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REVIEW

NITROGEN USE AND MANAGEMENT IN ORCHARDS AND VEGETABLE FIELDS IN CHINA: CHALLENGES AND SOLUTIONS

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KEYWORDS

nitrogen fate, nitrogen fertilizer, orchards, vegetable fields

HIGHLIGHTS

- Excessive application of N fertilizers in orchards and vegetable fields (OVFs) in China is particularly common.
- Long-term excessive application of N fertilizers has made OVFs hotspots for N surplus and loss in China.
- Nitrate accumulation in the soil profile is the main fate of N fertilizers in OVF systems.
- Reducing the N surplus is the most effective way to reduce N loss and increase NUE.

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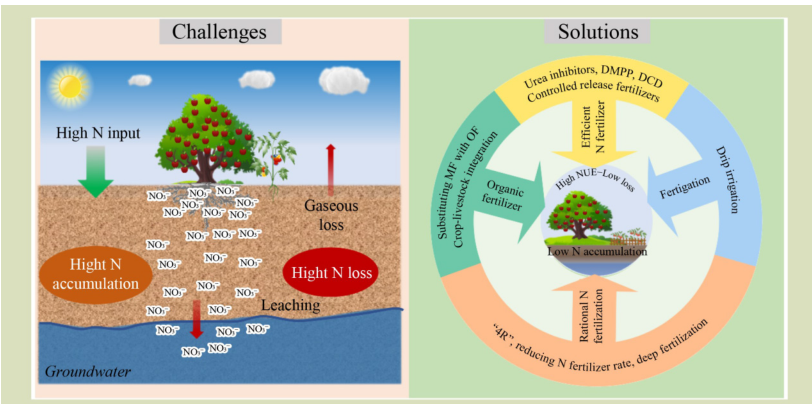
GRAPHICAL ABSTRACT



ABSTRACT

China is the largest producer and consumer of fruits and vegetables in the world. Although the annual planting areas of orchards and vegetable fields (OVF) account for 20% of total croplands, they consume more than 30% of the mineral nitrogen fertilizers in China and have become hotspots of reactive N emissions. Excess N fertilization has not only reduced the N use efficiency (NUE) and quality of grown fruits and vegetables but has also led to soil acidification, biodiversity loss and climate change. Studies using ^{15}N labeling analysis showed that the recovery rate of N fertilizer in OVFs was only 16.6%, and a high proportion of fertilizer N resided in soils (48.3%) or was lost to the environment (35.1%). Nitrate accumulation in the soil of OVFs is the main fate of N fertilizer in northern China, which threatens groundwater quality, while leaching and denitrification are the important N fates of N fertilizer in southern China. Therefore, taking different measures to reduce N loss and increase NUE based on the main pathways of N loss in the various regions is urgent, including rational N fertilization, substituting mineral N fertilizers with organic fertilizers, fertigation, and adding mineral N fertilizers with urease inhibitors and nitrification inhibitors.

1 INTRODUCTION

The application of nitrogen fertilizer has fed nearly half of the global population[1]. However, more than 50% of N fertilizer applied to agricultural systems is estimated to be lost to the environment in various ways, resulting in a series of problems, such as low N use efficiency (NUE), soil acidification, eutrophication, climate change and loss of biodiversity[2,3]. Clarifying the hotspots of N surplus and fates in an agricultural system is critical for controlling N losses and increasing NUE. China has consumed more than 30% of annual global N fertilizer production[4]. Compared to cereal crops, excessive application of N fertilizers in orchards and vegetable fields (OVFs) in China is common and is considered a hotspot of N surplus and loss[5–7]. Therefore, comprehensively understanding the fates of N fertilization of OVFs in different regions is urgent for optimizing agricultural N management in China.

