

Green intelligent fertilizers—A novel approach for aligning sustainable agriculture with green development

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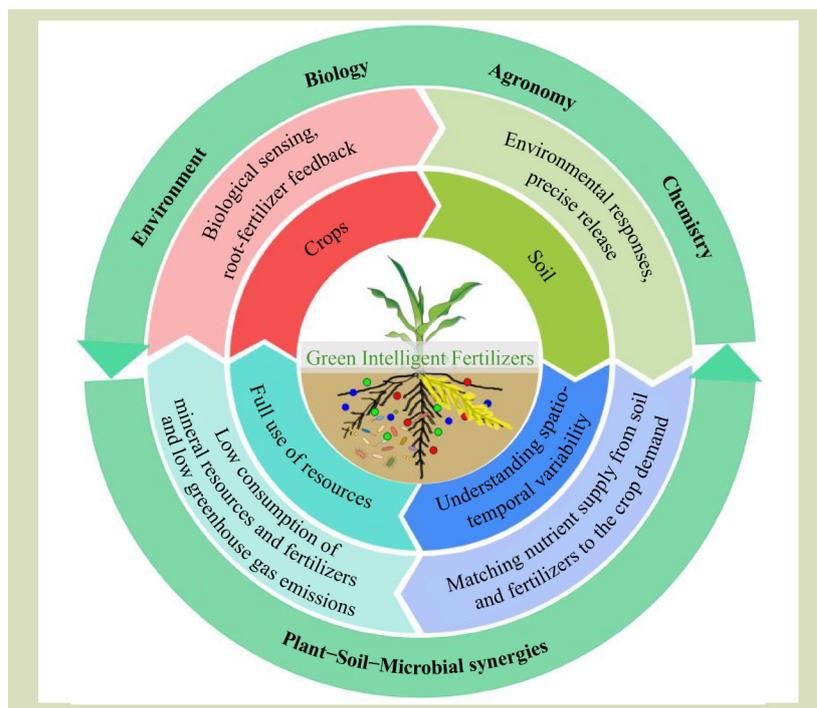
KEYWORDS

Root-nutrient feedback, green development, intelligent fertilizers, new fertilizer, plant–soil–fertilizer interaction, rhizosphere engineering

HIGHLIGHTS

- The pursuit of green development faces challenges of environmental impacts and low resource-use efficiency in fertilizer production.
- Green intelligent fertilizers can be designed to harness the synergy among plants, soils, microorganisms, nutrient sources and the environment.
- New strategies are proposed to align with the principles of green development in both industry and agriculture.
- Green intelligent fertilizers highlight a path toward harmonizing fertilizer production with the imperatives of green agriculture.

GRAPHICAL ABSTRACT



ABSTRACT

This review addresses the growing disparity between the current state of fertilizer production in China and the evolving demands of green agriculture in

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the 21st century. It explores major advances in fertilizers, proposes the concept of green intelligent fertilizers and develops new strategies aligned with the principles of green development in fertilizer industry and agriculture. Green intelligent fertilizers may be designed to maximize the synergistic effects among plants, soils, microorganisms, nutrient sources and the environment. This concept emphasizes the integration of industry and agriculture toward green development for entire industry chain, using an interdisciplinary approach to drive the green transformation of fertilizer industry, and promote green and sustainable development of agriculture. By bridging the gap between the current state of fertilizer industry and a growing need for environmentally responsible agricultural practices, this review highlights a path toward harmonizing fertilizer production with the imperatives of green agriculture.

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1 Challenges and issues in fertilizer development

Fertilizers are an important strategic material for ensuring food security at the national and personal levels. In the mid-19th century, synthetic fertilizers began with superphosphate, created by treating bones with sulfuric acid. By 1900, a shortage of reactive nitrogen became a pressing issue as the need for fertilizers to feed a growing population and produce nitrogen-based explosives increased. The solution came in 1908 with the Haber-Bosch process, enabling the cost-effective production of ammonia from atmospheric nitrogen and natural gas. This process was so successful that, within a century, human production of reactive nitrogen was more than double the global rates of biological nitrogen fixation, making a vital contribution to sustaining the world population^[1]. During the 1960s, the fertilizer industry experienced a rapid growth as the world sought to address food shortages by applying substantial amounts of fertilizers to increase crop yields. The global figures indicate that total fertilizer production, application and fertilizer application rates per unit area increased from 32.5 Mt, 31.7 Mt and 24.9 kg·ha⁻¹, respectively, in 1961 to 209 Mt, 191 Mt and 138 kg·ha⁻¹, respectively, in 2019. Notably, the most rapid production increase occurred between 1961 and 1988, with an annual growth rate of 4.32 Mt^[2,3]. China has emerged as a pivotal contributor to this development, now being the largest producer and consumer of synthetic fertilizers. The annual fertilizer production and consumption in China account for approximately one-third of the total globally.

