Review
Next Ten Years: Create a Better Future—Review

Interactions Among Food Systems, Climate Change, and Air Pollution: A Review

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ABSTRACT

Food systems are deeply affected by climate change and air pollution, while being key contributors to these environmental challenges. Understanding the complex interactions among food systems, climate change, and air pollution is crucial for mitigating climate change, improving air quality, and promoting the sustainable development of food systems. However, the literature lacks a comprehensive review of these interactions, particularly in the current phase of rapid development in the field. To address this gap, this study systematically reviews recent research on the impacts of climate change and air pollution on food systems, as well as the greenhouse gas and air pollutant emissions from agri-food systems and their contribution to global climate change and air pollution. In addition, this study summarizes various strategies for mitigation and adaptation, including adjustments in agricultural practices and food supply chains. Profound changes in food systems are urgently needed to enhance adaptability and reduce emissions. This review offers a critical overview of current research on the interactions among food systems, climate change, and air pollution and highlights future research directions to support the transition to sustainable food systems.

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1. Introduction

Climate change, air pollution, and food security are among the most significant challenges humanity faces today [1–4]. These issues are deeply interconnected (Fig. 1), with wide-ranging impacts on social, economic, and environmental systems. On the one hand, climate change and air pollution pose a formidable challenge to global food systems [5,6]. Climate change has led to increased global temperatures and more frequent extreme events such as droughts and floods, which severely impact agricultural production and disrupt food supply chains [7–9]. For example,

higher temperatures and shifting precipitation patterns have altered crop growth cycles, caused yield fluctuations, and increased uncertainty in food supply [9–11]. Beyond direct impacts on production, climate change also exerts cascading effects on livelihoods, communities, and sustainability by influencing economic, environmental, social, and political systems [5,12]. Air pollution—particularly ozone pollution—exacerbates these challenges by reducing agricultural productivity through damage to crop leaves and alterations in the growing environment [13,14]. Moreover, climate change and air pollution interact in complex ways. Climate change can moderate the formation, transport, and deposition of pollutants through changes in meteorological conditions [15,16], while air pollution can impact climate by altering the radiation balance of the Earth-atmosphere system [17]. These interactions may jointly exert significant effects on food systems.
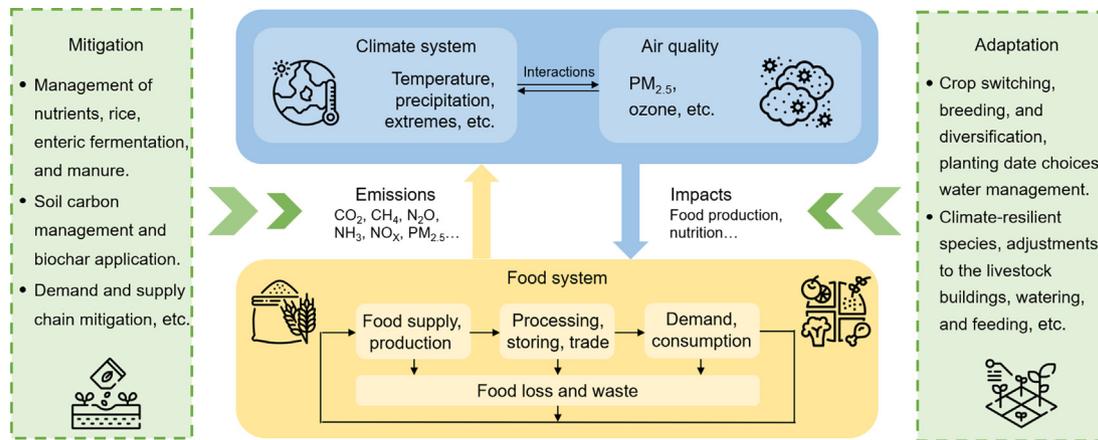
Fig. 1. The interactions among food systems, climate change, and air pollution. Climate change and air pollution (blue box) jointly affect the food system (yellow box) via intricate interactions. In turn, through greenhouse gas and air pollutant emissions, the food system makes a significant contribution to global climate change and air pollution. Mitigation measures to reduce food system emissions and adaptation measures to increase the resilience of the food system (green boxes) are critical to mitigating climate change, improving air quality, and ensuring food security.

On the other hand, the agri-food system is a major contributor toward global climate change and air pollution [18–20]. Climate change is primarily driven by the accumulation of greenhouse gases (GHGs) in the atmosphere. While energy-related activities—such as fossil fuel combustion in the power, industrial, and transportation sectors—dominate global GHG emissions [21], the agri-food system alone accounts for approximately one-third of global GHG emissions [1,19,22], underscoring its critical role in addressing the challenge of climate change. Its significant contribution stems from key activities such as livestock production, fertilizer application, rice cultivation, and land-use changes, which release methane (CH_4), nitrous oxide (N_2O), and carbon dioxide (CO_2) [2,23,24]. Spanning all stages from production and processing to transportation, distribution, and consumption [18], the food system also significantly contributes to air pollution, accounting for 10%–90% of air pollutant emissions, depending on the pollutant [3]. For example, in 2018, it was responsible for more than half of the world's total nitrogen (N) emissions (87% in the form of ammonia (NH_3)) and up to 35% of particulate matter emissions, leading to approximately 22.4% of air pollution-related deaths [3]. These facts highlight the urgent need to reduce emissions from the agri-food system in order to mitigate its impacts on climate change and improve air quality. However, current emission control measures within the sector remain insufficient [5,18].

Against this backdrop, future increases in food demand are expected to further drive emissions from the agri-food system [18]. If current trends persist, emissions from the global food system could jeopardize the achievement of the 1.5 °C and 2 °C climate goals [18,25]. Global food consumption alone could raise temperatures by nearly 1 °C, with 75% of this warming being attributed to methane-rich foods such as ruminant meat, dairy products, and rice [4,19,20]. Although improvements in agricultural production efficiency have led to some decoupling of emissions from agricultural output, the complexities of international trade make global emissions governance challenging [19,25]. Without swift changes to the operating models of agri-food systems, these emissions will continue to exacerbate climate change and environmental pollution, compromise the sustainability of the food system, and inflict long-term damage on global ecosystems [3,5,18,19].

Addressing these challenges requires profound changes across multiple areas. The Food and Agriculture Organization (FAO)'s Strategic Framework 2022–2031 suggests that transforming agri-food systems to become more efficient, inclusive, resilient, and sustainable is crucial for effectively mitigating the adverse effects of climate change and reducing the negative impacts of agri-food systems on the climate [26]. First, climate change mitigation should prioritize the transformation of agricultural production approaches and the adoption of sustainable practices to reduce GHG emissions and minimize environmental damage [27–29]. Second, improving resource utilization efficiency throughout the food supply chain, reducing food waste, and encouraging green consumption habits will also contribute to slowing climate change [30–32].

At the same time, adaptation strategies are equally critical. To strengthen the food system's resilience to climate change, it is necessary to improve agricultural infrastructure, enhance water resource management, boost crop resistance, and promote climate-smart agricultural technologies [33–38]. These actions will better prepare the agricultural system for extreme weather and long-term environmental changes. Finally, effective policies and regulations must be formulated and implemented. Such policies can not only drive emission reductions in the food system but also enhance its adaptive capacity [39,40]. By mitigating climate change and improving air quality, these climate policies will generate synergies within the food system, promoting sustainable development [41].

Research on the interactions between food systems, climate change, and air pollution has expanded rapidly, producing an extensive body of literature [3,6,19,39–44]. However, most studies [3,6,45] focus on the relationships between food systems and either climate change or air pollution, lacking a comprehensive review of the interactions among all three. Additionally, existing studies provide limited consideration of integrated adaptation and mitigation strategies [5,33]. Therefore, this paper aims to systematically review and summarize the existing research on the interconnections between climate change, air pollution, and food systems, as well as the mitigation and adaptation pathways of food systems. By organizing and synthesizing these issues, this review can help researchers better understand the current research landscape, identify key scientific questions and strategic priorities, and ultimately improve the relevance and efficiency of future research.

This paper comprehensively reviews the complex interactions among food systems, climate change, and air pollution, with a focus on the impacts of climate change and air pollution on agricultural production, as well as the GHG and air pollutant emissions from agri-food systems and their contribution to climate change and air pollution. Furthermore, it reviews mitigation and adaptation measures aligned with food security goals in the

context of climate change and air pollution and examines strategies for and challenges in developing sustainable food systems. Through this review, insights and directions for future research are offered, aimed at promoting the sustainable transformation of food systems.

2. Impacts of climate change and air pollution on food systems

The anticipated population growth and concurrent efforts to tackle hunger are placing significant pressure on future food security [2], while agricultural production—a vital source of food—is profoundly affected by the interplay of climate change and air pollution (Fig. 2). Climate change affects agricultural production through various mechanisms, including rising temperatures, elevated atmospheric CO_2 levels, alterations in water resources, and changes in other factors such as humidity, extreme events, and climate oscillation. Simultaneously, air pollution threatens global and regional agricultural productivity. Tropospheric ozone (O_3) damages crop leaves through stomatal reactions, leading to reduced crop yields. Moreover, aerosols may have dual effects on crop yields by reducing the total solar radiation reaching the surface for photosynthesis and increasing diffuse light, which is more efficiently utilized by plants [46,47]. Furthermore, beyond staple crops, which are the primary energy sources in human diets, attention is increasingly being directed toward perennial crops such as fruits and nuts, due to their high nutritional value, cultivation costs, and vulnerability to future climate change and air pollution [48,49].

Extensive studies [50–54] have examined the impacts of climate change and air pollution on crop yields using various methodologies, yet substantial uncertainties persist. Current approaches mainly include field experiments, empirical statistical models, and process-based crop models. While early field experiments allow precise control over environmental factors, their results are often confined to specific regions and time periods. With technological advancements, empirical statistical models and process-based crop models have become more prevalent. Empirical statistical models establish clear mathematical relationships between crop yields and environmental factors, but their dependence on historical data may constrain their accuracy for future projections. Process-based crop models, on the other hand, enable dynamic simulations of crop growth under changing conditions, yet their inherent uncertainties related to physiological processes and parameters can exceed 50% [55]. Correspondingly, initiatives such as the global gridded crop model intercomparison (GGCMI) seek to address these uncertainties by integrating multiple crop models, refining projections of how climate factors such as CO_2 levels, temperature, water, and nitrogen will influence crop yields at both regional and global scales [56]. This section, therefore, provides a comprehensive overview of how climate change and air pollution independently and jointly influence agricultural production. It systematically examines their impacts on both staple and perennial crop yields, highlights the methodologies used to estimate these impacts, and emphasizes the interactions and joint effects of these two critical drivers.