2 DEVELOPMENT AND N FERTILIZATION OF ORCHARDS AND VEGETABLE FIELDS

The production of fruit and vegetable crops in China has rapidly increased since the late 1980s. The areas of orchards and vegetable crops increased from 1.8 and 3.2 Mha in 1980 to 12.3 and 20.9 Mha in 2019, respectively, accounting for 20% of the total national cropland of China (Fig. 1(a))[8]. China has become the largest producer and consumer of apples and citrus in the world, and the planting areas of apples and citrus in China are 2.32 and 2.69 Mha, respectively[4]. The areas and yields of apple in China account for 48% and 54% of the world totals, respectively[4,8]. Orchards and vegetables are in second and third ranked in China's plantation production industry, respectively, and they are of substantial importance for China's agricultural economy and income of farmers.

The annual application of N fertilizers in China has greatly increased as the OVF area has increased (Fig. 1(a)). The areas of OVF in China only account for 20% of the national planting area; however, they have consumed 32% of the annual mineral N fertilizers in China (~10 $Tg \cdot yr^{-1}$ N; Fig. 1(b))[9]. The excessive application of N fertilizer in OVFs in China is particularly common[5,6,10]. For example, the average annual N input in the kiwifruit orchard on the northern slope of the Qinling Mountains in Shaanxi is 1201 $kg \cdot ha^{-1}$ N, which is 10 times that of the N harvested in fruit and prunings, resulting in a high N surplus[11–13]. The averages of N fertilizer application

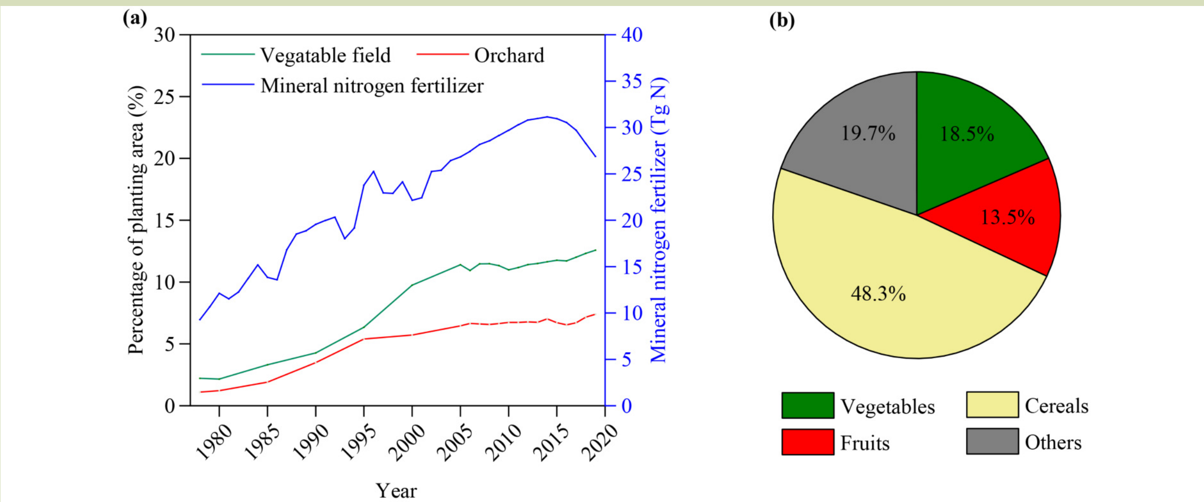


Fig. 1 The percentages of the areas of orchards and vegetable fields to the total planting areas, the use of mineral N fertilizers (a) from 1978 to 2019, and the percentage of N fertilizers used in different crop systems in 2014 (b) in China.

and N surplus in the orchards (including apple orchards, kiwifruit orchards and vineyards) in Shaanxi Province are 1066 and 876 kg·ha^{-1} N, respectively, and more than 94.8% of these orchards overuse N fertilizers[13]. The average N input in apple orchards in Shandong Province is 867 kg·ha^{-1} N, which is 7.2 times the crop N uptake[7]. High N surplus is also common in orchards in southern China. He et al.[14] reported that the average N fertilizer rate of mango orchards in Hainan Province is 275 kg·ha^{-1} N, 3.8 times the N removal by the crop.

