Front. Agr. Sci. Eng. 2022, 9(3): 373–385 https://doi.org/10.15302/J-FASE-2022455

REVIEW

SUSTAINABLE NITROGEN MANAGEMENT FOR VEGETABLE PRODUCTION IN CHINA

Fen ZHANG[1,2], Xiaopeng GAO[3], Junjie WANG[1,2], Fabo LIU[1,2], Xiao MA[1,2], Hailin CAO[1,2], Xinping CHEN[1,2], Xiaozhong WANG (✉)[1,2]

1 College of Resources and Environment, Academy of Agricultural Sciences, Southwest University, Chongqing 400716, China.
2 Interdisciplinary Research Center for Agriculture Green Development in Yangtze River Basin, Southwest University, Chongqing 400716, China.
3 Department of Soil Science, University of Manitoba, Winnipeg, MB, R3T2N2, Canada.

KEYWORDS

enhanced-efficiency nitrogen fertilizer, integrated knowledge and products strategy, nitrogen rate, reactive nitrogen loss, vegetable, yield

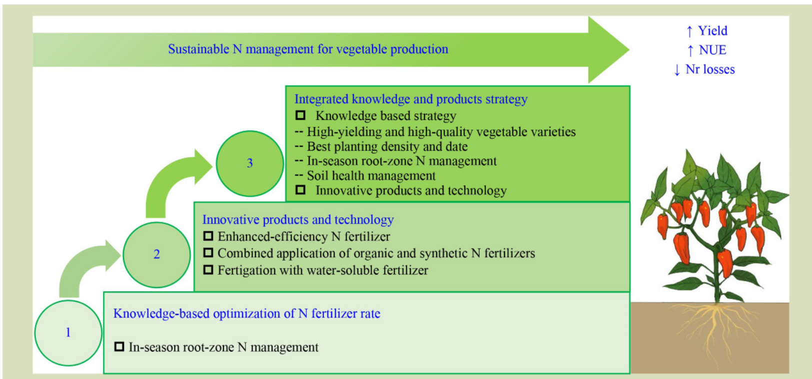
HIGHLIGHTS

- Sustainable nitrogen management strategies for Chinese vegetable production are summarized.
- Research on reactive N (Nr) losses in Chinese vegetable systems is limited compared to cereal crop systems.
- Knowledge-based optimization of N fertilizer rate strategy maintains soil N supply to meet the dynamic vegetable demand in time, space and quantity.
- Innovative products and technology strategy regulates the soil N forms and promotes the vegetable root growth to further control the Nr loss.
- Integrated knowledge and products strategy is needed to produce more vegetables with lower Nr losses.

Received January 30, 2022;
Accepted June 16, 2022.

Correspondence: wxz20181707@swu.edu.cn

GRAPHICAL ABSTRACT



ABSTRACT

Inappropriate nitrogen fertilizer management for the intensive Chinese vegetable production has caused low N use efficiency (NUE), high reactive nitrogen (Nr) losses and serious environmental risks with limited yield increase. Innovative N management strategy is an urgent need to achieve sustainable vegetable production. This paper summarizes recent studies on Nr losses and identifies the limitations from Chinese vegetable production systems and proposes three steps for sustainable N management in Chinese vegetable production. The three N management steps include, but are not limited to, (1) knowledge-based optimization of N fertilizer rate strategy, which maintains soil N supply to meet the dynamic vegetable demand in time, space and quantity; (2) innovative products and technology, which regulates the soil N forms and promotes the vegetable root growth to reduce the Nr loss; (3) integrated knowledge and products strategy (IKPS). The knowledge-based optimization of N fertilizer rate strategy and innovative products and technology, can maintain or increase vegetable yield, significantly improve NUE, and mitigate the region-specific and crop-specific Nr losses. More importantly, IKPS, based on combination of in-season root-zone N management strategy, innovative products and technology, and best crop cultivation management, is needed to produce more vegetables with lower Nr losses.

1 INTRODUCTION

Vegetables are popular in the human diet as a rich source of nutrients[1]. With the increasing vegetable demands and driven by agricultural policies, Chinese vegetable production has developed rapidly. From 2000 to 2018, the area sown and total yield of vegetables in China increased by 34.1% and 58.2%, respectively[2]. China is now the world's largest vegetable producer, accounting for 42.2% of global planting area and 52.3% of production[3]. Nitrogen fertilization is important for increasing yield and improving vegetable quality[4,5]. However, driven by economic interests and higher yield, intensive Chinese vegetable production has been characterized by high fertilizer application rates, especially N fertilizers[6,7]. The average N application rate for vegetable production in China is 352 $kg \cdot ha^{-1}$ N[8], which is 1.6 times greater than that for cereal production in China[9] and doubles that for vegetable cultivation in the USA[10]. However, the N recovery in vegetables is only about 23% of the total N inputs[11]. More N accumulates in the soil or is lost to the environment in the form of reactive N (Nr; all N species except N_2), which in turn leads to the environmental impacts such as greenhouse gas (GHG) emissions[12–14], eutrophication[12,15] and acidification[15–17]. Intensive Chinese vegetable production system has become a hotspot system with high input and high environmental costs worldwide[8,18]. Currently, Chinese vegetable production uses 7.8% of global fertilizers and emits 6.6% of global crop-sourced GHG emissions[18]. Inappropriate management of N fertilizer seriously restricts sustainable development of Chinese vegetable production.

With the increasing demand for vegetables due to the growing population, the environmental problems caused by excessive N application in the Chinese vegetable production systems will become increasingly serious[18–21]. Agricultural policy in China is undergoing a shift from one of zero growth of mineral fertilizer use to a focus on fertilizer use reduction, quality improvements and efficiency increases[22]. Therefore, producing more vegetables with less Nr losses and environmental costs is of great importance for vegetable production in China[20]. This paper reviews the current status of research on Nr losses in Chinese vegetable production systems and further proposes the key strategies to optimize N fertilizer management. This review aims to enhance understanding N cycling in the Chinese vegetable systems and promote the sustainable development of vegetable.

2 LIMITED RESEARCH ON NR LOSS IN VEGETABLE PRODUCTION SYSTEMS IN CHINA

Identifying the Nr losses is the foundation to optimize the region-specific and crop-specific N fertilizer management strategy[4,5,12,23–25]. In recent decades, Nr losses from vegetable systems have received increasing attention (Fig. 1). A recent meta-analysis reported that the N_2O emission[26] and nitrate leaching[27] from the Chinese vegetable production systems were 3.91 and 79.1 $kg \cdot ha^{-1}$ N per season, respectively, which was 1.68–13.8 times greater than those from cereal production systems[28], and mainly attributed to higher N inputs. However, compared to cereal crops (e.g., maize), the research on Nr losses from vegetable systems in China is still limited, and the number of the related scientific papers published for maize systems is 2.3 times greater than that for vegetable systems (Fig. 1). In addition, those studies were heavily focused on evaluating N_2O emission or N leaching, whereas studies on NH_3 volatilization and N runoff losses were relatively limited (Fig. 1(b)). More importantly, there is a lack of systematic studies on the whole Nr losses status in the Chinese vegetable systems. In addition, Nr losses vary greatly among different regions due to large differences of soil characteristics, climate condition and field management practices (e.g., N rate)[8,29,30]. Some observational studies have focused on the Taihu Lake basin[31–34] and North China[35–37], and few studies have been conducted in other regions (especially for south regions). Therefore, it is necessary to systematically quantify Nr losses and related driving factors for different vegetable production systems in different regions in the future, so as to provide theoretical basis for developing the optimal N management in Chinese vegetable systems.

