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REVIEW

Green technology for increasing grain crop production and efficiency: innovation and application in China

Wen-Feng CONG (✉)*, Hao YING*, Feiyu YING, Zhichao AN, Jianbo SHEN, Fusuo ZHANG

State Key Laboratory of Nutrient Use and Management, Key Laboratory of Plant-Soil Interactions (Ministry of Education),
College of Resources and Environmental Sciences, National Academy of Agriculture Green Development,
China Agricultural University, Beijing 100193, China.

*These authors contribute equally to the work

KEYWORDS

Food security, green technology, green intelligent fertilizer, resource use efficiency, environmental sustainability

HIGHLIGHTS

- Green technology comprises three key elements: high-yield population construction, efficient rhizosphere regulation technology and healthy soil cultivation.
- Green technology can close yield and nutrient use efficiency gaps, reducing environmental impacts.
- Green technology exemplifies the emerging paradigm of future agricultural research in China.

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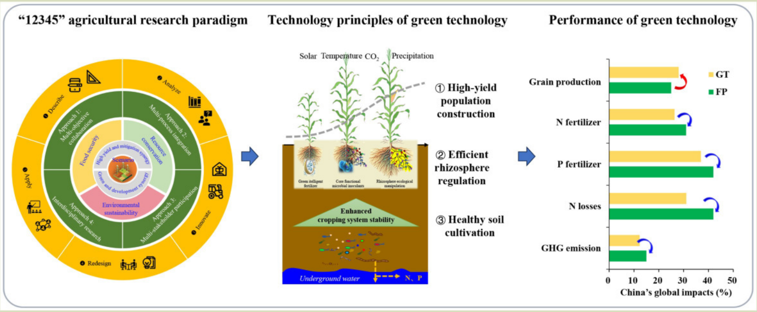
Correspondence: wenfeng.cong@cau.edu.cn

GRAPHICAL ABSTRACT



ABSTRACT

Securing sufficient, sustainable and resilient food production with judiciously using mineral fertilizers, while protecting the eco-environment is essential for agricultural sustainable development worldwide. However, the existing agricultural scientific paradigm fails to align with practical production realities, while confronting dual contradictions: reconciling higher grain yields with lower environmental impacts and balancing agricultural economic growth with environmental conservation imperatives. This paper proposes the next-generation "12345" agricultural research paradigm, rooting research in agricultural development, linking knowledge and action across multistakeholders via cross-discipline systematic research. Green technology for increasing grain crop production and efficiency, as a typical example, is used to implement this new scientific paradigm. The components of this paradigm are giving as comprising three key elements, (1) high-yield population construction, (2) efficient rhizosphere regulation technology and (3) healthy soil cultivation. Next the paper examines green technology versus common farmer practice for thousands of fields across the main agricultural production regions in China, achieving substantially increased crop yields and reduced mineral nitrogen fertilizer inputs, thereby enhanced nitrogen use efficiency and reduced environmental footprints. Green technology is offered as being an effective agricultural scientific paradigm to ensure food and environmental security, providing a new example for worldwide food security in the future.

Ensuring food security while achieving environmental sustainability in crop production is a challenging issue globally, especially for China where 19.1% of the global population needs to be feed from only 8.6% of global arable land[1]. Even though China has successfully feed their population in past decades, it consumes about 32% of global nitrogen fertilizers, which is much higher than most other countries[2]. However, current fertilization rates exceed crop uptake levels by 2 to 3 times, paradoxically coexisting with stagnant growth in agricultural productivity. This indicates that the continuous increase in mineral fertilizer inputs alone is unlikely to meet the growing food demand, instead will certainly exacerbate the already serious environmental problems.

