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REVIEW

Toward sustainable food systems: global initiatives and innovations

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KEYWORDS

Agricultural green development, food system, food production, optimization, transform pathways

HIGHLIGHTS

- Utilizing optimization technology in crop and livestock systems can enhance food production.
- Numerous technologies have the potential to contribute to the mitigation of environmental impacts within food systems.
- Three potential pathways are proposed that could transform the current food system to align with SDGs and agricultural green development.

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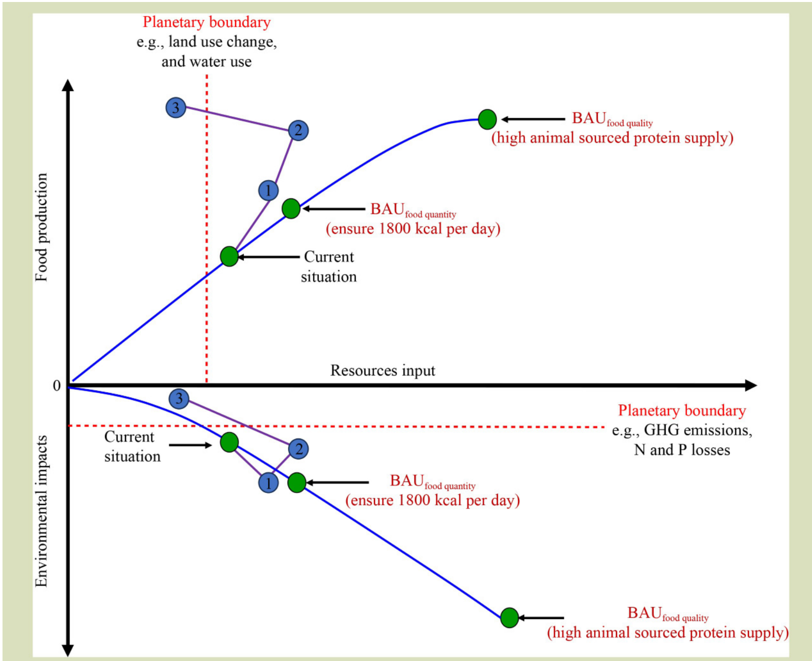
GRAPHICAL ABSTRACT



ABSTRACT

A recent UN Sustainable Development Goals (SDGs) analysis indicated a significant regression in the global SDG goal scores, particularly in SDG 2—Zero Hunger. The emissions of environmental pollution caused by meeting food demands have prompted some countries to intensify their climate change mitigation efforts. These circumstances have introduced significant uncertainty to the future global sustainable food development. Additionally, a notable global challenge is the persistence of hidden hunger, primarily characterized by the insufficient consumption of high-quality animal protein. Addressing this issue would necessitate increased environmental costs to attain high-quality food security. The future food system presents a significant challenge in coordinating food security, food quality and environmental quality. This article presents a comprehensive review and proposes a three-step strategy for future agricultural development based on food security, quality, and environmental aspects. This is a novel food system transfer strategy, as it concurrently addresses both global food security and environmental thresholds. It involves the construction of an efficient food system that operates within the constraints of environmental limits. The objective is to align with global SDG indicators and to maintain natural resource consumption and pollutant emissions within planetary boundaries.

1 Introduction

Contemporary food systems were originally developed to tackle challenges of the mid-twentieth century, aiming to supply abundant, efficient, non-perishable starchy calories to accommodate the expanding global population. Although substantial progress has been made in global food security over the past several decades, there still exist large populations experiencing hunger worldwide. The global number of hungry people is at a record high and continues to increase. In 2021, as many as 828 million people worldwide faced hunger, an increase of 46 million from the previous year, and a rise of 150 million since 2019[1,2]. Currently, global hunger primarily refers to insufficient calorie intake. Hidden hunger is the presence of multiple micronutrient in the absence of an energy-deficit diet[3]. There are over two billion people worldwide experiencing hidden hunger, accounting for approximately one-third of the global population[1,2]. Hidden hunger, particularly the inadequate consumption of high-quality protein, has resulted in significant but often unnoticed health consequences. Hidden hunger does not necessarily lead to obvious clinical symptoms, and so it can be more difficult to garner attention, investment, or action to solve it. However, resolving the hidden hunger for poorest people is the central to meeting the UN Sustainable Development Goals (SDGs), especially for SDG 2. Although the world SDG Dashboard at the midpoint of the 2030 agenda show the world has made some progress in some SDGs, the SDG 2 show a decreasing trend[4]. Globally, protein under nutrition is responsible for about six million deaths worldwide. In central Africa and South Asia, as many as 30% of children suffer from protein deficiency and the protein deficiency also occurs in some subpopulations in developed countries[5]. The number of people suffering from protein deficiency could continue to increase and could reach 150 million people by 2050[6]. The consumption of animal-based food is a simple and effective way to ameliorate protein deficiency. However, the environmental cost of producing high-quality animal protein is currently very high. The food system is currently exceeding planetary boundaries, such as greenhouse gas emissions and nitrogen losses, mainly due to the producing of high-quality animal protein[7–11]. Pressures placed on food production area cause deforestation, biodiversity loss and shortage of freshwater consumption[12–14]. The pandemic has also highlighted the significant adverse impacts on the environment, resources and climate caused by the food produced and the dietary choices people make. To against the environmental and policy challenges, some reports emphasize the importance of transforming the food system[15–17].