The N fertilizer application rates and N surplus of vegetable fields are usually greater than those of orchards in China due to the common use of organic fertilizers and multiple harvests annually (> 2 planting times). A survey in Shandong Province by Ju et al.[7] found that the average N surplus in vegetable fields is as high as 3327 kg·ha^{-1}·yr^{-1} N (n = 56). The survey by Fan et al.[15] in Shaanxi Province showed that the average N surplus in vegetable fields is 1407 kg·ha^{-1} per season. The average annual N surplus of vegetables in the solar greenhouse of the Guanzhong Plain is 1354 kg·ha^{-1} N, accounting for 72% of the total N input[16]. The application rates of N fertilizers in OVFs in China are significantly higher than those recommended by experts[17]. The average N surplus of China's OVFs also significantly exceeds the N surplus threshold suggested by the EU Nitrogen Expert Panel (80 kg·ha^{-1} N)[18]. The high economic benefits, the lack of knowledge of crop N requirements and N accumulation in soil profile and ignoring the N added by organic fertilizers, N deposition, and irrigation for smallholders are the main reasons for the overuse of N fertilizer.

3 FATE OF NITROGEN IN INTENSIVE ORCHARDS AND VEGETABLE FIELDS

The fate of N fertilizer applied in soil and plant systems include crop uptake, soil accumulation and loss. Compared with other methods, the ^{15}N isotopic labeling method is an accurate way to quantify the fate of N fertilizer[19,20]. Given that studies using containerized plants in the OVFs are not representative field conditions, we have summarized the results of the ^{15}N labeling analyses in microplots in fields of OVFs in China (Table 1). This showed that the average N recovery rate of the OVFs is 16.6% in the season of application, which is significantly lower than in the principal field crops (25%, 33% and 28% for wheat, corn and rice, respectively) determined by the same method[19].

3.1 Nitrogen accumulation in the soil profile

^{15}N labeling analyses showed that the fertilizer N accumulation in the soil of OVFs accounted for an average of 48.3% of the N fertilizer application (Table 1). Many field studies have provided clear evidence that nitrate accumulation in the soil profile is one of the main forms of residual N fertilizer in OVFs, especially in northern China[5,10,35]. For example, Bai et al.[5] reported that the nitrate accumulation in the 0–4 m soil profile of vegetable fields is 950–1487 kg·ha^{-1} N, and that the estimated nitrate accumulation in the 0–4 m profile of vegetable fields in China is 21.1 Tg N, being about 3.7 times the annual N fertilizer input of vegetable fields in China. The average accumulation of nitrate in the 0–6 m soil of apple orchards on the Loess Plateau is 4131–7250 kg·ha^{-1} N, of which more than 50% of the nitrate nitrogen accumulates in the deep unsaturated zone (2–6 m), which is difficult to reuse for fruit trees[36]. For the kiwifruit belt of the northern slope of the Qinling Mountains (with irrigation, a shallower vadose zone than apple orchards on the north Loess Plateau), the average nitrate accumulation in the 0–10 m soil profile is 7113 kg·ha^{-1} N [6]. We analyzed the fate of surplus N after land conversion from cereal lands to apple orchards at a county scale on the Loess Plateau and found that soil nitrate accumulation accounted for 52% of the total N input and was the main fate of input N[10]. A study of the hilly area in southern China also found that orchards (with vadose zone thicknesses > 4 m) have high nitrate accumulation in soil, and the nitrate accumulation increases with the vadose zone thickness[37]. Therefore, overuse of N fertilizer, a thick vadose zone, strong soil nitrification and weak denitrification (from

Table 1 Fate of N fertilizer in orchards and vegetable fields during the current season (^{15}N labeling method)

Crops	Types	n	N fertilizer rate (kg·ha^{-1} N per season)	N crop uptake (%)	N loss (%)	N accumulated in soil (%)	Soil depths (cm)	References
Vegetables	Greenhouse	7	225–1200	8.08–28.4	12.9–51.8	21.5–77.3	<100	[21–27]
Vegetables	Open field	5	250–537	8.65–29.0	29.0–46.7	30.3–53.8	<100	[28–32]
Fruit trees	Orchard	2	351–500	13.4–20.0	50.0–53.2	30.0–33.4	100–200	[33,34]
Total		14	459	16.6	35.1	48.3		

low soluble organic carbon content and good aeration) may explain why high nitrate accumulation is found in the vadose zones of intensive planting areas in China[5,6,10,38].