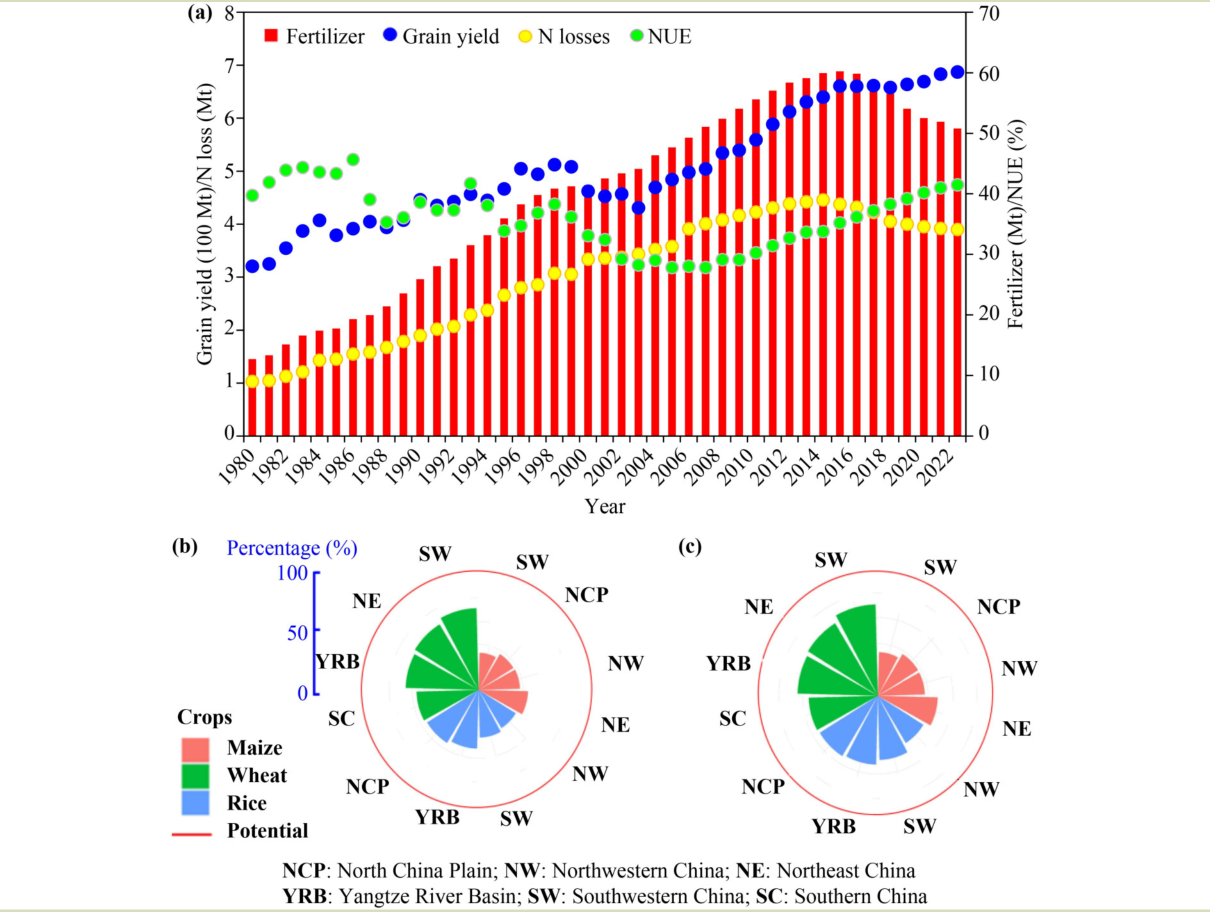
Indeed, intensive input of mineral fertilizers, targeting at high crop yield, has led to severe environmental problems, including air, water and soil pollution, and climate change, threatening regional and global sustainability[3]. For example, intensive use of N fertilizers has caused widespread air and water pollution across China, especially through nitrate leaching and N runoff. About 31% of river monitoring stations and more than 60% of its groundwater wells in China indicate serious nitrate pollution (> 30 $\mathrm{mg \cdot L^{-1}}$ N)[4]. China also faces the most severe fine particulate matter ($PM_{2.5}$) air pollution of any country[5], which was estimated to cause premature death of 850,000 people in 2017[6]. High $PM_{2.5}$ concentrations are caused, in part, by agricultural NH_3 emissions[7]. China's annual NH_3 emissions exceeds those of all other countries being more than threefold higher than those in the EU and USA. In addition, in major crop production regions of China, soil pH has decreased by 0.5 units from the 1980s to the 2000s, owing mainly to excessive use of N fertilizers[8]. Notably, the widespread air, water pollution and soil acidification are exerting additional constraints to agricultural productivity, given the multifaceted impacts of soil acidification on soil microbial activities, and biogeochemical cycling of macro- and micronutrients.

