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REVIEW

Research, production and use of stabilized fertilizers in China: pathways for green transition and sustainable development strategies

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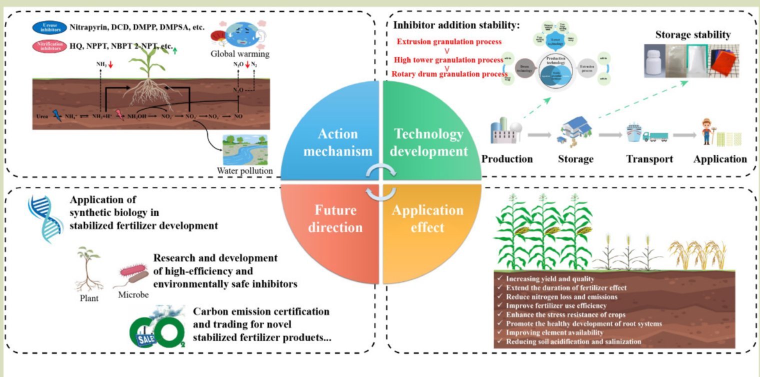
GRAPHICAL ABSTRACT



ABSTRACT

Stabilized fertilizers, enhanced with urease or nitrification inhibitors, have emerged as pivotal tools for China's agricultural green transition, balancing crop productivity, resource efficiency, and environmental sustainability. Globally, Germany and other EU countries have pioneered inhibitor-integrated fertilizer policies, driving emission reductions. Despite China's later start, breakthroughs in local production, diversified formulations (covering six major fertilizer categories) and standardized systems have positioned it as a global leader, with 90% of the raw material capacity and 3 Mt annual output (4% of the total fertilizer production). Meta-analysis of over 900 trials (2014–2018) demonstrates stabilized fertilizers increase yields by 9.2%, nitrogen use efficiency by 11.2% and lower N_2O emissions by 28.4% in staple crops. Field studies further reveal multifunctional benefits including 60% higher nitrogen efficiency, 60% emission cuts, 20%–50% fertilizer savings and enhanced climate resilience. To maximize impact, advancing technology innovation, refining application protocols and fostering cross-sector collaboration are critical. This paper provides strategic insights to accelerate China's sustainable agriculture transition and global climate goals.

1 New era of demand for stabilized fertilizer

1.1 Enhancing fertilizer efficiency is a critical aspect of China's green agricultural development

Improving nitrogen fertilizer efficiency is a key challenge for both food security and ecological sustainability in China. Nitrogen fertilizer accounts for about 45% of the increase in China's grain production and contributes to about 60% of the protein supply in the food chain, providing a vital means of sustaining China's 1.4 billion people[1]. However, the intensive use of nitrogen fertilizer depends on high energy consumption, particularly through coal combustion during production, leading to about 400 Mt of CO_2 emissions annually[2]. Also, N_2O produced during the application of nitrogen fertilizer accounts for 70% of the total global emissions and is an important source of greenhouse gas emissions[3]. NH_3 emissions represent 50% of total emissions and contribute about 30% to haze formation[4]. Additionally, ammonia deposition is a major contributor to water eutrophication, accounting for about 25% of total nitrogen input in surface waters.

Low nitrogen use efficiency is a primary driver of these environmental issues. Although China's nitrogen fertilizer consumption declined from 30 Mt in 2015 to 24 Mt in 2024, with use efficiency rising to nearly 43%[5], a significant gap remains compared to the green development target of 60% (Table 1)[7]. Several factors contribute to low nitrogen fertilizer utilization rates. First, nitrogen fertilizer formulations are relatively limited, primarily consisting of urea and ammonium-based fertilizers. These fertilizers dissolve and transform

Table 1 Current status and development goals of key indicators for nitrogen fertilizer loss reduction and efficiency enhancement in China

Key indicator	Status in 2024	Long-term goals
Nitrogen fertilizer application rate (Mt) [a]	24	18–21
Nitrogen use efficiency (%) [b]	42.6	60–70
Total nitrogen loss (%)[6]	40	< 20
NH_3 (%)[6]	15–20	< 5
N_2O (%)[6]	1	< 0.5
Nitrate leaching or runoff (%)[6]	9	4.5
Soil residue (%)[6]	18.7	10–20
Nitrogen in organic waste (Mt)[6]	32.5	25
Organic N returned to the field (Mt)[6]	7.5	15
Nitrogen loss from organic waste (Mt)[6]	13	6.25

Note: [a] National Bureau of Statistics of China; [b] Ministry of Agriculture and Rural Affairs of China.

rapidly, and are prone to volatilization and loss, and do not align well with crop nutrient uptake patterns. Second, nitrogen fertilizer application technology remains underdeveloped and mechanized infrastructure insufficient, making precise and targeted application challenging. Additionally, farmers have limited awareness and expertise in precision fertilizer application, hindering the full utilization of existing nitrogen fertilizer products. Consequently, excessive fertilizer application is often used as a risk mitigation strategy. Adapting to modern agricultural production is key to advancing nitrogen fertilizer product innovation and application technology.

The primary objective of agricultural nutrient management technology development in China is to further reduce and improve the efficiency of nitrogen fertilizer use. In recent years, China has actively promoted technologies for fertilizer reduction and efficiency enhancement. In February 2015, the Ministry of Agriculture and Rural Affairs issued the *Action Plan for Zero Growth of Fertilizer Use by 2020*, aiming to achieve zero growth of fertilizer use of major crops by 2020 through the establishment of a scientific fertilizer management and technology system. The annual growth rate of fertilizer use was capped at 1% from 2015 to 2019. In 2022, the Ministry of Agriculture and Rural Affairs, along with relevant departments, issued several policies: In May, the National Development and Reform Commission jointly issued the *Implementation Plan for Carbon Emission Reduction and Sequestration in Agriculture and Rural Areas*, emphasizing the promotion of nitrogen fertilizer reduction and efficiency in key areas such as major grain-producing areas. In September, the five departments jointly issued the *Implementation Plan for Building National Agricultural Green Development Pilot Zones and Promoting Comprehensive Green Transformation in Agricultural Modernization Demonstration Zones* guiding pilot and demonstration zones to formulate carbon emission reduction and sequestration plans, and promoting such emission reduction technologies as water management in rice fields, and nitrogen fertilizer reduction and efficiency improvement in farmland. In October, they issued the *Guiding Opinions on Promoting the High-quality Development of Rice-fishery Comprehensive Farming Industry* emphasizing the ecological cycle, green and low-carbon characteristics of rice-fishery comprehensive farming, and reducing the use of pesticides and fertilizers. In November, the *Chemical Fertilizer Reduction Action Plan by 2025* was released, with the goal of achieving a stable decline in the application of agricultural mineral fertilizers across China by 2025 and a more appropriate crop nutrition regime.

In February 2023, the Ministry of Agriculture and Rural Affairs issued the *Implementation Opinions on the Implementation of the Key Work Deployment of the CPC Central Committee and The State Council in 2023* to comprehensively promote rural revitalization, once again emphasizing the reduction of fertilizers and pesticides, along with efficiency improvements. This included the implementation of fertilizer reduction actions, the development of novel fertilizer application technologies, innovation products, creation of machinery and the establishment of integrated supporting model areas. Additionally, the application of intelligent fertilizer recommendation systems was highlighted. These policies reflect China's sustained efforts and firm determination in the green development of agriculture, and in the reduction and the enhancement of fertilizer efficiency. In recent years, the amount of nitrogen fertilizer application in China has dropped to about 24 Mt. In line with current policy directions and technological advancements, there is still potential for further reduction in nitrogen fertilizer application, with a target range of 18–21 Mt, aligning with crop absorption needs.

1.2 Stabilized fertilizer is the main way to decrease nitrogen loss and increase efficiency

To optimize the structure of fertilizer products, improve their utilization rate, and ensure food security, China's fertilizer industry continues to focus on developing more efficient fertilizer products. Currently, the enhanced fertilizer products that have achieved large-scale industrialization primarily include slow- or controlled-release fertilizers (e.g., polymer coatings and polymer sulfur coatings), biofertilizers (e.g., *Azotobacter*, mycorrhizal fungi, phospholysaccharides and rhizobia), value-added fertilizers (e.g., amino acids, fulvic acid, humic acid, protein hydrolysates and seaweed extracts), and stabilized fertilizers (e.g., with nitrification or urease inhibitors). Among them, stabilized fertilizers have attracted widespread attention due to their clear function, high safety and ease of application. In June 2019[8], the European Union introduced a new regulation on fertilizers, classifying products containing inhibitors into separate categories and establishing fertilizer standards. Since February 2020, the use of standard urea has been banned in Germany[9], with urease inhibitors required or deep application methods mandatory.

According to a report by Industry ARC, the global nitrification and urease inhibitors market has been growing at a compound annual growth rate of 3.26% from 2018 to 2023. According to the International Fertilizer Association, global consumption of stabilized fertilizers in 2022 was about 10 Mt, with stabilized nitrogen fertilizers containing nitrification and urease inhibitors accounting for about 7.3 and 2.6 Mt, respectively.

The primary markets for these products are expected to be concentrated in the EU and USA. Leading global enterprise clusters have been formed, including companies such as Compo and BASF in Germany, Solvay in Belgium, Corteva in USA and Koch Agronomic Services in USA. Global consumption of stabilized fertilizers is projected to reach nearly 13 Mt by 2030[10].

According to statistics from the China National Chemical Information Center Co., Ltd., in 2023, China's stabilized fertilizer production reached 2.6 Mt[11], all of which was used domestically. It is expected that by 2030, the consumption of stabilized fertilizer in China will reach 3.14 Mt (Table 2). Although the full potential for stabilized fertilizer application has not yet been realized, its rapid growth in recent years clearly indicates that China is accelerating toward a global leadership position.

2 Rapid development of stabilized fertilizers in China

2.1 China has emerged as the leading global producer of inhibitors

The core technology behind stabilized fertilizers primarily focuses on the application of nitrification and urease inhibitors. As attention on stabilized fertilizers increases, both domestic and international research, and development efforts in inhibitor technology are accelerating. Commercial nitrification inhibitors remain limited, with dicyandiamide (DCD), nitrapyrin and 3,4-dimethylpyrazole phosphate (DMPP) being the primary inhibitors still widely applied. DCD was first identified for its nitrification-inhibiting properties in 1918, although it only gained widespread use in US agriculture in the 1980s (Table 3)[13]. Advancements in technology have led to DCD becoming a widely used nitrification inhibitor. The nitrification-inhibiting properties of nitrapyrin were first identified by Goring in 1962[16], leading to the development of N-Server by Dow Chemical in the 1970s, which was approved for agricultural use by the US Environmental Protection Agency in 1975[17]. DMPP was developed and commercialized by BASF in Germany in the 1990s. Compared to the earlier nitrification inhibitors, such as DCD and nitrapyrin, DMPP offers higher efficiency, lower toxicity and environmental friendliness, making it widely used in agricultural production across Asia, Australia, Europe and South America[14].

The commercially available urease inhibitors primarily include HQ (hydroquinone), NBPT (N-(n-butyl) thiophosphoric triamide) and NPPT (N-(n-propyl) thiophosphoric triamide). In the 1970s, Bremner & Douglas[18] screened over 130 compounds and identified benzoquinone and HQ derivatives as effective urease inhibitors. Of these, HQ gained widespread international recognition as one of the earliest and most cost-efficient urease inhibitors, leading to extensive research and practical application (Table 4)[19]. Today, NBPT is one of the most widely used and effective urease inhibitors. Research and development began in the late 1980s, and in 1996, IMC-Agrotain, based in the USA, developed and launched the commercial product[22]. NPPT, a new inhibitor developed by BASF in Germany, is based on NBPT. Its representative product, LIMUS, enhances the ammonia volatilization inhibition rate and duration by combining NBPT and NPPT, while significantly improving storage stability. Domestic research and application of NPPT are in the early stages, with large-scale production yet to be established, and the product is primarily imported[23]. In addition to chemical nitrification inhibitors, biogenic inhibitors have also seen significant advancements (Table 5). Current research has identified several biogenic nitrification inhibitors from plant root exudates, including methyl p-hydroxyphenyl propionate, sakuranetin, sorghum ketone, brachialactone and 1,9-decanediol from various plants such as sorghum and rice[35]. Biologically derived nitrification inhibitors are advantageous for their long-

Table 2 Development and perspective of enhanced efficient nitrogen fertilizer globally and in China

Type of fertilizer	Global usage		Chinese usage	
	Usage in 2024 (Mt)	Expected usage in 2030 (Mt)	Usage in 2024 (Mt)	Expected usage in 2030 (Mt)
Stabilized fertilizer [a]	10.6	12.7	2.63	3.14
Slow- or controlled-release fertilizer [a]	3.46	5.19	1.73	2.60
Nano-urea [b]	20.0	25.6	–	–
Azadirachtin urea [b]	32.0	41.0	–	–

Note: [a] International Fertilizer Association and China National Chemical Information Center; [b] China Fertilizer Information Network.