3 SUSTAINABLE N MANAGEMENT STRATEGIES IN CHINESE VEGETABLE SYSTEMS

3.1 Knowledge-based optimization of N fertilizer rate

Determining the reasonable N fertilizer application rate is the first step to achieve sustainable N management (Fig. 2 and

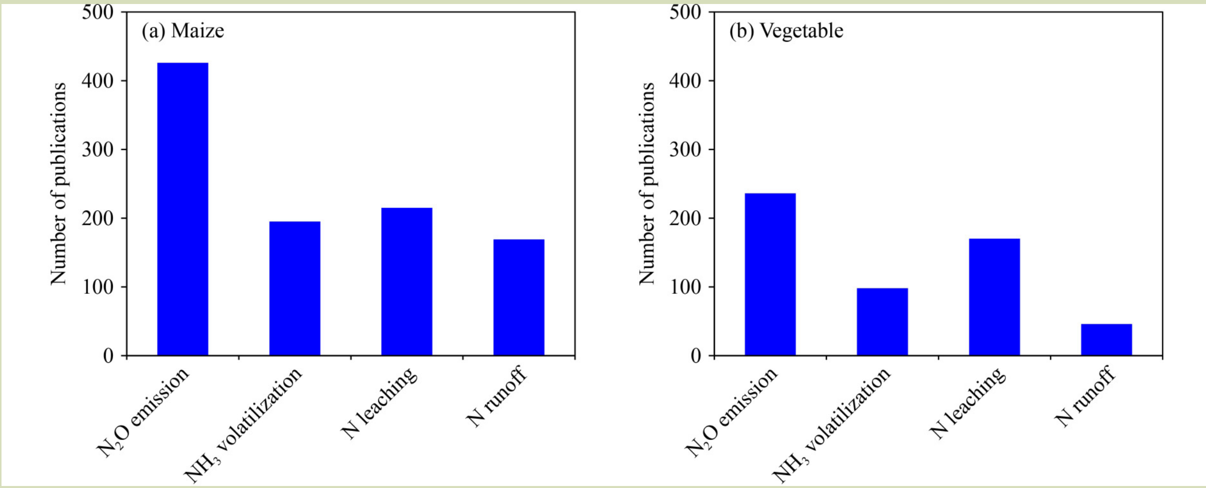


Fig. 1 Number of publications on Nr losses (N_2O emission, NH_3 volatilization, N leaching and N runoff) from maize (a) and vegetable (b) production during 2000–2021. Publications were identified via systematic searches of Web of Science and China National Knowledge Infrastructure databases.

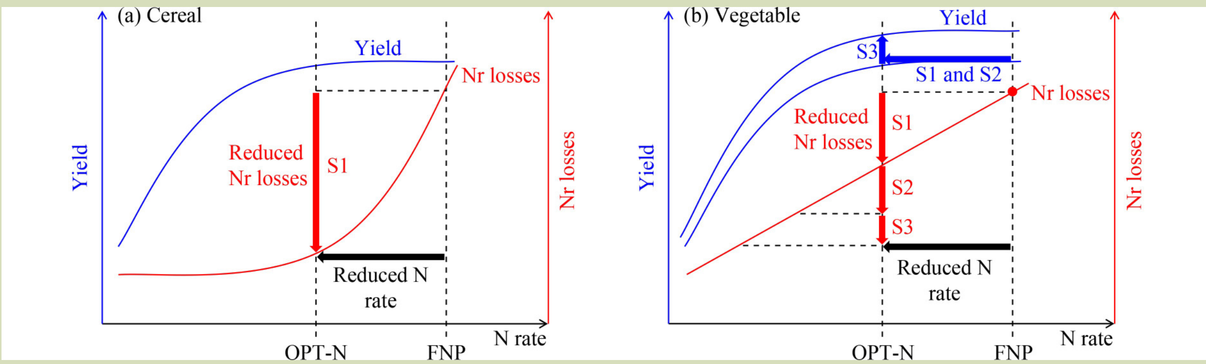


Fig. 2 Crop yield and reactive N loss for cereal (a) and vegetable (b) production systems in response to different N management strategies. S1, knowledge-based optimization of N fertilizer rate strategy; S2, innovative products and technology strategy; and S3, integrated knowledge and products strategy.

Fig. 3). Agricultural researchers have put forward a series of methods to determine the reasonable amount of N application according to local conditions[38]. Currently, there are three main types of methods for recommending N fertilizer rate.

3.1.1 N fertilizer recommendation based on soil analysis

The first type of methods is to determine whether the applied N is reasonable by testing the N content of soil during the critical growth stage, and then adjust the N application strategy. The representative methods include soil N_{min} system[39], Kulturbegleitende-N_{min}-Sollwerte (KNS) system[40], N-expert system[41], the pre-side-dress nitrate test (PSNT)[42], in-season root-zone N management[43], the Dutch 1:2 soil:water extract method[44], soil N supply (SNS) indices[38], soil nutrient abundance index method[45] and regional mean optimal N (RMON)[46].

N_{min} system is a method used for field-grown vegetable crops in central and north-western Europe. The N fertilizer requirement of the crop is the difference between the N required to achieve a certain target yield (N_{target}) and the accumulated soil inorganic N (N_{min}, including NH_4^+-N and NO_3^--N)[38,39]. N_{min} is determined from soil profile samples collected before planting based on the effective root depth of the crop. This method provides more accurate N application recommendations for soils if different fertility. However, this method does not consider the N_{min} values at different growing