To meet human calorie and protein demand with low environmental input, previous studies have discussed many technologies to improve the production of current food system[18–21]. Specifically, the study of Cui et al.[18] showed that the majority of smallholders increased 10% to 50% yield through Science and Technology Backyard platform in China. The integrated soil-crop system management practices implemented in China have been instrumental in increasing average crop yield[19]. Dietary change toward more plant-based flexitarian also considered as high efficiency pathways to solve food shortage. Damerau et al.[20] pointed out that a substantial shift in dietary habits in India could lead to environmentally sustainable agricultural production capable of providing sufficient food for its population of 1.7 billion. In recent years, there has been a growing interest in producing novel proteins as supplements for food production. Boland et al.[21] emphasized that the incorporation of new proteins, which are not presently used as animal feed, as well as the modification and enhancement of proteins currently used as animal feed for human consumption, are important contributions to the future protein sources for human nutrition. While these novel technologies enhance food production, the input of natural resources also poses environmental problem and exceeding planetary boundaries. Recent research has also introduced mitigation technologies aimed at addressing the environmental issues and planetary boundaries pressure stemming from the high input of natural resources. Zhang et al.[22] argued that improvement in technology for fertilizer application, and manure management and recycling to cropland could potentially reduce agricultural emissions by 38% to 67%. While these emerging technologies have achieved notable success in terms of improving food system yields and reducing environmental emissions, there is still a gap in the understanding of how various technologies can work together synergistically to bring about a comprehensive transformation of food systems. In the future, food systems will require the coordinated utilization of various advanced technologies to produce high-quality food and simultaneously mitigate environmental emissions based on at varying consumption needs of people at different stages.

Due to the growing population and changing dietary requirements, the food system is still facing challenges in the next few decades. To meet the diverse food demand in different stages of the future food system, this study proposes a three-step strategy to transform the food system by integrating various novel technologies. The primary task at the current global stage is to address the issue of hunger. The first step should focus on addressing human calorie needs, which are essential for achieving SDG 2—Zero Hunger. While addressing calorie requirements, efforts should be made to strengthen crop and livestock cycles to reduce environmental pollution caused during the food production process. The second step should consider human demand for high-quality protein, enabling the transition from simply eating enough to eating well. At this stage, emission reduction technologies should be introduced to reduce environmental pollution during the food production process. The third step would be to enhance global food production efficiency and environmental sustainability, ensuring that natural resource consumption and environmental emissions associated with food production remain within planetary boundaries.

2 Framework of food system transfer

Meeting food demands poses multiple challenges with notable environmental implications. For example, addressing the global demand for food due to population growth necessitates the implementation of intensive agricultural practices, which includes the use of synthetic fertilizers and pesticides. These practices can result in water pollution, loss of biodiversity, greenhouse gas emissions and soil degradation. Also, expanding food production by converting natural habitats into agricultural land leads to habitat loss, fragmentation and environmental degradation. Agricultural green development (AGD) aims to fully optimize the food supply and consumption, ensuring the provision of sufficient quantities of nutritious food to all consumers, while concurrently safeguarding the natural environment and the livelihoods of farmers[23]. This study developed a framework of food system transformation based on AGD. The framework presents the challenges of current food system and associated potential pathways to transform food systems. The three key pathways are illustrated in Fig. 1, which also highlights the priority of transform stages along with the primary objectives at each stage. The current food system undergoes two significant stages. To support a growing population while achieving SDG 2—Zero Hunger, the first objective is to meet the food quantity requirements, ensuring a daily intake of 1800 kcal per person. The second objective is to meet SDG 3—Good Health and Well-being, ensuring the provision of high-quality animal-sourced proteins for consumption.

To meet the AGD, three steps are proposed that could transform the current food system. The first step is to improve the food production efficiency to meet the food quantity requirements by innovation agriculture technology implication. In the first step, fewer natural resource inputs will be applied to produce the food production to meet the first goal of food system, and coupled crop system and livestock system made environmental pollution less than the original food system. In the second step, meeting the high demand for animal-sourced protein will require an increased utilization of novel food sources. While food production efficiency significantly increases in the second step, natural resource input would potentially contribute to environmental issues. As a result, mitigation technologies will be applied in the crop and livestock systems in the second step. Although these mitigation technologies reduce the environmental problems in the second step compared to the first step, they could still be insufficient to bring the environmental impact within planetary boundaries. The final step would entail enhancing food production efficiency through the optimization of global food trade and the reduction of environmental issues by spatial planning in environmental problem hotspot areas. Free trade agreements could expand the global market opportunities for producers and exporters. Such bilateral and multilateral trade agreements remove trade barriers, reduce or eliminate tariffs, and promote investment and economic growth. Future trade agreements should improve market access and take into account the agricultural production and environmental efficiency of each country. Future trade agreements should also encourage high efficient countries and regions take more responsibility to produce more crop and livestock products, and export them to countries with lower food productivity. This optimization would help maintain natural resource usage within planetary boundaries. Similarly, spatial planning of crop and livestock systems in environmental problem hotspots areas would ensure that environmental impacts remain within the limits of planetary boundaries. Compared to previous single target food system optimization measures, this approach partitions the