Table 3 Development of nitrification inhibitors

Type	Abbreviation	Time of development/use and country	Stability	Additive amount [a, c]	Comprehensive evaluation [b]
2-Chloro-6 -(trichloromethyl) pyridine[12]	Nitrapyrin N-Serve	The 1960s and the 1970s, America	Photolysis, pyrolysis, pungent odor	Pure nitrogen 0.25%–0.5%	High vapor pressure; strong smell; corrosiveness; explosive; insoluble in water; toxicological health issues
Dicyandiamide[13]	DCD	Developed the 19th century; used the 1970s, America	Well-received	Pure nitrogen 2.3%–4.5%	High rate addition; easy to wash; high price
3, 5-Dimethylpyrazole[14]	DMP	The 1980s, Germany	Low melting point, lower stability than DMPP	Pure nitrogen 0.4%–0.8%	Efficient; low toxicity; instability
3, 4-Dimethylpyrazole phosphate[14]	DMPP	The 1990s, Germany	Well-received	Pure nitrogen 0.8%–1.6%	Efficient; low toxicity; stable; higher price
An isomer mixture of 2-(3,4-dimethylpyrazol-1)-succinic acid and 2-(4,5-dimethylpyrazol-1)-succinic acid[15]	DMPSA	Still to be released, Russia	Well-received	Pure nitrogen 0.8%–1.6%	Efficient; low toxicity; stable; higher price

Note: [a] Amount of inhibitor added is based on EC Regulation 2003/2003 by mass percentage (w/w); [b] through the investigation of the application of inhibitors in China's fertilizer industry, a comprehensive evaluation of the inhibitors was conducted; [c] recommended application rates were extrapolated based on products sharing the same functional moiety (e.g., DMP and DMPP).

Table 4 Development of urease inhibitors

Type	Abbreviation	Time of development/use and country	Stability	Additive amount [a]	Comprehensive evaluation [b]
Hydroquinone[19]	HQ	The 1970s, America	Stable, but incompatible with strong oxidants, strong bases, oxygen, iron salts, photolysis	Amide nitrogen 0.9%–2%	Toxicity, teratogenicity
N-butyl thiophosphoryl triamine[20]	NBPT	The 1990s, America	Hydrolysis, pyrolysis, acid hydrolysis	Nitrogen in amide state 0.09%–0.2%	Stability issues, compatibility issues with other inhibitors, compound fertilizers
Triamine n-propyl thiophosphate[20]	NPPT	The 1990s, Germany	Hydrolysis, pyrolysis, acid hydrolysis	Generally, it is not added alone, but is added in combination with NBPT	Stability issues, compatibility issues with other inhibitors, compound fertilizers
N-(2-nitrophenyl) phosphoryltriamine[20,21]	2-NPT	Still to be released	Relatively stable	Nitrogen in amide state 0.04%–0.15%	Price is more expensive, the cost is more than 10 times that of NBPT

Note: [a] Amount of inhibitor added is based on EC Regulation 2003/2003 by mass percentage (w/w); [b] through the investigation of the application of inhibitors in China's fertilizer industry, a comprehensive evaluation of the inhibitors was conducted.

lasting, effective and natural properties, making them an ideal strategy for sustainable nitrogen management. Denitrification inhibitors, which suppress the activity of denitrifying bacteria and decrease the conversion of nitrate to dinitrogen or nitrogen oxides, have become a focal point of ongoing research.

China began researching inhibitors in the 1970s. The Shenyang Institute of Ecology, Chinese Academy of Sciences, successfully developed long-acting urea and ammonium carbide products containing DCD. Since the 1990s, the combined use of nitrification and urease inhibitors has been promoted[19]. In recent decades, Chinese research on pyrazoles and phospho-polysaccharides has made significant advancements[19]. Currently, inhibitor products in China are continuously being optimized for higher efficiency, lower cost and environmental friendliness, which has laid a solid foundation for the agricultural green development and the popularization of nitrogen fertilizer efficiency enhancement technologies.

China is the main global producer of current inhibitor products. According to the data provided by Wuwei Jincang

Table 5 Research progress on biological source inhibitors in China and internationally

Classification of inhibitor	Substance	Source	Development of the country
Biological nitrification inhibitors	1,9-Decanediol[24]	Rice root exudates	China
	Syringic acid[25]	Rice root exudates	China
	Methylp-hydroxyphenylpropionate (MHPP)[26]	Sorghum root exudates	Japan
	Sakuranetin[27]	Sorghum root exudates	Japan
	Sorgoleone[27]	Sorghum root exudates	Japan
	Brachialactone[28]	*Juncus effusus* root exudates	Japan
	Linoleic acid[29]	*Juncus effusus* stem tissue	Japan
	Linolenic acid[29]	*Juncus effusus* stem tissue	Japan
	Zeazone[30]	Maize root exudates	Japan
	2-Hydroxy-4,7-dimethoxy-2H-1,4-benzoxazine-3(4H)-ketone (HDMBOA)[30]	Maize root exudates	Japan
	6-Methoxy-2(3H)-benzoxazolone (MBOA)[31]	Maize root exudates	Japan
	Methyl-p-coumarate[32]	*Juncus effusus* root tissue	Japan
	Methyl ferulate[32]	*Juncus effusus* root tissue	Japan
	2,2-Hydroxy-7-methoxy-2H-1,4-benzoxazine-3(4H)-ketone (HMBOA)[30]	Maize root tissue	Japan
	2-Hydroxy-4,7-dimethoxy-2H-1,4-benzoxazine-3(4H)-β-glucoside (HDMBOA-β-glucoside)[30]	Maize root tissue	Japan
Biological denitrification inhibitor	Procyanidins[33]	*Polygonum multiflorum*	China
	Microbe-derived exudates: citrate, malate[34]	Extract of mycorrhizal fungi hyphae exudates	China

Biotechnology Co., Ltd., in 2024, the production of DCD, 2-chloro-6-(trichloromethyl) pyridine (CP) and DMPP in China has reached 3, 0.5, 2 kt, respectively, accounting for 80%, 90% and 50% of the global total production, and more than 10 enterprises have participated in the production of nitrification inhibitor (Table 6). As far as urease inhibitors are concerned, the common urease inhibitor HQ limits the scale of its industrial application due to the risk of biological toxicity, and the global production is about 210 $t\cdot yr^{-1}$, and China's production is 200 $t\cdot yr^{-1}$. The most widely used NBPT has an annual output of 6 kt in China, accounting for 90% of global production. On the consumption side, the a total of 1.6 kt nitrification inhibitors was used in China in 2023. Specifically, the consumption of DMPP was 800 t, of which 400 t was consumed as the active ingredient and the remaining 400 t was consumed as a formulated product (totaling 1.4 kt). The consumption of DCD was 500 t, of which 100 t was consumed as the active ingredient and the remaining 400 t was consumed in the form as a formulated product (totaling 1.3 kt). The consumption of CP is 300 t, of which 150 t are consumed as the active ingredient and the remaining 150 t are consumed as a formulated product (totaling 500 t). In addition, the total consumption of urease inhibitor NBPT in China in 2023 was 300 t, of which 60 t was consumed as the active ingredient, and

Table 6 Production of the inhibitor active ingredients in China and globally

Type of inhibitor	Total production in China (kt)	Total global production (kt)	China's share in the global scale
DCD	3	3.75	80%
DMPP	2	4	50%
Nitrapyrin	0.5	0.56	90%
NBPT	6	6.7	90%
HQ	0.2	0.21	95%

the remaining 240 t are consumed as a formulated product (totaling 800 t).

2.2 Technological innovation in stabilized fertilizer: breakthroughs and practices in inhibitor addition process

The key feature of stabilized fertilizers lies in the application of scientifically designed and appropriate inhibitor addition technologies. These technologies, when integrated with fertilizer products, enhance the nutrient use efficiency of crops and decrease environmental pollution. However, due to the chemical characteristics of inhibitors and the complexity of the fertilizer production process, the technology for their addition has long had numerous technical challenges (Table 7). In European and American countries, where terminal fertilizer dispensing technologies and equipment are relatively advanced, the strategy of mixing and using inhibitors has been predominantly adopted, with minimal demand on inhibitor addition technology. In contrast, China's current fertilizer technology and equipment are still under development. Consequently, there has been a strong focus on the addition of inhibitors during upstream fertilizer production, which has presented technical challenges, including inhibitor stability, equipment safety, safe production and uniformity of addition[17]. In recent years, through technological innovation, China has made significant breakthroughs in inhibitor addition technology for stabilized fertilizers, laying an important foundation for their industrialization. For example, Sinofert Holdings Limited developed a patented protection plus efficiency enhancement technology for DMPP. By optimizing and coating the molecular structure of DMPP, the retention rate of DMPP in the fertilizer system (over 6 months) was improved from a range of 20%–40% reaching 60%–70%, nitrogen use efficiency was boosted by 15%–20%, and a one-time fertilizer application approach for crops, such as maize, was achieved. This approach reduces mineral fertilizer usage by 10%–20%, while simultaneously increasing crop yield by 5%–15%.

In the production of stabilized fertilizers, the inhibitor addition technology is critical for ensuring the production of high-quality products. For example, nitrapyrin is prone to both decomposition and volatilization under high-temperature and high-light conditions, NBPT tends to be inactivated under conditions of high temperature, high humidity and acidity, and the chloride ions present in NBPT need to be strictly controlled to prevent corrosion of processing equipment. These factors limit the application of these inhibitors in urea-based products. In response to these challenges, domestic enterprises have adopted solvent carrier and biochemical inhibitor composite technologies, which enable complete miscibility and uniform distribution of the inhibitor with a urea slurry. Additionally, optimizing the instant addition process has allowed for the integration of inhibitors into the urea production process, significantly improving both production efficiency and product stability[19].

Also, the instant addition system, developed based on rotary centrifugal separation technology, effectively addresses the issue of inhibitor decomposition during the addition process and significantly reduces the risk of equipment corrosion[36]. This innovative technology has enhanced the production process of stable large-particle urea and provided technical support for the large-scale production of urea-based stabilized fertilizers.

2.3 Diversification of downstream products

To meet the diverse agricultural demands, the types and functions of stabilized fertilizers in China have become increasingly varied and comprehensive. Stabilized fertilizer technology has been extensively applied across a range of fertilizer categories, including standard compound fertilizers, nitrogen fertilizers, water-soluble fertilizers and others (Table 8). For example, stabilized nitrogen fertilizers containing urease inhibitors have seen significant application. The Pu Zilan, stabilized nitrogen fertilizer launched by Nanning Harworld Biological Technology, Inc. and the Chao Kongshi stabilized fertilizer produced by Henan Xinlianxin Chemical Industry Group Co., Ltd., both incorporate Limus technology (Table 9). These products are suitable for fertilizer application in large fields, fruit tree cultivation and horticultural crops. Additionally, the nitrification inhibitor DMPP has been successfully used in the Wistom stabilized fertilizer by Sichuan Jinxiang Chemical Co., Ltd and the Meizile stabilized compound fertilizer by Yunnan Yuntianhua Co., Ltd, among numerous other applications.