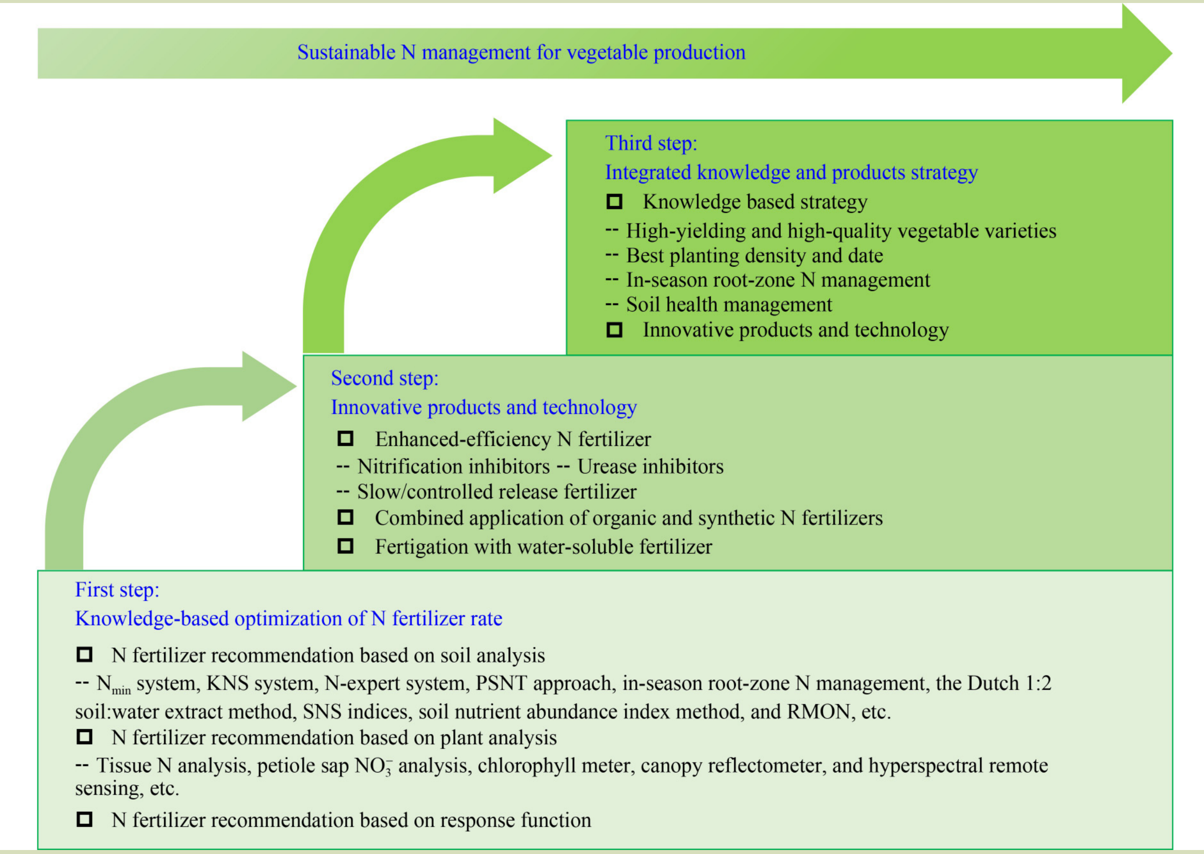


Fig. 3 Sustainable N management strategies for vegetable production in China.

periods of the crop. Therefore, it cannot provide satisfactory recommended fertilization rates for vegetables that require the top dressing N fertilizer during critical crop fertility periods.

The KNS system was developed based on the improvement of the N_{min} system[38,40]. Its recommended N application principle is similar to that of the N_{min} system, except that the KNS method incorporates the effects of critical crop fertility periods, N uptake, root depth, and other factors to calculate the N_{min} value. It also introduces an N_{min} buffer value, i.e. the minimum soil inorganic N residue to ensure normal crop growth, so that it can be recommended for the dynamic balance of N in different nutritional stages of vegetables[47]. It should be noted that this method is only effective when multiple soil mineral N analyses are performed for each crop. In practice, vegetable growers may be unwilling to do even one analysis for each crop.

N-expert system is a further development of the KNS[41], introducing a general N loss term for the calculation of N_{target} values. The estimated unrecovered N (assumed to be lost) and the estimated mineralization of soil organic matter are combined into a net apparent N mineralization value[38,48]. Considering the cost of soil mineral N analysis and the unwillingness of growers to conduct soil analysis, the authors of the N-expert system recommend that only one analysis be done for each crop[35].

The PSNT approach is similar to the KNS system, with the exception that it considers only the NO_3^--N content of dryland soils and ignores the relatively small NH_4^+-N content[38,42]. The PSNT approach was first applied to maize production in North America, and then gradually applied to vegetable N management[49,50]. The PSNT thresholds for specific vegetables were determined through multi-site field trials, ignoring influences such as vegetable management practices and soil texture. When the soil NO_3^--N is below the threshold, N fertilizer was applied to reach the PSNT threshold.

In-season root-zone N management is based on the KNS system. The in-season root-zone N management technique, in which the N rate is determined based on the soil mineral N content and crop N uptake at different crop growth stages, is a common method for optimizing N fertilizer rate in Chinese vegetable systems[18,37,43,51,52]. The in-season root-zone N management strategy can maintain the soil N supply in the root zone and synchronize N application with soil N supply to match vegetable N requirements in time, space and quantity[18]. However, there are still some difficulties in the promotion of this method in Chinese vegetable production. Factors need to be considered include the willingness of farmers to collect soil samples, logistic of transportation of samples to the laboratory from rural areas, the proximity of a suitable laboratories and timelines for provision of results.

The Dutch 1:2 soil:water extraction method was developed for crops in high-tech greenhouses in the Netherlands, and also used for greenhouse conditions in Italy and Greece[38,44,53]. Species-specific fertigation programs have been developed to adjust standard nutrient solutions based on the results of analyses of 1:2 soil:water extractions performed periodically during the crop cycle. To optimize the management of frequent nutrient additions, it is possible to conduct relatively frequent tests, which need simple and fast processes to obtain and prepare soil samples.

SNS indices provides a method in which soil N supply is estimated rather than measured[4,38]. The *Nutrient Management Guide (RB209)*[54] is presented in the form of booklet. It contains a series of tables that can be used to estimate the SNS index value for a specific field and provide a recommended N fertilizer rate for that field specific crop. The SNS index estimates the soil mineral N available to the crop, which includes the estimated N mineralized from organic material during crop growth. The SNS index is determined by considering average annual rainfall, soil texture and residues from previous crops.

Soil nutrient abundance index method is the classic method of soil testing and fertilizer recommendation in China[45]. Based on the yield classification obtained at different soil nutrient measurement values, the measured soil values are graded into a guidance table containing nutrient abundance and corresponding fertilizer application recommendations. In practice, as long as the soil nutrient concentrations are determined, the fertilizer application rate can be calculated by nutrient grade from the guidance table.

The RMON method was proposed by Zhu[46] based on the characteristics of decentralized smallholder land management in China. It is considered that economic optimum N application rate of each field can be replaced by the mean N application rate in a certain region where the soil, climate, production conditions, agronomic management and yield level are relatively consistent. RMON is the mean of the economic optimum N application obtained through a large number of field trials. This method can control the N application rate of most fields within a reasonable range. However, there are many kinds of vegetables in China, and a large number of field trials under different production conditions are needed in the early stage.

3.1.2 N fertilizer recommendation based on plant analysis

The second type of methods takes the nutritional status of the aboveground crop as a basis for diagnosing whether the crop is growing normally or not, which is then used as a basis for making decisions about top dressing N fertilizer. The representative methods include tissue N analysis[55], petiole sap NO_3^- analysis[56], chlorophyll meter[57], canopy reflectometer[58] and hyperspectral remote sensing[59].

Tissue N analysis is a method for diagnosing the nutrient status of crops by measuring the N content of plant tissues, which can be used to guide fertilization[38,53,55,56]. Tissue N analysis can reveal the N status of crops more accurately. However, it is difficult to promote because the procedure is tedious, work-intensive, subject to errors and the operation requires specialized workers.

Petiole sap NO_3^- analysis measures the NO_3^- in the conducting tissue of leaf petioles, and is considered to be a sensitive indicator of crop N status at the time of sampling[38,53,56]. The sensitivity of petiole sap NO_3^- to crop N status has been established for various vegetable crops[56,60,61]. Petiole sap NO_3^- test is highly sensitive to crop N status and is easily used on farm. This method can provide information on the adequacy of crop N status for a given species within a given region. Small portable rapid analysis systems, such as nitrate reflectometers, can be used for on-farm measurements of NO_3^- in petiole sap, thus providing growers/consultants with almost instantaneous results after sample collection[62].

A chlorophyll meters can provide a non-destructive, rapid and relatively accurate measurement of relative leaf chlorophyll content, and are used to diagnose the N status of crops[38,53,57]. However, the application of this method requires the determination of SPAD thresholds for different management systems, crops and fertility periods, which in turn are influenced by various factors such as crop species, soil and climate characteristics[53].

The canopy color of a crop directly indicates the nutritional status of the crop. Some simplified portable spectral testers are gradually developed. These instruments can acquire multispectral reflectance information of plant canopy directly in the field, digitize the spectra, establish the relationship with plant N status, and then obtain the corresponding recommended fertilizer application rate[53]. The multispectral remote sensing technology based on canopy scale, such as GreenSeeker hand-held spectrometer, has been applied in the crop N diagnosis[58]. However, the method has the disadvantage of low number of wavebands and low resolution, which limits the accurate identification and diagnosis of crop nutrition and its widespread application. Additionally, some optical sensors are costly and expensive for smallholder farmers.