Compared with the soils and climates in northern China, the OVFs in the tropical and subtropical regions of southern China have higher rainfall and temperature and shallower vadose zones. N leaching and denitrification losses may be the primary fate of N fertilizer in these agroecosystems (Fig. 2). For example, in the OVFs of the Taihu Lake Basin in China (with average annual rainfall of 1344 mm, the vadose zone thickness is usually less than 1–2 m), low nitrate accumulation is found under high N fertilizer input (590–600 kg·ha^{-1} N) due to the leaching and high denitrification under the anaerobic environment (the dissolved oxygen concentration of groundwater is < 2 mg·L^{-1}) and the high soluble organic carbon content[39]. Similar results were found in other intensive agricultural areas with relatively shallow vadose zones around the world, that is, that denitrification is the main fate of N fertilizers. Castaldelli et al.[40] reported that denitrification is an significant fate of N inputs (37%) in an intensive agricultural watershed in Italy (with wheat and maize the major crops, accounting for 52% of the total; their average N input rate was 194 kg·ha^{-1} N) due to the simultaneous conditions of hypoxia/anoxia and the availability of nitrate and labile organic carbon. Overall, soil nitrate accumulation in northern China with a thick vadose zone is the main fate of N fertilizer, while N leaching and denitrification loss may be the main fate of OVF in regions with high rainfall and shallow vadose zones in southern China (Fig. 2).

3.2 Loss pathways of N fertilizer

The average N loss from OVFs in China is 35.1% (^{15}N loss rate (%) = 100% – ^{15}N utilization rate (%) – ^{15}N residual rate (%)) (Table 1). It is worth noting when quantifying the N fate based on the ^{15}N labeling method that most studies only measured ^{15}N accumulation in the shallow soil layer (less than 100 cm) and ignored ^{15}N accumulation in the deep soil layer (Table 1; Fig. 2). However, many studies have shown that the nitrate