The diversified development of stabilized fertilizers is not only reflected in the expansion of product types but also in their ability to precisely meet the specific demands of different soils, climates and crops. For example, spring fertilizer application in winter wheat often poses significant ammonia volatilization risks. In regions characterized by frequent rainfall and alkaline soils, strong nitrification can lead to a substantial emission of greenhouse gases, such as N_2O, and cause the loss of nitrate through leaching. The application of fertilizers containing nitrification inhibitors and urease inhibitors offers an effective

Table 7 Technologies advances in stabilized fertilizer production

Problem with the use of inhibitor	Current obstacle to adding inhibitor into fertilizer	Breakthrough	Technology implementation
Light, temperature, and moisture stability	NBPT ● NBPT can avoid caking at low temperatures (−20 to 0 °C), maintain stability for six months at 20 °C, and briefly (5 min) remain active at 130 °C, according to international patents. However, its overall production cost increases by 4–5 times ● Under high temperature (40–45 °C) and humidity (85%), the degradation rate significantly increases, drastically shortening its shelf life ● Light exposure further accelerates its degradation, reducing storage stability by about 6% compared to dark conditions DMPP ● DMPP has demonstrated good stability in storage and transportation, but in high-temperature industrial processes, especially in urea tower granulation at 105–130 °C, there is still a lack of effective incorporation methods	Technological breakthrough ● New compound design ● Analysis of key technologies of active protective substances ● Green protective solvent screening and formulation design ● Breakthroughs in the technology of stable fertilizer addition process and the matching design of addition equipment ● Customize storage and transportation methods (packaging, temperature, humidity, etc.) based on the degradation mechanism Cost breakthrough ● Establishing manufacturing bases in western China, the geographical and policy advantages can enable large-scale production and reduce costs in terms of raw materials, tariffs and brands	● Various storage and transportation conditions (dark, light), storage and transportation temperature (−20 to 40 °C) active components do not degrade, product properties do not change, adapt to a wide range of areas ● High temperature production stability for urea tower granulation process (105–130 °C)
Acid-base and fertilizer ion stability	● Current formulations of NBPT are incompatible with acidic fertilizers, while DMPP exhibits poor performance in alkaline conditions ● Though DMPSA, a modified derivative of DMPP, performs better under alkaline conditions, its cost (2.5–3 times higher) limits broader adoption	● Design of new compounds ● Innovation in the supporting cultivation technology of nitrification inhibitors ● Breakthroughs in the technology of stable fertilizer addition process and the matching design of addition equipment	● NBPT improves stability under acidic conditions ● DMPP improves stability under alkaline conditions ● Improve the stability of DMPP and NBPT under the conditions where elements such as phosphorus and sulfur are present
Technological requirements	● The dosage of inhibitors added is small and the uniformity of addition is difficult	● Breakthroughs in the technology of stable fertilizer addition process and the matching design of addition equipment.	● Improve the particle strength of the finished fertilizer ● The inhibitor is evenly distributed in the fertilizer
	● Some inhibitors pose corrosion risks to production equipment, particularly under high temperature and humidity. While certain products such as CENTURO have demonstrated corrosion tolerance exceeding 18 months, there is still a need for comprehensive solutions to eliminate corrosion risks at the molecular level	● Design of new compounds ● Highly stable protective solvent screening and corrosiveness testing	● Reduce the corrosiveness of the inhibitor to the equipment
Agronomic application	● Research on the synergistic effect of pleiotropic inhibitors is lacking ● The verification of the effects of field experiments on different crops, farming systems, etc. and the database are not complete ● There is a shortage of agronomic machinery suitable for freshly mixed and used inhibitors	● Design of new compounds ● Agronomic networking experiments and big data analysis of inhibitors ● Research on soil degradation mechanisms of DMPP and NBPT ● Promote the design and application of specialized efficiency packages ● Develop agronomic machinery suitable for freshly mixed and used inhibitors	● Extend the availability in the soil ● Regional variability that reduces the effect of action ● The convenience of adding products that are mixed and used immediately needs to be improved

solution to these challenges[37,38]. This technology has also been successfully applied in the fertilizer application of fruit trees and other horticultural crops. For example, in perennial fruit trees, such as citrus and apples, long-lasting and stabilized fertilizers with slow-release characteristics are used to extend nutrient release over time, meeting the nutritional needs of the

Table 8 Product information of nitrification or urease inhibitors registered with the Ministry of Agriculture and Rural Affairs of China [a]

Company	Formulation type	Active ingredient	Registered specification	Suitable range
BASF SE	Water aqua	DMPP	420–518 $g \cdot L^{-1}$ (liquid chromatography); pH (stoste) 0.1–1.0; density 1.3–1.5 $g \cdot mL^{-1}$; water-insoluble ⩽ 10 $g \cdot L^{-1}$	Mixed with ammonium nitrogen and amide nitrogen fertilizer limited application
BASF SE	Water aqua	NBPT, NPPT	NBPT 199–224 $g \cdot L^{-1}$; NPPT 64–78 $g \cdot L^{-1}$; pH (stoste) 8.0–10.0; density 1.0–1.2 $g \cdot mL^{-1}$; water-insoluble ⩽ 10 $\cdot L^{-1}$	Mixed with amide nitrogen fertilizer limited application
BASF SE	Water aqua	NBPT, NPPT	NBPT 325–359 $g \cdot L^{-1}$; NPPT 107–121 $g \cdot L^{-1}$; pH (stoste) 8.0–10.0; density 1.1–1.2 $g \cdot mL^{-1}$; water-insoluble ⩽ 10 $g \cdot L^{-1}$	Mixed with amide nitrogen fertilizer limited application
Zhejiang Sunfit Advanced Materials Co., Ltd.	Powder	NBPT	NBPT ⩾ 97.0%; pH (stoste) 6.5–8.5; water-insoluble ⩽ 1.0%	Mixed with amide nitrogen fertilizer limited application
Shanxi Sunger Road Bioscience Co., Ltd.	Water aqua	Nitrapyrin	230–250 $g \cdot L^{-1}$; pH (stoste) 3.5–5.5; density 0.9–1.1 $g \cdot cm^{-3}$; water-insoluble ⩽ 10 $g \cdot L^{-1}$	Mixed with ammonium nitrogen and amide nitrogen fertilizer limited application

Note: [a] Fertilizer Registration and Management Information System of the Ministry of Agriculture and Rural Affairs of China.

Table 9 Representative stabilized fertilizer products and enterprises in China

Enterprise	Nitrification or urease inhibitor	Product
Sinofert Holdings Limited	DMPP	Jin Xiangyu compound fertilizer; Lan Lin phosphorus fertilizer
CNSIG Anhui Hongsifang Fertilizer Co., Ltd.	DMPP	Sailiaosu urea-ammonium fertilizer
Hubei Xinyangfeng Agricultural Technology Co., Ltd.	DMPP	Nuo Taike compound fertilizer
Henan Xinlianxin Chemicals Group Co., Ltd.	NBPT/DMPP	Chao Kongshi stabilized urea fertilizer; Chao Kongshi stabilized water-soluble fertilizer
Hubei Disco Chemical Group Co., Ltd.	DMPP/DCD	Cai Hongzhen water-soluble fertilizer
Shanxi Tianji Coal Chemical Group Co., Ltd.	DMPP/nitrapyrin	Tian Ji Stabilized Compound fertilizer
Kingenta Ecological Engineering Group Co., Ltd.	DMPP	San + 3 compound fertilizer
Dazhou Jiuyuan New Materials Co., Ltd.	NBPT	Stabilized urea fertilizer
Sichuan Lutianhua Company Limited By Shares	DMPP	Stabilized nitro-fertilizer
Chengdu Wintrue Holding Co., Ltd.	DCD/DMPP	Stabilized compound fertilizer
Guizhou Phosphorus Chemical (Group) Co., Ltd.	DMPP/nitrapyrin	Stabilized compound fertilizer
Guangdong Lardmee Chemical Fertilizer Co., Ltd.	DMPP/nitrapyrin	Jin Se 2.0 compound fertilizer
Shikefeng Chemical Industry Co., Ltd.	DCD	Stabilized compound fertilizer
Yunnan Nongjiale Agricultural Co., Ltd.	DCD/DMPP	Nong Jiale enhanced nitrogen fertilizer
Nanning Harworld Biological Technology, Inc.	NBPT/DMPP	Pu Zilan enhanced nitrogen fertilizer
Shanxi Huaxin Fertilizer Co., Ltd.	DMPP	Stabilized nitro-compound fertilizer
Zhongde (Yantai) Fertilizer Co., Ltd.	DCD/NBPT	Shuang Taike Compound fertilizer
Sichuan Golden-Elephant Sincerity Chemical Co., Ltd.	DMPP	Wistom
Yunnan Yuntianhua Co., Ltd.	DMPP	Jin Shajiang stabilized urea fertilizers, Mei Zile compound fertilizer
Jilin Beifeng Agricultural Means of Production Co., Ltd.	DCD	Fu Mangen stabilized compound fertilizer
Zhejiang Julong Fertilizer Co., Ltd.	Nitrapyrin	Enjiu compound fertilizers Enbeili compound fertilizer
Shenzhen Batian Ecotypic Engineering Co., Ltd.	DMPP	Stabilized compound fertilizers
Shanxi Tianfeng Chemical Industry Group Co., Ltd.	DMPP	Stabilized nitrogen fertilizer
Hebei Monband Water Soluble Fertilizer Co., Ltd.	DMPP	Su Biduo compound fertilizer

trees during their fruit expansion period and the stage of nutrient accumulation.

The diversification of stabilized fertilizers can be attributed to their ability to mitigate environmental pollution, such as ammonia volatilization and nitrate leaching, while significantly improving fertilizer use efficiency. This, in turn, promotes the sustainable development of agriculture. Urease inhibitors and nitrification inhibitors are crucial to achieving these outcomes. For example, Limus technology effectively decreases ammonia volatilization by inhibiting the activity of urease during urea decomposition[39]. This not only decreases ammonia loss but also ensures better nitrogen absorption by crops, thereby increasing yields and reducing the overall use of nitrogen fertilizers. Also, nitrification inhibitors such as DMPP help mitigate the leaching and loss of nitrogen when using nitrate fertilizers. These inhibitors also decrease nitrogen loss caused by soil nitrification by lowering the nitrification rate, making them particularly suitable for regions with strong nitrification, high humidity and abundant rainfall[14].

3 Stabilized fertilizers facilitating agricultural green development in China

Over the past 50 years, significant advancements have been made in the development of stabilized fertilizers, supported by numerous field experiments conducted both in China and internationally, as well as extensive meta-analyses. The effects of urease inhibitors, such as NBPT, on reducing ammonia emissions have been largely clarified. However, uncertainties remain for the mitigation of N_2O emissions and nitrate leaching. Similarly, while the functions of nitrification inhibitors, such as DMPP, in lowering N_2O emissions and nitrate leaching have been well-established, there are still questions about their effectiveness in mitigating NH_3 emissions.

Despite these advancements, a common challenge with both nitrification and urease inhibitors in previous trials has been their limited impact on increasing yield and improving efficiency. This results in insufficient benefits for farmers, diminishing their enthusiasm for adopting these technologies and affecting the willingness of enterprises to invest. To address these challenges, collaborative efforts involving institutions, such as China Agricultural University, Wuwei Jincang Bioscience Co., Ltd. and CNSIG Anhui Hongsifang Co., Ltd. with support from the Laboratory of Stabilized Fertilizers and the Research Institute of Green Intelligent Compound Fertilizers, have led to experimental demonstrations across 23 locations in China, covering 14 different crop species (Table 10). In addition, these efforts have involved the extensive collection of relevant scientific data from both domestic and international sources.