Hyperspectral remote sensing method is the most advanced spectral information technology for non-destructive diagnosis of crop N nutrition. Its fine spectral resolution can fully reflect the rich and subtle change characteristics of vegetation spectrum, and has been widely recognized in the accurate monitoring of crop N status[59]. However, data on precise diagnosis of vegetable N nutrition, real-time N regulation and intelligent in situ monitoring technology based on modern hyperspectral information technology is still scarce.

3.1.3 N fertilizer recommendation based on response function

The third type of methods is to establish effect equations between N application and indicators such as yield, N uptake, and economic efficiency, and to determine the optimal N application based on different indicators[63]. In addition to the agronomic effects and economic benefits of N fertilizer application, effect equations can also be established between N fertilizer application and environmental indicators such as NH_3 volatilization, N_2O emission, N leaching, and N runoff[64]. These equations are mostly in the form of linear or exponential functions, and such functions can be used to compare the environmental risks of different N applications.

These monitoring methods have proven to be useful tools for guiding N fertilizer management. Many studies have indicated that the optimized N application strategy can maintain or increase yields, increase NUE, and mitigate Nr losses and environmental costs[43,52,64–66]. For example, a recent meta-analysis reported that the optimized N application had significantly improved the NUE by 80% without a reduction in crop yield, compared to excessive N application in cereal and vegetable production systems[65]. He et al.[43] showed that in-season root-zone N management strategy reduced N fertilizer rate by 69% and further reduced N_2O emissions by half while maintaining yields in a greenhouse tomato production system. It is urgently needed to optimize the N fertilizer rate based on appropriate N fertilizer recommendation strategy in more regions and more vegetable production systems, and further achieve a goal of zero growth of mineral fertilizer use.

Generally, the selection of the best monitoring method for a particular farm will depend on various factors such as crop and farm characteristics, the skill farmers, the support provided and economic considerations. In practice, it is essential to consider the actual conditions in rural China to select the appropriate N fertilizer recommendation method: (1) the small size and large number of vegetable fields, resulting in a heavy testing workload; (2) the high vegetable multiple cropping index and tight stubble, resulting in a tight testing time; and (3) the lack of testing equipment and few technicians, resulting in a small number of samples that can actually be tested[46]. In addition, it is also important to consider the effective parameters that can be obtained under current conditions, as well as the cost of money and time to obtain these parameters[38,53]. Therefore, it is usually appropriate to combine multiple recommended methods according to local conditions to overcome the limitations of a single method and improve the scientific and practicality of the N fertilizer recommended method.

Reducing Nr losses and improving root N uptake by crops are core to optimal N management strategies. In cereal cropping systems, some studies indicated that Nr losses increased exponentially with the increase of N fertilizer rates[9,28], and optimizing N fertilizer rate could ensure the low Nr losses (Fig. 2(a)). However, unlike cereal crops, Nr losses increase linearly with increasing N fertilizer rates in vegetable systems[26,27] due to the shallow root systems, frequent water inputs, high soil N residues and relatively frequent top dressing of N fertilizer[6,7,18]. Although the optimized N application strategy can significantly reduce Nr losses with lower N fertilizer use in vegetable systems, Nr losses were still relatively high (Fig. 2(b)), especially for high temperature and high rainfall regions (e.g., southern region)[67–69]. For example, the cumulative N_2O emissions for pepper season in south-western China were still as high as 10.6 $kg \cdot ha^{-1}$ N_2O-N under a 66.7% reduction in N application rate compared to commonly used management practices[67]. Therefore, an innovative products and technology strategy combined with optimized N fertilization rates, is needed to further mitigate Nr losses and improve N uptake.

3.2 Innovative products and technology

Innovative products and technology under the optimized N rate conditions is the next step toward sustainable N management for vegetable production, which can regulate soil N transformation process to further reduce Nr losses (Fig. 2 and Fig. 3). This strategy includes the application of enhanced-efficiency N fertilizers (EEFs), combined application of organic and synthetic N fertilizers, and the fertigation with water-soluble fertilizer.

3.2.1 Enhanced-efficiency N fertilizers

Many studies have indicated that the EEFs, such as nitrification inhibitors (NIs), urease inhibitors (UIs), and slow/controlled release fertilizers, have been effective in achieving synchronization between N supply and crop uptake, and further decreasing Nr losses and improving NUE[70–72]. NIs (e.g., 3,4-dimethylpyrazole phosphate, dicyandiamide and 2-chloro-6-(trichloromethyl)-pyridine) are chemical compounds that can slow the nitrification process from NH_4^+-N to NO_2-N through inhibiting the activity of ammonia oxidizing bacteria, thus further prolonging the fertilizer efficiency of NH_4^+-N fertilizers and reducing the formation, leaching and denitrification losses of NO_3^--N[70]. The results of many studies have indicated that NIs can mitigate N_2O emissions and N leaching from vegetable production system[33,68,70–72]. In contrast, the response of NH_3 volatilization to NIs addition varies with types of NIs, crop, and soil[73]. In a field experiment, Min et al.[33] found that 2-chloro-6-(trichloromethyl)-pyridine application at optimal N rate reduced N leaching and N_2O emission by 22% and 33%, respectively. UIs (e.g., N-(n-butyl) thiophosphoric triamide and Limus) can slow down the hydrolysis of urea through inhibiting urease activity. Recent studies reported that UIs reduced NH_3 volatilization and N_2O emission from vegetable production[70,72,74]. Slow/controlled release fertilizers have the advantages of synchronizing nutrient release with crop absorption, converting into effective plant nutrients at a slower rate than standard fertilizers, applying fertilizer at once during the whole fertility period of the crop, and saving the labor input of top dressing[4,38,70,72]. Published studies have shown that the application of slow/controlled release fertilizers reduced N_2O emission, N leaching, NH_3 volatilization and N runoff losses from vegetable system compared to conventional fertilizers[70,75–78]. For example, Saha et al.[76] found that slow-release fertilizer reduced N_2O emissions and NH_3 volatilization by 29% and 36%, respectively, while improving NUE by 34%, compared to conventional urea.

Overall, EEFs are important options for reducing Nr losses and improving NUE in vegetable production. However, there are still some limitations of EEFs in Chinese vegetable production. Firstly, most EEFs currently on the market lack specificity, resulting in nutrient release that does not fully match the nutrient demand of vegetables. Therefore, it is necessary to develop special EEFs suitable for different regions and vegetables in accordance with the rules of nutrient requirements of vegetables and the climate and soil characteristics of the regions[4,38,79]. Secondly, EEFs are not attractive to vegetable farmers because of their higher market price than standard mineral fertilizers[80]. It is essential to develop low-cost coating materials and improve production processes to reduce the production and distribution costs of EEFs. In addition, the government should increase the subsidies for farmers to purchase EEFs and for enterprises to research and develop EEFs. Finally, the recognition and acceptance process of new products and technologies by Chinese vegetable farmers is slow due to their relatively high average age and low education level[80]. The government and enterprises should jointly make efforts to enhance publicity, promotion and service skills to improve the recognition and application of EEFs by farmers in China.