2.1. Impacts of climate change on agricultural production

2.1.1. Temperature

Human activities have unequivocally caused global warming, and an elevated ambient temperature can alter key physiological processes of crops and influence critical growth and yield formation processes, thereby affecting crop yields [6]. Due to substantial anthropogenic GHG emissions, the global surface temperature in 2011–2020 was around 1.09 °C higher than that in 1850–1900, with land areas experiencing even greater warming of 1.59 °C [55]. Moreover, research predicts that this warming trend will persist until at least mid-century and may even exceed the 2 °C target by the end of the 21st century. Multi-model mean results indicate widespread warming across all shared socioeconomic pathway (SSP) scenarios in both the mid- and long-term future, with the affected geographical areas expanding as the degree of warming intensifies [55]. Consequently, it is beyond doubt that global warming will affect agricultural activities in more regions worldwide, while also impacting livestock productivity and the incidence of related diseases and parasites.

Warming has been shown to typically alter the phenology of staple crops. Studies [58–60] have shown that higher temperatures generally shorten the key growth phases of major crops such as wheat, rice, maize, and soybean. This shortening can occur during the vegetative growth period, when plants focus on leaf and stem development, the reproductive period, which is crucial for final crop yield, or both [60]. Based on results from crop models, statistical regression methods and field-warming experiments, it is estimated that, on a global scale, with every 1 °C increase in average surface temperature, wheat yields decrease by 6.0%, rice by 3.2%, maize by 7.4%, and soybean by 3.1% (without CO_2 fertilization effect) [61]. On top of that, a recent study [62] based on ensembles of the latest crop and climate models predicted that the future crisis in major crop supplies due to climate change is likely to occur sooner than expected, primarily driven by rising temperatures.

However, the impact of warming on agriculture production varies significantly depending on geographical location and baseline temperatures. Drawing on previously published meta-analyses and recent crop simulation data, the projected impacts of warming on major crop yields are generally positive in regions where annual mean temperatures are below 10 °C. However, these effects may become detrimental as mean temperatures rise above 15 °C, with more severe negative impacts beyond 20 °C [63]. In tropical regions such as Africa and Central and South America, crop yields usually respond more acutely to elevated temperatures exacerbated by global warming, leading to greater declines compared with those in temperate regions [64]. In contrast, higher temperatures can bring beneficial effects to agricultural productivity in high-latitude areas. Global warming has caused a pole-ward expansion of cropland areas, extended crop growing seasons in temperate regions, reduced cold stress, and alleviated frost damage. Typical examples include increased wheat yields in Northern

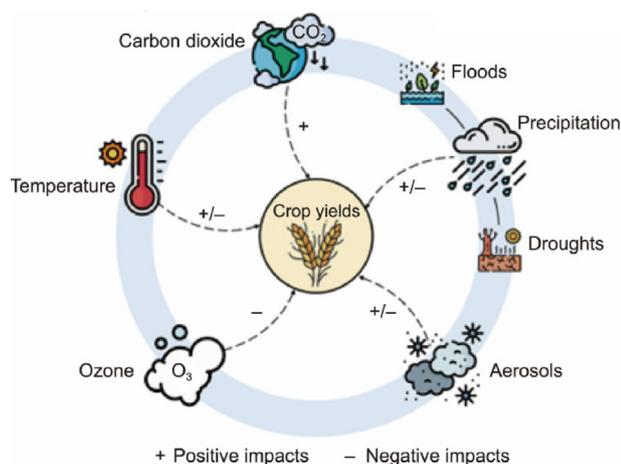**Fig. 2.** Impacts of climate change and air pollution on crop yields. CO_2 promotes crop yields through the fertilization effect, while O_3 reduces yields by causing oxidative damage. The impacts of temperature change vary by region, and the effects of average and extreme precipitation differ. Meanwhile, aerosols exert dual effects on crop yields by altering surface radiation for photosynthesis.

Europe [65,66] and improved maize, rice, and wheat yields in eastern Asia [67–69]. Similarly, a study [49] using empirical statistical methods suggests that climate change has recently boosted banana yields in countries where warming has led to more favorable temperatures, although this benefit is expected to diminish in the future.

2.1.2. CO_2

Increasing atmospheric CO_2—a key resource for plant growth—has the potential to boost crop yields by enhancing fundamental physiological processes. Since 1750, anthropogenic activities have driven a 47% increase in atmospheric CO_2 concentration, raising the current level to 410 parts per million (ppm) [55]. Under different future climate scenarios, CO_2 concentrations may continue to rise to varying levels. In addition to being one of the most important and abundant GHGs, CO_2 serves as an essential substance for crop growth and development [70]. Elevated CO_2 concentrations enhance the photosynthesis process in plants, while concurrently suppressing photorespiration [71]. This results in greater carbon (C) absorption during plant growth, ultimately boosting crop yields—a phenomenon known as the CO_2 fertilization effect [72].

The response of crop yields to the CO_2 fertilization effect has been a major source of uncertainty in assessing the potential impacts of climate change on food security [70]. With the increasing number of laboratory studies and free air CO_2 enrichment (FACE) experiments, along with process-based crop models simulating the effects of varying CO_2 concentrations on crop growth and yields, more insights have been gained into the impact of the CO_2 fertilization effect on crop production [73]. In general, the CO_2 fertilization effect increases crop yields, although the specific impact varies by crop. The yield increase due to CO_2 fertilization effect is typically more pronounced in C3 crops (e.g., wheat, rice, and soybean) than in C4 crops (e.g., maize), due to differences in their photosynthetic pathways [74]. Theoretically, if CO_2 concentrations reach 550 ppm by 2050, photosynthesis in C3 plants is projected to increase by 38% at a constant temperature of 25 ℃, in comparison with levels at 380 ppm [75]. Under warmer conditions, the enhancement of photosynthesis in C3 species may be even more significant [76]. Besides their effects on photosynthesis, elevated CO_2 concentrations increase crop yields by improving water use efficiency in both C3 and C4 crops. Higher CO_2 levels reduce stomatal conductance by 19%–22% [77], leading to decreased transpiration and water loss, which in turn increase crop yields [71]. Remarkably, C4 plants benefit more from this mechanism [78].

It is important to note that elevated CO_2 concentrations may negatively impact various nutrient levels in crops, including those of protein, iron, and zinc [9]. This detrimental impact is particularly concerning for vegetables and fruits, which are vital sources of dietary nutrition for humans. In addition to examining the fertilization impact on crop yields, future research should not neglect changes in crop quality in order to provide a more comprehensive understanding of the effects of CO_2 fertilization.

2.1.3. Water resources

Water resources are a crucial factor in agriculture production and may show significant regional variations under future climate change. To ensure unhindered crop growth, maintaining the balance between crop water demand (e.g., evaporation) and water supply (e.g., precipitation) is essential, especially in rain-fed regions [6]. Temperature fluctuations significantly influence precipitation patterns, yet estimates of these changes from different global and regional climate models remain highly uncertain. Since the 1980s, global land precipitation has risen sharply, marked by significant interannual variability and regional disparities [55].

Regarding the agricultural impacts of average precipitation, empirical statistical models have shown that, from 1961 to 2002, the positive relationship between growing season precipitation and global crop yields explains about 30% of the year-to-year variability in yields for rice and around 50% for soybeans [79]. Other studies [80,81] have found a similar positive correlation for wheat, maize, and barley. On the other hand, research indicates that certain regions are experiencing an upward trend in the frequency and intensity of extremes such as heavy precipitation, floods, and droughts, all of which contribute to substantial crop yield losses. A key point to highlight is that quantifying the impact of these extremes on crop yields is challenging, as multiple factors such as timing, duration, intensity, and frequency affect crop growth, and a deeper understanding is still needed [82].

Heavy precipitation and floods lead to waterlogged soil, which reduces oxygen levels and hinders nutrient uptake, ultimately stunting plant growth. Furthermore, excess moisture causes stomatal closure, which disrupts photosynthesis and damages crop yields [83]. Field experiments have shown that crop yield sensitivity to flooding varies by species; for example, maize is more sensitive than wheat, with their flood-induced yield reductions being 35% and 28%, respectively [84]. Historical observations reveal an increase in heavy precipitation and flood events across Asia, North America, and Europe. Global hydrological models project that, with ongoing global warming, more regions will face these extremes more frequently and with greater intensity in the future, raising concerns for agriculture production.

Likewise, droughts harm crop yields by causing stomatal closure and impairing photosynthesis. Drought-induced stomatal closure also raises crop temperatures, accelerates leaf senescence, and leads to crop failure [85]. Under moderate drought stress, wheat shows greater resilience compared with rice and maize; their respective drought-induced yield reductions are 20%, 25%, and 38% [86]. Since the 1950s, regions such as southern Europe and West Africa have experienced progressively longer and more severe droughts. As global warming intensifies, studies [9,87,88] have also indicated that more regions will face increasingly frequent and severe droughts, with the extent of the impact expanding in line with the level of warming. Beyond this, recent studies have emphasized the critical role of moisture in moderating the heat sensitivity of crops [89]. These studies found that maize and soy yields declined more significantly in the past under hot and dry conditions due to reduced precipitation and increased heat-induced evaporation. Furthermore, they predict that future temperature-moisture couplings will exacerbate yield losses for these crops, leading to a further 5% decline compared with the effects of temperature increases alone [90].

2.1.4. Other climatic factors

Climatic factors such as near-surface relative humidity (RH), extreme events, and climate oscillations are also likely to threaten future agricultural productivity and contribute to interannual yield variability. A machine learning study examining maize, sorghum, and soybean yield in the United States from 1980 to 2016 found that all three crops negatively respond to increased vapor pressure deficit (decreased RH), with maize being the most sensitive [91]. Furthermore, research has shown that RH, rather than precipitation, dominates the hydrological effect on the yields of rainfed crops, accounting for much of the interannual variability in climate impacts [92].