Amid the environmental issues and relevant pressure to curb the pollution, recent studies focusing on agricultural sustainability have identified opportunities to simultaneously produce more with less inputs and minimal environmental impact through closing crop yield gaps, innovating crop-specific field management and optimizing crop spatiotemporal layout. To attain sustainable food production, it requires a fundamental shift in the way farming is routinely practiced. Here we present green technology (GT) as a means to increase production and efficiency of grain crops, a concept first introduced by Zhang et al.[9] and Chen et al.[10], as an innovative model for producing more grains with lower inputs and less pollution. In this paper, we introduce the research paradigm, scientific principles, innovations and regional application of GT in China, and discuss ways to broaden its benefits for food security in China and globally.

1 Grain crop production in China: status and gaps

China's current agricultural practice, characterized by high-input and high-output per unit area, has successfully realized national food self-sufficiency but at the cost of excessive mineral N fertilizer input and environmental impacts (Fig. 1(a)). However, 2003 was an important turning point in fertilizer use efficiency when nitrogen use efficiency (NUE) of grain crops reached a minimum (~25%). Since then, there has been a continuous increase in NUE largely attributed to increased crop yields up to 2015 and increased crop yields at a lower growth rate accompanied by decreased N fertilizer input from 2015 to 2022. During the latter period, national fertilizer use decreased from 60.2 to 53.5 Mt, with estimated reactive N losses per unit yield decreased by 27% to 30%.

We quantify yield potential and NUE potential for the three major cereals (i.e., maize, rice and wheat) based on a comprehensive nationally representative agricultural producer survey, which is a prerequisite for assessing maximal production capacity on existing cropland. In this paper, we consider benchmarking county-specific yield potential and NUE potential based on the mean actual yield of the top 10% producers in each county from a national large-scale survey (Fig. 1(b,c)), which better reflects local socioeconomic and agronomic conditions. Across China, that national yield potential was 9.2 $\mathrm{t \cdot ha^{-1}}$ for maize, 8.6 $\mathrm{t \cdot ha^{-1}}$ for rice and 6.3 $\mathrm{t \cdot ha^{-1}}$ for wheat, and that the average yields of farmers for



NCP: North China Plain; **NW**: Northwestern China; **NE**: Northeast China
YRB: Yangtze River Basin; **SW**: Southwestern China; **SC**: Southern China

Fig. 1 (a) Historical changes of grain yield, mineral nitrogen fertilizer use, nutrient use efficiency (NUE), N loss in China from 1980 to 2022, and (b) grain yield, and (c) NUE gaps for of maize, wheat and rice in the major production regions of China.

this being 80%, 86% and 79% of the yield potential, respectively. The national NUE potential was 57% for maize, 59% for rice and 50% for wheat, and that the average NUE of farmers 70%, 76% and 76% of the NUE potential, respectively. Yield and NUE gaps of these cereals occurred across all major production regions in China but varied in magnitude. The lowest gaps were for rice southern China and highest for maize in north-eastern China and wheat in south-western China. Thus, closing the yield and NUE gap for targeted crops and regions is key to pursuing sustainable food security regionally and nationally.

2 Next-generation agricultural research paradigm in China

Against the backdrop of escalating global agricultural crises, encompassing food security threats, resource depletion and ecological degradation, established paradigms that rooted in unidimensional optimization (e.g., yield-centric genetic engineering or input-intensive cultivation) have been found to have systemic limitations in resolving interconnected sustainability challenges[11]. Legacy frameworks, exemplified by the Green Revolution paradigm, generated asymmetric progress. Although achieving substantial gains in crop productivity, they led to systemic disruptions to hydrological equilibrium and biogeochemical cycles through unsustainable resource exploitation. Within the agricultural sector of China, the persistent dualism between economic expansion and ecological preservation exposes the structural deficiencies of such reductionist approaches, compelling transformative innovation at the paradigm level[12].