3.2.2 Combined application of organic and synthetic N fertilizers

Combined application of organic and synthetic N fertilizers is a common practice in Chinese vegetable production[30,81]. In a farm survey conducted by Zhang et al.[82], a total of 78% of vegetable growers surveyed were using organic fertilizers. Combined application of organic and mineral N fertilizers has been an effective measure to reduce the Nr losses and maintain vegetable yield[30,34,83–85]. A study based on a meta-analysis indicated that the substitution of $\leqslant$ 70% of mineral N with organic source at the recommended N rate can increase vegetable yields by 5.6% and reduce N leaching and GHG emissions by 48.1% and 34.9%, respectively[30]. This was attributed to several factors. Firstly, the low release of N from the organic fertilizers maintains a long-term supply of N to better match crop requirements and reduce Nr losses[86]. Secondly, organic fertilizer can increase soil organic carbon sequestration and improve the abundance and activity of soil microorganisms, thus promoting nutrient cycling in the soil and vegetable root development[87]. Lastly, organic application can promote the formation and stabilization of soil aggregate structure, improve soil fertility properties and soil water holding capacity, and facilitate the formation of soil organic-inorganic complex colloids, which can in turn improve soil quality and vegetable production[34]. Therefore, the combined application of organic and mineral fertilizers should be advocated in Chinese vegetable production systems.

The application of organic fertilizer needs to pay attention to the following principles: (1) selection of an appropriate organic fertilizer with full consideration of safety functionality, source and economic costs; (2) clarification of the amount of organic fertilizer with full consideration of nutrient content and availability; (3) selection of a suitable application method with full consideration of labor and equipment cost and availability[82]. There is a need to develop special and small organic fertilizer application machines suitable for vegetable production. It is worth noting that the Chinese Government has recently provided significant subsidies for the use of organic fertilizers[88]. Agricultural extension departments, agricultural advisors and scientists can raise the awareness of farmers about the potential benefits of rational application of organic fertilizers through farmer training, field demonstrations and distribution of brochures.

3.2.3 Fertigation with water-soluble fertilizer

Frequent water and fertilizer inputs are an important cause of Nr losses in Chinese vegetable production[27]. Fertigation, in which fertilizers are dissolved in the irrigation water and as such delivered to the root zone (usually micro-irrigation system), can synchronize the water and N supply with crop demand[4,89]. Numerous studies have demonstrated that fertigation can provide various benefits over standard practices (e.g., flood/furrow irrigation with broadcast N), such as increasing vegetable yield, increasing N and water use efficiency, and decreasing N_2O emissions and nitrate leaching[36,90–92]. Since the 1960s, the application of fertigation technology has been widely promoted in developed countries. The Chinese Government has introduced a series of policies in recent years to promote the development of fertigation technology. In 2015, the Ministry of Agriculture issued the guiding document, *Action Plan for Zero Growth of Fertilizer Use by 2020*, pointing out that fertigation technology is one of the important safeguards for the implementation of a goal of zero growth of mineral fertilizer use[93]. The development of fertigation technology and water-soluble fertilizer industry has provided important support for promoting precise fertilization, adjusting fertilization structure and improving fertilization methods.

There are still limitations for application of fertigation technology in China. Firstly, some formulations of water-soluble fertilizers are formulated inconsistently[89]. The formulation of water-soluble fertilizer needs to be developed based on the type of vegetables and their nutrient requirements at each growth stage. Also, it is important to develop irrigation and fertilization regimes for the whole fertility period of different vegetables according to their water and nutrient demands. Secondly, the high cost of production and promotion of water-soluble fertilizers has led to their high price and limited consumer demand. Therefore, it is necessary to encourage technological innovation for water-soluble fertilizer production to reduce product costs and improve product quality and cost-effectiveness[89]. Finally, most fertigation equipment currently used in China does not have intelligent decision making and system support technology. There is an urgent need to innovate and develop a range of advanced fertilization equipment and technologies based on regional and vegetable characteristics. In the future, the development of fertigation technology will follow three major trends: (1) water-soluble fertilizer products will be developed for functionality, as liquids, in suitable package and with a consumer focus; (2) fertilization equipment will be multifunctional, low-energy and accurate; and (3) fertigation systems will be more informative and intelligent.

3.3 Integrated knowledge and products strategy

Although the knowledge-based optimization of N fertilizer rate, and the innovative products and technology strategy has been proved to significantly reduce the environmental risks in intensive vegetable production, as most of the single nutrient management practices could not further improve vegetable yields. Therefore, to meet the growing demand for vegetables to be produced sustainably, new integrated strategies are needed to increase vegetable yields and reduce environmental impacts (Fig. 2 and Fig. 3). In China, an integrated soil-crop system management approach has been developed and successfully applied to increase crop yields, improve NUE, and minimize Nr losses and GHG emissions for cereal crop systems[9,94]. Similarly, by comprehensively considering the regional ecological conditions and vegetable species characteristics, a recent study has designed the integrated knowledge and products strategy (IKPS) for vegetable production[18]. The IKPS is designed to manage nutrient supply using a combined strategy that can integrate the best nutrient management, crop management, and innovative product and technology to meet the dynamic needs of vegetable plants in time, space and quantity for high yield while minimizing environmental losses (Fig. 2 and Fig. 3). The theoretical techniques of IKPS include two aspects. Firstly, it combines the in-season root-zone N management and soil health management to ensure that the seasonal supply of root-zone N matches the growth and development of vegetables during the critical growth stages. In addition, it optimizes the planting date and planting density by screening the high-yielding and high-quality vegetable varieties to make full use of light and heat resources. Secondly, the product innovation strategy is based on the regional vegetable characteristics to improve root growth and nutrient uptake, while reducing nutrient losses. The results of 54 site-years of field trials in major agroecological zones of China indicated that the implementation of IKPS can effectively reduce N application by 38%, N surplus by 65%, Nr losses by 43% and GHG emissions by 28%, while increasing yields by 17%, compared to current farming practices[18]. IKPS, as an innovative management program, takes into account the 4Rs of fertilizer management and provides the opportunity to produce more vegetables at lower environmental cost in China. However, further research is needed to promote the broad application of IKPS to different regions and different vegetable species under site-specific conditions.

The promotion and implementation of IKPS in vegetable production in China is still constrained by labor, resources and finance. Therefore, it is recommended to establish cooperation among government, industry, universities and researchers through the Science and Technology Backyard platform[95] to innovate monitoring tools and equipment, to promote experimental demonstrations and innovative extension services, on which to explore technical ways and organizational models to enhance the scientifically-informed farming of vegetables, and achieve increased vegetable yield and efficiency on a large scale.

Acknowledgements

This work was supported by the Regional Innovation and Development Joint Fund project of National Foundation of China (U20A2047).