Through systematic analysis of this data, it has become evident that stabilized fertilizers not only offer reliable environmental

Table 10 Field trials: Crop species and test sites in China

Crop	Test site
Apple	Yantai, Shandong Province; Luochuan, Shannxi Province; Sanmenxia, Henan Province; Luannan, Hebei Province
Cotton	Guazhou, Gansu Province; Shihezi, Xinjiang Uygur Autonomous Region
Lettuce	Luannan, Hebei Province; Beijing
Maize	Minqin, Zhangye, Jiuquan, Gusu Province; Jimusaer, Fuhai, Xinjiang Uygur Autonomous Region; Quzhou, Hebei Province; Linyi, Shandong Province
Orange	Yanting, Sichuan Province; Congming, Shanghai; Quzhou, Zhejiang Province
Peanut	Quzhou, Hebei Province
Pepper	Minqin, Gansu Province; Luannan, Hebei Province; Beijing; Anhui Province
Potato	Minqin, Wuwei, Gansu Province
Radix isatidis	Minqin, Wuwei, Gansu Province
Rice	Yanting, Sichuan Province; Congming, Shanghai; Quzhou, Zhejiang Province; Jingzhou, Hubei Province
Squash	Minqin, Gansu Province; Jimusaer, Xinjiang Uygur Autonomous Region
Sunflower	Minqin, Gansu Province
Wheat	Minqi, Gasu Province; Shunyi, Beijing; Luannan, Quzhou, Hebei Province; Jinan, Shandong Province; Yuzhou, Henan Province

emission reduction benefits but also hold significant potential for improving crop yields and enhancing efficiency. The key to maximizing these benefits lies in their appropriate application. To further elucidate the advantages of stabilized fertilizers, case studies have been conducted, which explore their effects across eight key areas: (1) increasing yield and quality, (2) extending fertilizer effect period, (3) lowering nitrogen loss and emissions, (4) improving fertilizer use efficiency, (5) enhancing crop stress resistance, (6) promoting root development, (7) improving element availability, and (8) reducing soil acidification and salinization.

3.1 Increase in yield and quality

Stabilized fertilizers, with their long-lasting nature and ammonium-nitrate nutrient regulation characteristics, provide crops with a balanced nutrient supply throughout their growth stages. This ensures that crops can effectively absorb and use the nutrients, preventing issues of both nutrient deficiency and excess. As a result, the overall yield and quality of crops is enhanced. Numerous experiments and studies have been conducted across various regions, including northern, north-western and eastern China, focusing on a variety of crops. For example, in the major apple-producing areas of northern and north-western China, the application of stabilized fertilizers containing nitrification inhibitors has demonstrated significant improvements in both yield and quality. During the apple fruit expansion period, the inclusion of a nitrification inhibitor with a nitrogen content of 1% enables slow nitrogen release. This approach has led to an average yield increase of 18.6% and an average improvement of 20.9% in the acid-to-sugar ratio of the fruit (Fig. 1).

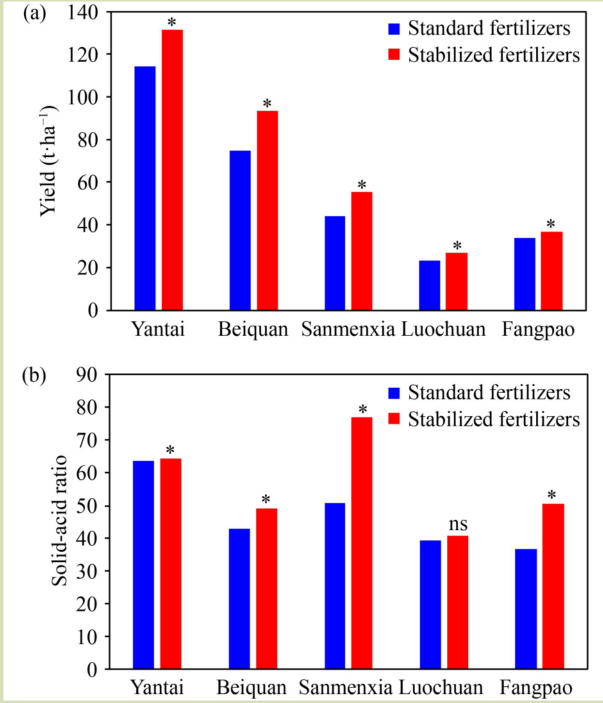


Fig. 1 Differences in apple yield and quality with standard versus stabilized fertilizer application in five locations in China. (a) Apple yield; (b) solid-acid ratio of apple. * Significant difference at $P < 0.05$; ns, no significant difference.

Similar results were also obtained in a vegetable system in northern China. For example, when applied to loose-leaf lettuce and head lettuce, a single application of stabilized fertilizer containing a nitrification inhibitor (with 1% nitrogen content), compared with multiple applications of standard fertilizer, the yields increased by 48.8% and 17.3% respectively, and the nitrate content decreased by 38.2% and 49.8% respectively (Fig. 2)[40].

In addition to economic crops, stabilized fertilizers also significantly increase the yield of food crops. A study conducted in eastern China on maize, rice and wheat showed that the average yield increase from stabilized fertilizers was 8.68%. Also, in the practice of rice production in eastern China, a fertilizer application management model combining rice-specific fertilizers with urease inhibitors further clarified that applying stabilized fertilizers can significantly increase the number of grains per spike, thereby increasing rice yield by 24%–30% (Fig. 3)[41].

In addition to field trials, large-scale demonstrations and applications of stabilized fertilizers have consistently resulted in stable yield increases. In 2024, the cumulative demonstration area for stabilized fertilizers in Northwest China reached nearly 2.4 kha, with varying degrees of yield enhancement across eight crop systems, including maize, wheat, potato, cotton, seed-producing zucchini, pepper, sunflower, and *Isatis* root. For example, maize yields increased by 5.9%–24%, wheat by 16%–25%, and potato by 6.5%–37% (Table 11). These demonstration results clearly illustrate the positive role of stabilized fertilizers in enhancing crop productivity.

3.2 Extension of the duration of fertilizer effectiveness

Standard fertilizers typically have a short effective period, with nutrients being rapidly released after application. Under conditions of heavy rainfall or intensive irrigation, nutrients are prone to leach beyond the root zone, reducing their

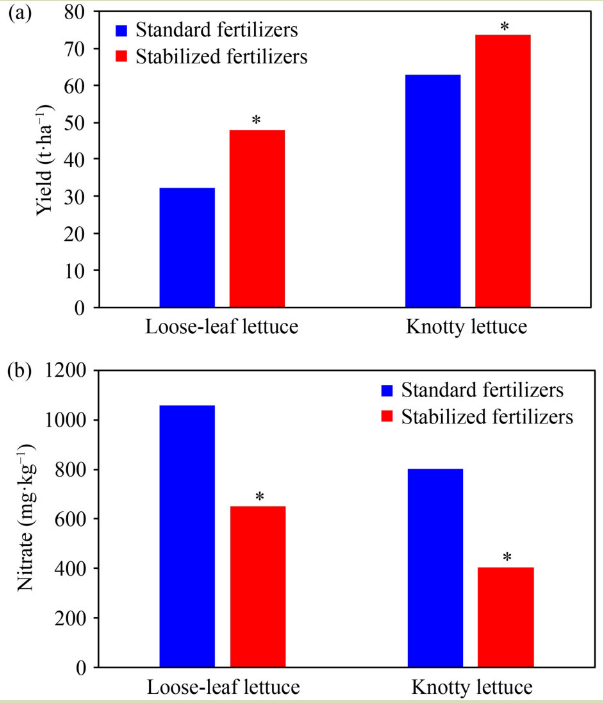


Fig. 2 Differences in yield and quality of loose-leaf lettuce and head lettuce with standard versus stabilized application. (a) Lettuce yield; (b) nitrate content of lettuce.

availability to crops and leading to low fertilizer use efficiency. In contrast, stabilized fertilizers use controlled nutrient hydrolysis and transformation mechanisms to ensure a more uniform and prolonged nutrient release. This approach extends the effective duration of fertilizers, maintaining continuous nutrient availability throughout the crop growth cycle. Previous studies using inhibition rate analysis have demonstrated that NBPT remains effective for more than 20 days, while DMPP sustains efficacy for 50–60 days.

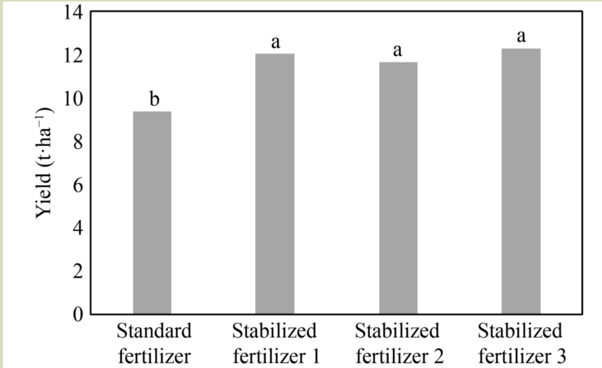


Fig. 3 Effect of four fertilizers on rice yield. Standard fertilizer refers to urea applied at 195 kg·ha^{-1}, stabilized fertilizer 1 contained 0.2% NBPT applied at 300 kg·ha^{-1}, stabilized fertilizer 2 contained 0.2% NBPT applied at 384 kg·ha^{-1}, and stabilized fertilizer 3 contained 0.2% NBPT applied at 467 kg·ha^{-1}. All fertilizers were applied during tillering.

Practical agricultural applications have shown that this sustained and stable nutrient supply not only significantly enhances crop growth potential but also reduces fertilizer application frequency and costs for farmers. For example, field trials in apple orchards in Yantai (Shandong Province), Sanmenxia (Henan Province), Luannan (Hebei Province) and Luochuan (Shaanxi Province) indicate that applying stabilized fertilizers containing DMPP twice, once in late June and again in early August during the fruit expansion stage, significantly increased yield by ensuring a continuous nutrient supply for 60 days (Table 12). Similarly, a trial conducted on lettuce in Tangshan, Hebei Province demonstrated that incorporating DMPP into fertilizers allows a single application to meet the nitrogen demands and high-yield requirements of lettuce throughout its growth period while extending the fertilizer effectiveness to 50 days.

Table 11 Yield increase with various inhibitors in different demonstration sites

Crop	Demonstration area (ha)	Yield increase (%)
Capsicum	26.7	8.4–18.5
Cotton	40	5.0–8.8
Isatis tinctoria (woad)	200	15.0–47.5
Maize	2000	5.9–24.4
Potato	33.3	6.5–37.7
Squash	46.7	18.8–20.2
Sunflower	20	2.5–13.3
Wheat	20	16.1–25.0

Table 12 Estimation of the effect of prolonging nitrogen fertilizer efficiency using stabilized fertilizer

Stabilized fertilizer	Crop	Application period	Expected nutrient supply period (day)
DMPP	Apple	Two applications during fruit expansion	60
	Lettuce	One application throughout the entire growth period	50
	Maize	Sowing to large trumpet stage	60
NBPT	Rice	Spike differentiation stage	90
	Wheat	Regreening stage	30–40

Also, comparable benefits have been observed in grain crop systems. For example, in the maize production system in Quzhou County, Hebei Province, applying DMPP-stabilized fertilizer at sowing eliminates the need for supplementary fertilizer application later. Based on calculations from sowing to the large ear stage, the fertilizer effectiveness period is expected to extend to 60 days.

Extensive field trials with stabilized fertilizers containing NBPT have demonstrated even more pronounced effects in enhancing fertilizer efficiency when applied as panicle fertilizer. For example, in the rice production system in Chongming, Shanghai, the addition of NBPT to panicle fertilizer, applied from the young panicle differentiation stage to harvest, ensured a sustained nutrient supply for about 90 days. In wheat production, multisite studies conducted at experimental locations in Shunyi (Beijing), Luannan (Hebei Province), Quzhou (Hebei Province), Jinan (Shandong Province), and Yuzhou (Henan Province) revealed that NBPT application enables early fertilizer application with delayed nutrient release. Specifically, applying NBPT-stabilized fertilizer at the regreening and tillering stages ensures nutrient availability during the jointing stage, thereby optimizing crop population structure and extending fertilizer efficacy by an estimated 30–40 days.

3.3 Improvement in fertilizer use efficiency

In standard fertilizer application, the low use efficiency of fertilizers has long been a critical issue demanding immediate resolution. Due to factors such as nutrient volatilization, leaching and transformation, the utilization rate of standard fertilizers commonly ranges from 30% to 40%. In contrast, stabilized fertilizers significantly enhance fertilizer use efficiency by controlling release and mitigating nutrient losses. In numerous cases, the nitrogen use efficiency can be increased to over 50% through the application of stabilized fertilizers (Table 13). This not only reduces fertilizer input costs but also alleviates environmental burdens.