Future climate change is likely to increase the intensity of tropical cyclones and associated peak wind speeds, directly threatening food production (e.g., Cyclone Nargis is estimated to have reduced Myanmar's crop production by 19%, with impacts lasting for the following three years) [9]. Large-scale climate oscillations have also been shown to cause crop yield anomalies through changes

in seasonal temperature and precipitation [93,94]. From 1961 to 2010, yields in two-thirds of global cropland were significantly affected by at least one large-scale climate oscillation [93]. For example, El Niño tended to improve global soybean yield by 2.1%−5.4%, whereas global yields of all major crops were generally below normal in La Niña years [95]. The Madden–Julian Oscillation (MJO) can increase or reduce maize yields throughout the tropics, depending on its different phases and the resulting changes in the crop growth environment [96]. Moreover, as revealed by principal component analysis (PCA), the first principal component explaining historical maize and winter wheat yield anomalies in the United States is strongly associated with the Atlantic Multidecadal Oscillation (AMO) [97].

2.2. Impacts of air pollution on agricultural production

2.2.1. Ozone

Tropospheric O_3 pollution—one of the most severe air quality challenges at present—can add significant risks to global food security by impairing crop growth and reducing yields through oxidative damage to plant tissues [98]. Largely attributed to precursor emissions and accelerated formation due to warming [99], surface O_3 concentrations have exhibited a fair amount of increase, with regional variations, since the pre-industrial period [100]. In the northern hemisphere, O_3 levels have reached 50 parts per billion (ppb), with particularly rapid growth being observed in Asia; given this region's role as a major crop producer, food security in Asia is becoming a growing concern [101].

As a potent oxidant, O_3 enters plant leaves through the stomata, oxidizing plant tissues, and impairing physiological functions such as photosynthesis, ultimately leading to reduced crop yield and quality [102]. Accumulated daytime O_3 concentrations exceeding a threshold of 40 ppb (AOT40) during the plant growing season is a crucial indicator in statistical models for assessing O_3 impact on plants, with a higher value suggesting that plants are exposed to harmful levels for longer periods [103]. The global impact of O_3 on crop yield losses has been quantitatively assessed by means of various chemical transport models and O_3 metrics (Table 1 [13,104–108]). A recent study based on data from about 3000 air

monitoring sites indicated that O_3 pollution has caused respective yield losses of 33%, 23%, and 9% for wheat, rice, and maize in China [103]. Furthermore, O_3 pollution has damaged the yields of various perennial crops. For example, research estimated that O_3-related yield reductions in California varied from −2% for strawberries to −22% for table grapes [48]. Regarding future yields, a recent study based on a crop model predicted that, in regions with high O_3 levels such as south Asia and China, O_3-induced yield reductions will partly offset the increases brought by the CO_2 fertilization effect [109].

Periods of high O_3 concentration often coincide with periods of high temperature, which typically overlap with the plant growing season [13], exacerbating regional crop yield losses. In addition to stimulating O_3 formation, higher temperatures can increase O_3 uptake by plants, and crop yield losses under the combined stresses of heat and O_3 may be more severe [9]. Studies have also found that typical crops may exhibit greater sensitivity to either heat (e.g., maize) or O_3 pollution (e.g., wheat) stress depending on region, highlighting the need to evaluate the effectiveness of climate adaptation strategies versus air pollution control efforts in different regions to ensure food security [98].

2.2.2. Aerosols

Aerosols from both anthropogenic (e.g., combustion of fossil fuels and biomass burning) and natural (e.g., wildfire) sources not only pose threats to human health [110] but also present significant challenges to global agricultural productivity [111]. Unlike O_3, which exerts direct detrimental effects on crop yields, aerosols have complex impacts on agricultural productivity. For example, absorptive aerosols such as black carbon (BC) reduce the total (both direct and diffuse) solar radiation reaching the Earth's surface, limiting the light available for plant photosynthesis and thereby reducing crop yields [43]. In contrast, scattering aerosols increase the diffuse fraction of solar radiation reaching the ground [44]. Studies [112,113] suggest that plants typically utilize diffuse radiation more efficiently for photosynthesis, potentially enhancing crop productivity.

Research [114] based on GEOS-Chem simulations quantifying the impacts of air pollution on global staple crop yields found that

Table 1
Estimated global relative yield loss due to O_3 pollution.

Time	Models	Metrics	Crops	Relative yield loss (%)	Reference
2000	MOZART-2	AOT40, M7, M12	Wheat	3.9–15.4	[13]
			Maize	2.2–5.5	
			Soybean	8.5–13.9	
	TM5	AOT40, M7, M12	Wheat	7.3–12.3	[104]
			Rice	2.8–3.7	
			Maize	2.4–4.1	
			Soybean	5.4–15.6	
2006–2010	GEOS-Chem	AOT40, W126, M7, M12	Wheat	7.2 ± 7.3	[105]
			Rice	2.6 ± 0.8	
			Maize	3.6 ± 1.1	
			Soybean	6.7 ± 4.1	
2008–2010	Models provided by the ACCMIP and HTAP2 projects	AOT40	Asian wheat	4–39	[106]
			Western wheat	0–27	
			Soybean	2–10	
2010–2012	EMEP MSC-W	AOT40, M7, POD₃IAM	Wheat	9.4–13.8	[107]
2030	MOZART-2	AOT40, M7, M12	Wheat	4.0–17.2	[108]
			Maize	2.5–6.0	
			Soybean	9.5–14.6	

M7: seasonal 7-h O_3 mean concentration during daytime; M12: seasonal 12 h O_3 mean concentration during daytime; W126: sum of weighted hourly O_3 concentrations accumulated during daytime over the three months growing period; POD₃IAM: phytotoxic O_3 dose above 3 nmol·m^{-2}·s^{-1}, with model adapted for large-scale integrated assessment modeling. MOZART-2: Model for ozone and related chemical tracers, version 2; TM5: tracer model, version 5; GEOS-Chem: global three-dimensional model of atmospheric chemistry driven by meteorological input from the Goddard earth observing system (GEOS); ACCMIP: atmospheric chemistry and climate model intercomparison project; HTAP2: hemispheric transport of air pollution phase 2; EMEP MSC-W: European Monitoring and Evaluation Programme, meteorological synthesising centre–west.

airborne particulate matter (PM) can scatter light, creating more even and efficient surface radiation for photosynthesis; however, large uncertainties exist in crop response to changes in diffuse radiation. In agricultural regions of the American Midwest, smoke plumes produced by wildfires in western North America have been found to slightly enhance maize and soybean yields, primarily due to changes in solar radiation [115]. Research [14] has also found that PM pollution mitigation during 2010–2018 in China resulted in net crop yield increases of 0.5%−1.9%, outweighing the negative impacts of concurrent climate change.

2.2.3. Other pollutants

Numerous studies have explored the effects of O_3 and aerosols on agricultural production; however, other pollutants such as nitrogen oxides (NO_x) and sulfur dioxide (SO_2) are also widely emitted, affecting crop yields through both direct damage and indirect contributions to the formation of O_3 and aerosols [116]. For one thing, NO_x and SO_2 have been identified as phytotoxins that directly alter photosynthesis, disrupt stomatal control, and lead to premature leaf senescence, ultimately reducing crop yields [117,118]; for another, they contribute to the formation of aerosols, including ammonium nitrate [119] and ammonium sulfate aerosols [120]. As typical scattering aerosols, they further affect crop growth by weakening the solar radiation reaching the surface. For example, the negative effects of SO_2 exposure on maize and soybean yields in the United States have been investigated [116]. Moreover, NO_x serves as a key precursor to tropospheric O_3, with further detrimental effects on crop growth and agricultural production [121]. Recent research [122] suggests that reducing NO_x levels to the current fifth percentile would enhance yields by approximately 25% for winter crops and about 15% for summer crops in China.

2.3. Climate change and air pollution: Interactions and joint impacts on agriculture

Climate change and air pollution are intricately interconnected through complex coupling effects. Climate change alters meteorological conditions, thereby influencing the formation, transport, and removal of pollutants [15,16]. In turn, air pollutants such as aerosols directly affect radiative forcing by absorbing or scattering solar radiation, and indirectly impact climate systems by modifying the microphysical properties of clouds [17]. These interdependencies highlight the profound implications of their joint effects on regional and global agricultural production.

Some studies have evaluated the relative contribution of climate change and air pollution to crop yield changes. In India, air pollution has likely been the dominant factor in regional yield losses in the past [43]. In China, the drastic mitigation of PM pollution from 2010 to 2018 offset the negative impacts of concurrent climate change, resulting in a net yield increase [14]. However, for most regions in the future, excluding CO_2 fertilization effects, the warming-driven impacts of climate change are likely to surpass those of air pollution, resulting in yield reductions [14,98].

Several studies have also explored the agricultural impact of the interactions between climate change and air pollution. Research [123] separating climate-driven and emission-driven pollution effects suggests that future warming can increase O_3 concentration in most regions, leading to a climate penalty for crop yields. Moreover, yield losses due to O_3 are particularly severe when high temperature and dry conditions act together. Under such conditions, O_3 exacerbates crop yield losses by disrupting the formation of abscisic acid, a hormone that signals leaves to reduce stomatal conductance and alleviate water loss [124]. In turn, quantitative studies have shown that air pollutants can indirectly affect crop yields by modulating regional climate variations—even dominating the

overall impact in certain highly polluted areas [125,126]. For example, studies [111] have shown that BC and other aerosols in the atmospheric brown clouds over India can absorb solar radiation, reducing the radiation reaching the surface. This results in surface cooling and reduced monsoon precipitation, ultimately affecting regional crop yields.

Nevertheless, considerable uncertainty remains regarding how climate affects crop yields through its impact on air quality and how air pollution influences crop yields by modifying climate factors such as crop yield responses to diffuse light [114]. Further research is still needed to explore the pathways of the interactions of climate change and air pollution and quantify the agricultural impacts of these interactions. A deeper understanding is crucial for ensuring future food security, which will then guide the development of more effective and targeted policies.