The demand for fertilizers fluctuates across different periods and environmental conditions, despite their potential to

increase crop yields by up to 50%^[4]. However, extensive fertilizer use in the late 20th century has resulted in nutrient surpluses in many regions. Excessive application of fertilizers has led not only to resource wastage but also to severe environmental problems affecting soil, air and water quality. The nutrient use efficiency of nitrogen, phosphorus and potassium stands at 25% to 30%, 18% to 20%, and 35% to 49%, respectively^[5,6]. Lost nutrients can follow various paths, including escaping into the atmosphere (e.g., as N₂O or NH₃), binding to the soil (e.g., phosphorus fixation, decreasing nutrient availability and drop in soil pH), or leaching into groundwater (causing water eutrophication)^[7,8]. Compounding these concerns, the global population is anticipated to reach 9.7 billion by 2050, while arable land remains limited^[9]. This intensifies the pressure on food production per unit area^[10]. It is imperative to strive to increase crop productivity through innovating fertilizers and fertilizer application to promote sustainable agricultural development while improving environmental preservation.

Fertilizer production has a high requirement for resources in China, accounting for 2% of coal, 3% of natural gas, 80% of phosphate rock, and 60% of sulfur utilization in the country^[11]. The considerable resource consumption and greenhouse gas emissions associated with the fertilizer industry and intensive agriculture no longer align with the sustainable and environmentally-friendly requirements of green agriculture. To address these pressing concerns, the integration of fertilizer industry and agriculture is crucial, facilitating the green transformation of the entire fertilizer industry chain to match the new demands of sustainable agricultural production. Thus, promoting innovation in the development of new fertilizers tailored to agricultural demands is crucial.

Fertilizers are vital for achieving sustainable development in agriculture. In the new era, the pursuit of green development faces multiple challenges, characterized by high environmental costs during production of fertilizers and their low resource utilization efficiency. Notably, in the fertilizer production processes, a substantial portion of nutrient resources remains unused, resulting in huge losses of mineral nutrients (e.g., Ca, Mg, Zn and Fe) and beneficial elements (Si) that could have been used for crop production. To align with the principles of sustainability, it is imperative to bridge the gap between fertilizer industry and agriculture, promote ecofriendly green chemical technology practices throughout the fertilizer industry chain and foster innovation in the development of novel fertilizers.

For this review, our goal is to explore the major advances in fertilizers, especially the concept of green intelligent fertilizer. We aim to uncover the new fertilizer strategies that address the complexities of agricultural production while addressing environmental challenges. These new fertilizers may have the potential to be pivotal for achieving sustainability in both fertilizer industry and agriculture. Moving forward, it is imperative to seek new paths for the transformation of fertilizer industry, striking a delicate balance between enhancing agricultural productivity and preserving the environment.

2 Major advances in fertilizers

With the increasingly serious agricultural non-point source pollution, the global agriculture is embarking on a new road of sustainable development. This paradigm shift means that the fertilizer industry is moving away from its historical focus on quantity and marks a major shift toward quality in the 21st century. A central theme in this changing landscape is the development of innovative fertilizers.

2.1 Single and binary fertilizers

From the 1930s to the 1960s, the development of the fertilizer industry was in its infancy, concentrating only on nitrogen fertilizers, including ammonia water, ammonium chloride, ammonium sulfate, ammonium bicarbonate and urea. The development of binary (nitrogen and phosphorus) fertilizers progressed from the late 1960s to the early 1980s, with the main products being superphosphate, calcium magnesium phosphate, steel slag phosphate fertilizer, monoammonium phosphate, and diammonium phosphate. China completed the pilot test of diammonium phosphate and carbonized nitrophosphate fertilizer in 1962 and 1964, respectively. In

1967, a 30 kt-yr⁻¹ diammonium phosphate plant was built in China. However, the fertilizer development was relatively slow during that time due to the low average fertilizer application rates of arable land and the inability to guarantee the basic raw materials for producing compound fertilizers.