A comprehensive meta-analysis of extensive research has revealed that the application of both nitrification inhibitors and urease inhibitors significantly enhances nitrogen use efficiency[42]. For example, in wheat-maize cropping systems, the use of nitrification inhibitors and urease inhibitors increased nitrogen use efficiency by 12.7% and 14.3%–17.5%, respectively. In grassland management, the application of these inhibitors resulted in nitrogen use efficiency improvements of 48.4% and 17.9%, while in paddies, nitrogen use efficiency was enhanced by 11.1% and 28.7%[43]. In spring maize trials conducted in the Hexi region in Gansu Province, results

Table 13 Effect of nitrification and urease inhibitors on nitrogen use efficiency (NUE) in a range of crops

Classification of inhibitor	Crop	NUE (no inhibitor)	NUE (inhibitor)	Sample size	Data source
Nitrification inhibitor	Apple	40.0	83.1	20	[1]
	Grasslands	37.6	86.1	57	[7]
	Paddies	8.4	19.5	6	[7]
	Spring maize	53.2	71.5	–	[11]
	Wheat-maize	29.2	41.9	16	[7]
Urease inhibitor	Grasslands	8.8	26.7	37	[7]
	Paddies	24.9	53.6	12	[1]
	Spring maize	53.2	73.2	–	[11]
	Wheat-maize	27.5–32.0	49.5–51.5	5	[7]

demonstrated that when nitrogen application was maintained at 180 kg·ha^{-1}, the addition of DMPP (a nitrification inhibitor applied at 1% of the fertilizer nitrogen content) and NBPT (a urease inhibitor applied at 0.2% of the fertilizer nitrogen content) to urea increased nitrogen use efficiency from 53% to around 73%[44]. In the wheat cropping system of Quzhou, Hebei Province, a two-year trial revealed that the use of stabilized nitrogen fertilizer containing NBPT (urease inhibitor applied at 0.2% of the fertilizer nitrogen content) significantly improved nitrogen fertilizer efficiency from 27.5% to 51.5%[45]. In rice production in Chongming, Shanghai, the application of stable urea-ammonium nitrogen fertilizer (containing 19% urea nitrogen and 12% ammonium nitrogen) effectively leveraged the rapid efficacy of ammonium nitrogen and the slow-release characteristics of stabilized urea nitrogen, increasing nitrogen fertilizer efficiency from 32.0% to 49.5%. Among economic crops, the stabilized fertilizers have a more significant effect on improving nitrogen use efficiency. For example, in apple planting experiments conducted in Sanmenxia (Henan Province), Luannan (Hebei Province), Luochuan (Shaanxi Province) and Yantai (Shandong Province), the results showed that applying DMPP during the fruit expansion period could significantly enhance nitrogen use efficiency, increasing it from an average of 40.0%–83.1%. In the lettuce planting system of Luannan, Hebei Province, the application of stabilized fertilizers could increase nitrogen use efficiency to 70.0%–73.2%[40].

Nitrogenous inhibitors decrease the rate of conversion of ammonium to nitrate by inhibiting the activities of nitrifying bacteria in the soil, thereby slowing the accumulation and loss of nitrate. This leads to a slower and more stable release of nitrogen in the soil, allowing crops to more effectively absorb nitrogen from these sources during the growing season and thereby improving nitrogen use efficiency. Under the action of urease inhibitors, the rate of nitrogen transformation slows down, enabling nitrogen to remain in the soil for a longer time. This helps stabilize the supply of nitrogen sources and enables crops to have continuous and uniform access to nitrogen from these sources throughout the growing season, thereby enhancing the fertilizer use efficiency. In summary, the use of inhibitors can achieve balanced release of nitrogen. By regulating the rate of nitrogen transformation, inhibitors delay the supply process of nitrogen from fertilizers to crops, allowing nitrogen to be released continuously and uniformly during the crop growth process, thereby significantly improving nitrogen use efficiency.

3.4 Enhance the stress resistance of crops

In recent years, as climate change becomes increasingly severe, achieving green development in agriculture faces numerous challenges. The application of stabilized fertilizers provides a potential pathway to enhance crop stress resistance. Taking the Hetao Irrigation District in 2022 as an example, the annual rainfall in this region was only 68 mm. If standard nitrogen loss minimization measures were adopted, it could lead to a 12.8% risk of yield reduction. Conversely, adding inhibitors while decreasing nitrogen loss can strengthen ammonium nitrogen supply, promote nutrient uptake and avoid yield reduction. Similarly, under low-temperature conditions, the use of inhibitors can enhance crop resistance. For example, in the fruit trees of Luannan, Hebei Province, frequent low temperatures during the bud burst period can limit flowering. However, the use of inhibitors can increase ammonium nitrogen supply, balance the ammonium-to-nitrate ratio, and thereby promote nutrient absorption, mitigating the impact of low-temperature damage. Also, the continuous supply of nutrients can alleviate growth suppression caused by nutrient deficiency, thereby improving crop resilience and yield under adverse conditions. For example, in Quzhou, Hebei Province, when waterlogging occurs, it is difficult for maize to apply timely fertilizer supplementation. The application of stabilized nitrogen fertilizers can effectively extend the fertilizer efficiency period, thereby reducing the risk of yield reduction due to insufficient nutrients in the later growth stages.

In addition to adverse conditions caused by climatic factors, the excessive input of nutrients also imposes stress on the normal growth and development of crops by affecting soil pH and salinity. This is particularly evident in enclosed production of vegetables and fruit trees, where the over-application of fertilizers significantly exacerbates soil salinization, thereby restricting the normal growth of crops. The application of stabilized fertilizers, through efficient nutrient uptake and the regulation and absorption of ammonium and nitrate, alleviates the salinity stress induced by high nutrient input, improves soil fertility, and substantially enhances crop yield. In the enclosed vegetable production system in Luannan, Hebei Province, the soil EC value reached as high as 1470 μS·cm^{-1}, far exceeding the normal range of 200–1000 μS·cm^{-1}. Under high salinity stress, the application of stabilized fertilizers containing DMPP significantly increased the ammonium content in the soil while decreasing nitrate content. This improved nutrient absorption through the synergistic effect of the ammonium and nitrate forms as well as further reducing the risk of aggravated salt damage. Also, experiments with leafy vegetables revealed that when the DMPP addition accounted for 1% of the nitrogen content, the maximum leaf area increased by 44.9%, the number of leaves increased by 32.4%, the fresh weight per plant increased by 51.5% and the yield increased by 48.8%.

Additionally, the nitrate content in leafy lettuce decreased by 61.9%. These findings fully demonstrate that the application of stabilized fertilizers under high salinity stress conditions helps enhance crop stress resistance.

3.5 Promote the healthy development of root systems

Stabilized fertilizers promote the healthy development of root systems by regulating the release of nutrients. A stable supply of nutrients can promote the expansion and distribution of root systems, increase the absorption area of roots, and thereby enhance the water and nutrient absorption capacity of roots. In the growth and development process of many crops, the healthy development of root systems is crucial for final yield and quality. For example, when crops suffer from nutrient deficiency or excessive application, the growth of root systems is often inhibited, leading to the small and shallow root systems, which further affects the absorption of water and nutrients. Stabilized fertilizers, by providing a continuous supply of nutrients, can effectively avoid nutrient deficiency, promote the deep development of root systems, and enable roots to better adapt to complex soil environments.

Currently, the mechanisms by which stabilized fertilizers influence root system development are primarily focused on three aspects. First, this is by regulating of nutrient forms to influence root growth. For example, ammonium can promote the density of secondary and tertiary lateral roots, leading to the formation of a highly branched root system. This increases the root absorption area and enhances plant nutrient uptake capacity. Also, nitrate stimulates the secretion of plant growth hormones, promoting the growth and differentiation of plant tissues, including root elongation and development. Additionally, nitrate can increase the number of fine roots (capillary roots) and improve their development, further expanding the plant nutrient absorption area and enhancing uptake efficiency. Secondly, it is by regulating the spatial distribution of nutrients in soil, which influences root system development. Certain inhibitors, such as DMPP, can inhibit nitrification in the soil, thereby altering the distribution of nitrate. Since nitrate is more mobile than ammonium, the inhibition of nitrification changes the distribution pattern of nitrate in the soil, ultimately affecting the efficiency of nutrient absorption and use by plants. Lastly, it is by regulating nutrient concentration, which also influences root growth. Stabilized fertilizers can delay nitrogen release, effectively preventing the rapid release of nutrients that could lead to excessively high nutrient concentrations, which may inhibit root growth and development. When nitrogen concentrations are low, the main and lateral roots of the plant tend to elongate, and root hairs become denser and longer. This is an adaptive mechanism that helps roots acquire nutrients moving by diffusion. In a pot experiment with maize conducted in Gansu Province, the addition of nitrification inhibitors was found to enhance the supply of ammonium, promoting root growth and development in ammonium-preferring crops. This was evidenced by increases in root length, root surface area and root volume (Fig. 4 and Table 14)[44].

3.6 Improving element availability

In addition to improving nitrogen use efficiency, the application of stabilized fertilizers also has a positive impact on the availability of other elements. Firstly, the application of stabilized fertilizers alters the availability of other elements by influencing soil pH. Taking phosphorus as an example, the application of nitrification inhibitors increases the supply of ammonium and promotes its uptake by plants. This, in turn stimulates the release of H^+ by plants, lowering the pH of the rhizosphere soil. This acidic environment facilitates the release of phosphorus in the soil and enhances its uptake by plants. Concurrently, it decreases the conversion of ammonium to nitrate, thereby alleviating nutrient competition between phosphorus and nitrate and promoting the absorption and use of phosphorus. For trace elements, when ammonium is the

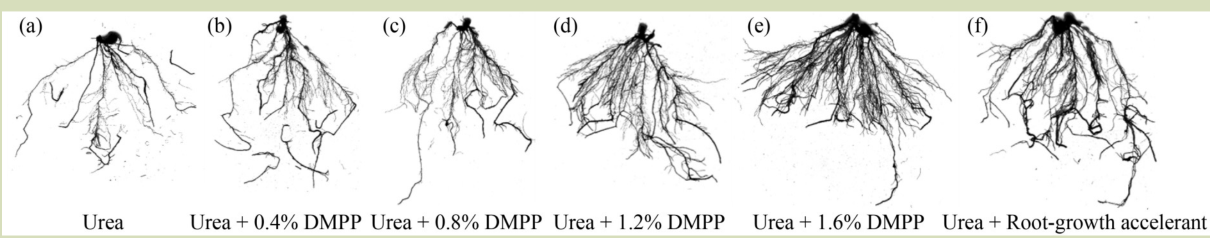


Fig. 4 Effects of DMPP on root length, root surface area and root volume. (a) Single application of urea; (b) urea + 0.4% DMPP; (c) urea + 0.8% DMPP; (d) urea + 1.2% DMPP; (e) urea + 1.6% DMPP; (f) urea + root-growth accelerant.

Table 14 Effect of stabilized fertilizer on the growth and development of maize roots

Type of fertilizer	Root length (cm)	Root surface area (cm^2)	Root volume (cm^3)
Urea	630	70	0.71
Stabilized fertilizer	990	130	1.32
Increase (%)	57.1	85.7	85.9

dominant form of nitrogen in the soil, the uptake of ammonium by plants leads to the release of H^+, causing rhizosphere acidification. This may increase the availability of iron, manganese and copper. Additionally, in alkaline soils, the inhibition of nitrification may slightly lower the pH, enhancing the solubility of iron, manganese and zinc.

Secondly, stabilized fertilizers affect the mobility of trace elements in the soil by altering the rate of nitrogen transformation. There is a close relationship between the forms of nitrogen in the soil and the mobility of trace elements. For example, when ammonium is the dominant form of nitrogen in the soil, rhizosphere acidification promotes the reduction of Fe^{3+} to Fe^{2+} (which has higher water solubility), thereby increasing the availability of iron. Additionally, certain rhizosphere-promoting bacteria (e.g., *Pseudomonas*) exhibit enhanced activity in ammonium-enriched environments, secreting organic acids or siderophores (e.g., ferrioxamines), which facilitate the solubilization of iron and zinc. The use of stabilized fertilizers can delay the nitrification process, thereby reducing the negative impact of nitrate on trace elements. This helps maintain the stable presence of trace elements in the soil and promotes their uptake by plants.