3. Impacts of food production on climate change and air pollution

In addition to being affected by climate change and air pollution, food systems make a significant contribution to global climate change and regional air pollution. The food supply chain generates considerable quantities of GHG and air pollutant emissions during the agricultural production, land use, and beyond-farm stages. Understanding the sources and drivers of food system emissions and their contribution to climate change and air pollution is essential in developing effective mitigation strategies. Therefore, this section provides a comprehensive overview of GHG and air pollutant emissions from agri-food systems, as well as the contribution of the food system to global climate change and air pollution.

3.1. Greenhouse gas emissions from agri-food systems

GHG emissions from agri-food systems are classified into three main sources: emissions from agricultural activities, emissions from land use and land-use change (LULUC), and emissions beyond the farm gate [127]. Emissions from agricultural activities mainly include CH_4 emissions from rice cultivation, N_2O emissions from fertilizer use, CH_4 emissions from enteric fermentation, and CH_4 and N_2O emissions from manure management. LULUC emissions primarily consist of the CO_2 released during the conversion of forests to cropland. Emissions beyond the farm gate—namely, those from food transport, processing, packaging, and retail and from food loss and waste (FLW)—are more challenging to quantify due to data limitations, leading to greater uncertainty.

The Intergovernmental Panel on Climate Change (IPCC)'s special report on climate change and land indicated that, from 2007 to 2016, annual GHG emissions from food systems ranged between 10.8 and 19.1 gigaton CO_2 equivalent per year ($GtCO_2eq·a^{-1}$), accounting for 21%–37% of total anthropogenic emissions [128]. Fig. 3 [129] illustrates the GHG emissions from global agri-food systems by process in 2015. The data reveals that emissions of CO_2 (8.2 gigaton (Gt)) and non-CO_2 gases (6.5 $GtCO_2eq·a^{-1}$ for CH_4 and 2.2 $GtCO_2eq·a^{-1}$ for N_2O) are roughly equal in magnitude. Approximately half of CO_2 emissions originate from LULUC, while the other half is linked to energy consumption beyond the farm gate. In contrast, CH_4 and N_2O emissions are predominantly generated by agricultural activities, such as rice cultivation, enteric fermentation, and manure management. These findings highlight the varied sources of emissions in the agri-food system, underscoring the need for more comprehensive research to better understand and mitigate their impacts.

The understanding of agri-food system emissions has evolved significantly over time, progressing from sector- and region-specific studies to comprehensive assessments of full life-cycle
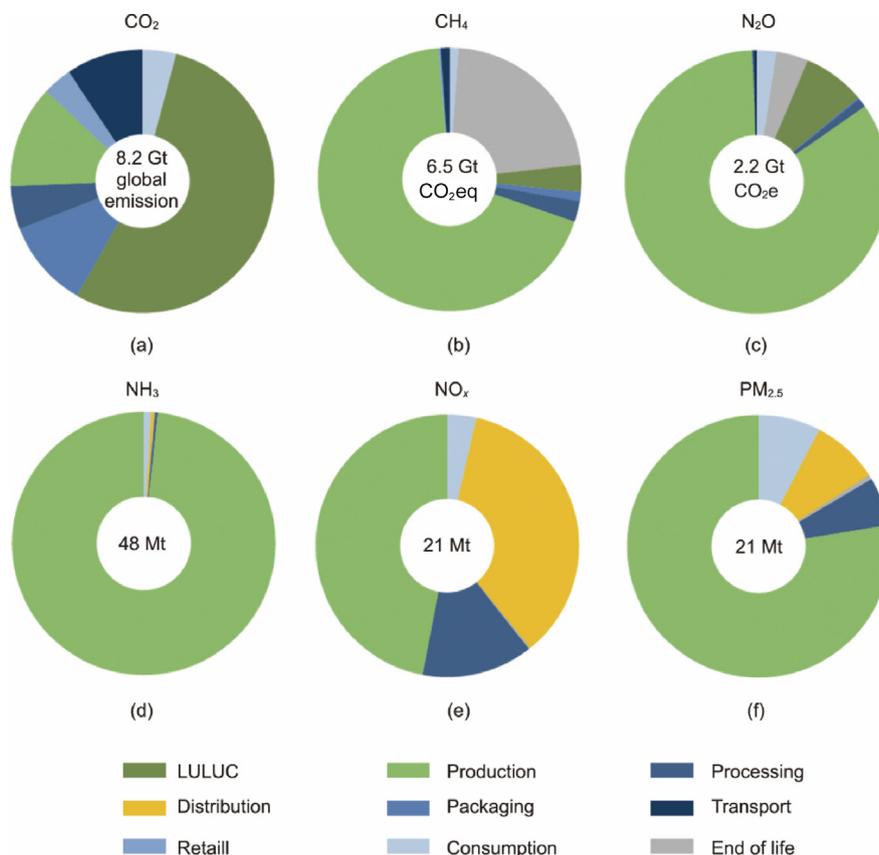
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Fig. 3. Emissions of GHGs and air pollutants from the global food system (by process). The main GHGs (including CO_2, CH_4, and N_2O) and air pollutants (NH_3, NO_x, and $PM_{2.5}$) are shown. Numbers inside the pie charts represent global total emissions from the food system in 2015. The distribution process includes packaging, transport, and retail. (Derived from EDGAR-FOOD [129])

emissions at the global level. Due to varying research objectives, scholars have approached food system emissions from different perspectives [23,130]. Early studies primarily concentrated on specific agricultural processes, laying the groundwork for broader assessments. For example, global cropland emissions were found to be disproportionately influenced by rice cultivation and peatland practices [131]. Similarly, a study on global livestock estimated annual emissions at 5.6–7.5 $GtCO_2eq·a^{-1}$ from 1995 to 2005, with non-CO_2 emissions contributing 2.0–3.6 $GtCO_2eq·a^{-1}$ [132].

In recent years, the scope of research has expanded to include comprehensive national-level assessments of global food system emissions [133]. Growing focus has been placed on emissions beyond the farm gate, encompassing processing, packaging, transport, retail, consumption, and FLW. These beyond-farm emissions now account for 25%–35% of total food system emissions [19,134,135]. Over the past three decades, emissions beyond the farm gate have nearly doubled, emerging as a primary driver of emissions growth in the agri-food system [134]. Notably, FLW has received particular attention, with related emissions in 2019 reaching 1.28 $GtCO_2eq·a^{-1}$, accounting for 20.7% of the total beyond-farm-gate emissions and marking a 30% increase since 1990. Other processes, including food retail, transport, and processing, collectively contributed approximately 2.34 $GtCO_2eq·a^{-1}$. Among these, food retail experienced the most dramatic growth, with emissions increasing by 631% compared with 1990 [134].

Understanding the drivers of changes in agri-food system emissions is vital for designing effective mitigation strategies. Key drivers such as population growth, increasing food demand, and the expansion of animal-based diets are all expected to further exacer-

bate emissions from the agri-food system [23,130]. Recent comprehensive research [136] systematically assessed the drivers of agricultural system emissions, including emissions from agricultural activities and LULUC across various processes and scales (global, regional, and national), along with product-specific impacts. The research showed that global agricultural production has nearly tripled since 1961, while emissions from agricultural systems have increased by only 24%. This relative stability in emissions is largely attributed to a significant reduction in the land requirement per unit of agricultural production, which has decreased by 70%. Despite these improvements, current per-capita emissions from agriculture and land use remain high, exceeding 0.5 $tCO_2eq·a^{-1}$. Evaluations of emissions drivers, including those beyond the farm gate, have also incorporated factors such as trade structures and domestic supply ratios [137]. Population growth in developing countries has been identified as a major factor contributing to the rise in emissions associated with the international food trade. Research on emission drivers provides valuable insights into mitigation efforts.

3.2. Air pollutant emissions from agri-food systems

Agri-food systems are major contributors to atmospheric pollution, posing significant threats to human health. Among various air pollutants, NH_3 emissions have drawn particular attention due to their prevalence in food systems [138], primarily originating from livestock husbandry and crop production. In livestock systems, NH_3 is released into the atmosphere from animal waste. Similarly, fertilizer application in cropland contributes significantly to NH_3 volatilization, as a large portion of the nitrogen in fertilizers is con-

verted to NH$_3$ and emitted shortly after being applied to fields. These two sources collectively account for the majority of NH$_3$ emissions in the agri-food system.

To better quantify and manage these emissions, several global gridded NH$_3$ emission inventories have been developed using emission factor approaches or process models [139–141]. Recent advancements include a machine learning model that leverages field observations to generate crop-specific and spatially explicit NH$_3$ emission factors globally, reducing uncertainties in cropland NH$_3$ emission estimates [142]. These developments provide a foundation for more comprehensive analyses of air pollutant emissions across the entire food system.

Expending on the understanding of specific pollutants such as NH$_3$, recent studies have broadened their focus to encompass air pollutant emissions across the entire food system [143,144]. The life cycle of food systems contributes substantially to global anthropogenic air pollutant emissions, accounting for 72% of NH$_3$, 13% of NO$_x$, 9% of SO$_2$, 58% of fine particulate matter (PM$_{2.5}$), and 19% of non-methane volatile organic compounds (NMVOC) emissions [143].

The sources of these pollutants vary across different stages of the food system. NO$_x$ emissions primarily originate from the burning of crop residues, with secondary contributions from fuel combustion during agricultural transportation and other processes. PM$_{2.5}$ emissions are largely attributed to land use changes and the burning of crop residues. Other pollutants, such as SO$_2$ and NMVOCs, are primarily generated beyond the farm gate, particularly during food processing and distribution. As shown in Fig. 3, the total emissions from the food system in 2015 were 48 million tonnes (Mt) of NH$_3$, 21 Mt of NO$_x$, and 21 Mt of PM$_{2.5}$. Most of these NH$_3$ emissions were emitted from agricultural production activities, while approximately 50% of the NO$_x$ emissions were linked to farming; the remainder came from activities beyond the farm gate, particularly transportation. Over 75% of PM$_{2.5}$ emissions were attributable to farming practices, with the rest generated by other processes. These findings underscore the diverse sources of air pollutant emissions within the food system, emphasizing the need for targeted mitigation strategies across different processes and stages of the food life cycle.