2.2 Ternary compound fertilizers

After 1980, fertilizer production in China entered the rapidly developing phase of ternary compound fertilizers. The manufacture of water-soluble fertilizers also began to rise during this period. The production of nitrophosphate fertilizer using the mixed acid method and the preparation of solid ammonium phosphate using the neutralization slurry concentration method achieved success. In the late 1980s, the industrialization of ammonium phosphate production process was promoted widely, increasing the production of compound fertilizers in China. The compound fertilizer industry in China has entered a phase of vigorous development, combined with importing equipment for the construction of facilities and production of fertilizers.

Prior to 1999, the majority of compound fertilizers were based on the 15-15-15 (N-P₂O₅-K₂O) type. The main production process for highly concentrated compound fertilizers at that time was based on ammoniation-granulation. The 15-15-15 production technology was relatively mature, and the product quality was optimized and reliable. However, due to the planned economy of fertilizer production and use in the 1990s, the potential of innovation and research on new fertilizers have not been fully released. The production and marketing of fertilizers were strictly controlled by the planned economy. The main work focuses on the old factory technical transformation and product structure adjustment, in order to eliminate backward production technology. There are fewer new projects for research and development of new types of fertilizers.

After 1999, in order to meet the requirements of the market economy in China, the fertilizer market gradually opened up due to the reform of the fertilizer distribution system. The mandatory and unified procurement plan for fertilizers were abolished, and a fertilizer distribution system with market allocation of resources was implemented. Many new fertilizer distribution and production enterprises entered the market. Most fertilizer companies shifted to the production of highly concentrated compound fertilizers, including various region- and crop-specific compound fertilizers, substantially diminishing the production and use of the universal 15-15-15 fertilizers as the mainstream product.

China became the largest producer and consumer of fertilizers at the turn of the 21st century. Although the fertilizer industry has begun to develop toward crop-specific fertilizers, the products were still mainly composed of highly concentrated products and bulk-blending fertilizers, with specialized fertilizers containing the nutrient ratios based on attempts to match soil nutrient supply and crop nutrient requirements. However, there was still no precise and targeted matching of fertilizers to the properties of regional soils (e.g., acidic vs alkaline soils) and crops.

2.3 New fertilizers

The development of new fertilizers began based on the increasing demand for innovative solutions in agriculture and fertilizer industry. Since 2014, China has instituted multiple policies and plans for the development of new fertilizers. For example, in 2015, the Ministry of Agriculture and Rural Affairs issued the “Action Plan for Zero Growth in Fertilizer Use by 2020”; the Ministry of Industry and Information Technology issued the “Guiding Opinions on Promoting the Transformation and Development of the Fertilizer Industry”, highlighting the development goals and directions of the Chinese fertilizer industry. The fertilizer industry has been presented with new development opportunities, and the promotion of new fertilizers in China has accelerated. The aggregation in the fertilizer industry has increased against the backdrop of eliminating outdated production capacity and exacerbated environmental pressure. Adjusting the products offered, accelerating the improvement of technological and innovation capabilities, and focusing on promoting the production of new green fertilizers that can reduce the emissions of three wastes in industrial production and non-point source pollution caused by unreasonable agricultural applications have become development priorities. The development of compound fertilizers was aimed toward high efficiency, specialization, long-term effectiveness, functionalization and low-carbon footprint based on the requirements of green and sustainable development. Various new fertilizers appeared, including efficiency-enhanced fertilizers, coated slow-release fertilizers and nanofertilizers, biofertilizers^[12].

The demand for new fertilizers indicates great potential for fostering the scientific and technological progress of fertilizer industry to increase nutrient use efficiency. Compared to traditional fertilizers, new fertilizers are based on novel formulas or technologies by incorporating effective additives. For example, coated slow-release fertilizers serve the crucial purpose of achieving a slow and/or controlled release of

nutrients by delaying the physical contact between the nutrients and the soil^[13–15]. Nanofertilizers adsorb nutrients in their unsaturated structure to reduce nutrient fixation in soil and leaching losses^[10,16–18]. Biofertilizers bring about a host of benefits by boosting soil microbial activity, stimulating plant root exudation, improving soil nutrient availability and facilitating the absorption of essential nutrients by plants^[19–21]. These potential fertilizers are also called smart fertilizers, which refers to nanomaterials, multi-components or bioformulations that adjust the timing of nutrient release through physical, chemical and biological processes to match the needs of plants. This adaptation may enhance crop yields and reduce environmental impact at a favorable cost/benefit ratios compared to normal fertilizers^[4,22,23].