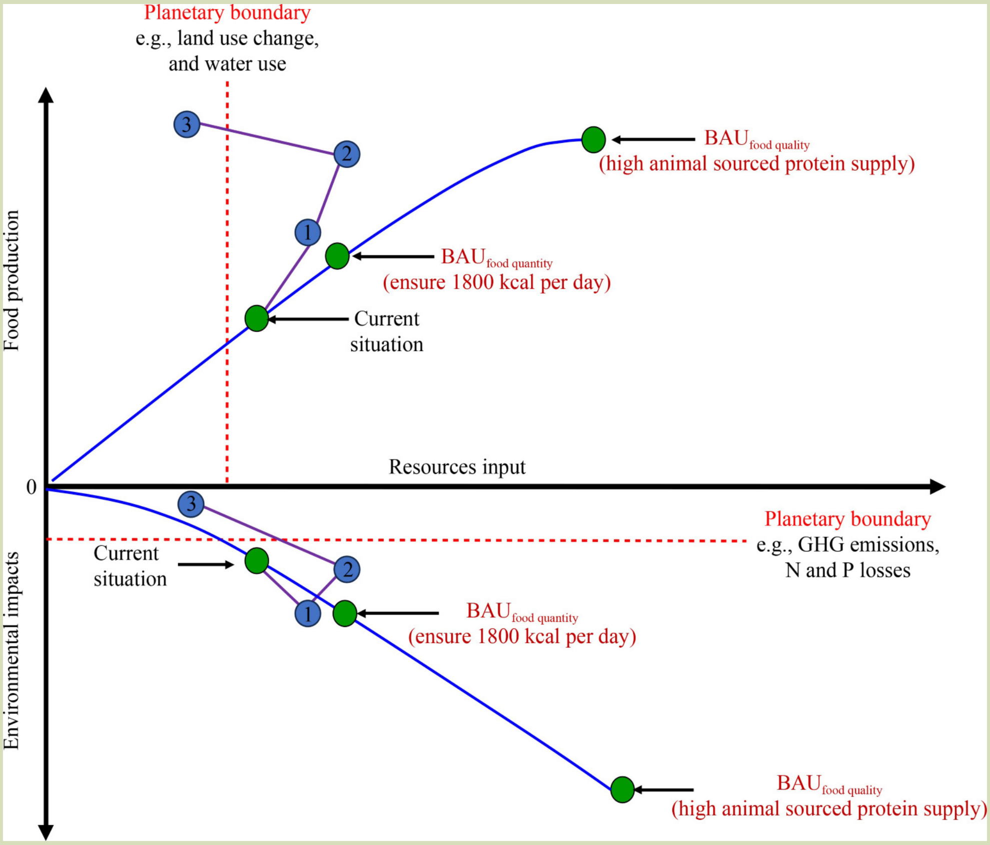


Fig. 1 Framework of food system transfer. The blue line represents development of food system under business as usual, and the current stage of the food system has already exceeded the planetary boundaries such as climate change, land-system change, freshwater use and biogeochemical flow.

ultimate goal of eliminating hunger into phased objectives. Each stage introduces corresponding technologies to maximize food production while meeting environmental thresholds. The transformed food system would simultaneously address multiple objectives, including grain yield, grain quality and environmental thresholds. It could ensure the achievement of global SDG goals as well as AGD objectives.

3 Potential transformation of global food system

The global food system is at a critical juncture, facing a confluence of challenges and opportunities that demand a profound transformation. Transforming the food system could improve access to nutritious and affordable food for vulnerable populations and enhance global food security. In this exploration of food system transformation, this section provides three potential pathways to transform the food system which highlights the priority and sequences of food system (Fig. 2). The transformed agriculture could protect natural resources, reduce pollution and improve resource efficiency while maintaining food security. In the future agriculture system, each country should first invest significantly in developing agricultural technologies according to its own circumstances. This is needed to achieve maximum food production within the limits of environmental thresholds to meet the increasing demand for food quantity. As a second step, countries should focus on developing novel protein technologies to meet the rising demand for high-protein foods. The third step involves a heightened emphasis on production efficiency and environmental concerns within the food system. Globally, there should be efforts to establish trade agreements to increase inter-country trade and optimize the distribution of livestock and poultry, aiming to enhance production efficiency and reduce environmental pollution.