Comprehensive tracking of air pollutant emissions from agri-food systems is essential for developing effective mitigation strategies. However, the high spatial and temporal variability of these emissions make this task challenging. Unlike GHGs, air pollutants undergo complex processes of formation, reaction, and degradation in the atmosphere, leading to substantial variations in their environmental impacts across different regions and time periods. These spatial and temporal variations underscore the need for emission inventories with finer resolution. High-resolution inventories are necessary for accurately capturing the dynamics and behavior of agri-food system emissions, which enables a more precise understanding of their environmental impacts. In addition, improving the characterization of emissions across multiple scales will help reduce uncertainties and improve the accuracy of air quality models. Such advancements are crucial for providing policymakers with reliable, timely, and actionable information, enabling more effective decision-making in addressing the air pollution from agri-food systems.

3.3. Consumption-based emissions

Emissions accounting is a key focus of global climate change and air quality research, with production-based accounting being the most widely used method [145,146]. Production-based accounting attributes emissions to producers, focusing on the emissions generated within a region's production processes, including exports [145–147]. While previous studies have quantified GHG emissions from global food production [19,20,136,148], production-based accounting overlooks emissions tied to the final consumption of goods, creating a geographical disconnect in emission responsibility [145,150,150]. To address this issue, consumption-based accounting has gained attention. Consumption-based accounting assigns emissions to final consumers, regardless of where the goods are produced, accounting for imports while excluding exports [151–153]. Complementing production-based accounting, consumption-based accounting quantifies the virtual flow of emissions outsourced to other countries and offers a tool for developing consumption-focused emission reduction policies [137,154]. There are two main approaches to consumption-based GHG emissions accounting: bottom-up approaches, in a form of process analysis commonly known as life-cycle assessment (LCA); and top-down approaches in the form of multi-regional input-output (MRIO) models and physical trade flow (PTF) analyses [137,155]. These approaches differ in system boundaries, detail levels, and temporal and spatial resolutions [137,156].

LCA is a method used to systematically analyze the environmental impact of a product, service, process, or policy throughout its entire life cycle, from production to use and disposal [157]. It offers a detailed depiction of each stage in the supply chain, with higher spatial and temporal resolution than other methods, making it especially suitable for household consumption analysis [156]. LCA typically relies on the life cycle of representative products, with overall consumption emissions being extrapolated using upscaling techniques [158]. Some studies [157,159–161] have employed this bottom-up approach to assess the full life-cycle emissions of specific foods. For example, one study used LCA to evaluate the GHG emissions from beef, covering its life cycle from breeding and slaughter to the consumer's table. The results revealed that the production stage—especially the breeding process—contributed the majority of emissions [160]. This finding highlights the precision of LCA in evaluating the environmental impact of food consumption. However, due to variations in scope and methodology, LCA results are often not comparable on a global scale [157,159]. Furthermore, LCA requires extensive data, particularly for complex global food supply chains, which limits its broader application [157,162].

In contrast, MRIO uses broader system boundaries to quantify emissions related to final food consumption by analyzing input-output relationships in the supply chain (in monetary terms) [163,164]. It excels at capturing cross-regional trade relationships, offering a comprehensive view of the GHG footprint of the global food supply chain [163,164]. For example, research has shown that, from 2004 to 2017, 27% of land use emissions were linked to the consumption of agricultural products outside their production regions [163]. Although MRIO provides a global perspective, its reliance on industry or product group averages makes it less precise for product-specific emissions [137,165].

PTF, another top-down method, focuses on tracking actual material flows and provides high-resolution analysis of agricultural trade between countries [165,166]. It captures direct GHG emissions from food consumption by utilizing more detailed industry and product data [166,167]. For example, a PTF-based study found that, in 2019, 31% of global GHG emissions originated from the food supply chain, with 19% being outsourced through international trade and developing countries such as China and India contributing the most [137]. PTF's high-resolution tracking of material flows makes it an ideal tool for analyzing emissions at the product level [166,167].

These different methods offer complementary insights into the global food system's emissions. While LCA is detailed but limited in scope, MRIO and PTF provide broader, regional, and material-flow-based perspectives, which are crucial for understanding the global dynamics of food system emissions.

3.4. Contribution of the food system to global climate change and air pollution

The substantial GHG and air pollutant emissions from agri-food systems have led to severe environmental and health impacts. GHG emissions contribute significantly to global warming through the greenhouse effect, while air pollutant emissions play a major role in worsening air pollution. Global warming and air pollution trigger respiratory and cardiovascular diseases, exacerbating public health risks and disproportionately affecting vulnerable populations [168–170].

Between 1855 and 2022, the global average warming caused by GHG emissions from agricultural activities and land use reached 0.55 °C. Of this, CO_2 emissions contributed approximately 0.33 °C, CH_4 around 0.16 °C, and N_2O about 0.06 °C [171]. This historical data highlights the long-term contributions of agri-food systems to global warming. Recent studies [131,132] have provided a more detailed analysis of sector-specific contributions, particularly from livestock. In 2010, of the 0.81 °C warming caused by all anthropogenic factors, non-CO_2 emissions directly generated by livestock accounted for approximately 19%. In addition, CO_2 emissions from pasture conversion contributed a further 0.03 °C, making livestock-related warming responsible for 23% of the total warming in that year [172]. These contributions to global warming are typically quantified using climate models that simulate their impact on radiative forcing. By assessing changes in radiative forcing, these models calculate the corresponding temperature increases, offering critical insights into the role of agricultural emissions in the greenhouse effect.

In contrast to other GHG-emitting sectors, the agri-food system emits significant amounts of CH_4 and N_2O in addition to CO_2. Unlike CO_2, CH_4 is a short-lived GHG that accumulates and is removed from the atmosphere over shorter timescales. As a result, CH_4 contributes the majority of its warming effects within a few decades, with a diminished impact over the longer term. To quantify the greenhouse effects of these gases, the 100-year global warming potential (GWP100) metric is widely used in the literature. This method converts N_2O and CH_4 into CO_2 equivalents, which provides a simple and standardized approach to assess the contribution of agri-food system emissions. However, GWP100 overlooks the varying impacts associated with the distinct emission pathways of GHGs. For example, recent research indicates that CH_4's contribution to climate warming over the past century may be underestimated using this metric [172]. Given that CH_4 emissions have been rising at approximately 1% per year, reliance on GWP100 could downplay its short-term impact on global warming [173]. These findings suggest that policymakers should place greater emphasis on reducing non-CO_2 emissions from agri-food systems. Targeted reductions in CH_4 and N_2O could provide more substantial environmental benefits in the near term, complementing longer-term CO_2 mitigation strategies.

In addition to its significant contributions to climate change, the agri-food system profoundly impacts air quality, with far-reaching consequences for human health and agricultural productivity. Agriculture is a major source of NH_3 emissions, which can transform into secondary $PM_{2.5}$ in the atmosphere. Between 1990 and 2013, the contribution of NH_3-nitrogen to global $PM_{2.5}$ concentrations increased from 25% to 32% [138], with the majority of NH_3 originating from agricultural activities. This increase poses serious health risks, including cardiovascular and respiratory diseases and, in severe cases, even mortality. In 2018, air pollution from food system emissions was responsible for approximately 22.4% of global mortality due to poor air quality [3].

Over the years, the environmental and health impacts from agri-food systems have gained increasing recognition. Nonetheless, significant gaps remain in the assessment of global and regional agri-food system emissions, particularly for LULUC and activities beyond the farm gate [174]. Addressing these gaps requires comprehensive tracking across all stages of the supply chain, supported by localized data to improve accuracy [175]. Non-CO_2 emissions from agricultural production also demand greater attention because of their pronounced short-term warming effects relative to CO_2 equivalents [171,172]. For air pollutants, advancing high-resolution emission inventories is a key step toward achieving more precise assessments. These advancements will enable the development of targeted and effective mitigation strategies. Going forward, further development of integrated assessment models will be effective in refining our understanding of agri-food system emissions and designing effective policies to mitigate their environmental and health impacts.

4. Sustainable food systems to address climate change, air pollution, and food security

The interactions among food systems, climate change, and air pollution pose challenges to the sustainable transition of food systems. Climate change and air pollution may threaten future food security. In addition, food system emissions contribute significantly to global climate change and air pollution. Mitigation efforts to reduce food system emissions and adaptation measures to increase the resilience of the global food system are vital in order to mitigate climate change, improve air quality, and ensure food security. This section provides an overview of mitigation and adaptation strategies for food systems and the concept of climate-smart and environmentally friendly agri-food systems.

4.1. Mitigation of emissions from food systems

Food systems hold significant potential for mitigating climate change through the adoption of various emission mitigation technologies [27,28]. According to the IPCC report, the food system offers an technical mitigation potential of more than 15 $GtCO_2$-eq·a^{-1} from 2020 to 2050, encompassing both supply- and demand-side measures (Table 2 [39,176]). On the supply side, measures targeting agricultural GHG emissions, such as crop nutrient management, rice management, enteric fermentation mitigation, and manure management, could achieve reductions of 1.7 (0.5–3.2) $GtCO_2eq·a^{-1}$. Additionally, carbon sequestration strategies, including soil carbon management, biochar application, and agroforestry, present a substantial mitigation potential of 9.5 (1.1–25.3) $GtCO_2eq·a^{-1}$. On the demand side, strategies such as promoting dietary shifts toward lower-emission foods, reducing FLW, and improving resource use efficiency could contribute an additional 4.2 (2.2–7.1) $GtCO_2eq·a^{-1}$.

4.1.1. Crop nutrient management

Nitrogenous fertilizers, such as urea, ammonium nitrate, and ammonium sulfate, constitute the principal N inputs in croplands but require careful management to minimize their environmental impacts. Effective mitigation focuses on inhibiting nitrification and denitrification in soils while reducing ammoniacal nitrogen volatilization. The principal strategies include refining fertilization techniques, optimizing application timing and rates, switching fertilizer types, and incorporating nitrification inhibitors [29].