The slow-release fertilizers represent only the first stage of developing new fertilizers and are hampered by the intricate production processes, elevated costs and environmental pollution. In some situations, the regulation of nutrient release from fertilizers is based on utilizing the biological characteristics of soil microbial communities and crops, and on differential soil and climate characteristics, rather than simply adding exogenous substances to fertilizer. However, there are currently no standards to guide implementation of specific slow-release technologies and a poor understanding of various limitations associated with different approaches^[4,22].

To fully align with the demands of contemporary agriculture and the imperatives of environmental sustainability, there is a pressing need to establish new standards and explore more advanced novel fertilizers. These innovative fertilizers should comprehensively take into account the characteristics of crops, soils, climates and fertilizers to facilitate cost-effective and environmentally-friendly agricultural production practices^[23] (Table 1).

3 Developing green intelligent fertilizers for sustainable agriculture

3.1 Concept and framework of green intelligent fertilizers

Green intelligent fertilizers are new types of high-quality fertilizers produced based on the principles of optimized plant nutrition that matches crops, soils and the environment, using the big-data intelligent algorithms for targeted supply-demand matching, activating root-fertilizer synergy or feedback by intensifying crop biological potential, developing advanced green manufacturing technology to stimulate crop rhizosphere

Table 1 Differences between common fertilizers and green intelligent fertilizers

Fertilizers	Characteristics	Breakthroughs
Common fertilizers (e.g., coated fertilizers, nanofertilizers, biofertilizers and stable fertilizers)	Adding exogenous substances to enhance fertilizer efficiency; slowing or controlling nutrient release; and reducing nutrient loss in agricultural applications	Regulating nutrient release solely by mechanical addition or production methods; high cost of external materials; and high environmental impact
Green intelligent fertilizers	Full use of mineral resources; fully mobilize the biological potential of crops themselves; matching crops, soil, and environment; nutrient release conforms to the pattern of crop nutrient requirements; and low consumption, emissions and losses	New intelligent materials and efficiency-enhanced nutrient formula; maximizing root-fertilizer interaction and feedback; new technological breakthroughs; and agricultural precision application technology

effects and fully exploiting mineral resources contained in raw materials (e.g., phosphate rock) (Fig. 1). Such fertilizers have the characteristics of high nutrient efficiency, low-carbon production and use footprint, and maximized utilization of nutrient resources in the whole industry chain (Table 1). Green intelligent fertilizers not only increase yield and improving quality of food, but also serve as an important entry point for integrating the fertilizer industry and agricultural chain via green transformation of the fertilizer production^[24].

3.2 Innovative strategies and pathways of green intelligent fertilizers

Green intelligent fertilizers represent a transformative

approach to optimizing crop nutrient management that takes into account a number of the sustainability, efficiency and circular economy principles.

3.2.1 Activating root-fertilizer synergy by intensifying crop biological potential

A fundamental aspect of green intelligent fertilizers may lie in their capacity to harness biological sensing and foster dynamic interactions between roots, soil microorganisms, and nutrient supply^[25]. Plant roots (and soil microorganisms) possess remarkable nutrient-sensing capabilities, enabling mutual feedback mechanisms that yield synergistic effects^[26]. This synergy is further amplified within the rhizobiont, maximizing