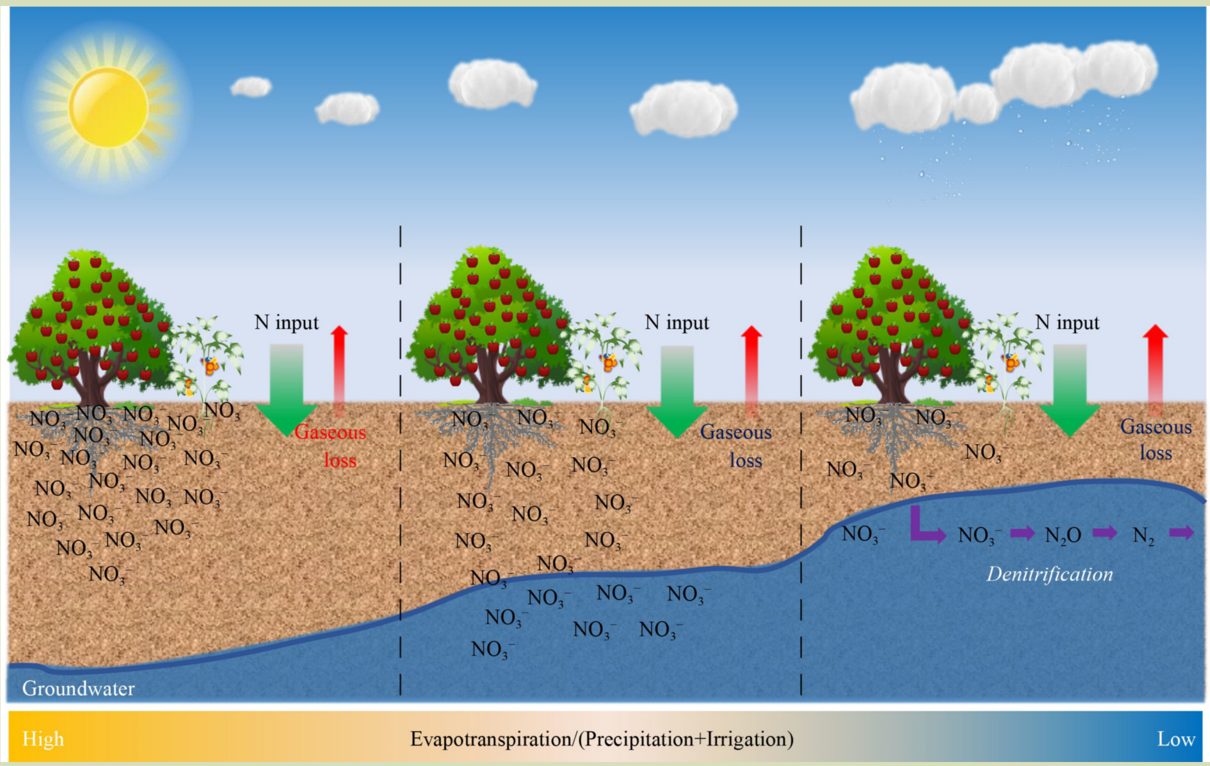


Fig. 2 Schematic of the main loss pathways of N in orchards and vegetable fields and the potential effect on groundwater quality in the different climatic zones. Left panel: soil has a deeper vadose zone and the evapotranspiration (EP) is higher than precipitation and irrigation (P + I), so nitrate mainly accumulates in the upper soil profile. Middle panel: soil has a deep vadose zone, and the EP is nearly equal to P + I, so nitrate accumulated in the soil profile has been leached into groundwater. Right panel: soil has a shallow vadose zone and the EP is lower than P + I, so N leaching and denitrification is the important fate of N loss.

accumulation depth in OVFs may exceed 200 cm[5,6,10,36,41]. Therefore, the residual fertilizer N in soil may be underestimated, resulting in the overestimation of the loss of N fertilizer, especially in the regions with a thick vadose zone in northern China.

The gaseous loss of N from soil includes NH_3 volatilization and N_2O and N_2 emission from nitrification-denitrification. Some studies have reported that the loss by NH_3 volatilization and N_2O for vegetable systems in China are 8.97%–13.6%[42,43] and 0.69%–1.41% of the total N fertilizers added[44,45], respectively. The total annual losses by NH_3 volatilization and N_2O emissions in vegetable systems in China are estimated to be about 0.63 and 0.085 Tg N, respectively[43,46]. The losses of NH_3 volatilization and N_2O for apple orchards were 11% and 0.27%–0.7%[33,47], respectively, and the N_2O emission factor is lower than 1% reported by the IPCC (2007)[48]. Compared with vegetable fields, N fertilizers in orchards are usually more deeply applied (> 25 cm deep), which markedly reduces NH_3 volatilization in orchards[49].

Production of facility vegetables is a key part vegetable production in China. NH_3 volatilization from the soil surface in the facility system can be absorbed again by the plant canopy or dissolved in greenhouse film water and returned to the soil due to the semiclosed structures. A three-season study found that ammonia volatilization in the entire greenhouse (NH_3 emissions from the venting zone of the solar greenhouse) accounted for only 13.4%–33.7% of the NH_3 volatilization from the soil surface, and the NH_3 emission factor was only 0.46%–1.48%[50]. If the NH_3 emission factor of the soil surface is used to estimate the NH_3 loss of facility vegetable system, it would overestimate the NH_3 loss in these contexts[50]. Therefore, newer methods for determining N fertilizer loss pathways require further improvement due to the special environment and different management practices of OVFs in China.

4 CONSEQUENCES OF EXCESSIVE N INPUT TO ORCHARDS AND VEGETABLE FIELDS

OVFs are the hotspots for high N surplus and low NUE in China's agriculture system due to the long-term overuse of N fertilizer. This not only wastes resources but also affects vegetable and fruit quality. For example, the overuse of N fertilizer negatively affects fruit color, soluble solids, and other quality indicators[51,52], decreases the vitamin C content of vegetables and causes nitrate accumulation in leafy vegetables[53,54].