The proposed three-step strategy for food system

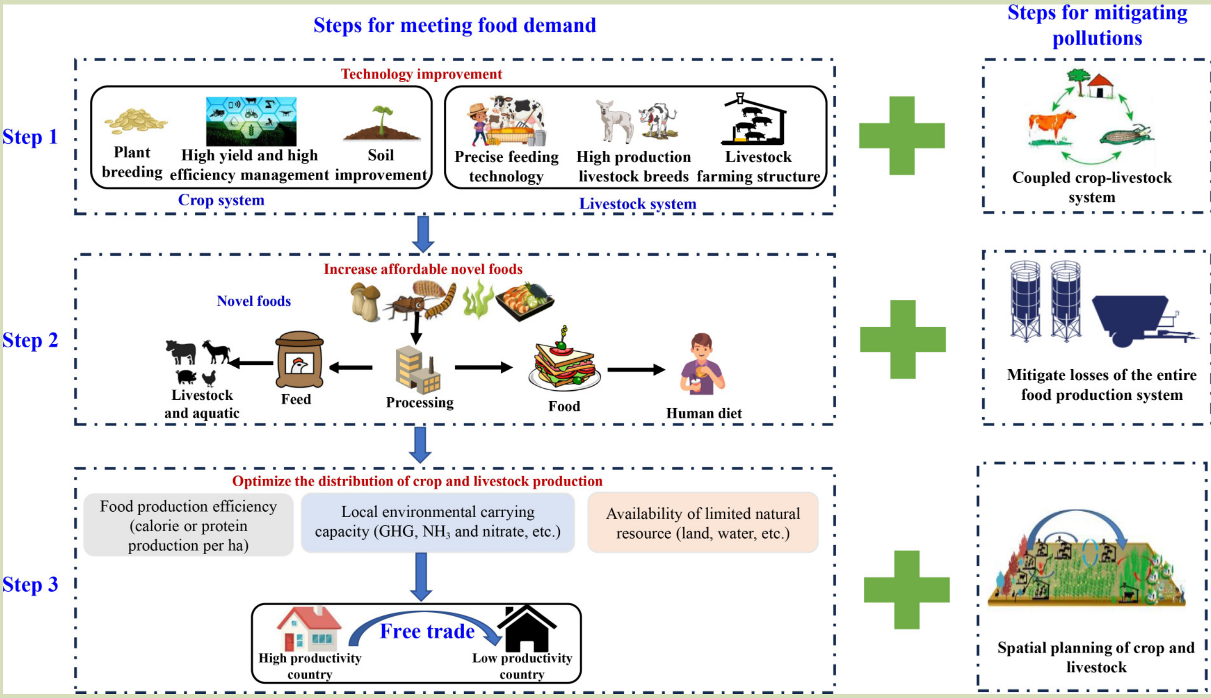


Fig. 2 Three potential pathways to transform food system.

transformation aligns with several key global SDG indicators particularly for SDGs 2, 12 and 15. The three-step strategy (especially for adopting precision farming technologies) directly addresses SDG 2 by aiming to maximize food production to meet global food demands. The sustainable farming methods such as agroecological practices can reduce chemical inputs and decrease the environmental impact which aligning with SDG 12. Additionally, implementation of precision agriculture (such as plant breeding and soil improvement) has positive effect on soil health and biodiversity which aligns with SDG 15.

3.1 Advancing technology and optimizing agriculture for sustainable food production

To address these food systems challenges necessitates a holistic approach that harnesses the power of advanced technologies to enhance food system productivity. Currently, food production worldwide still cannot meet the food demand of growth population. Hunger still persists in many regions around the world. Therefore, food system transformation should prioritize addressing the basic food needs of people. To meet the food demand, each country can improve agricultural, reduce food waste and enhance sustainable food production by adopting advanced agricultural technologies. Here we propose a potential pathway to improve the production of crop system and livestock system (Fig. 3). For crop system, based on various limiting factors for each country, such as soil fertility, arable areas and irrigation capabilities, a quantitative analysis is conducted to determine the maximum yield potential and efficiency potential of crops in each country. Subsequently, in conjunction with the relevant policy guidelines related to food production in each country, corresponding technical optimization such as seed breeding, field reclamation and better management practice are recommended to increase crop yield[24–26]. These technical optimizations are then applied nationwide to promote and achieve high crop yields and efficiency, ultimately reducing food deficits in each country. For livestock system, each country should enhance meat production by optimizing feeding structure and high production performance livestock breeds to improve feed conversion rates[27]. Given the significant disparity in feed conversion rates between developing and developed countries, increasing the feed conversion rates in developing countries to match those of developed countries would result in a substantial increase in production efficiency. With the development of artificial intelligence, its role in agricultural production is becoming increasingly significant. Artificial intelligence facilitates large-scale data analysis, enabling farmers to make informed decisions based on comprehensive insights. Particularly in the implementation of precision farming measures, artificial intelligence can utilize sensors,