Finally, stabilized fertilizers not only influence nitrogen dynamics in the soil, they can also affect soil microbial communities. Certain trace elements (e.g., copper and zinc) are critical for the metabolism and functionality of soil microorganisms, and these microbial activities, in turn, influence the availability of trace elements[46]. Studies have shown that the use of inhibitor fertilizers can alter the structure of soil microbial communities, thereby affecting the transformation and availability of trace elements[47]. For example, soil microorganisms contribute to the release of trace elements through processes such as organic matter decomposition and mineralization of nutrients. The application of stabilized fertilizers may enhance microbial activity, thereby improving the availability of trace elements.

3.7 Reducing soil acidification and salinization

Soil acidification can degrade soil structure, impair crop root growth and increase the solubility of heavy metal elements (e.g., aluminum and manganese) in the soil. Stabilized fertilizers mitigate the risk of soil acidification by regulating nutrient release, thereby reducing their acidifying effects. Given the characteristics of acidic soils in southern China, particularly the higher risk of soil acidification and severe nitrogen loss, DMPP is a more suitable choice. It effectively slows the conversion of nitrogen fertilizers and reduces acidification caused by nitrification. However, NBPT is more effective in reducing ammonia volatilization losses from urea, especially when urea is used under high-temperature and high-humidity conditions. However, in terms of controlling acidification in acidic soils, NBPT is less effective compared to DMPP. In calcareous soils in northern China, acidification is not a significant concern and receives less attention. However, these soils are prone to nitrogen loss through ammonia volatilization. NBPT is suitable for reducing ammonia volatilization during urea application, making it effective in improving nitrogen use efficiency in such contexts.

In addition, the slow-release properties of stabilized fertilizers can effectively reduce salt accumulation caused by fertilizer application, particularly in arid regions and irrigated agriculture, where this issue is especially problematic. By controlling the release rate of fertilizers in a rational manner, stabilized fertilizers can mitigate the formation of saline-alkali soils and maintain soil health. Research has shown that when urea is applied in combination with nitrification inhibitors, it can reduce the losses of calcium and magnesium ions through leaching, prevent salt accumulation in the soil and lower the risk of soil salinization (Table 15)[48].

4 Precision application technologies for stabilized fertilizer

4.1 Application domains of stabilized fertilizers

Until recently, the application for nitrification inhibitors and urease inhibitors was inadequately defined. However, with ongoing research, gradually several highly promising

Table 15 Total annual leaching of Ca^{2+} and Mg^{2+} to drainage water from lysimeters

The addition ratio of inhibitor	Ca^{2+} (kg·ha^{-1}·yr^{-1})	Mg^{2+} (kg·ha^{-1}·yr^{-1})
Urea	184	116
Urea + 5 kg·ha^{-1} DCD	164	111
Urea + 10 kg·ha^{-1} DCD	90	80

application contexts have been identified. For example, the use of nitrification inhibitors in low-temperature regions and high-pH soils has been demonstrated to be particularly suitable (Table 16). In low-temperature areas, these inhibitors not only maintain their activity but also enhance the supply of ammonium nitrogen, thereby promoting root development. In high-pH regions, controlling the nitrification rate to increase ammonium nitrogen supply has also shown significant advantages. Contrary to previous beliefs, high-pH soils do not predominantly cause the degradation and deactivation of DMPP. Additionally, while it was once thought that DMPP should be avoided in areas with heavy rainfall, current experimental results indicate that in such regions or irrigation zones, DMPP can effectively leverage the advantage of decreased ammonium loss, thereby improving nutrient supply.

The efficacy of urease inhibitors remains relatively stable, consistently reducing ammonia volatilization losses in most scenarios. Their potential for emission reduction is particularly pronounced in regions or soils with substantial ammonia volatilization losses. Also, they reliably enhance crop yield and production efficiency. However, it is important to note that in low-temperature conditions (e.g., regions with an average annual temperature below 10 °C), the yield-increasing effects may not be significant. It is recommended to apply urease inhibitors in high-pH soils and in areas with high temperatures and surface-applied nitrogen fertilizers.

4.2 Technological innovations in stabilized fertilizer application

In the current relevant standards of China, only the upper limit of the inhibitor addition amount is set, but no lower limit is specified. This has led to the common phenomenon of the inhibitor addition being insufficient, thereby affecting its potential effect. The standards in Europe and America stipulate that the addition range of inhibitors is 0.8%–1.6% for DMPP and 0.09%–0.2% for NBPT. However, this standard may not be fully applicable to the actual situation in China (Table 17).

The research team of China Agricultural University conducted in-depth studies on five representative soils across China and found that there is a correlation between the usage amount of urease inhibitors (e.g., NBPT) and the application amount of urea fertilizer (Fig. 5). According to different studies and field trials, the common rate of urease inhibitor used should be in the range of 0.09%–1.0% of the total amide nitrogen content in

Table 16 Suitable conditions for stabilized fertilizer

Type of inhibitor	Different view	pH	Precipitation	Temperature
DMPP	Initial views (preventing inhibitor deactivation)	Low efficacy in alkaline soils; suitable for acidic soils	Fertilizer and inhibitor washout due to heavy rainfall	High temperature decreases inhibitor effect
	Euro-American views (emission reduction target)	High NO_x emissions from alkaline soils	Nitrate leaching due to heavy rainfall	High temperatures lead to high NO_x emissions
	New views (increasing production and efficiency)	Good inhibition in alkaline soils	Inhibition of ammonium transformation and reduction leaching	Nitrification inhibitors effective at high temperatures
NBPT	Initial views (preventing inhibitor deactivation)	Low efficacy in acidic soils; suitable for alkaline soils	Good inhibition of ammonia volatilization with little rainfall	Inhibitor inactivation due to high temperatures
	Euro-American views (emission reduction target)	Strong ammonia volatilization in alkaline soil	Low rainfall and strong ammonia volatilization	Strong ammonia volatilization at high temperatures
	New views (increasing production and efficiency)	Alkaline soil inhibits well, but the effect is decreased by too much alkalinity	Less effective under low rainfall and drought	Effective at high temperatures, better inhibition of ammonia volatilization

Table 17 Inhibitor application rates

Type of inhibitor	Influencing factor	Chinese standard	European and American standard	Recommended application rate
DMPP	Range	⩽ 2%	0.8%–1.6%	0.05%–1.2%
	Soil	–	–	pH > 7.5, use ⩾ 0.05%; pH 6–7.5, use ⩾ 0.3%
	Climate	–	–	Heavy rainfall-increase application rate Light rainfall-decrease application rate
	Crops	–	–	–
NBPT	Range	⩽ 1%	0.09%–0.2%	0.04%–0.2%
	Soil	–	–	pH > 7, use ⩾ 0.09% pH 5.5–7, use ⩾ 0.04%
	Climate	–	–	High temperature-increase application rate Low temperature-decrease application rate
	Crops	–	–	–

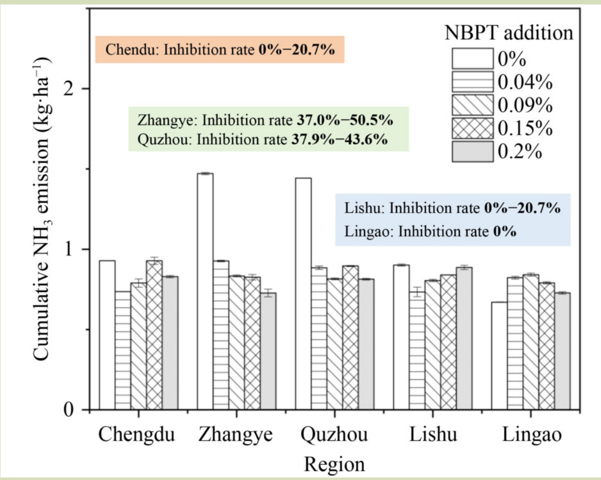


Fig. 5 Inhibitory effect of NBPT on NH_3 emissions in five locations in China.

the applied fertilizer. For example, 0.05–0.5 kg of NBPT is usually added per 100 kg of urea. This rate range can effectively delay the decomposition of urea and decrease ammonia volatilization. The rate can be appropriately adjusted according to the application environment. For example, in warm and humid environments, due to the faster hydrolysis rate of urea, a higher rate of inhibitor may be needed whereas e in cold or dry areas, the urea hydrolysis process itself is slower, and the rate of inhibitor can be appropriately reduced.

4.2.1 Rate of the nitrification inhibitor

The rate of nitrification inhibitors is usually closely related to the type of nitrogen fertilizer and the application method. The common concentration of nitrification inhibitors is in the range 0.05%–1.2% of the total amount of amide nitrogen and ammonium nitrogen in the applied fertilizer. Generally, the standard concentration of nitrification inhibitor DMPP is 0.5–1.0 $kg \cdot t^{-1}$ of fertilizer. When adding DMPP to urea or ammonium nitrogen fertilizers, the concentration is usually between 0.5 and 2 $kg \cdot ha^{-1}$, and the specific concentrations can be appropriately adjusted according to the application type of the fertilizer and the actual needs of the crops (Fig. 6). The application rate for nitrate-containing fertilizers (e.g., ammonium nitrate) may need to be adjusted appropriately according to the soil conditions and the needs of the crops. When DMPP is applied in a liquid form (e.g., through drip irrigation systems), the recommended concentration range is 0.5 to 2 $kg \cdot ha^{-1}$.

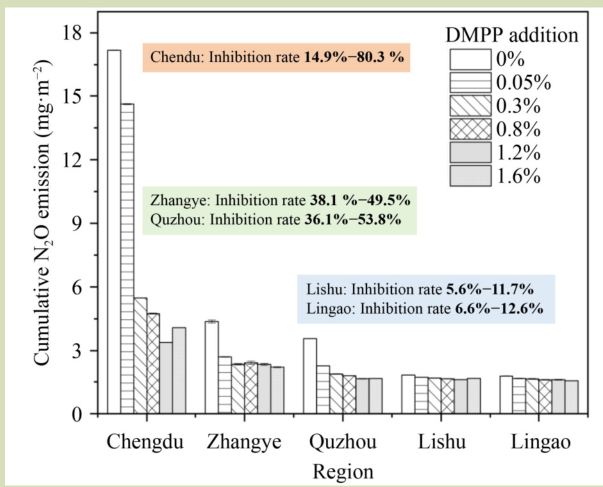


Fig. 6 N_2O emission suppression effect of DMPP in five locations in China.

4.2.2 Adjustment and optimization of inhibitor concentration

The optimal concentration and application methods of urease inhibitors vary depending on environmental conditions. They need to be adjusted according to factors such as soil pH value, temperature, urease activity, fertilizer application methods and plant type. For example, in red soil double-cropping paddies, the addition of NBPT should be 1.0% for urea to achieve the goals of economic efficiency, increased yield and decreased fertilizer usage. When 0.5% NBPT is added, the total nitrogen content, nitrogen uptake, and nitrogen fertilizer use efficiency of rape are all relatively high, and no significant reduction in quality indicators such as VC content and soluble sugar content have been observed.

The effect of applying nitrification inhibitors is influenced by various factors, including their type, rate and physicochemical properties, as well as soil and environmental conditions, and field management. The effect of applying nitrification inhibitors varies greatly in different types of soil. For example, the effects of DCD and nitrapyrin on nitrification in loamy soil and paddy soil have significant rate response. Specifically, when the concentration of DCD and nitrapyrin reaches 5%–10% of the elemental nitrogen and 0.5%–1.0%, respectively, their effects are the most significant (Fig. 7). Numerous studies have confirmed that adding 1% of the nitrogen content as DMPP is the optimal choice. Therefore, when selecting the best inhibitor type, it is necessary to comprehensively consider the local climate and ecological environment, adopt a local approach, and also fully consider the environmental benefits brought by different rates.

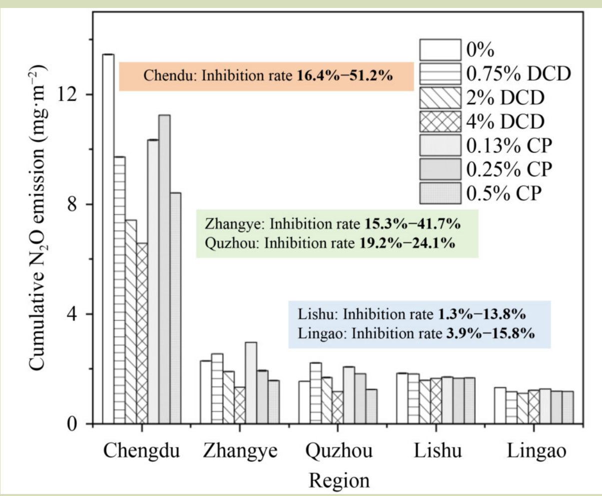


Fig. 7 Inhibition effects of two nitrification inhibitors at three rates in five locations in China.