This imperative is further intensified through emergent policy imperatives. China’s Agriculture Green Development strategic framework, aligned with global sustainability accords such as the UN Sustainable Development Goals (SDGs), now mandates multidimensional innovation ecosystems that transcend reductive single-axis objectives. These frameworks explicitly reject the independent technological fixes of the past, advocating instead for systemic solutions that harmonize productivity, resource efficiency and ecological resilience, a tripartite equilibrium unattainable under established paradigms[1]. Thus, we propose the "12345" agricultural research paradigm (Fig. 2). The core concept of this paradigm is to tightly integrate the practical demands of agricultural production with innovation, comprising five essential elements. (1) Taking the agricultural production-oriented context as the *one* entry point, technological innovation must be rooted in actual problems and needs within agricultural production, rather than being confined to laboratory or theoretical discussions. This requirement ensures that scientific advancements can be effectively applied in agricultural practices, addressing real-world challenges[13]. (2) Recognizing *two* synergies[2], aiming to synergistically solve two pair of paradoxes[3] of agricultural production: high agricultural yields counterpoised to high environmental emissions; and agricultural economic development counterpoised to green eco-environment. First, while striving for increased food production, it is crucial to prioritize environmental protection, achieving a balance between production efficiency and ecological benefits. Second, it focuses on the coordination of agricultural green development with economic advancement, leveraging innovation to enhance production efficiency and resource utilization, thereby reducing negative environmental impacts in agricultural practices[14]. (3) Setting *three* long-term targets: food security, resource conservation and environmental sustainability. By improving agricultural productivity and resource efficiency, this approach aims to boost food production and farmer incomes while effectively decreasing greenhouse gas emissions and environmental pollution[15]. (4) Establishing *four* principle-based approaches: multiobjective collaboration, multiprocess integration, multistakeholder participation and interdisciplinary research. Multiobjective collaboration emphasizes the balance among food production, resource efficiency, environmental protection, and farmer income. Multiprocess integration refers to the comprehensive integration from planting to harvesting. Multistakeholder participation involves the collective engagement of government, enterprises, research institutions, universities and farmers to ensure the widespread application of innovative outcomes across policy, market and technical dimensions. Interdisciplinary research highlights the collaboration among disciplines such as agronomy, socioeconomics and engineering to foster cross-domain innovation[16]. (5) Implementing a systematic research framework based on the key *five* steps—describe, analyze, innovate, redesign and apply (DAIRA)—to analyze and creatively resolve issues encountered in agricultural production. Specifically, it begins with problem description based on actual production scenarios, followed by data analysis to identify core issues, subsequently leading to innovative solutions and the optimization and restructuring of production processes, ultimately facilitating application and dissemination in real agricultural scenario[17].

This research innovation paradigm, by comprehensively considering the practical demands of agricultural production and multidimensional collaboration, presents significant implementation advantages and potential. First, innovation rooted in real scenarios ensures the practicality and operability of scientific outcomes. It couples the scientific processes of generating sustainable crop production knowledge from researcher-designed field experiments with the practical application of such knowledge in farmer systems. Second, collaborative innovation across multiple objectives and processes not only enhances food production efficiency but also effectively reduces resource waste and environmental pollution. Additionally, multistakeholder participation and interdisciplinary research facilitate the broad application and dissemination of research outcomes, promoting technology transfer and marketization. Finally, through the DAIRA five-step method, the research innovation process becomes more systematic and controllable, enabling flexible responses to complex issues across diverse agricultural production scenarios. The systemic design of the "12345" model positions it as a potential paradigm for guiding future agricultural innovation, particularly in contexts requiring multiobjective optimization.

3 Principles and innovations of green technology for grain crop production

Below, we apply the "12345" agricultural research paradigm, combining a multidisciplinary approach to the development of green technologies for site-specific crop production environment. By exploring the principles of innovation, we

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[1] In this context, "paradigm" refers to a conceptual framework encompassing shared assumptions, methodologies, and objectives that guide scientific inquiry and technological innovation within a discipline.

[2] "Synergies" denote interactions between system components where combined effects exceed the sum of individual actions.

[3] "Paradox" here describes the apparent contradiction between achieving high productivity and maintaining environmental sustainability under conventional agricultural models.