Compliance with ethics guidelines

Fen Zhang, Xiaopeng Gao, Junjie Wang, Fabo Liu, Xiao Ma, Hailin Cao, Xinping Chen, and Xiaozhong Wang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. Septembre-Malaterre A, Remize F, Poucheret P. Fruits and vegetables, as a source of nutritional compounds and phytochemicals: changes in bioactive compounds during lactic fermentation. *Food Research International*, 2018, **104**: 86–99
2. National Bureau of Statistics of China (NBSC). China statistical yearbook. Beijing: *China Statistics Press*, 2019
3. Food and Agriculture Organization of the United Nations (FAO). FAO statistical yearbook. Rome: *FAO*, 2019. Available at FAO website on December 18, 2021
4. Tei F, De Neve S, de Haan J, Kristensen H L. Nitrogen management of vegetable crops. *Agricultural Water Management*, 2020, **240**: 106316
5. Zhang X, Davidson E A, Mauzerall D L, Searchinger T D, Dumas P, Shen Y. Managing nitrogen for sustainable development. *Nature*, 2015, **528**(7580): 51–59
6. Chen Q, Zhang X, Zhang H, Christie P, Li X, Horlacher D, Liebig H. Evaluation of current fertilizer practice and soil fertility in vegetable production in the Beijing region. *Nutrient Cycling in Agroecosystems*, 2004, **69**(1): 51–58
7. Zhang Q, Chu Y, Xue Y, Ying H, Chen X, Zhao Y, Ma W, Ma L, Zhang J, Yin Y, Cui Z. Outlook of China's agriculture transforming from smallholder operation to sustainable production. *Global Food Security*, 2020, **26**: 100444
8. Zhang F, Liu F B, Ma X, Guo G Z, Liu B, Cheng T H, Liang T, Tao W L, Chen X P, Wang X Z. Greenhouse gas emissions from vegetables production in China. *Journal of Cleaner Production*, 2021, **317**: 128449
9. Chen X, Cui Z, Fan M, Vitousek P, Zhao M, Ma W, Wang Z, Zhang W, Yan X, Yang J, Deng X, Gao Q, Zhang Q, Guo S, Ren J, Li S, Ye Y, Wang Z, Huang J, Tang Q, Sun Y, Peng X, Zhang J, He M, Zhu Y, Xue J, Wang G, Wu L, An N, Wu L, Ma L, Zhang W, Zhang F. Producing more grain with lower environmental costs. *Nature*, 2014, **514**(7523): 486–489
10. United States Department of Agriculture (USDA). Agriculture-Data and statistics. *USDA*, 2011. Available at USDA website on December 18, 2021
11. Ti C, Luo Y, Yan X. Characteristics of nitrogen balance in open-air and greenhouse vegetable cropping systems of China. *Environmental Science and Pollution Research International*, 2015, **22**(23): 18508–18518
12. Beeckman F, Motte H, Beeckman T. Nitrification in agricultural soils: impact, actors and mitigation. *Current Opinion in Biotechnology*, 2018, **50**: 166–173
13. Carlson K M, Gerber J S, Mueller N D, Herrero M, MacDonald G K, Brauman K A, Havlik P, O' Connell C S, Johnson J A, Saatchi S, West P C. Greenhouse gas emissions intensity of global croplands. *Nature Climate Change*, 2017, **7**(1): 63–68
14. Wang X, Liu B, Wu G, Sun Y, Guo X, Jin G, Jin Z, Zou C,

Chadwick D, Chen X. Cutting carbon footprints of vegetable production with integrated soil-crop system management: A case study of greenhouse pepper production. *Journal of Cleaner Production*, 2020, **254**: 120158
15. Lee E K, Zhang X, Adler P R, Kleppel G S, Romeiko X X. Spatially and temporally explicit life cycle global warming, eutrophication, and acidification impacts from corn production in the U.S. Midwest. *Journal of Cleaner Production*, 2020, **242**: 118465
16. Guo J H, Liu X J, Zhang Y, Shen J L, Han W X, Zhang W F, Christie P, Goulding K W T, Vitousek P M, Zhang F S. Significant acidification in major Chinese croplands. *Science*, 2010, **327**(5968): 1008–1010
17. Shi W, Yao J, Yan F. Vegetable cultivation under greenhouse conditions leads to rapid accumulation of nutrients, acidification and salinity of soils and groundwater contamination in South-Eastern China. *Nutrient Cycling in Agroecosystems*, 2009, **83**(1): 73–84
18. Wang X Z, Dou Z X, Shi X J, Zou C Q, Liu D Y, Wang Z Y, Guan X L, Sun Y X, Wu G, Zhang B G, Li J L, Liang B, Tang L, Jiang L H, Sun Z M, Yang J G, Si D X, Zhao H, Liu B, Zhang W, Zhang F, Zhang F S, Chen X P. Innovative management programme reduces environmental impacts in Chinese vegetable production. *Nature Food*, 2021, **2**(1): 47–53
19. Ma L, Bai Z, Ma W, Guo M, Jiang R, Liu J, Oenema O, Velthof G L, Whitmore A P, Crawford J, Dobermann A, Schwoob M, Zhang F. Exploring future food provision scenarios for China. *Environmental Science & Technology*, 2019, **53**(3): 1385–1393
20. Shen J, Zhu Q, Jiao X, Ying H, Wang H, Wen X, Xu W, Li T, Cong W, Liu X, Hou Y, Cui Z, Oenema O, Davies W J, Zhang F. Agriculture green development: a model for China and the world. *Frontiers of Agricultural Science and Engineering*, 2020, **7**(1): 5–13
21. Springmann M, Clark M, Mason-D'Croz D, Wiebe K, Bodirsky B L, Lassaletta L, de Vries W, Vermeulen S J, Herrero M, Carlson K M, Jonell M, Troell M, DeClerck F, Gordon L J, Zurayk R, Scarborough P, Rayner M, Loken B, Fanzo J, Godfray H C J, Tilman D, Rockström J, Willett W. Options for keeping the food system within environmental limits. *Nature*, 2018, **562**(7728): 519–525
22. Wang R, Shi W M, Li Y L. Phosphorus supply and management in vegetable production systems in China. *Frontiers of Agricultural Science and Engineering*, 2019, **6**(4): 348–356
23. Gu B, Ju X, Chang J, Ge Y, Vitousek P M. Integrated reactive nitrogen budgets and future trends in China. *Proceedings of the National Academy of Sciences of the United States of America*, 2015, **112**(28): 8792–8797
24. Sainju U M. Determination of nitrogen balance in agroecosystems. *MethodsX*, 2017, **4**: 199–208
25. Yin Y, Zhao R, Yang Y, Meng Q, Ying H, Cassman K G, Cong W, Tian X, He K, Wang Y, Cui Z, Chen X, Zhang F. A steady-state N balance approach for sustainable smallholder farming. *Proceedings of the National Academy of Sciences of the United States of America*, 2021, **118**(39): e2106576118
26. Wang X, Zou C, Gao X, Guan X, Zhang W, Zhang Y, Shi X, Chen X. Nitrous oxide emissions in Chinese vegetable systems: A meta-analysis. *Environmental Pollution*, 2018, **239**: 375–383
27. Wang X, Zou C, Gao X, Guan X, Zhang Y, Shi X, Chen X. Nitrate leaching from open-field and greenhouse vegetable systems in China: a meta-analysis. *Environmental Science and Pollution Research International*, 2018, **25**(31): 31007–31016
28. Cui Z, Yue S, Wang G, Zhang F, Chen X. In-season root-zone N management for mitigating greenhouse gas emission and reactive N losses in intensive wheat production. *Environmental Science & Technology*, 2013, **47**(11): 6015–6022
29. Gu J, Wu Y, Tian Z, Xu H. Nitrogen use efficiency, crop water productivity and nitrous oxide emissions from Chinese greenhouse vegetables: a meta-analysis. *Science of the Total Environment*, 2020, **743**: 140696
30. Liu B, Wang X, Ma L, Chadwick D, Chen X. Combined applications of organic and synthetic nitrogen fertilizers for improving crop yield and reducing reactive nitrogen losses from China's vegetable systems: a meta-analysis. *Environmental Pollution*, 2021, **269**: 116143
31. Min J, Shi W. Nitrogen discharge pathways in vegetable production as non-point sources of pollution and measures to control it. *Science of the Total Environment*, 2018, **613–614**: 123–130
32. Min J, Zhang H, Shi W. Optimizing nitrogen input to reduce nitrate leaching loss in greenhouse vegetable production. *Agricultural Water Management*, 2012, **111**: 53–59
33. Min J, Sun H J, Kronzucker H J, Wang Y, Shi W M. Comprehensive assessment of the effects of nitrification inhibitor application on reactive nitrogen loss in intensive vegetable production systems. *Agriculture, Ecosystems & Environment*, 2021, **307**: 107227
34. Zhou J, Li B, Xia L, Fan C, Xiong Z. Organic-substitute strategies reduced carbon and reactive nitrogen footprints and gained net ecosystem economic benefit for intensive vegetable production. *Journal of Cleaner Production*, 2019, **225**: 984–994
35. Zhang J, He P, Ding W, Ullah S, Abbas T, Li M, Ai C, Zhou W. Identifying the critical nitrogen fertilizer rate for optimum yield and minimum nitrate leaching in a typical field radish cropping system in China. *Environmental Pollution*, 2021, **268**(Part B): 115004
36. Zhao Y, Lv H, Qasim W, Wan L, Wang Y, Lian X, Liu Y, Hu J, Wang Z, Li G, Wang J, Lin S, Butterbach-Bahl K. Drip fertigation with straw incorporation significantly reduces N_2O emission and N leaching while maintaining high vegetable yields in solar greenhouse production. *Environmental Pollution*, 2021, **273**: 116521
37. He F, Chen Q, Jiang R, Chen X, Zhang F. Yield and nitrogen balance of greenhouse tomato (Lycopersicum esculentum Mill.) with conventional and cite-specific nitrogen management in Northern China. *Nutrient Cycling in Agroecosystems*, 2007, **77**(1): 1–14
38. Thompson R B, Tremblay N, Fink M, Gallardo M, Padilla F M.