4.2.3 Soil type

Different types of soil have differences in their adsorption capacity of fertilizers and the rate of nutrient release. In light soil (e.g., sandy soil), nutrients are lost more quickly, so the rate of inhibitors can be appropriately increased, whereas in heavy soil (e.g., clay soil), nutrient release is slower, and the application rate of inhibitors can be appropriately reduced.

4.2.4 Climatic conditions

Climatic conditions significantly influence the release of fertilizers and nutrient loss. In hot and humid climates, urea and nitrate fertilizers decompose and transform more quickly, and the rate of inhibitors may need to be increased whereas in arid or cold regions, the decomposition speed of fertilizers is slower and the application rate of inhibitors can be reduced.

4.2.5 Crop requirements

Different crops have different requirements for nitrogen and their absorption rates. Therefore, the application rate of inhibitors should also be adjusted according to the growth requirements of the crops. For crops with a long growth period (e.g., maize and rice), the supply of nitrogen needs to last longer, and controlled-release fertilizers and inhibitors can be used to ensure that the crops can obtain balanced nutrient supply throughout their growth period.

4.2.6 Fertilizer application methods

Different fertilizer application methods (e.g., banding, broadcasting and fertigation) also have different requirements for inhibitors. Local fertilizer application methods such as banding and fertigation have more precise control over fertilizers, and the rate of inhibitors can be appropriately reduced whereas broadcast methods may lead to uneven distribution of fertilizers, the application rate of inhibitors needs to be adjusted according to the total amount of fertilizers.

4.3 Synergistic integration of inhibitors and fertilizers

When the application rate of nitrogen fertilizer is usually high enough that nitrogen element is no longer limiting for crop yield, the effect of applying inhibitors is often poor. For example, when DMPP and NBPT inhibitors are applied to maize in Northwest China, significant yield-increasing effects are observed under low-nitrogen conditions, but the yield-increasing effect is not obvious under high-nitrogen conditions. Therefore, the main problem is currently not if inhibitors can enhance yield, but rather will it is necessary to determine if the application rate of nitrogen fertilizer should be reduced to be consistent with crop demand when inhibitors are also used.

During the application of inhibitors, it is necessary to ensure that they are applied concurrently with fertilizers so that the inhibitors can effectively combine with the fertilizers and exert their effects, and prolong the fertilizer efficacy. In areas with large rainfall, applying inhibitors after rainfall may cause the inhibitors to be washed away by rain, resulting in their spatial separation from the fertilizers and thus failing to fully exert their effects. To ensure effectiveness, the application rate of inhibitors can be appropriately increased. Especially in the application of water-fertilizer integration, the inhibitors and fertilizers need to be fully mixed to ensure that they are spatially consistent.

5 The vast potential of inhibitors in China’s green agricultural transition

In the face of global environmental challenges, green, low-carbon and sustainable development have become core issues. How to jointly promote the green transformation of fertilizers, enhance their use efficiency and effectively reduce environmental pollution has become an urgent task for sustainable agricultural development. Through scientific nitrogen fertilizer management and vigorously developing stabilized fertilizers, China has achieved initial results in promoting the green transformation of fertilizers. In the future, China will continue to firmly promote the green transformation of fertilizers, demonstrating national commitment to and responsibility in environmental governance.

5.1 Advancing nitrogen fertilizer upgrades with stabilized fertilizers to enhance efficiency and sustainability

To adapt to the requirements of agricultural green development, China’s nitrogen fertilizer products are undergoing a comprehensive upgrade. The nitrogen fertilizer industry is undergoing supply-side reform from scale expansion to quality and efficiency improvement (Fig. 8)[49]. During this process, in combination with fertilizer application methods and regional characteristics, stabilized fertilizers will have the following development trends.

The output of ammonium chloride and ammonium sulfate in China is equivalent to about 5 Mt of N, accounting for about 20% of the total nitrogen fertilizer output. As they are industrial byproducts, they have low energy consumption and low emissions, and have a relatively low nitrification rate. When combined with urea to produce urea-ammonium nitrogen fertilizers (urea-ammonium sulfate and urea-ammonium chloride), they are particularly suitable for high pH

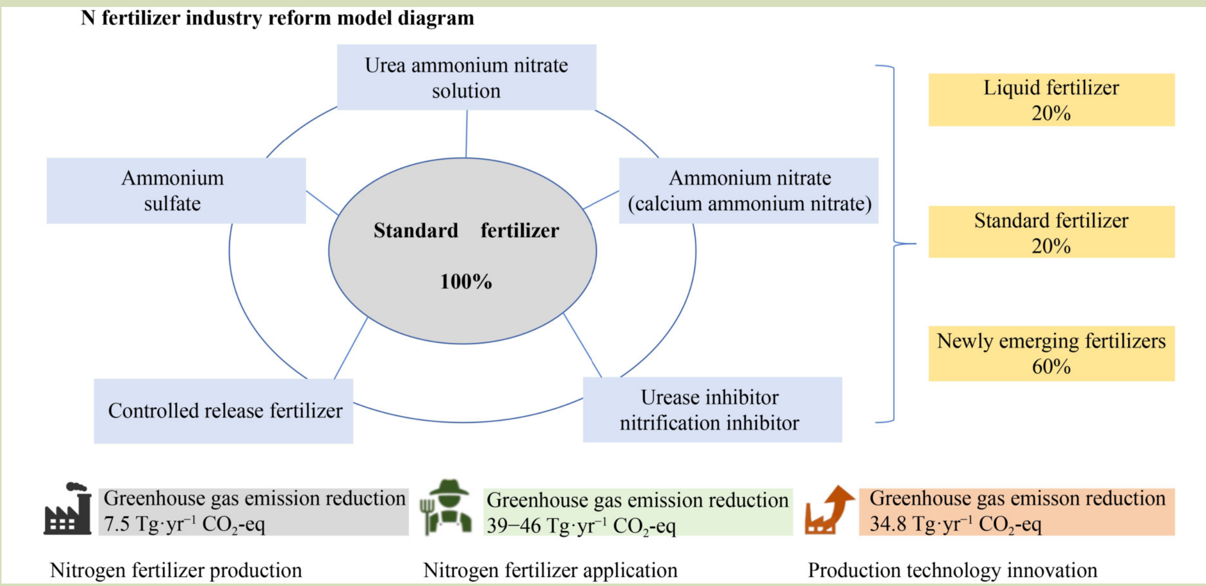


Fig. 8 Reform model diagram of the nitrogen fertilizer industry.

soils and rice. However, there is still a problem of high ammonia emissions. By adding inhibitors, comprehensive effects such as emission reduction and delayed release can be achieved[45,50].

In China, about 50% of the cultivated land is irrigated. While developing liquid nitrogen fertilizers (e.g., urea nitrate solution applied in northern and north-western China) in 20% of the irrigation systems, inhibitors are added simultaneously to delay nitrogen release and control nitrogen in the root zone[51]. During the topdressing of wheat and rice, a certain proportion of the area still requires the method of spreading urea (accounting for about 20% of the total nitrogen fertilizer application in China). Whether using ground-level or aerial (drones) spreading of urea, there is a risk of NH_3 volatilization. Adding urease inhibitors can effectively control losses and improve fertilizer efficiency[52,53]. The economic crop system consumes 40% of the nitrogen fertilizer, mainly through compound fertilizers and water-soluble fertilizers. Considering the large-scale flood irrigation methods and the need for lower root density of economic crops, adding inhibitors can achieve better benefits.

5.2 Extending nitrogen regulation to aquaculture, grassland management and manure treatment

Aquaculture, grassland management and manure treatment are important components of agricultural ecosystems and are significant fields for achieving sustainable agricultural development at present. Their coordinated development is crucial for promoting the widespread application of stabilized fertilizers and the continuous improvement of the agricultural ecological environment (Table 18).

In aquaculture, the application of stabilized fertilizers is a key measure for regulating the content of nitrite in water bodies, improving the oxygen supply level of water bodies, enhancing the ecological quality of water bodies, and promoting the healthy development of aquaculture. For example, developing green stabilized fertilizers designed for aquaculture characteristics, through scientific proportioning, optimizing the nitrogen, phosphorus, potassium and other nutrient elements in water bodies, promoting the healthy growth of aquatic organisms, regulating the content of nitrite in water bodies, and improving the oxygen supply level of water bodies. In the future, biotechnology and microbial preparations can be introduced to further increase fertilizer use efficiency and reduce nutrient loss.

In pastures, especially in artificially managed pastures, animal manure and urine produce a large amount of ammonia volatilization[54]. By adding urease inhibitors and/or nitrification inhibitors, these fertilizers can slow the rate at which urea decomposes into ammonia, reducing the loss of ammonia volatilization, while concurrently inhibiting the

Table 18 Demand forecast for inhibitors in China

Nitrogen regulation pathway	DMPP	Basis of calculation	NBPT	Basis of calculation
Nitrogen fertilizer efficiency enhancement	5–122 kt	About10 Mt of ammonium nitrogen and urea nitrogen, which requires the addition of DMPP, with the current recommended concentration of DMPP is 0.05%–1.2%	1.3–7.2 kt	About 3.4 Mt of nitrogen fertilizer may require NBPT. The current recommended rate of NBPT is 0.04%–0.2%
Artificial grassland	21.8–2090 t	Area of artificial grassland is 580,600 ha [a]. According to the standard DB34/T 4127-2022, 75 $kg\cdot ha^{-1}$ of N was applied, and the highest amount of nitrogen applied in the literature reached about 300 $kg\cdot ha^{-1}$. Inhibitors were applied according to the recommended rate	17–348.4 t	Area of artificial grassland is 580,600 ha [a]. According to DB34/T 4127-2022, 75 $kg\cdot ha^{-1}$ of N was applied, and the highest amount of nitrogen applied in the literature reached about 300 $kg\cdot ha^{-1}$. Inhibitors were applied at the recommended rate
Aquaculture	Inconclusive		Inconclusive	
Livestock manure	Inconclusive		213.5 kt	Annual production of poultry manure is 3.05 Gt, based on a collection factor of 70%. According to the *Technical Guidelines for Ammonia Reduction in Large-Scale Livestock and Poultry Farms*, the recommended rate of the urease inhibitor NBPT is 100 $mg\cdot kg^{-1}$
Urban wastewater treatment	Inconclusive		Inconclusive	

Note: [a] Third National Land Survey.

conversion of ammonium to nitrate, reducing the loss of nitrogen through leaching. Thus, the fertilizer use efficiency can be improved, and the productivity of pastures can be enhanced. The nitrogen in livestock manure is an important component of the nitrogen cycle in pastures. By reducing the loss of nitrogen in manure, stabilized fertilizers help maintain soil fertility in pastures, promote the growth of forage grass, and thereby increase the overall productivity and sustainability of pastures[55,56].

Animal manure treatment is one of the important directions for the green transformation of fertilizers in the future[57]. During the processes of manure generation, collection, storage and treatment, there is a large amount of ammonia volatilization. Adding inhibitor products can effectively inhibit the emission of ammonia gas, N_2O and other odorous gases, thereby decreasing nitrogen loss and producing green organic fertilizers rich in nitrogen. After adding stabilized fertilizers or inhibitor products to the manure and returning it to the field, it can achieve a dual effect of simultaneously realizing soil improvement and environmental emission reduction. Through the recycling and complementary effect of resources, more efficient and sustainable agricultural development can be achieved.

5.3 Leveraging stabilized fertilizers to adapt to and mitigate climate change impacts

Global climate change poses significant challenges to agricultural production. Stabilized fertilizers can meet the demand for precise nutrient regulation brought about by climate change.