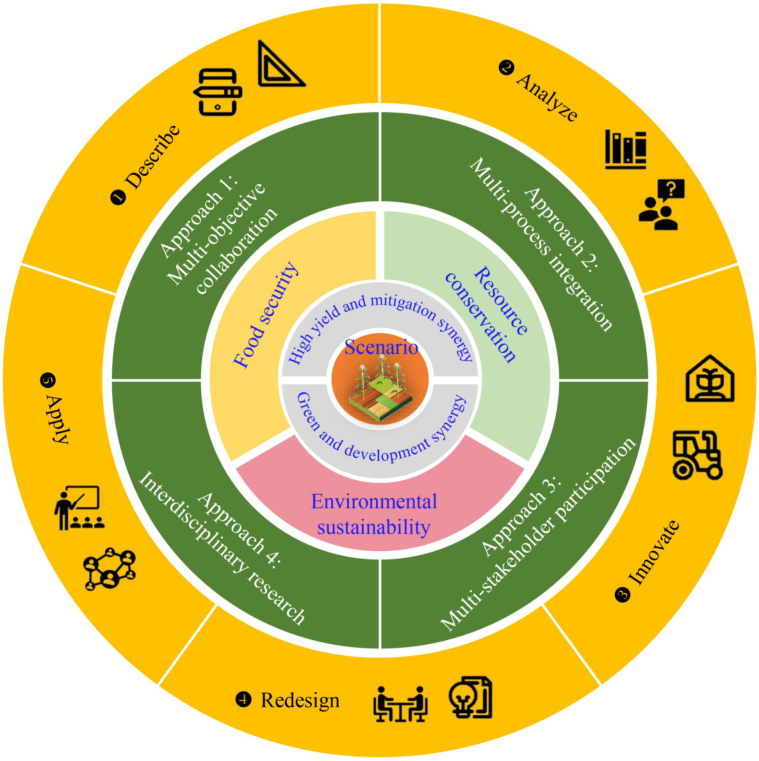

Fig. 2 New "12345" scientific paradigm for agricultural research in China.

thereby propose practical technological solutions for relevant stakeholders.

We developed GT targeting the maximization of the canopy-root-soil interactions to achieve the synergies between high crop yields, efficient nutrient use and environmental emission reductions. It comprises three core aspects: (1) high-yield populations construction, which is to regulate the aboveground population to achieve maximum photosynthetic carbon flux, thereby optimizing the cropping system yield; (2) efficient rhizosphere regulation, which aims to regulate nutrient flow at key rhizosphere interfaces to match the nutrient demands of the aboveground population; and (3) healthy soil cultivation, which refers to the improvement of soil structure and microbial diversity through management practices (e.g., intercropping, no-tillage and organic fertilizers) to support high-yielding population. (Fig. 3).

Crop growth is influenced by multiple aspects of the atmospheric environment, such as solar radiation, CO_2, temperature and rainfall, so it is important to determine how to maximize the use of light and temperature resources to improve population productivity and achieve increased yields. Breeding high-yielding, density-tolerant and resource-efficient crop cultivars is an important way to maximize the utilization light (photosynthetically-active radiation) and thermal resources. High-yielding cultivars have higher population photosynthetic capacity, population biomass and optimal leaf area index and canopy structure, which can fully utilize light and thermal resources[18]. A study conducted in China, based on field trials at 212 sites, found that increasing maize planting density by 15,000 plants ha^{-1}, without additional N fertilizer application, could increase maize yield by 5.6% while significantly lowering environmental impacts[19]. Designing resource-complementary and sustainable cropping systems, such as intercropping, where different plant types or root systems are grown together, fully utilize canopy light resource efficiency. For example, maize-faba bean intercropping leverages the fact that maize is a C_4 plant, which can more efficiently absorb and assimilate CO_2 for photosynthesis. Intercropping systems have greater productivity due to different spatiotemporal ecological niches and increased nutrient resource compensation effects[20,21]. The advantage of maize/peanut intercropping lies in aboveground interspecies light competition, which promotes maize growth and belowground interspecies mutualism, which promotes peanut growth[22].