The right source, right rate, right timing, and right placement (4R) nutrient stewardship program [177] aligns nutrient supply with crop needs, improving fertilizer efficiency and reducing emissions. This method has been shown to decrease N_2O emissions by 20%–50%, NH_3 emissions by 30%–60%, and nutrient losses from croplands and grasslands [178,179]. Precision agricultural technologies, such as variable rate prescriptions, automated fertiliza-

Table 2
Annual global mitigation potential of different options in agri-food system in 2020–2050.

Option	Mitigation potential ($GtCO_2eq·a^{-1}$)	
	Economic	Technical
Agriculture—reducing CH_4 and N_2O emissions	0.6 (0.3–1.3)	1.7 (0.5–3.2)
Crop nutrient management	0.2 (0.1–0.6)	0.3 (0.1–0.7)
Rice management	0.2 (0.1–0.3)	0.3 (0.1–0.8)
Enteric fermentation mitigation	0.2 (0.1–0.3)	0.8 (0.2–1.2)
Manure management	0.1 (0.1–0.1)	0.3 (0.1–0.5)
Agriculture—carbon sequestration	3.4 (1.4–5.5)	9.5 (1.1–25.3)
Soil carbon management in croplands	0.6 (0.4–0.9)	1.9 (0.4–6.8)
Soil carbon management in grasslands	0.9 (0.3–1.6)	1.0 (0.2–2.6)
Biochar application	1.1 (0.3–1.8)	2.6 (0.2–6.6)
Agroforestry	0.8 (0.4–1.1)	4.1 (0.3–9.4)
Demand-side measures (shift to sustainable diets, reduce food waste, etc.)	2.2 (1.1–3.6)	4.2 (2.2–7.1)

Annual mitigation potential, based on data from the IPCC [39] and Roe et al. [176], predominantly uses GWP100 IPCC Fifth Assessment Report values (CH_4 = 28, N_2O = 265), although some use GWP100 IPCC Fourth Assessment Report values (CH_4 = 25, N_2O = 298). Economic mitigation potential refers to the potential constrained by carbon price up to 100 dollar per ton CO_2 equivalent ($USD·tCO_2eq^{-1}$), and technical mitigation potential is the biophysical potential or amount possible with current technologies.

tion systems, and decision support tools, further enhance nutrient uptake by preventing over-application of fertilizers and tailoring nutrient delivery to crop requirements [30].

Integrated soil–crop systems have become an efficient strategy for simultaneously improving fertilizer efficiency, crop yield, and climate mitigation [180]. Through the utilization of crop simulation models to optimize planting dates, cultivar, and density, along with 4R nutrient models, this approach provides actionable recommendations for effective fertilizer application and can significantly reduce nutrient losses [181].

Enhanced efficiency nitrogen fertilizers, which typically incorporate urease inhibitors, nitrification inhibitors, or a combination of both, are particularly effective in reducing N_2O and NH_3 emissions by delaying the conversion of urea to ammonium and ammonium to nitrate [182]. For example, deep placement of urea combined with nitrification inhibitors can reduce N_2O emissions by 73%–100% and NH_3 emissions by 67%–90% compared with surface broadcasting [183]. However, trade-offs between N_2O and NH_3 emissions and potential negative effects from certain practices highlight the importance of combining multiple measures to address these challenges [183].

According to the IPCC, improving fertilizer application practices in croplands could mitigate 0.1–0.7 $GtCO_2eq·a^{-1}$ between 2020 and 2050 [39]. Regions with high fertilizer use, such as the Asia-Pacific region and developed countries, hold the greatest potential for such emission reductions. Enhancing nutrient efficiency in these areas is therefore critical for achieving significant environmental and climate benefits [32].

4.1.2. Rice management

Rice is a staple food for half the global population, and rice paddies account for approximately 48% of GHG emissions from croplands [184]. Effective mitigation measures include water management, cultivar selection, soil improvement, and organic matter management, targeting reductions in CH_4 and N_2O emissions.

Non-continuous flooding practices are a key strategy to reduce CH_4 emissions in paddy fields [33]. This practices achieves a 33% reduction in CH_4 emissions with single drying and up to a 64% reduction with multiple drying [34]. Optimal implementation involves multiple drainage events, moderate soil drying severity, and drainage during high CH_4 emissions stages in the planting sea-

son and keeping fields unflooded during the fallow season. Although non-continuous flooding can increase N_2O emissions by 105% owing to higher soil O_2 concentrations and enhanced nitrogen cycling, the baseline N_2O emissions are relatively low, and the CH_4 emissions reductions typically offset the increase in N_2O when converted into CO_2 equivalents [34,185].

Breeding and selecting cultivars with high plant biomass or yield can further enhance mitigation. High biomass varieties with larger root systems promote CH_4 oxidation by simulating methanotrophic activity [186,187], reducing CH_4 emissions by about 24% in soils with high organic carbon [187]. High-yielding varieties allocate more photosynthates to grain production, limiting the substrates for methanogenesis and lowering CH_4 emissions, particularly in continuous flooded systems [188,189].

Liming acidic paddy soils (pH < 5.5) can enhance yields while simultaneously reducing CH_4 emissions by approximately 20%, achieved by decreasing the substrate availability for methanogens and promoting root growth [35,190]. Besides, N_2O emissions can be reduced by enhancing reductase enzyme activity and bacterial dominance in the soil microbial community [190]. Improving the physiochemical and biological properties of the soil further supports these benefits [191]. Moreover, the removal of organics such as straw, residue, and manure from paddy fields effectively reduces substrate availability for methanogenesis [192]. Additional measures, including no tillage, dry-direct seeding [193], and mineral nitrogen management [194], can also contribute to lower GHG emissions.

Combining agronomic practices such as cultivar selection, water management, and organic matter removal has been proven to be effective in reducing GHG emissions. For example, adaptive rice varieties, intermittent flooding, and straw removal lower CH_4 emissions by approximately 24%, 44%, and 46%, respectively [33]. Integrated approaches are essential to maximize mitigation potential while maintaining productivity.

4.1.3. Enteric fermentation mitigation

Enteric fermentation—a significant source of CH_4 emissions—occurs during the microbial decomposition of dietary carbohydrates in the rumen. Mitigation strategies target both direct and indirect pathways, including controlling livestock numbers, optimizing feeding strategies, and incorporating feed additives. According to the IPCC report, the global technical potential for reducing CH_4 emissions is estimated at 0.8 (0.2–1.2) $GtCO_2eq·a^{-1}$ [39].

Controlling ruminants (e.g., cattle, sheep, and goats) numbers could result in lower CH_4 emissions [195,196]. Correspondingly, intensive animal production systems, such as concentrated animal feeding operations (CAFOs) [197], facilitate population size control, precision feeding, and selective breeding programs to enhance feed efficiency [198]. These approaches improve nutrient utilization by reducing the proportion allocated to maintenance functions and increasing productivity [199].

Shifting dietary and regulating nutritional feeding of livestock can achieve a certain reduction of enteric CH_4 emissions by specific percentages: about 40% by increasing the dietary concentrates, about 22% by replacing fiber concentrates with starch concentrates, about 7% by utilizing biodegradable starch, and about 15% by improving feed digestibility [200]. The potential for emission reductions varies across species. However, diet transition could change the emissions associated with feed manufacture; therefore, attention should be paid to synergies and trade-offs between livelihoods and specific mitigation strategies [201].

Feed additives such as algae, plant metabolites, lipids, and 3-nitrooxypropanol could biologically control ruminants' CH_4 emissions by inhibiting methanogenic microorganisms and their enzymes in the rumen [202]. Emerging approaches to curb CH_4

that are supported by the Global Methane Pledge include technology against methanogens [203], early-life intervention [204], elimination of protozoa [205], and CH_4-oxidizing devices [206].

While grain-feeding livestock in CAFOs offers efficiency gains, the livestock may be vulnerable to health risks due to confined conditions and grain-based diets, potentially compromising food safety and nutritional quality [207]. Despite having longer breeding periods and higher CH_4 emissions, grass-fed animals offer superior nutritional benefits, including increased vitamins A and E and reduced fat [208]. Thus, policymakers should balance emission mitigation goals with considerations of animal health, food quality, and consumer preferences. Improved enteric fermentation mitigation strategies, including dietary adjustments and additive use, hold significant potential for reducing CH_4 emissions. However, successful implementation requires these measures to be integrated with broader agricultural policies to address trade-offs and ensure sustainable livestock management.

4.1.4. Manure management

Effective manure management is critical for minimizing emissions from livestock husbandry and reducing their environmental impact. Key strategies involve optimizing storage and handling practices, improving housing designs, and adopting advanced treatment technologies to suppress nitrification, denitrification, and methane production.

Minimizing manure emissions begins with controlling excreta, moisture, temperature, and soil pH to inhibit the biological processes that release GHGs. Balanced livestock diets can prevent excessive labile nitrogen excreta [209], reducing NH_3 emissions and their downstream contribution to nitrogen-related pollution. Covered manure storage is widely adopted in intensive livestock systems, with reductions of NH_3 emissions ranging from 61% (solid manure with compaction and covering) to 98% (slurry storage with artificial films) [40]. However, certain storage systems, such as slurry tanks, may inadvertently increase CH_4 and NH_3 emissions while reducing N_2O emissions [210].

Livestock housing adaptation can further reduce GHG and NH_3 emissions by incorporating features such as improved ventilation, non-porous surfaces, slatted or sloped floors for efficient drainage, and liquid-solid manure separation systems [40]. Alternative measures involve animal spatial change, nitrification inhibitors, and stand-off pads [211]. Anaerobic digestion presents a promising solution for processing collected manure. Common types of anaerobic digesters include covered lagoons, plug-flow digesters, and complete-mix digesters, which effectively reduce emissions during manure breakdown [41].

Limiting manure storage time is key in minimizing emissions. Strategies such as daily spreading during favorable weather conditions can significantly reduce CH_4 emissions. Composting improvements, including proper aeration, moisture control, and the addition of biochar or other amendments, can lower NH_3 emissions by 30%–70%. Additionally, pH regulation during composting can further reduce emissions by 30%–50% [212–214].

Manure management improvements—particularly in developing countries with inefficient practices—hold significant potential for reducing emissions and minimizing nutrient losses [215]. Implementing integrated strategies that combine optimized storage, advanced technologies, and adaptive management practices can address both environmental and public health challenges associated with manure emissions.