Tools and strategies for sustainable nitrogen fertilisation of vegetable crops. In: Tei F, Nicola S, Benincasa P, eds. Advances in Research on Fertilization Management of Vegetable Crops. Switzerland: *Springer*, 2017, 11–63

39. Wehrmann J, Scharpf H C. The Nmin-method-an aid to integrating various objectives of nitrogen-fertilization. *Journal of Plant Nutrition and Soil Science*, 1986, **149**(4): 428–440
40. Lorenz H P, Schlaghecken J, Engel G, Bloetz M. Systematic nitrogen supply in vegetable crops following to the supplemental N_{min} required value-KNS-System. *Neustadter Hefte*, 1986 (in German)
41. Fink M, Scharpf H C. N-expert-a decision support system for vegetable fertilization in the field. *Acta Horticulturae*, 1993, **339**: 67–74
42. Magdoff F R, Jokela W E, Fox R H, Griffin G F. A soil test for nitrogen availability in the northeastern United States. *Communications in Soil Science and Plant Analysis*, 1990, **21**(13–16): 1103–1115
43. He F, Jiang R, Chen Q, Zhang F, Su F. Nitrous oxide emissions from an intensively managed greenhouse vegetable cropping system in Northern China. *Environmental Pollution*, 2009, **157**(5): 1666–1672
44. Sonneveld C, van den Ende J, de Bes S S. Estimating the chemical compositions of soil solutions by obtaining saturation extracts or specific 1:2 by volume extracts. *Plant and Soil*, 1990, **122**(2): 169–175
45. Chen X P, Zhang F S. Establishing a technical index system for soil formula and fertilizer application through the “3414” experiment. *China Agricultural Technology Extension*, 2006, **22**(4): 36–39 (in Chinese)
46. Zhu Z L. On the methodology of recommendation for the application rate of chemical fertilizer nitrogen to crops. *Plant Nutrition and Fertilizer Science*, 2006, **12**(1): 1–4 (in Chinese)
47. Ziegler J, Strohmeier K, Brand T. Nitrogen supply of vegetables based on the “KNS system”. *Acta Horticulturae*, 1996, **428**: 223–234
48. Feller C, Fink M. Nmin target values for field vegetables. *Acta Horticulturae*, 2002(571): 195–201
49. Hartz T K, Bendixen W E, Wierdsma L. The value of presidedress soil nitrate testing as a nitrogen management tool in irrigated vegetable production. *HortScience*, 2000, **35**(4): 651–656
50. Bottoms T G, Smith R F, Cahn M D, Hartz T K. Nitrogen requirements and N status determination of lettuce. *HortScience*, 2012, **47**(12): 1768–1774
51. Guo R, Li X, Christie P, Chen Q, Jiang R, Zhang F. Influence of root zone nitrogen management and a summer catch crop on cucumber yield and soil mineral nitrogen dynamics in intensive production systems. *Plant and Soil*, 2008, **313**(1–2): 55–70
52. Ren T, Christie P, Wang J, Chen Q, Zhang F. Root zone soil nitrogen management to maintain high tomato yields and minimum nitrogen losses to the environment. *Scientia Horticulturae*, 2010, **125**(1): 25–33
53. Padilla F M, Farneselli M, Gianquinto G, Tei F, Thompson R B. Monitoring nitrogen status of vegetable crops and soils for optimal nitrogen management. *Agricultural Water Management*, 2020, **241**: 106356
54. Agriculture and Horticulture Development Board (AHDB). Nutrient Management Guide (RB209). Available at AHDB website on May 4, 2022
55. Geraldson C M, Tyler K B. Plant analysis as an aid in fertilizing vegetable crops. In: Westerman RL, ed. Soil Testing and Plant Analysis, volume 3, 3rd ed. Madison: *Soil Science Society of America*, 1990, 549–562
56. Olsen J K, Lyons D J. Petiole sap nitrate is better than total nitrogen in dried leaf for indicating nitrogen status and yield responsiveness of capsicum in subtropical Australia. *Australian Journal of Experimental Agriculture*, 1994, **34**(6): 835–843
57. Gianquinto G, Sambo P, Borsato D. Determination of SPAD threshold values for the optimisation of nitrogen supply in processing tomato. *Acta Horticulturae*, 2006(700): 159–166
58. Hatfield J L, Gitelson A A, Schepers J S, Walthall C L. Application of spectral remote sensing for agronomic decisions. *Agronomy Journal*, 2008, **100**(S3): S117–S131
59. Feng W, Yao X, Zhu Y, Tian Y C, Cao W X. Monitoring leaf nitrogen status with hyperspectral reflectance in wheat. *European Journal of Agronomy*, 2008, **28**(3): 394–404
60. Hartz T K, Bottoms T G. Nitrogen requirements of drip-irrigated processing tomatoes. *HortScience*, 2009, **44**(7): 1988–1993
61. Farneselli M, Tei F, Simonne E. Reliability of petiole sap test for N nutritional status assessing in processing tomato. *Journal of Plant Nutrition*, 2014, **37**(2): 270–278
62. Parks S E, Irving D E, Milham P J. A critical evaluation of on-farm rapid tests for measuring nitrate in leafy vegetables. *Scientia Horticulturae*, 2012, **134**: 1–6
63. Zhang Y T, Wang H Y, Lei Q L, Zhang J Z, Zhai L M, Ren T Z, Liu H B. Recommended methods for optimal nitrogen application rate. *Scientia Agricultura Sinica*, 2018, **51**(15): 2937–2947 (in Chinese)
64. Zhao H, Li X, Jiang Y. Response of nitrogen losses to excessive nitrogen fertilizer application in intensive greenhouse vegetable production. *Sustainability*, 2019, **11**(6): 1513
65. Quemada M, Baranski M, Nobel-de Lange M N J, Vallejo A, Cooper J M. Meta-analysis of strategies to control nitrate leaching in irrigated agricultural systems and their effects on crop yield. *Agriculture, Ecosystems & Environment*, 2013, **174**: 1–10
66. Li J L, Zhang J W, Wang L Y, Jin S A, Chen Q. Effects of integrated root zone management on greenhouse tomato growth and nitrogen utilization. *China Vegetables*, 2011, (22/24): 31–37 (in Chinese)
67. Zhao M, Jiang C, Li X, He X, Hao Q. Variations in nitrous oxide emissions as manipulated by plastic film mulching and fertilization over three successive years in a hot pepper-radish rotated vegetable production system. *Agriculture, Ecosystems & Environment*, 2020, **304**: 107127

