to rise in Africa, raising sustainability concerns due to limited regulatory oversight.

Finally, China's emission reduction policies emphasize technological innovation and policy support, focusing on efficiency and low-carbon practices in production. In contrast, Africa prioritizes food security and productivity through subsidies and international cooperation, with ecological sustainability efforts such as ISFM and agricultural insurance to mitigate climate risks.

5.2 Policy implications

Based on the main conclusions, policy developments in the following areas are recommended.

First, local adaptation of technological innovation is key to sustainable agriculture. The high efficiency and lower carbon intensity achieved in China's agrifood systems underscore the value of adopting innovative technologies, such as precision and circular agriculture, in sustainable development. Developing countries can integrate technologies and water-fertilizer systems to enhance productivity and sustainability. It is essential, however, to adapt these technologies to local conditions, prioritizing cost-effective solutions like low-cost irrigation systems for resource-limited areas. Circular agriculture, which repurposes agricultural waste to enhance soil health and sequester carbon, also offers a viable pathway for developing countries to transition toward low-carbon agriculture.

Second, improving energy efficiency and expanding renewable energy use reduces agricultural emissions. China's progress in reducing agricultural emissions demonstrates the impact of improving energy efficiency and using biomass energy. To minimize fossil fuel reliance, developing countries should prioritize accessible, low-carbon options, such as energy-efficient agricultural machinery, and locally adapted biomass energy sources from crop residues and livestock manure. This approach supports emission reductions while also enhancing energy resilience, particularly in regions with limited infrastructure.

Third, policy support and international cooperation are essential for low-carbon agriculture. China's emission reductions are largely attributed to strong policy support, including subsidies for organic fertilizers, agricultural machinery, and crop insurance. Developing countries could implement similar incentives to promote low-carbon agricultural practices. Also, international cooperation is crucial for accelerating sustainable transitions, particularly through technical training, joint research, and regional cooperation focused on both mitigation and climate adaptation. Enhanced global collaboration enables resource-sharing, knowledge access, and resilience-building, ultimately supporting sustainable agriculture and contributing to global emissions reduction goals.

5.3 Contributions and limitations

The contributions of this study are threefold. First, it bridges the gap in existing research by systematically comparing China and Africa's agrifood systems, highlighting the differential roles of production, land-use changes and pre- and post-production activities in carbon emissions. Second, the study offers a policy-centric perspective by evaluating how technological innovation, international collaboration, and financial incentives shape mitigation outcomes in distinct regional contexts, providing actionable insights for policymakers in developing countries. Third, the research contributes to the global discourse on sustainable agriculture by demonstrating the potential for mutual learning between regions at different stages of development, fostering a more inclusive pathway toward achieving climate goals.

Despite these contributions, the study has limitations. It relies on aggregated data sets, which may obscure local variations in emissions and mitigation practices, and its scope does not include field-level empirical validation of policy impacts. Additionally, the evolving nature of emission reduction technologies and climate policies means that some recommendations may require periodic updates to remain relevant. Addressing these limitations in future research could provide a more nuanced understanding of regional dynamics and enhance the practical applicability of findings.

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Compliance with ethics guidelines

Xia Li, Yumei Zhang, Shenggen Fan, and Issa Ouedraogo 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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