4.1.5. Soil carbon management

Enhancing soil carbon and soil health effectively mitigates and sequesters agricultural emissions while reducing atmospheric GHG concentrations [216]. Crop and vegetation management is crucial for soil carbon enhancement [217], which emphasizes the importance of improving and diversifying crop variety, promoting perennial cropping systems for stable carbon sequestration, and adopting sustainable farming practices such as crop rotation, intercropping, and appropriate stocking density [218]. For croplands, diversifying traditional cereal monocultures with cash crops and legumes can increase the equivalent yield by up to 38%, reduce N_2O emissions by 39%, and improve the system's overall GHG balance by 88%, as demonstrated by a six-year field experiment in the North China Plain [219]. For grassland, key strategies include improving grass varieties, optimizing sward management, and introducing deep-rooting grasses [220]. Enhancing soil health and carbon sequestration involves applying organic fertilizers, maintaining optimal soil moisture, and promoting biological nitrogen fixation. Effective fire management and prevention measures prevent the carbon leakage caused by extreme wildfires [221–223], thereby mitigating climate-fire feedbacks.

4.1.6. Biochar application

Biochar application and management have gained recognition in agri-food system mitigation over the past two decades, as they offer substantial mitigation potential through GHG emissions reduction and carbon dioxide removal (CDR) [224]. Biochar has broad applicability as a soil amendment in agriculture; it can enhance the growth of cereals, legumes, root crops, and vegetables, with its effectiveness largely being determined by soil characteristics, specific crop demands, and prevailing environmental conditions [225]. Allocating organic residues and wastes to biochar, planting annual and perennial biomass crops, and implementing multipurpose agroforestry are effective strategies to increase mitigation potential [226]. On a global scale, biochar application is estimated to be able to mitigate 3.4–6.3 petagram CO_2 equivalent per year ($PgCO_2eq \cdot a^{-1}$), with about half being attributed to CDR [227].

A complex mechanism governs biochar's role in regulating soil CO_2 emissions, in which negative priming and environmental factors synergistically influence both CO_2 absorption and its suppressed emissions. The negative priming of biochar, which is done via the use of slow pyrolysis to convert biomass into less-degradable biochar and other byproducts (e.g., syngas) at high temperatures (350−900 ℃), reduces soil carbon mineralization while increasing the retention of new plant residue inputs by 4%–6% [228,229]. With negative priming and higher persistence, pyrolyzed biomass reduces GHG emissions in comparison with unhydrolyzed biomass, achieving the largest net GHG emission reductions for biochar (48%−54%) [228,227]. Interactions among biochar, clay minerals and the organic matter in soil also introduce additional CDR benefits [230]. High-temperature biochar, high lignin content, low ash content, high organic carbon content, low pH, and the presence of certain toxic substances (e.g., polycyclic aromatic hydrocarbons) are favorable conditions for negative priming [231].

By adsorbing free C and N compounds onto its surface, biochar can also reduce the emissions of CH_4, N_2O, and air pollutants. It reduces soil CH_4 emissions by an average of 7%, with wood-based biochars, high pyrolysis temperatures, neutral soil pH (6.6–7.3), and nearly saturated water content being particularly effective for CH_4 mitigation [232]. Biochar application reduces soil N_2O emissions by an average of 38% [233], with rapid reductions of 52%–84% occurring within 14 days [234]; according to meta-analyses, this approach is particularly effective in paddy and sandy soils. Key factors enhancing N_2O reduction include high-temperature biochars (> 400 °C), wood-based biochar, high C/N ratios, and soils with low organic matter content [233].

Indirect climate benefits are associated with enhancing soil properties (e.g., pH, acidity, microorganisms), increasing productivity, improving nitrogen efficiency, improving water use and

holding capacity, reducing the risk of crust formation and soil erosion, reducing the mobility and toxicity of soil pollutants, and inhibiting soil-borne diseases caused by pathogens. Biochar can contribute to plant growth by acting as a nutrient source, promoting crop growth by 8% [235]; it also increases biomass, which can be further converted into biochar or other long-lasting carbon products. It has been shown to increase the average yield by 9%–16% in field and greenhouse experiments and by 15% in fertilized field experiments [236,237], which are comparable to fertilizer responses [227]. Recent research [238] in China indicates that an increased supply of biomass feedstocks, coupled with a trade-off in biomass allocation for agri-food systems and traditional fuel use, could significantly enhance the potential for biochar application.

4.1.7. Demand-side mitigation

Beyond production-side mitigation, shifting demand toward sustainable diets with more plant-based foods and fewer animal-derived products (particularly from ruminants) can alleviate associated emissions and land use [239]. Concurrently, the revegetation of saved land can sequester carbon, in what has been recognized as the land-sparing effect. Consequently, global and national dietary guidelines have been established regarding recommended energy intake and consumption of red meat, sugar, fruits, and vegetables. Widespread adherence to these guidelines could reduce global GHG emissions (29%) and other environmental impacts (5%–9%) by 2050 [240]. Regionally, such guidelines support GHG reduction in agri-food systems (28% in Argentina [241], 4%–42% in the New Zealand [242], and 25% in Portugal), while offering the co-benefits of water conservation, land productivity, and public health [243]. Individual dietary shifts also warrant attention. Males, who tend to eat more meat, have greater mitigation potential than females [244]. The GHG mitigation potentials associated with diet change vary by diet type: 0.4–2.1 ton CO_2 equivalent per capita for a vegan diet, 0.01–1.5 for a vegetarian diet, and 0.1–2.0 for Mediterranean and similar diet [245]. However, low-emission dietary shifts are constrained by income, cultural norms, and associated economic and caloric costs, underscoring the need for appropriate policies, financial and non-financial incentives, and awareness-raising campaigns to drive changes in consumer behavior and harness potential synergies. A "contract and converge" model, which focuses on reducing food consumption in over-consuming populations while increasing consumption in populations with unmet nutritional needs, is encouraged to prevent FLW and equalize overall food intake, leading to a mitigation of 0.3 ton CO_2 equivalent per capita [245,246].

4.1.8. Food supply chain and trade management

Approximately 28.2% of primary food products and nutrients are lost or wasted along food supply chains, making FLW responsible for 8%–10% of total GHG emissions and highlighting the urgent need for demand-side mitigation [247]. Therefore, the Three Rs—namely, reduce, reuse, and recycle—must be prioritized across packaging, transportation, and storage [248,249]. In fact, the consumption, post-harvest handling and storage, and production stages have even greater potential for reduced environmental footprints, including GHGs, nitrogen, land, water, and phosphorus [250]. The consumption of local food, higher efficiency of processing and transportation, electrified distribution systems, and cleaner storage technologies could reduce FLW and lower environmental footprints [175,251].

Global food trade and consumption-based emissions, which are primarily driven by animal-source foods (particularly ruminant meat and dairy products), underscore the critical need for a transition toward sustainable trade and healthier diets rich in lower-emission meats and plant-based foods [25,252]. Importing and

selecting products from regions with less emissions-intensive production help to ameliorate emissions [163], but such efforts are constrained by political relations and trade policies [253,254]. Liberalized trade policies, production subsidies, environmental cost taxes, and eco-labeling could encourage low-emissions food trade and avoid potential emissions leakage [249,255]; thus, related proposals (e.g., EU's carbon border adjustment mechanism) should extend to agricultural and food-related emissions [137,163].

4.2. Adaptation of the food systems

Adaptation of food systems for enhanced resilience is essential to mitigate the challenges posed by climate change, including global warming, water scarcity, and the increasing frequency of extreme weather events. This section explores targeted adaptation strategies for crop and livestock production.

4.2.1. Crop production

To mitigate the impacts of global warming and extreme events, crop production systems could adopt optimized management practices and biophysical adaptations. Key strategies include breeding climate-resilient crops, adjusting cultivation methods, and improving resource efficiency.

Crop switching and the development of stress-tolerant cultivars offer significant potential for stabilizing yields, especially for staple crops and vegetables [256]. However, the commercial adoption of such cultivars remains limited [257]. Advances in biotechnology and genome sequencing can accelerate the development of crops' resilience to temperature and water extremes, as well as their resistance to pests and diseases [258]. Adaptive management practices, such as optimizing sowing dates and selecting appropriate cultivars, have been shown to boost crop yields by approximately 12%, alleviating the adverse effects of climate change while enhancing the CO_2 fertilization effect [259]. Furthermore, redistributing crop types across regions can enhance yield stability. For example, global warming has increased agriculture suitability in high-latitude regions while extending growing seasons in middle- and low-latitude areas [260]. In China, recent crop-switching initiatives under central coordination resulted in maintained yields while promoting sustainable agricultural development goals through spatial optimization [261].

A precision composting strategy tailored to specific crop needs and local environmental conditions can enhance food production. Key factors include nitrogen supply, carbon-to-nutrient ratios, pH, salinity, soil texture, soil organic carbon, temperature, and rainfall/irrigation. Diversified farming systems, including mixed planting, intercropping, crop rotation, and diversified management, strengthen resilience to climate change and improve soil health [261–263]. High-yield farming strategies, such as the spatial optimization of fertilizer use and strategic crop allocation, could reduce required cropland area by nearly 50%, freeing up land for carbon sequestration through natural vegetation restoration [264].

Water availability and reliability are critical for crop production. Adaptation measures include rainwater harvesting and storage, deficit irrigation techniques, efficient irrigation systems, and advanced techniques such as drip-irrigation and hydroponics, which are particularly effective under extreme drought conditions [265]. These strategies not only enhance water use efficiency but also improve crop yield stability in water-scarce regions. Climate change has increased the frequency and severity of pest and disease outbreaks, necessitating the establishment of integrated crop-environment management systems. These systems enhance the detection and control of pests and diseases, ensuring sustainable crop production under changing environmental conditions.

4.2.2. Livestock production

Global warming exerts a localized influence on aboveground plant biomass, leading to higher temperatures, increased humidity, and the expansion of temperate grasslands, which may enhance yields and boost overall livestock productivity in some regions [266]. However, these potential benefits are often offset by heat and water stress, necessitating comprehensive adaptation strategies [267].