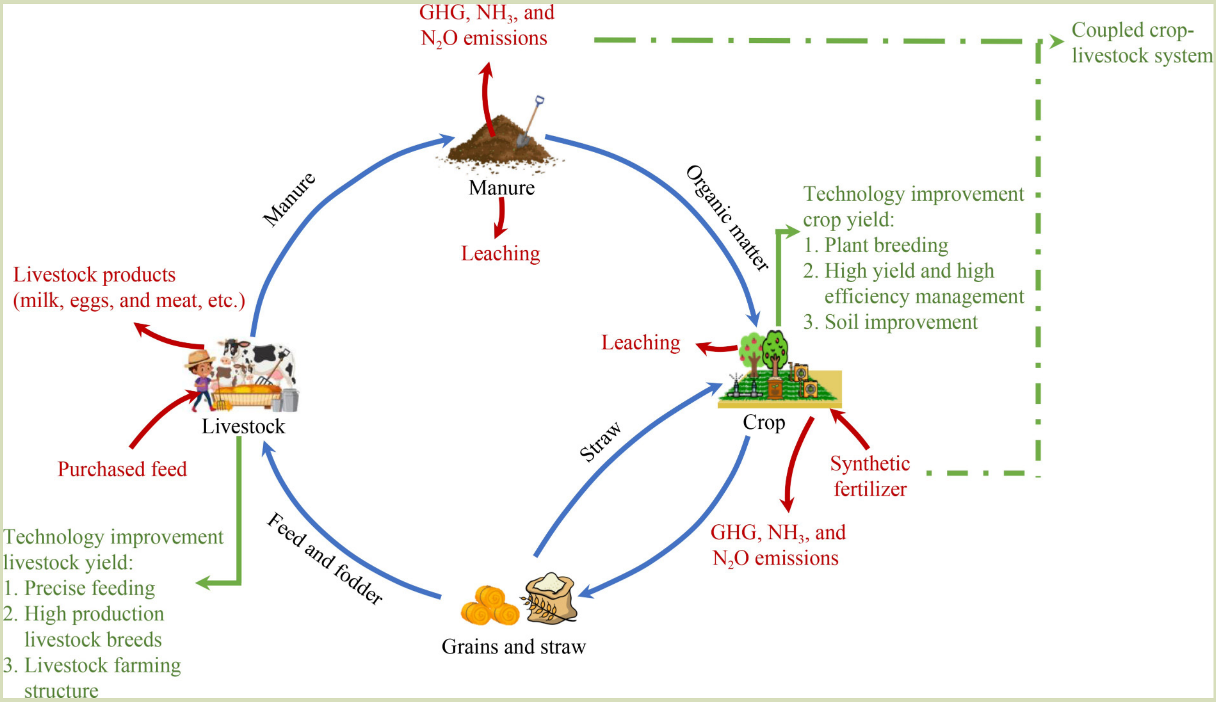


Fig. 3 Technology improvements in crop and livestock system.

satellite imagery, and other data sources for precise monitoring of crops and fields, thereby enhancing both yield and efficiency. Therefore, the innovative technologies applied in crop and livestock system can significantly enhance the food production.

The innovative technologies have been shown to improve the productivity of the whole food systems. Springmann et al.[28] argued that reducing food loss and waste was a significant measure for reducing global food demand. They suggested that food loss and waste could be reduced by 75% through advancements in agricultural technology[28]. Davis et al.[29] also showed that the agricultural technology could improve efficiencies to meeting the future food demand with current agricultural resources even though its environmental burden will grow. Given the magnitude of the yield gap is particularly large in developing countries, addressing the substantial yield gap in developing countries is crucial for reducing the global yield gap. In China, Zhang et al.[30] has proposed an innovative approach that allows smallholders to achieve sustainable high yields and economic returns through the Science and Technology Backyard platform. Romeo et al.[31] reported that the diversified cropping system could enhance crop productivity and improve food security in Kenya. Crop switching in India has the potential to significantly increase calorie production while reducing water consumption[32]. In addition, Wang et al.[33] reviewed the root-soil-microbe interactions studies and highlighted manipulation of the root-soil-microbe interactive processes to maximize the biological potential for improving crop yields. Also, numerous previous studies have also demonstrated that advanced agricultural can lead to higher food production[34–36]. Therefore, using advanced agricultural technology to increase food production is a direct and highly feasible approach for each country. The increased food production achieved through the adoption of advanced agricultural technology in these countries demonstrates that achieving the first step goal globally through advanced technology is feasible.

As the disconnect between livestock and crop systems has increased, there has been a growing focus on the impact of agricultural environmental pollution. To mitigate agriculture-induced environmental pollution, the crucial measure is the application of manure to cropland to reduce nitrogen losses[37]. The coupled of crop and livestock system can be considered the priority measure to reduce environmental pollution. Xu et al.[38] demonstrated that the restructuring the crop and livestock system could reduce GHG emission of 28% to 41%. Additionally, according to Zhang et al.[39], the integration of livestock systems and crop systems on a regional scale in China could ensure that manure production in all provinces remained within the manure recycling capacity of local crops. In North

America, the integrated crop-livestock system has been implemented to attain multiple environmental benefits while reducing natural resource degradation[40]. Lemarie et al.[41] has shown that integrated crop-livestock system was the key measure for achieving future food security and environmental sustainability. This integrated approach can effectively reduce environmental pollution caused by manure. Therefore, a coupled crop and livestock system can be considered as an essential means for reducing environmental pollution and advancing AGD[42,43].