It is important to enhance the stability of crop yields and lower greenhouse gas emissions. Stabilized fertilizers can maintain the stability of crop yields under the influence of climate change. Long-term field trials have shown that the use of stabilized fertilizers can reduce the fluctuations in crop yields between different years and improve the stability of crop yields. This is crucial for ensuring food security and agricultural productivity. Also, stabilized fertilizers can lower the emissions of volatilized ammonia and N_2O from the soil, lower the nitrification and denitrification processes in the soil, and increase the use efficiency of nitrogen fertilizers. Through precise design, scientific management and technical services, stabilized fertilizers can increase the nitrogen fertilizer use efficiency to 60%, lower N_2O emissions by more than 60% and decrease nitrogen usage by 20%–50%[43].

Intelligent sensing of soil environment and precise release of nutrients need to be adopted. Environmental conditions, such as temperature and moisture, affect crop growth and nutrient absorption. Stabilized fertilizers combined with temperature-sensitive or water-sensitive materials can autonomously regulate the release of nutrients and water according to environmental changes, meet the nutrient requirements of crops and regulate the release of nutrients based on soil pH and root exudates to ensure precise delivery[58].

It is also important to develop new types of stabilized fertilizers with the corresponding functions to achieve the synergy of resistance, low-carbon and high-efficiency. Develop resistant fertilizers to enhance the adaptability of crops to extreme climates (e.g., cold and drought tolerance). By adding substances such as biological stimulants, improve the growth and yield of crops in harsh environments and reduce the impact of climate change on agriculture[59].

In the future, the green transformation of fertilizers will comprehensively cover nitrogen fertilizer innovation, manure treatment, aquaculture and grassland management, actively respond to climate change, relying on scientific and technological innovation, policy support and international cooperation, China will continue to lead this transformation process and make important contributions to the sustainable development of global agriculture.

5.4 Developing and implementing plans designed for local conditions

Scientific and technological innovation should serve agricultural reality and enhance farmer trust and willingness to use new types of fertilizers. This will strengthen technical promotion at the front line and encourage fertilizer enterprises to go deep into the production front line to demonstrate the efficiency-enhancing effects of stabilized fertilizers and optimize application methods. Through demonstration fields and data feedback, farmer awareness can be enhanced and scientifically-based management promoted. It is important to explore precise fertilizer application systems based on soil monitoring and remote sensing data to help achieve the goal of green and efficient agricultural production. In 2024, with the support of the Provincial Agricultural Soil Conservation and Protection Station and the Agricultural Technology Extension Center, Wuwei Jincang Bioscience Co., Ltd. conducted experimental demonstrations on crops including maize, potatoes and wheat. This was done through on-site surveys, based on local soil and climate conditions and crop requirements, select inhibitor types and ultimately determine the optimal nitrogen, phosphorus and potassium ratios, and the best application methods for fertilizers. For example, in the wheat demonstration, by optimizing the formula, the final choice was the additive fertilizer formula of Enhancing No. III (Added DMPP and NBPT), and the wheat agronomic traits were excellent, with an increase in yield of 25%. Currently, the total experimental area is over 2.7 kha, and crop yields have generally increased by 8%–10%, with significant growth in the net income of farmers, contributing to increasing farmers awareness of stabilized fertilizers and improving market acceptance.

5.5 Strengthening legal compliance and governance in fertilizer management

Promoting the development of stabilized fertilizer industry requires a sound institutional mechanism. However, there are currently a range of problems including the absence of relevant laws and regulations, weak market supervision, low fertilizer use efficiency and insufficient technical proficiency of agricultural practitioners in the management of stabilized fertilizers.

The novel fertilizer industry in China started relatively late and lacks core technologies and innovation capabilities, resulting in weak product competitiveness. There are also no specific laws and regulations to for fertilizer production and operation, leading to ineffective fertilizer market supervision and overlapping responsibilities among various departments without effective coordination. Concurrently, the standards for stabilized fertilizers are not yet sufficiently refined, there is no unified assessment standards for products and the market products are not adequately monitored[60]. According to the *Fertilizer Registration Management Measures*, fertilizer enhancers need to be registered with the Ministry of Agriculture and Rural Affairs. As of July 2023, only two enterprises, Zhejiang Sunfit Advanced Materials Co. Ltd. and Shanxi Sunger Bioscience Co., Ltd., have completed the registration of inhibitor products. The professional ability of agricultural technicians is insufficient, and the lack of financial support for agricultural development further restricts the scientific management of stabilized fertilizers and the sustainable development of agriculture. To solve these problems, efforts should be made from multiple aspects including technological innovation, improvement of laws and regulations, strengthening market supervision, improving fertilizer use efficiency and enhancing the quality of agricultural practitioners. This will promote the scientific management of stabilized fertilizers and the green development of agriculture. China should accelerate the construction and improvement of a modern agricultural institutional system with clear orientation, scientific decision-making, strong execution and effective incentives, and continuously enhance governance efficiency in green agricultural development, providing a solid guarantee for the promotion and high-quality development of stabilized fertilizers and the industry[19].

6 Innovation and upgrading directions for stabilized fertilizer

6.1 Application of synthetic biology in stabilized fertilizer development

With the rapid development of synthetic biology, the potential of this field in enhancing agricultural productivity, improving crops, reducing production costs and achieving sustainable development is increasingly prominent. Particularly, by adopting microbial or metabolic engineering approaches to reduce the use of agricultural fertilizers, it should significantly overcome the current agricultural constraints and bring about breakthrough growth in agricultural production capacity and nutrition, thus realizing the, so called, second green revolution in agriculture[61]. For example, through genetic engineering to optimize fertilizer carriers (e.g., biological and microbial carriers), the release efficiency and stability of fertilizers can be enhanced, and the risks of fertilizer loss and pollution can be mitigated[62].

6.2 Research and development of high-efficiency and environmentally safe inhibitors

It is important to develop novel inhibitors that are safer, more effective and harmless to soil and crops. These inhibitors should have obvious inhibitory effects on nitrogen transformation process, possess low environmental toxicity, low bio-toxicity and degradability[63]. During the deployment of the new products, problems such as optimization of production process, stability of products, validation of effectiveness and market promotion will need to be solved. These new products will also need to meet the actual needs of farmers, such as convenience of use, reasonable cost (reducing research and development costs, lowering the final product price through large-scale production and thereby generating strong market competitiveness) and acceptable plant-growth effects.

6.3 Integrating inhibitors with novel biological agents for enhanced efficiency

Biological agents, especially biological nitrogen fixation technology, rely on the interactions of soil, soil microorganisms, microbial metabolites, plants and plant metabolites, which can efficiently convert atmospheric nitrogen into nitrogen sources that plants can absorb and utilize[64]. Integrating nitrification inhibitors with nitrogen fixation technology can, to a certain extent, overcome a reliance on standard mineral nitrogen fertilizers and construct a new nitrogen cycle model of increasing income and reducing expenditure. At the front end, biological nitrogen fixation provides a sustainable nitrogen supply channel. At the back end, nitrification inhibitors are used to enhance nitrogen use efficiency, forming a closed-loop system from nitrogen source supply to nitrogen regulation. This system will exhibit considerable agricultural sustainable production vitality. The key to this technology integration lies in breaking through the compatibility problem between inhibitors and biological technology carriers and formulating technical integration plans based on different soil types and crop nitrogen demand patterns.

6.4 Enhancing compatibility technologies for inhibitors and fertilizers

The future development trend of inhibitor and fertilizer compatibility technology will focus on greening and environmental friendliness to meet the global demands for reducing environmental pollution and improving fertilizer use efficiency[17]. Technological innovation will drive the development of novel and efficient inhibitors, and enhance the performance of existing types, while promoting the upgrading of fertilizer products, such as value-added fertilizers and microbial fertilizers[60]. The research and development of specialized fertilizers will target specific crops and regions to enhance the specificity and effectiveness of fertilizers. The addition of technology of inhibitors and functional substances in combination will further develop to maximize fertilizer effects and enhance the stress resistance of crops. The improvement of production processes will increase the persistence and stability of stabilized fertilizer products, and concurrently, cost control and market competitiveness improvement will be key factors.

6.5 Priority areas and target crops for stabilized fertilizer promotion

In the future, the key promotion areas for stabilized fertilizer will be concentrated in regions with high agricultural production intensity, low fertilizer use efficiency and severe soil nutrient loss, particularly in northern and north-eastern China and the middle and lower reaches of the Yangtze River, but also in other major grain-producing areas. These regions have long applied large amounts of nitrogen fertilizers, resulting in nitrogen fertilizer loss and environmental pollution. Therefore, stabilized fertilizers can effectively improve nitrogen fertilizer use efficiency and decrease environmental pollution. Additionally, in arid and semiarid areas, and ecologically fragile regions, such as the north-western region, stabilized fertilizers can decrease water and fertilizer loss, save water resources and mitigate soil salinization problems[65]. Crops, including cereal crops (e.g., wheat, maize and rice), economic crops (e.g., fruit trees and vegetables) and high-yield crops in facility agriculture (e.g., capsicum and tomato), as well as improved grasslands, all have high demand for nitrogen fertilizers and are susceptible to nitrogen fertilizer waste and environmental pollution. Stabilized fertilizers can ensure that crops receive sufficient nutrients during critical growth periods by improving fertilizer use efficiency, delaying nitrogen transformation processes, and reducing environmental pollution[43].

6.6 Carbon emission certification and trading for novel stabilized fertilizer products

The carbon emission certification and trading of stabilized fertilizer products will become a key link in promoting the green development of agriculture. With the intensification of global climate change, stabilized fertilizers have significant potential for decreasing nitrogen fertilizer loss in the agricultural sector and lowering greenhouse gas emissions[66]. Establishing a scientific carbon emission efficiency assessment and certification system is necessary to provide authoritative carbon emission certification for stabilized fertilizers and lay the foundation for entering the carbon emission market. On this basis, agriculture, enterprises and farmers can obtain economic returns through the carbon emission trading market and promote the adoption of more green and low-carbon technologies. Also, government policy support, incentives from the carbon trading market and the promotion of green product certification will further promote the popularization and application of stabilized fertilizers. Concurrently, with the unification of carbon emission standards among countries, the carbon emission certification of stabilized fertilizers is expected to enter the international carbon market, promoting green agricultural development on a global scale. Through these measures, stabilized fertilizers will not only enhance fertilizer use efficiency and decrease environmental pollution, but also deliver economic returns to agricultural enterprises and promote global sustainable agricultural development.

7 Conclusions

Amid the global agricultural resource scarcity and escalating environmental challenges, stabilized fertilizers are poised to make a crucial contribution to achieving sustainable agricultural development. These fertilizers enhance nutrient use efficiency and decrease environmental pollution. At present, scientific and technological innovations are driving the green transformation of agriculture. The application of stabilized fertilizers not only ensures food security but also fosters ecological balance.

In the future, through the use of stable fertilizers, it is expected that an increase in the nitrogen fertilizer use efficiency in China from 40% to 60%, and the use of nitrogen fertilizer from 23 to 21 Mt. DMPP demand is expected to range from 5 to 122 kt and NBPT demand from 1.3 to 7.2 kt. Nationwide, it is estimated that 2 Mt of nitrogen fertilizer can be saved, the increase effect is conservatively estimated to reach 5%–8%, and the income per ha can be increased by 600–960 yuan. The national application area of stable fertilizer inhibitors is expected to be about 13–20 Mha, and the total increase is expected to be about 8–19.2 billion yuan.

We urge research institutions, agricultural enterprises, government agencies and farmers to collaborate in advancing the research and adoption of stabilized fertilizer technology, jointly safeguarding the land, achieving sustainable agricultural development and contributing to a green future.

Compliance with ethics guidelines

Rui Liu, Weifeng Zhang, Tikun Guan, Dongjia Li, Zhiping Duan, Zixin Zeng, Jiawei Li, Kaitong Wang, Sen Du, Yang Xu, Li Gao, Jiahuan Liu, Yong Chen, Bing Shen, Li Chen, Yingxiang Sun, Minghua Zhou, Jianhao Sun, Shengdong Li, Youliang Ye, Mingshan Qu, Xinxin Ye, Yanfeng Wang, Yuexiu Ji, Ruijie Liu, Xinping Chen, and Fusuo Zhang declare that they have no conflict of interest or financial conflicts to disclose. All applicable institutional and national guidelines for the care and use of animals were followed.

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