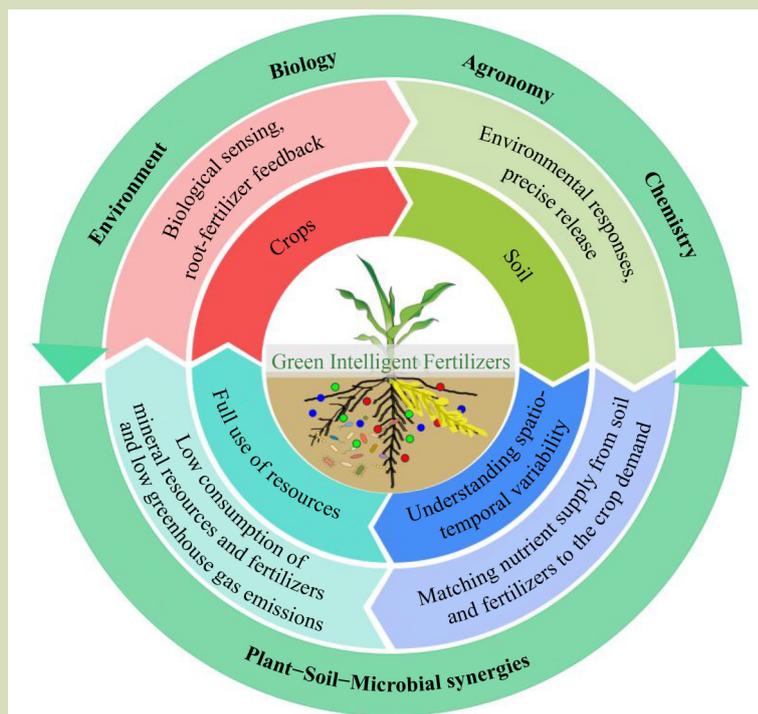


Fig. 1 Conceptual model and research framework of green intelligent fertilizer.

the functional potential of fertilizers^[27]. For example, nitrate can promote lateral root elongation, whereas ammonium can stimulate root initiation and branching, significantly enhancing overall plant growth^[28,29]. Yan et al.^[30] found that nitrate confers rice adaptation to high ammonium in the root zone by suppressing ammonium uptake but promoting its assimilation. Hence, the manipulation of ammonium:nitrate ratio in compound fertilizers can effectively regulate crop growth. Even though microorganisms may influence this ratio in soil, the manipulation of ammonium:nitrate ratio in fertilizers may provide an intriguing approach to regulate biological effects. For example, localized supply of ammonium and phosphorus can stimulate root proliferation and rhizosphere acidification resulting in increased nutrient uptake and yield^[31,32].

The development of intelligent fertilizers that respond to plant signaling mechanisms will be a breakthrough innovation in agriculture. Normal fertilizers, even when designed to meet (at least to some extent) plant nutrient demands, fall short of responding to real-time plant–soil–microbe interactions. The proposed intelligent fertilizers can improve this by being designed to exploit the dynamic relationship between plants and rhizosphere through two distinct pathways (Fig. 2). The first pathway hinges on below-ground communication

orchestrated by signaling molecules like proteins, peptides, lipids, small RNAs, phytohormones and metabolites^[33,34]. High-throughput metabolomic technologies are essential for identifying crop-specific signaling molecules. These molecules, when incorporated into fertilizers, hold the potential to stimulate root growth or attract beneficial microbes, thereby promoting enhanced nutrient cycling and bolstering crop tolerance to stress. The other revolutionary feature of the intelligent fertilizers is a sensor coating that responds to plant signals related to nutrient acquisition, triggering the release of nutrients exactly when plants require them. This approach is tailored to the real-time nutrient demands of plants, promoting environmentally-friendly and sustainable agricultural practices.

3.2.2 Sensing soil environment by intelligent materials for precise nutrient release

Environmental conditions significantly influence crop growth and nutrient uptake. Factors, such as low temperature and soil moisture, profoundly impact crop development and nutrient absorption. Soil moisture has a significant impact on root development and nutrient transport, influencing the utilization of almost all nutrients^[35]. Green intelligent fertilizers aim to intelligently adjust nutrient release in response to changing