3.2 Promoting the adoption of novel food and mitigation technology

Crops and livestock can provide high-quality food, but they require a substantial amount of land and other resources, such as nitrogen fertilizer, to produce food and feed[44]. While advanced agricultural technology can enhance food production efficiency, the food system still has a dramatic impact on the environment[8]. In this context, crop and livestock production sector faces a dilemma of whether to produce enough food or reduce environmental impacts. Reducing regular food consumption and using alternative novel food source have been recognized as efficient strategies for resolving food yield gap and reducing environmental impacts[45]. Novel foods encompass a wide range of innovations, including insect-based products, algae, aquatic products and laboratory-grown meats. All of these offer unique opportunities to revolutionize our food systems. One of the key advantages of novel foods lies in their potential to alleviate the growing issue of food scarcity[46]. As current agricultural practices struggle to keep pace with population growth, these alternative food sources can serve as sustainable and resource-efficient alternatives. For example, insect-based products require significantly less land and water compared to current livestock farming, making them a viable solution in regions facing agricultural constraints[47]. Also, the adoption of novel foods can contribute to mitigating the environmental impacts associated with conventional agriculture. The livestock industry, for example, is a major contributor to greenhouse gas emissions, deforestation and biodiversity loss[48]. By shifting toward plant-based and laboratory-grown alternatives, it would be possible to significantly reduce the carbon footprint of food production and alleviate the pressure on natural ecosystems[49,50]. The details of the potential pathway for substituting domestic products with novel food source are illustrated in Fig. 4. Specifically, there are currently two potential substitution strategies to achieve the substitution of novel food for domestic food. First, novel foods can reduce the pressure on feed supply by replacing traditional animal feed for livestock and poultry. Second, they can directly substitute for human consumption to alleviate food demand pressures. However, to successfully

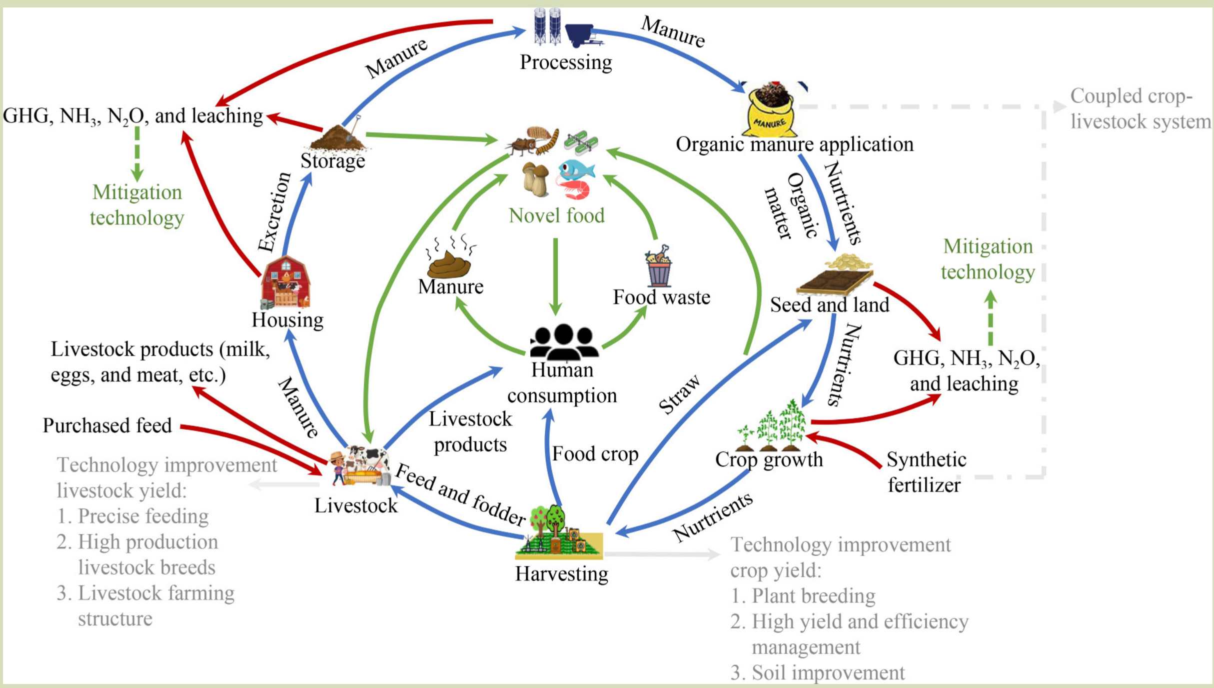


Fig. 4 Substituting domestic products with new food source and implementing the mitigation technology.

promote the adoption of novel foods, various challenges must be overcome, including consumer acceptance and economic viability.

Govorushko[51] has shown that insect farming was the one of many ways to address food and feed security. Insects are highly nutritious, containing high levels of protein, fat and minerals, and they can be consumed whole, or ground into a powder or paste to be incorporated into other foods. Also, the large-scale utilization of insects as a feed ingredient is technically feasible, and the use of insects as livestock feed is expected to become more prevalent in the future. In Bangui in the Central African Republic, 29% of annual animal protein consumption per person is provides by insect[52]. Bai et al.[45] indicates that the total potential production of insect for food is 4–7 Tg and insect protein for feed is 17–24 Tg in China. In China, the substitution of insects for food can alleviate 48% of food demand, while the substitution of insects for feed can alleviate 58% of feed demand. The use of algae as candidates for alternative protein sources to address global food demand and meet future nutritional needs[53]. With the recent technique improvement, microalgae have been promoted as having the potential to supply a substantial portion of global food and feed market with a limited production, which was feasible way to increase food security[54]. Laboratory-grown meats can be considered as a promising technology to substitute products that have produced through livestock[55]. Laboratory-grown meat has the potential to address the food pressure and environmental issues associated with traditional livestock farming. However, given that commercial production of laboratory-grown meat has not yet been developed, its high production cost made it unlikely to provide sufficient affordable food[56]. In summary, the large-scale use of novel food as a feed ingredient or food production is technically feasible, substitutes domestic food production with novel food can be achieved by reducing production cost and increasing public acceptance in the future. Analyzing literature on several countries that have already achieving high-protein food through emerging novel food technology shows that global adoption of these technologies for the second-step goal is feasible.