Efficient rhizosphere regulation can maximize the activation of

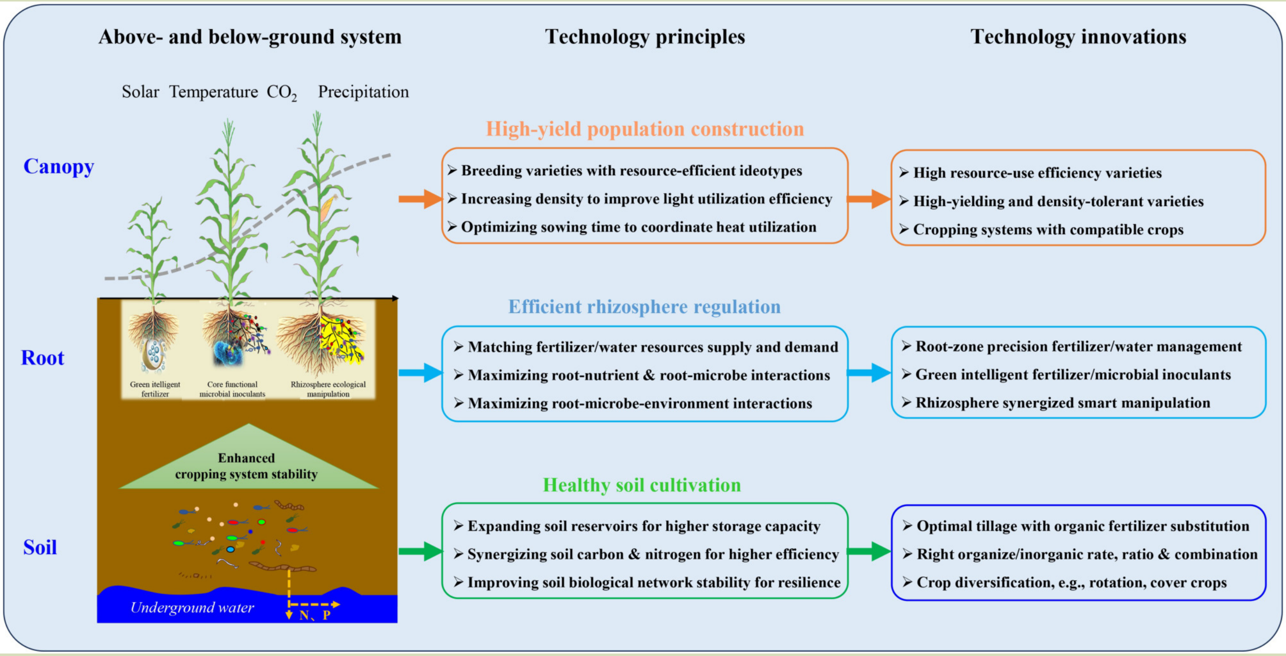

Fig. 3 Technology principles of green technology for increasing production and efficiency of major grain crops.

rhizosphere cascading interaction effects, thereby improving crop production efficiency[23]. It is based on the nitrogen demand patterns at different growth stages of crops, the soil nitrate content, and the nutrient abundance and deficiency at key growth stages, such that real-time nitrogen monitoring technology ensures that nitrogen supply in the root zone quantitatively matches, temporally synchronizes and spatially couples with crop nitrogen demand[24]. Maximizing root-nutrient and root-microbe interactions can further enhance nutrient use efficiency, leading to higher yields. For example, green intelligent fertilizers comprising right ratio and form of nutrients can stimulate rhizosphere effects, exploiting the biological potential of the root-nutrient interactions. Also, localized nutrient supply (especially phosphorus with ammonium) can promote maize root elongation, lateral root proliferation and ammonium transporter gene expression. Ammonium-induced rhizosphere acidification increases the activity of acid phosphatase, improving maize yield and nutrient use efficiency[25,26]. Water and fertilizer are key factors influencing crop growth. Integrated water and fertilizer technology can ensure precise, balanced, demand-based water and nutrient supply throughout the crop growth cycle, leading to sustained yield increases. Water-fertilizer coupling can improve maize yield, water efficiency and NUE, as well as wheat filling dynamics and grain weight in semiarid regions of China[27]. In addition, future rhizosphere regulation should consider root-microbe-microenvironment interactions through rhizosphere smart manipulation. For example, Zhang et al.[28] used fructose to stimulate phosphorus-solubilizing bacteria using to improve phosphorus use efficiency. The microbial targeted regulation technologies and products based on root-microbe interaction will significantly enhance crop yield and nutrient use efficiency.