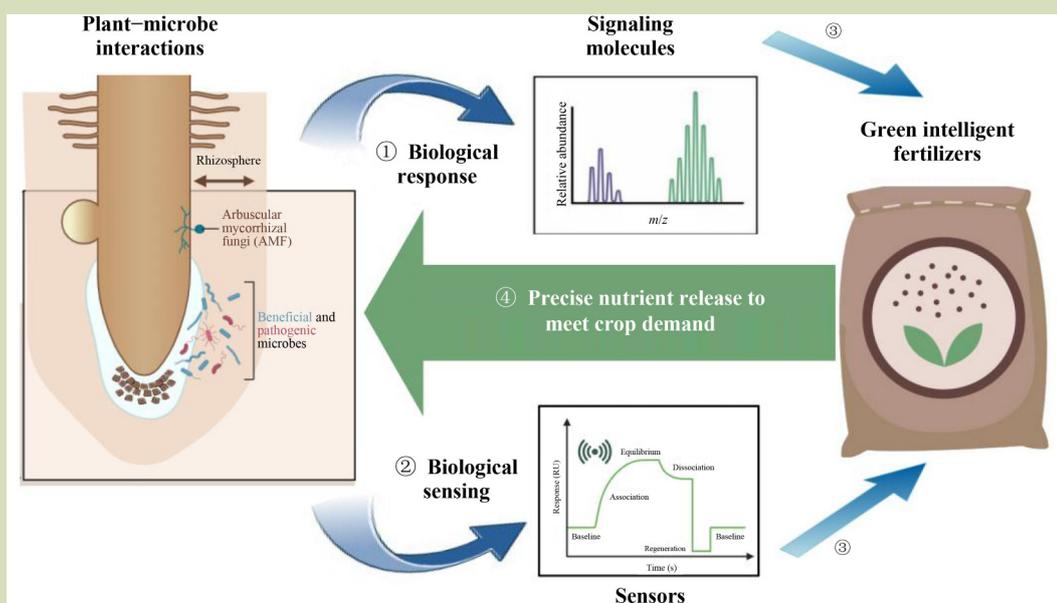


Fig. 2 Proposed pathways for the development of intelligent fertilizers featuring precise nutrient release to meet crop demand. ① The first pathway involves extracting and identifying plant signaling molecules that can modify root systems and attract beneficial microorganisms, thereby enhancing plant nutrient acquisition and resilience to environmental stresses. ② The second pathway focuses on identifying rhizosphere signal molecules produced under stress conditions to inform the design of sensors in intelligent fertilizer. ③ These signaling molecules, either in their original form or following modifications to enhance stability and effectiveness, can be integrated into fertilizers. ④ These sensors release nutrients when exposed to these signaling molecules. Created with BioRender.com.

environmental conditions, with low emission and full use of raw mineral nutrients, aligning with the specific nutritional needs of crops. Such responses are underpinned by incorporating intelligent materials to respond to the environmental cues. The interactions between intelligent materials (e.g., temperature-sensitive or water-absorbing materials) and environmental factors influencing plant nutrition (e.g., optimal growth temperature and water supply) can be used to create intelligent fertilizers and coordinate the fertilizer nutrient supply with the plant demands. Encapsulation of nutrients into hydrophilic materials allows fertilizers to control water absorption and release nutrients only when soil moisture reaches a specific threshold. Additionally, the nutrient release can be modulated in response to changes in soil pH, organic ligands in root secretions, and ambient temperature, ensuring precise nutrient delivery by controlling responses to environmental cues. For example, appropriately designed fertilizers may absorb water from the soil environment even in arid/semiarid regions to promote fertilizer dissolution and plant nutrient absorption. In hot summers, the temperature-sensitive fertilizers can achieve quick release of fertilizer nutrients through the temperature-triggered phase change of materials to meet the increasing nutrient demands of crops. Some crops intensively acidify the rhizosphere under low-phosphorus stress and pH-responsive fertilizers can respond to changes in the rhizosphere pH to increase or decrease fertilizer nutrient release^[36].

3.2.3 Dynamically matching nutrient release and crop demand

To maximize nutrient use efficiency, green intelligent fertilizers must match crop nutrient demand dynamically in both time and space. Nutrient requirements by crops vary significantly during different growth phases. Fertilizer application timing and spatial distribution must consider soil conditions and their impact on nutrient transformations, losses, and plant growth rates. The combination of quick- and slow-releasing nutrients not only meets the urgent nutritional needs in the early growth stage of crops, but can also release nutrients slowly later to match the crop nutrient demand. In some cases, the nutrient requirements of crops throughout entire growth period could be met by one-time fertilization and a variable nutrient release from green intelligent fertilizers over time (even though a need for top-dressing at appropriate crop growth stages cannot be excluded).

The dynamic nature of root system physiology as well as distribution in soil, coupled with varying nutrient mobility, underscores the importance of localized nutrient

application^[37]. This can be achieved through mechanized, precisely positioned fertilizers that promote root proliferation and enhance nutrient absorption in the rhizosphere. Ma et al.^[31] accurately targeted fertilizer application during maize sowing and jointing period to optimize the regulation of root growth by the rhizosphere management strategies. Considering the current nutrient surplus in many agricultural soils coupled with soil heterogeneity, more accurate root-zone fertilization via banding should be considered to augment the effect of localized fertilization.

Crop root systems can be regulated by optimizing nutrient application. For example, the root system architecture and function are shaped selectively by inducing lateral root proliferation and inhibiting main root development under low-phosphorus stress. Localized fertilizer supply promotes root proliferation and relatively intense acidification in the rhizosphere, enhancing the contact area between roots and nutrient-rich fertilizers, and altering solubilization of fertilizers, thus improving the nutrient absorption by roots^[31]. In addition, the localized fertilizer supply also strengthens physiologic processes such as the exudation of protons and organic acid anions by the root system to mobilize nutrients. This maximizes the synergistic potential, improving nutrient absorption and utilization by crops. It stimulates above-ground growth, with the enhanced growth of the above-ground plant parts, in turn, strengthening root growth, achieving a dynamic demand-supply synergy.