In terms of environmental concerns, despite the enhanced food production efficiency achieved through novel food technologies, the environmental pollution resulting from agricultural food production still exceeds the environmental planetary boundaries. Thus, it is essential to implement mitigation technologies in crop and livestock systems to reduce environmental pollution emissions. Bai et al.[57] have shown that optimizing manure management and fertilizer application could reduce 27% of manure N losses. Crippa et al.[58] estimated that 10% to 90% of air pollution emissions were linked to the food system, contributing to 22% of global mortality. Therefore, implementing mitigation technologies in the food system can help reduce air pollution and decrease global mortality. Gu et al.[59], employing a nitrogen flow model and an air quality model, estimated that improper nitrogen management in global agricultural production led to health losses as high as 420 billion USD annually. They also suggested that taking mitigation technology to reduce ammonia emissions could substantially alleviate nitrogen losses and the related health impacts. Biofuels from crops have been produced for several years, contributing to a reduction in greenhouse gas emissions compared to conventional fossil fuels. According to Hanssen et al.[60], the potential impact of bioenergy is estimated to lead to a reduction of 2.5 Gt CO_2. The increased demand of bioenergy for bio products could potentially strain food production and compete for arable land. This research provides new perspectives for optimizing agricultural management worldwide in the future. In summary, implementing agricultural and livestock emission reduction measures in the second step can achieve a reduction in pollution emissions while maintaining the existing food production levels.

3.3 Optimize global trade and spatial distribution of crop and livestock production

To further enhance food production and environmental efficiency, ensuring the achievement of both global SDGs and AGD objectives, in the third step, we propose optimization global trade and spatial planning techniques. Optimizing global trade emerges as a critical strategy to tackle food production challenges[61]. This approach recognizes the importance of efficient resource allocation, sustainable land use and international cooperation in ensuring food security. Effective global trade involves strategically allocating land and resources to maximize agricultural productivity while minimizing environmental degradation[62]. Regarding to the environmental pollution hotspots area, the spatial planning technology can improve natural resource efficiency, reduce environmental pollution and enhance sustainability of food system[63]. The global trade framework and spatial planning are illustrated in Fig. 5. The first step is to establish classification criteria for various countries around world, including food production efficiency, environmental thresholds and natural resource constraints. In the second step, countries are categorized globally into high food production efficiency and low food production efficiency based on established classification criteria. Additionally, countries are classified in