Healthy soil is the basis for food security, ecological environment and arable land capacity enhancement. Organic carbon, aggregates and microbiota are important regulators of soil health[29,30]. We propose three ways for prompting healthy soils, consisting of expanding soil reservoirs for higher nutrient and water storage capacity, synergizing soil carbon and nitrogen for higher efficiency, and improving soil biological network stability for resilience. Meta-analysis has shown that organic-inorganic fertilizers combination significantly increased soil organic carbon and microbial carbon and nitrogen in maize, rice and wheat, and increased maize and wheat yields in dryland crops by stimulating microbial activities[31]. Enhancing soil health through soil biological processes based on the interactions of carbon sources, nutrients and soil structure. For example, nutrient management with peat vermicompost significantly increased soil organic carbon, improved the physical stability of soil aggregates, increased the abundance of microbiome symbiotic networks and promoted significant enrichment of specific beneficial microorganisms, and increased maize yield[32,33]. Compared to the rice-wheat system, the rice-rapeseed system increased soil carbon sequestration with higher abundance of aromatic carbon and more complex molecular configurations[34]. Long-term intercropping increases soil fertility by increasing macroaggregates, soil organic matter and total nitrogen compared to monocropping, which is important for intercropping to obtain yield and stability[35]. Therefore, enhancing crop diversity interactions can improve the multifunctionality of soil ecosystems.

4 Application of green technology at regional scales

Below we present GT for increasing production and efficiency, with integrated soil-crop system management as the core, as an innovative model for producing more grains with less input and less pollution. We derived data on fertilizer use and nutrient use efficiency for established versus enhanced practices from field trials of more than 12,403 site-years conducted during 2005–2020 through national collaboration networks. Each trial featured side-by-side comparison of local farmer practice versus GT-based recommendations. Consequently, the GT approach increased yields by 21% to 87% compared to farmer practice without substantially increasing N fertilizer inputs. Nitrogen use efficiency increased by 24% to 32%; total reactive N losses and GHG emission density decreased respectively by 50% to 56% and 31% to 47% compared to farmer practice (Fig. 4(a)). From 2005 to 2015, about 20.9 million farmers in 452 counties in China adopted these enhanced management practices across a total of about 40 Mha[37].

From this large data set obtained from field trials, we calculated crop production, fertilizer usage for the projected production, their nutrient use efficiencies and N loss under established versus enhanced (implementing GT-based recommendations) practices. On average with GT, N fertilizer inputs decreased by 16%, yields increased by 11%, NUE increased by 33%, and N losses decreased by about 26%[37]. This demonstrated success using both experimental plots and farmer fields provides sound evidence that GT is an effective approach for increasing crop productivity and NUE, which represents an important case for sustainable intensification of agriculture.

Globally, environmental and economic constraints (e.g., rising cost of fossil fuels) dictate that future food supplies must be attained through enhancing production efficiency rather than