3.2.4 Fully utilizing rock mineral nutrient resources and industrial byproducts to create new green fertilizers with low resource and environmental costs

The green aspect of intelligent fertilizers focuses on resource utilization and environmental considerations throughout the product lifecycle. Full use of resources by applying advanced green manufacturing processes and technologies emphasizes retaining and efficiently utilizing mineral nutrient resources (e.g., from the phosphate rock). Mining of raw materials and manufacturing of fertilizers aim to minimize mineral nutrient loss and maximize nutrient use. Additionally, secondary processes are employed to transform nutrient resources in byproducts into new fertilizer products, further improving resource utilization. Increased efficiency of utilization of raw materials can be achieved by creating new products via innovative production processes or blending technologies. Low energy consumption, low greenhouse gas emissions and minimal waste generation are key considerations throughout the products lifecycle, aligning with green, low-carbon and environmentally-friendly practices^[38].

Crop nutrient requirements have been well-established through research. However, applying this knowledge to fertilizer science is hindered by complexities of precise formulation and industrial manufacturing. Nitrate, a key nitrogen source as well as a nutrient signal, is essential for crop development. Combined application of ammonium and nitrate often yields better results for many crops than the single-nitrogen-form fertilizers.

In production of phosphate fertilizers, precipitation of phosphate ions with calcium and magnesium hampers nutrient efficacy, presenting challenges in compound fertilizer production. Innovative techniques in green intelligent fertilizers, including layered granulation and chelation to separate calcium and magnesium from phosphorus layers or microdomain compartments to avoid precipitation, would enhance fertilizer efficiency^[39]. The new fertilizers containing Ca and Mg may benefit the regions with low-calcium and low-magnesium soils, such as acidic soils.

Adding citric acid as chelator during the production of monoammonium phosphate fertilizer (that has soil-acidifying properties) facilitates the activation and synergistic availability of phosphorus and trace elements, enhancing the utilization of both phosphorus and trace elements, particularly in the soils of high pH^[40]. These innovative green production processes enable high stability and availability of fertilizer nutrients.

The feasibility of production and significant efficiency of the green intelligent fertilizers have been proven for several plant species. For example, Green Intelligent Macadamia Fertilizer has been designed based on the nutrient demand dynamics and cluster root characteristics of macadamia and the unique attributes of acidic soil. The Green Intelligent Macadamia Fertilizer combines water- and citrate-soluble phosphorus, effectively meeting the early growth demands of macadamia. In the early stage, a small amount of water-soluble phosphorus supports the early root growth. Subsequently, citrate-soluble phosphorus was mobilized by the development of cluster roots in macadamia plants. This process facilitates the exudation of carboxylates, protons and acid phosphatases in the rhizosphere for efficient phosphorus acquisition^[41–45]. Additionally, the fertilizer synergizes ammonium and nitrate nitrogen, maximizing macadamia root growth through the principles of ammonium nitrogen promoting lateral root initiation and nitrate nitrogen promoting root elongation^[32,45]. Notably, the citrate-soluble phosphorus raw material is derived from acid ore intermediates, utilizing low-grade phosphate ore and slag acid as industrial byproducts, exemplifying a sustainable green industry. Remarkably, the application of Green Intelligent