68. Zhang B, Li Q, Cao J, Zhang C, Song Z, Zhang F, Chen X. Reducing nitrogen leaching in a subtropical vegetable system. *Agriculture, Ecosystems & Environment*, 2017, **241**: 133–141
69. Huang R, Liu J, He X, Xie D, Ni J, Xu C, Zhang Y, Ci E, Wang Z, Gao M. Reduced mineral fertilization coupled with straw return in field mesocosm vegetable cultivation helps to coordinate greenhouse gas emissions and vegetable production. *Journal of Soils and Sediments*, 2020, **20**(4): 1834–1845
70. Li T, Zhang W, Yin J, Chadwick D, Norse D, Lu Y, Liu X, Chen X, Zhang F, Powlson D, Dou Z. Enhanced-efficiency fertilizers are not a panacea for resolving the nitrogen problem. *Global Change Biology*, 2018, **24**(2): e511–e521
71. Xia L, Lam S K, Chen D, Wang J, Tang Q, Yan X. Can knowledge-based N management produce more staple grain with lower greenhouse gas emission and reactive nitrogen pollution? A meta-analysis. *Global Change Biology*, 2017, **23**(5): 1917–1925
72. Kanter D R, Searchinger T D. A technology-forcing approach to reduce nitrogen pollution. *nature sustainability*, 2018, **1**: 544–552
73. Qiao C, Liu L, Hu S, Compton J E, Greaver T L, Li Q. How inhibiting nitrification affects nitrogen cycle and reduces environmental impacts of anthropogenic nitrogen input. *Global Change Biology*, 2015, **21**(3): 1249–1257
74. Ti C, Xia L, Chang S X, Yan X. Potential for mitigating global agricultural ammonia emission: a meta-analysis. *Environmental Pollution*, 2019, **245**: 141–148
75. Yang J, Liao S, Li Y, Cao B, Sun Y, Zou G, Liu B. Reducing nitrogen pollution while improving tomato production by controlled-release urea application. *Soil Science and Plant Nutrition*, 2018, **64**(5): 632–641
76. Saha B K, Rose M T, Wong V N L, Cavagnaro T R, Patti A F. A slow release brown coal-urea fertiliser reduced gaseous N loss from soil and increased silver beet yield and N uptake. *Science of the Total Environment*, 2019, **649**: 793–800
77. Shan L, He Y, Chen J, Huang Q, Lian X, Wang H, Liu Y. Nitrogen surface runoff losses from a Chinese cabbage field under different nitrogen treatments in the Taihu Lake Basin, China. *Agricultural Water Management*, 2015, **159**: 255–263
78. Zhou M, Ying S, Chen J, Jiang P, Teng Y. Effects of biochar-based fertilizer on nitrogen use efficiency and nitrogen losses via leaching and ammonia volatilization from an open vegetable field. *Environmental Science and Pollution Research International*, 2021, **28**(46): 65188–65199
79. Zhou W, Lyu T F, Yang Z P, Sun H, Yang L J, Chen Y, Ren W J. Research advances on regulating soil nitrogen loss by the type of nitrogen fertilizer and its application strategy. *Chinese Journal of Applied Ecology*, 2016, **27**(9): 3051–3058 (in Chinese)
80. He Y, Wang X R, Chen X P. Review of slow/controlled release fertilizer and its prevention and control effects of farmland nitrogen loss. *Journal of Anhui Agricultural Sciences*, 2021, **49**(21): 7–10, 14 (in Chinese)
81. Chadwick D R, Williams J R, Lu Y, Ma L, Bai Z, Hou Y, Chen X, Misselbrook T H. Strategies to reduce nutrient pollution from manure management in China. *Frontiers of Agricultural Science and Engineering*, 2020, **7**(1): 45–55
82. Zhang T, Hou Y, Meng T, Ma Y, Tan M, Zhang F, Oenema O. Replacing synthetic fertilizer by manure requires adjusted technology and incentives: a farm survey across China. *Resources, Conservation and Recycling*, 2021, **168**: 105301
83. Geng Y J, Wang J Y, Sun Z R, Ji C, Huang M Y, Zhang Y H, Xu P S, Li S Q, Pawlett M, Zou J W. Soil N-oxide emissions decrease from intensive greenhouse vegetable fields by substituting synthetic N fertilizer with organic and bio-organic fertilizers. *Geoderma*, 2021, **383**: 114730
84. Zhang M, Li B, Xiong Z Q. Effects of organic fertilizer on net global warming potential under an intensively managed vegetable field in southeastern China: a three-year field study. *Atmospheric Environment*, 2016, **145**: 92–103
85. Diao T, Xie L, Guo L, Yan H, Lin M, Zhang H, Lin J, Lin E. Measurements of N_2O emissions from different vegetable fields on the North China Plain. *Atmospheric Environment*, 2013, **72**: 70–76
86. Wei W, Yan Y, Cao J, Christie P, Zhang F, Fan M. Effects of combined application of organic amendments and fertilizers on crop yield and soil organic matter: an integrated analysis of long-term experiments. *Agriculture, Ecosystems & Environment*, 2016, **225**: 86–92
87. Watts D B, Torbert H A, Feng Y, Prior S A. Soil microbial community dynamics as influenced by composted dairy manure, soil properties, and landscape position. *Soil Science*, 2010, **175**(10): 474–486
88. Pan D, Zhou G, Zhang N, Zhang L. Farmers' preferences for livestock pollution control policy in China: a choice experiment method. *Journal of Cleaner Production*, 2016, **131**: 572–582
89. Chen Q, Zhang Q, Chang R X, Chen H K, Chen L, Liang B, Li J L. Developing trends and challenges of water-soluble fertilizer industry in China. *Journal of Plant Nutrition and Fertilizer*, 2017, **23**(06): 9 (in Chinese)
90. Fan Z, Lin S, Zhang X, Jiang Z, Yang K, Jian D, Chen Y, Li J, Chen Q, Wang J. Conventional flooding irrigation causes an overuse of nitrogen fertilizer and low nitrogen use efficiency in intensively used solar greenhouse vegetable production. *Agricultural Water Management*, 2014, **144**: 11–19
91. Li H R, Mei X R, Wang J D, Huang F, Hao W P, Li B G. Drip fertigation significantly increased crop yield, water productivity and nitrogen use efficiency with respect to traditional irrigation and fertilization practices: A meta-analysis in China. *Agricultural Water Management*, 2021, **244**: 106534
92. Lv H F, Zhou W W, Dong J, He S P, Chen F, Bi M H, Wang Q Y, Li J L, Liang B. Irrigation amount dominates soil mineral nitrogen leaching in plastic shed vegetable production systems. *Agriculture, Ecosystems & Environment*, 2021, **317**: 107474
93. Ministry of Agriculture and Rural Affairs of the People's

Republic of China (MARA). Circular of the Ministry of Agriculture and Rural Affairs on printing and distributing the Action Plan for Zero Growth in the Application of Fertilizer by 2020. Beijing: *MARA*, 2015. Available at MARA website on May 6, 2022

94. Chen X P, Cui Z L, Vitousek P M, Cassman K G, Matson P A, Bai J S, Meng Q F, Hou P, Yue S C, Römheld V, Zhang F S. Integrated soil-crop system management for food security. *Proceedings of the National Academy of Sciences of the United States of America*, 2011, **108**(16): 6399–6404

95. Zhang W, Cao G, Li X, Zhang H, Wang C, Liu Q, Chen X, Cui Z, Shen J, Jiang R, Mi G, Miao Y, Zhang F, Dou Z. Closing yield gaps in China by empowering smallholder farmers. *Nature*, 2016, **537**(7622): 671–674