Adaptation efforts can be categorized into technical, ecological, and behavioral measures. Technically, adopting climate-resilient livestock species (e.g., camels) [268], implementing crossbreeding programs, and improving ventilation and building designs can strengthen livestock resilience to extreme weather [269]. Ecological approaches such as silvopasture systems—that is, integrating the grazing of livestock, tree growth, and forage growth on the same land—can store carbon, counteract local temperature increases, and provide sustainable livelihoods for vulnerable communities [269]. Behavioral measures include seasonal adjustments to herds and watering places, feeding with climate-resilient fodder, maintaining emergency reserves of fodder and water, and improving disease prevention [269]. Enhancing pastoralists' understanding of climate and ecological changes through targeted education programs can improve decision-making and long-term planning [270]. Finally, policy interventions supporting disease prevention, sustainable grazing practices, and market access for climate-resilient livestock products are critical for building adaptive capacity in livestock systems.

4.3. Climate-smart and environmentally friendly agri-food systems

To maximize synergies, manage trade-offs, and harness co-benefits across the agri-food system, climate-smart agriculture—an integration system of crops, livestock, fisheries, and agroforestry—has been proposed to achieve food security, as well as climate change mitigation and adaptation. As a holistic approach, climate-smart agriculture extends beyond production technologies to encompass supportive policies and governance, such as stable agricultural policies, enhanced information transparency, coordinated institutional arrangements, and adaptive incentive mechanisms [271]. The operation of such integration systems and their ecosystem services are leveraged to enhance productivity, adaptation, and mitigation in climate-smart agriculture. The implementation of climate-smart agriculture could achieve multiple benefits and contribute toward the Sustainable Development Goals (SDGs), especially the goals of zero hunger (SDG 2), good health and well-being (SDG 3), and climate action (SDG 13) [272,273].

Key measures of climate-smart agriculture include the coordinated management of nutrients, water, and pests; enhanced management of pastures and forestry, along with the restoration of degraded lands; and enhanced soil quality, which improves productivity, adaptation, and mitigation by regulating carbon, oxygen, and nutrient cycles, increasing resilience to droughts and floods, and promoting carbon sequestration. Furthermore, digital agriculture and artificial intelligence (AI) technologies are emphasized and applied to monitoring, fertilization, irrigation, and management, thereby enhancing the climate resilience and mitigation potential of agri-food systems [274,275].

The implementation of climate-smart agriculture has been recommended and has achieved success, contributing to agricultural upgrades and productivity improvements. Examples include climate-smart villages in South and Southeast Asia [276], climate-smart forestry in Europe [278,279], and climate-smart projects in African countries [277]. For example, in sub-Saharan Africa, sustainable practices such as conservation tillage and agroecology have successfully reduced GHG emissions while improving soil health and protecting biodiversity [276,277]. Similarly, in countries such as Pakistan and Kenya, climate-smart technologies such as solar-powered irrigation systems and AI-driven precision agriculture have been instrumental in boosting crop resilience against droughts and other extreme weather [277].

In low- and middle-income countries, where climate change exacerbates food crises and malnutrition, there is a heavy reliance on agricultural output to meet basic food needs, and certain mitigation measures—such as changing agricultural and land-use practices—may inadvertently affect agricultural production, exacerbating food insecurity. This introduces trade-offs between mitigation strategies and ensuring food availability. Climate-smart agriculture and its interventions offer a pathway to enhance productivity while minimizing environmental impacts. Furthermore, low- and middle-income countries and smallholder farmers, which have less accessibility to financial resources and technology, require greater investment, supportive policies, and technology transfer to guide their production and climate adaptation without compromising food security [280].

5. Conclusions

This study systematically reviewed the literature on food systems, climate change, and air pollution, identifying the diversified impacts of climate change and air pollution on food systems and underscoring the critical contributions of food systems to global climate change and air pollution, with a focus on GHG and air pollutant emissions from food systems. It further summarized mitigation and adaptation measures within agri-food systems in response to climate and environmental changes (Section 4 and Fig. 4) and outlined key pathways for building a sustainable food system in the context of climate change and air pollution.

This review article provides a strong academic foundation and practical guidance for the sustainable development of food systems by comprehensively summarizing the interactions among climate change, air pollution, and the food system. As both a driver and a casualty of environmental issues, the food system's role in these global challenges cannot be overstated. Addressing how we can mitigate and adapt to these impacts is essential in securing global food security and advancing sustainable agriculture. The insights provided in this review serve as an important reference for policymakers and stakeholders, helping to strengthen the food system's resilience to climate change and aligning with the broader goals of carbon neutrality and environmental protection.

While existing research has uncovered the broad interactions among food systems, climate change, and air pollution, we suggest the following important research directions that deserve special focus:

(1) Inter-method comparison results should be pursued and the roles of extreme events and combined effects should be investigated further to provide a more accurate and comprehensive assessment of the impacts of climate change and air pollution on crop yields.

(2) Researchers should not only focus on crop yields but also consider the potential impacts on nutrient composition and pest and disease damage, as well as disruptions in the transportation and trade of crops, all of which critically affect food safety and availability.

(3) The comprehensive tracking of food system emissions across all supply chain stages should be prioritized, and localized high-resolution data should be incorporated to improve estimates and reduce uncertainties.

(4) Attention should be paid to non-CO_2 agricultural emissions due to their significant short-term warming effects, and air pollutant emission inventories with high spatial and temporal resolution should be developed to improve air quality modeling.
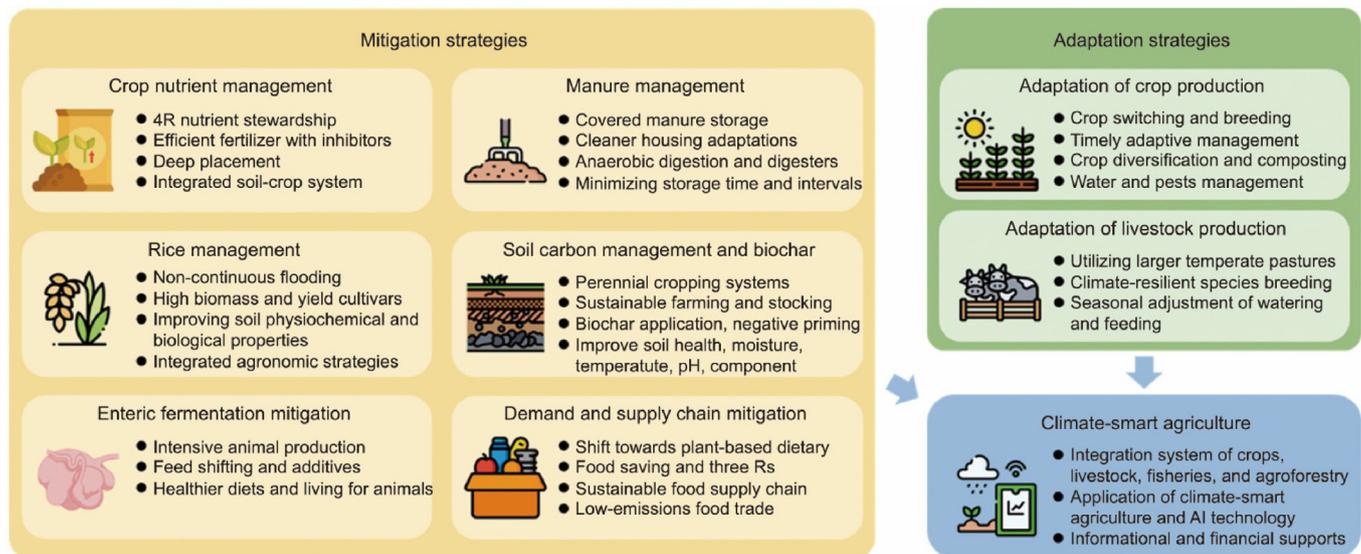
Fig. 4. Representative mitigation and adaptation strategies toward climate-smart agriculture. Mitigation strategies (yellow box) aimed at reducing emissions of GHGs and air pollutants from agri-food systems include interventions in crop nutrients, rice cultivation, enteric fermentation, manure management, soil carbon and biochar, and the demand and supply chain. Adaptation strategies for crop and livestock production (green box) aim to reduce adverse climate impacts and increase the resilience of food systems. The integration of strategies for mitigation and adaptation further supports climate-smart agriculture (blue box).

(5) Estimations of mitigation potential and adaptation should be refined by deepening comprehensive analyses of environmental impacts and cost-effectiveness, and cross-agricultural, socio-economic, and atmospheric model assessments should be facilitated, in order to achieve a holistic understanding of the impacts and interactions of measures across localities and contexts.

(6) The effectiveness of interventions should be enhanced by establishing a comprehensive system of measures and advancing the deep integration of AI to maximize co-benefits and minimize trade-offs across strategies.

Addressing the complex challenges of climate change and air pollution requires swift and coordinated action from governments and relevant agencies worldwide to establish a more sustainable and resilient food system. Achieving this goal hinges on comprehensive policies that integrate climate mitigation and adaptation strategies throughout the entire food supply chain. However, hunger and food shortages in low- and middle-income countries present significant challenges to implementing emission mitigation strategies in agri-food systems. Mitigation efforts must carefully balance reducing emissions with ensuring food availability, particularly in regions where food insecurity is already severe. National efforts alone may be insufficient to tackle these interconnected challenges, making international support essential—particularly for low- and middle-income countries whose technical, financial, and institutional capacities may be limited. Global cooperation is critical in promoting standardized sustainability indicators, sharing best practices, and providing funding and technical support to enable low- and middle-income countries to adopt climate-smart agricultural practices. Such collaboration will not only accelerate the global transition to climate-resilient agriculture but also enhance the effectiveness of emission mitigation strategies and contribute to the global goals of food security and sustainability. Finally, integrating agricultural policies with broader environmental goals—such as carbon neutrality and clean air—can create synergies that not only ensure food security but also strengthen global efforts to mitigate climate change and improve environmental health.

Compliance with ethics guidelines

Chaopeng Hong, Rui Zhong, Mengyao Xu, Peidong He, Huibin Mo, Yue Qin, Danna Shi, Xinlei Chen, Kebin He, and Qiang Zhang declare that they have no conflicts of interest or financial conflicts to disclose.

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