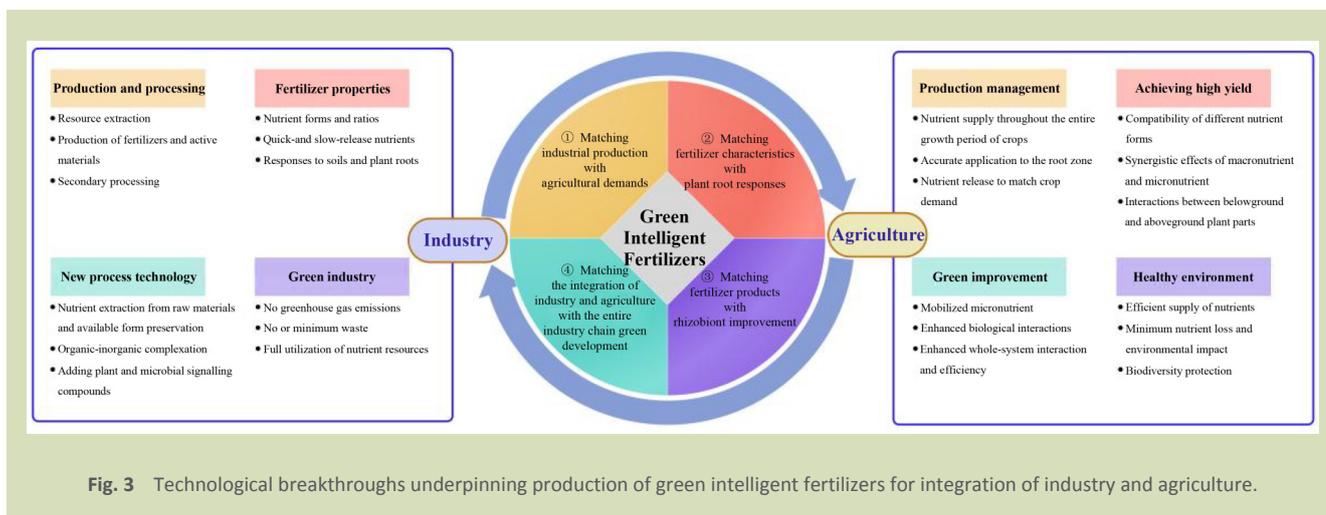
Macadamia Fertilizer has led to a 20% increase in average yield, even with a 35% reduction in fertilizer usage, achieving synergistic goals of fertilizer efficiency, yield enhancement and quality improvement. This success extends to green intelligent fertilizers for maize, potato and rice, using innovative layered granulation or industrial byproducts, leading to significant yield increases compared to standard fertilizer application methods.

In essence, green intelligent fertilizers embody a strategy of engaging root-fertilizer synergy through biological sensing and soil environment monitoring, dynamically aligning nutrient release with crop demand. The comprehensive utilization of rock mineral resources and industrial byproducts contributes to the creation of environmentally-friendly fertilizers with minimal resource and environmental costs. Using advanced green manufacturing processes, these new fertilizers trigger and augment crop rhizosphere effects, ensuring precise nutrient supply-demand matching and efficient use of mineral resources. More importantly, these fertilizers facilitate the integration of the entire fertilizer and agricultural industry chain, propelling the fertilizer industry toward a green and sustainable transformation. Intelligent fertilizers are also important for in responding to diverse factors such as soil conditions, crop characteristics, climate variables and management practices.

The integration of machine learning and big data further amplifies the capacity to extract intelligent insights from the experiments and chemical reactions, thereby facilitating the development of sophisticated agricultural fertilizer formulas. In the context of regional fertilizer management, some techniques such as controlling total fertilizer input, via (1) split applications of nitrogen fertilizer, and (2) maintenance and buildup strategies for phosphorus and potassium, and the data-driven analysis of extensive field trials may enable the identification and quantification of key technical indicators and parameters. This information, in turn, would facilitate the optimized formulation and refinement of fertilizer compositions.

4 Perspectives

In the new era, green development is the new concept for national development in China, and the research and development of new green agricultural inputs is of importance. Changing the existing model for fertilizer products with high nutrient concentration, high water solubility and high pollution risk, the development of green intelligent fertilizer has become an important starting point for the green



transformation of the whole fertilizer and agriculture industry chain. Green intelligent fertilizers can promote a shift of fertilizer industry toward a green development paradigm, but extensive testing of the green intelligent fertilizers is still needed under field conditions. This green transformation can be realized through the integration of fertilizer industry and agriculture demands to develop a complete industrial chain connecting industry to agriculture, fostering interdisciplinary collaboration (Fig. 3). During this transition, agriculture should define its specific fertilizer needs, encompassing

nutrient ratios, forms and other properties. This specification will be guided by dynamic sensing and monitoring of the crop, soil and climate conditions, facilitated by advanced big-data intelligent algorithms. Concurrently, the fertilizer industry should meet the increasing demand for agricultural fertilizers by enhancing process innovations and technological breakthroughs. Critically, both ends of the industry-agriculture spectrum will engage in synchronized and systematic analyses of the entire industry chain, ensuring alignment with the green and sustainable agriculture in the future.

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Compliance with ethics guidelines

Maoying Wang, Lingyun Cheng, Chengdong Huang, Yang Lyu, Lin Zhang, Zhenya Lu, Changzhou Wei, Wenqi Ma, Zed Rengel, 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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