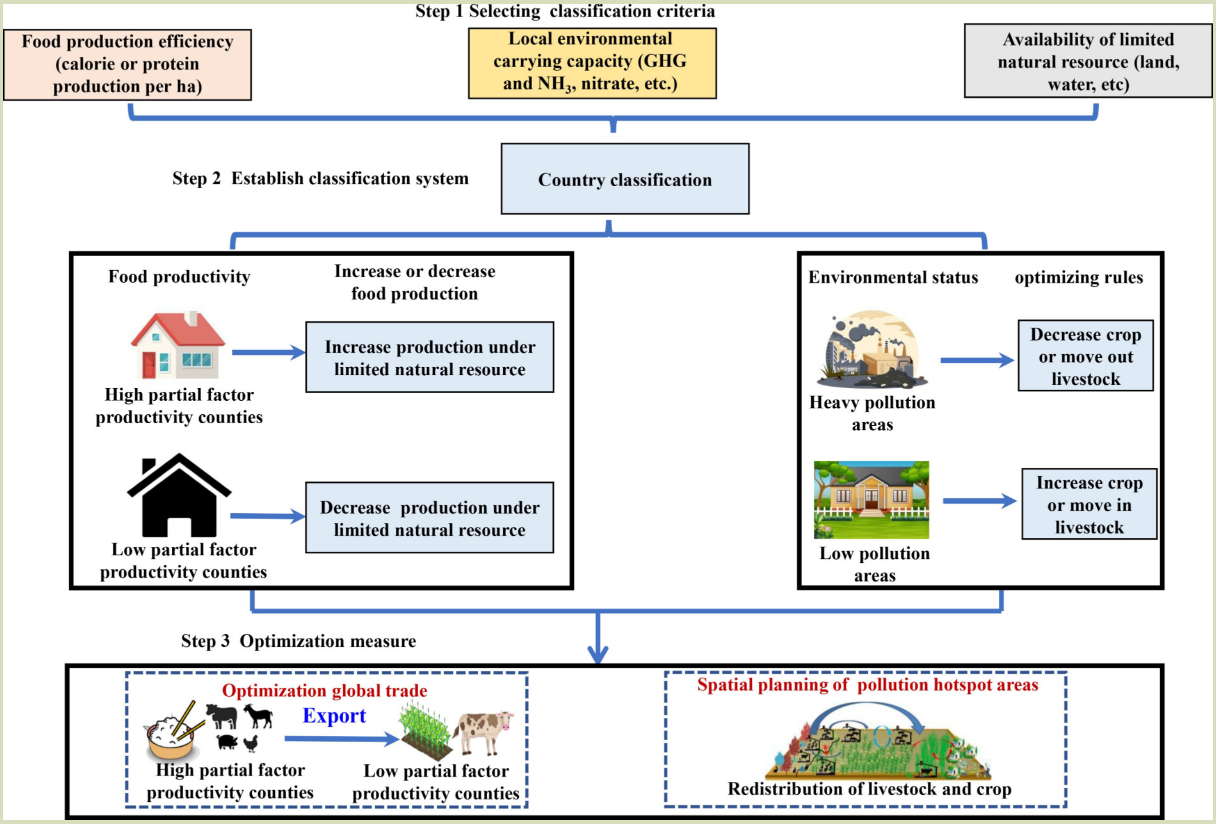


Fig. 5 Global trade and spatial planning implemented to increase food production efficiency and minimize environmental pollution.

terms of their environmental impact, distinguishing between high-pollution and low-pollution countries. The third stage encourages high food production efficiency to maximize food production within the limits of environmental and natural resource thresholds and export to countries with low food production efficiency, thereby enhancing global resource efficiency. To address hotspot areas with high environmental pollution, the redistribution of livestock and crops can reduce pollution.

Although most countries will attempt to achieve food system sustainability, limited natural resources and low agricultural productivity present significant challenges to environmental sustainability[64,65]. Previous studies have shown that the spatial planning and optimized global trade could improve agricultural productivity and reduced environmental pollution[66,67]. Specially, Folberth et al.[66] suggested that spatially optimizing major crops across global croplands would reduce arable land by 50% to maintain current production levels, simultaneously reducing greenhouse gas emissions and the strain on natural resources due to a decreased area of arable land. Davis et al.[68] also found that optimizing the global distribution of crops not only improved crop production to feed an additional 825 million people but also reduced water consumption by 12%. At a country scale, China has the potential to reduce nitrogen emission by two-thirds and halve the number people exposed to high ammonia emission through the spatial planning of livestock[67]. Through the recoupling of livestock and feeding production, one of the spatial planning methods, the Netherlands can meet human demand even while reducing livestock numbers and decreasing food exports by 59%[69]. Elliott et al.[70] suggested that relocating agricultural areas presented an opportunity to mitigate environmental pollution. In addition, the global trade of crop has increased global land and improved partially fertilizer nitrogen productivities, resulting in savings equivalent to 2270 Mha of cropland and 480 Tg of synthetic fertilizer nitrogen[71]. Bai et al.[72] suggested that agricultural products should be increased in exports from high-productivity countries to low-productivity countries. Therefore, global trade and spatial planning can be the feasible way to meet global food demand while achieving global SDGs and AGD objectives. The above examples indicates that some countries have optimized the environment through optimize global trade and spatial distribution. Thus prompting these technologies globally to achieve the third-step is feasible.

4 Conclusions

This paper has presented three pathways for the transformation of the global food system, reviews the challenges and development goals at various stages of the food system, and employs a systematic approach to demonstrate the feasibility of food system transformation. Food system is the fundamental to achieving the AGD goals. In the new development phase, the world has raised higher demands and expectations for the food system. This study proposes three potential pathways to promote the food transformation based on AGD theory. The primary objective of the three-step strategy in terms of food production is to ensure both quantity and quality of food. Firstly, countries would improve agricultural technology to maximize local grain production and meet their domestic food needs. Secondly, as food demands shift from quantity to quality, there would be a growing need for increased protein consumption. Therefore, the second step involves introducing novel protein sources to meet the growing demand for high-quality protein. The third step involves optimizing global trade to improve food production efficiency, ensuring the efficient use of resources. In addition, the objective of the three-step strategy in terms of environmental issue is to reduce environmental pollution emission and minimize excessive natural resource input. The first step involves establishing a coupled crop system and livestock system to reduce excessive resource inputs. The second step focuses on applying advanced emission reduction technologies to minimize pollution emissions in the food production process. The third step entails spatial planning targeted at environmental pollution emission hotspots. Based on these three pathways, countries would need to formulate corresponding policies and actively promote the transformation of the food system to achieve agricultural green and sustainable development. To better drive the transformation of the food system, there are three key recommendations for stakeholders: (1) allocation of resources to explore innovative technologies and farming practices to enhance efficiency, reduce waste and improve sustainability; (2) facilitation of collaboration among stakeholders (farmers, policymakers, industry representatives and consumers) to implement a standardized approach for achieving approach to food system transformation; (3) advocacy for and participation in the formulation of policies that support sustainable food systems, while coordinating national and regional policies to promote environmentally friendly practices and ensure equitable distribution.

Compliance with ethics guidelines

Xiangwen Fan, Xiaomeng Zhang, Xiaofei Wu, Wenqi Ma, Zhaohai Bai, and Lin Ma declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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