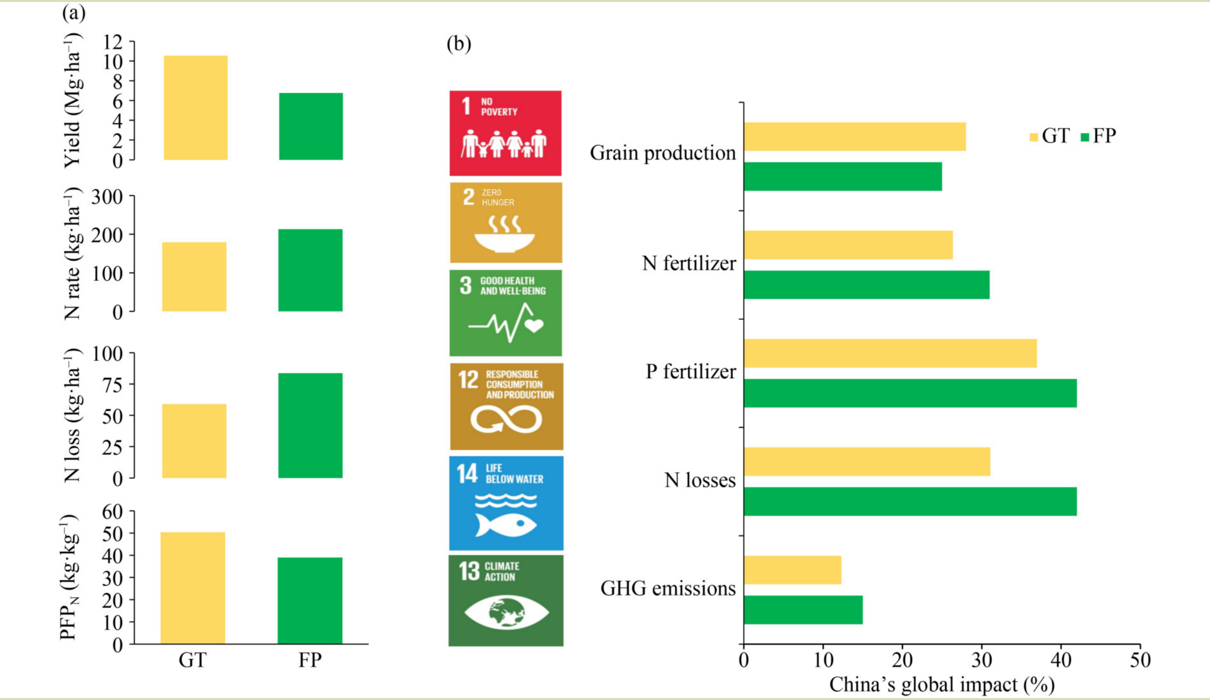

Fig. 4 Overall performance of green technology (GT) versus farmer practices (FP) on grain yield, nitrogen rate, reactive nitrogen loss and nitrogen use efficiency (PFP_N) (a); relative contribution of China' s crop production to the global crop production, in terms of crop production, N and P fertilizer use, N losses and GHG emissions for the FP and GT (b). These relate to the Sustainable Development Goals: SDG 1, No Poverty; SDG 2, Zero Hunger; SDG 3, Good Health and Well-Being; SDG 12, Responsible Consumption and Production; SDG 14, Life Below Water; and SDG 13, Climate Action. The SDG icons are from the United Nations website[36] and wear open source, under Creative Commons.

further increasing fertilizer inputs, especially N and P. As evidenced in China using the GT approach, producing more grain with fewer resources and environmental costs is attainable. Also, GT would result in effective mitigation of the impact of China's crop production on resources use, losses N and P, and GHG emissions at a global level, providing results can be linked to 6 SDGs (Fig. 4(b)). We believe that the GT principle and approach is applicable elsewhere, particularly in rapidly developing countries, including Brazil, India and Mexico. It should be possible to meet the growing food demand with more sustainable intensive agriculture on existing cropland, thereby sustaining other natural resources by avoiding the conversion of forest, grassland and marginal lands to agriculture, and supporting other ecosystem services, such as wetland preservation, wildlife conservation and carbon sequestration.

5 Conclusions

Synergy of food security, resource efficiency and environmental protection is an inevitable requirement for sustainable agricultural development. In this paper, we have proposed the "12345" research innovation paradigm for agriculture in China. The key being to couple the four approaches of multiobjective coordination, multiprocess integration and multisubject participation to make technological innovations in actual scenarios. Secondly, we have proposed the principles and technical measures of GT for increasing production and efficiency approach, the key is to improve the productivity of the soil-crop system based on the principles of plant–soil–microbe interaction. Then, we described the implementation of a large-scale trial demonstration through the nutrient management collaboration network. At the national scale, GT approach synergistically achieved increased yields, reduced nitrogen losses and improved nutrient efficiency. The implementation and application of GT technology in China provides a model for other countries to likewise achieve green agricultural transformation.

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Compliance with ethics guidelines

Wen-Feng Cong, Hao Ying, Feiyu Ying, Zhichao An, Jianbo Shen, and Fusuo Zhang 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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