The excessive application of N fertilizer in OVFs results in soil salinization and acidification. These effects are more severe in facility vegetable production systems due to the semi-enclosed environment. For example, the soluble salt and EC contents of the surface soil (0–20 cm) in facility vegetable fields are 2.43 $g·kg^{-1}$ and 630 $μS·cm^{-1}$, respectively, which are higher than the critical contents of soluble salt (2 $g·kg^{-1}$) and EC (500 $μS·cm^{-1}$)[55]. There is a linear positive correlation between soil EC and nitrate content ($R^2 = 0.84$)[56]. Soil pH significantly decreases and EC content significantly increases with the increase in cultivation years of facility vegetable crops[16]. Compared with open vegetable fields, the soil pH of facility vegetable fields is lower in the same region; in contrast, the EC in facility vegetable fields (547 $μS·cm^{-1}$) is three times higher than that in open vegetable fields (157 $μS·cm^{-1}$)[15]. This is related to the high H^+ and basic cations generated by excessive N fertilizer application and nitrification of N fertilizer, and high temperature and strong evaporation lead to the accumulation of base ions in the surface soils. Long-term pear production in southern China has aggravated red soil acidification and has caused severe early defoliation[57]. Therefore, the overuse of N fertilizer in OVFs causes soil degradation, which in turn will negatively affect crop growth.

A high N surplus in agroecosystems also results in biodiversity loss and climate change[58]. We will focus on the effect of nitrate accumulation in soil profiles on water quality. Excessive nitrate accumulation in deep soil profiles increase groundwater pollution risk. A recent study in the kiwifruit belt of Shaanxi found that 97% of groundwater samples exceeded the nitrate concentrations of the WHO standard for drinking water (50 $mg·L^{-1}$)[59,60]. The dissolved oxygen concentration (between 3.5 and 8.3 $mg·L^{-1}$) in the groundwater of the region was > 2 $mg·L^{-1}$[60], indicating that nitrate denitrification in the groundwater in the region is inhibited. Nitrate pollution in the groundwater is also prevalent in other intensive OVF planting regions in northern China[7]. It is difficult to effectively remove nitrate from groundwater by denitrification[61]. In addition, the time lag caused by high soil nitrate accumulation and migration brings great challenges for controlling groundwater nitrate pollution. For example, a study on the Mississippi River revealed that more than 50% of the nitrate exported from the watershed is from N fertilizer applied 30 years ago[62]. Therefore, groundwater is difficult to improve once contaminated, and more attention should be given to regions with high N surpluses, rainfall and irrigation.

5 SUGGESTIONS FOR SUSTAINING N MANAGEMENT IN ORCHARDS AND VEGETABLE PRODUCTION

Quantifying the main fates of applied N fertilizer in OVFs is the key for improving NUE and controlling N loss. However, compared with cereal crops, studies of the fate of N fertilizer in OVFs in China are still far from clear. Given the different climates, soils, and management practices in OVFs in China, more studies are needed to understand the main fates of N fertilizers in these systems. Unlike vegetable crops, fruit trees are perennial crops that have large plant sizes, and N storage in perennial organs (roots, stems and branches) can delay the response of trees to the N added in the year of application. Therefore, more long-term studies are needed. At present, most of the studies on the fate of N fertilizer and N losses in OVFs have focused on the field scale, and few studies have focused on the watershed or at the regional scale. It is difficult to provide decision-making and consulting suggestions for N fertilizer management in the development of the fruit and vegetable industry in China. For example, to prevent pollution of groundwater, it is necessary to clarify nitrate-vulnerable zones or potential vulnerable zones according to nitrate concentration of groundwater, long-term N surplus, water balance, soil texture, vadose zone thickness and topography, similar to the establishment of nitrate-vulnerable zones in the EU[63], and prioritize the optimization of water and N management in these regions to control N loss and reduce environmental risks. Practical suggestions to reduce N loss and increase NUE are as follows (Fig. 3).

5.1 Rational N fertilization

Optimizing N input with by the 4R (right source, right rate, right time and right place) method is a basic solution. Given the overuse of N fertilizers is very common in OVFs in China, reducing the N fertilizer rate is the most direct and effective way to reduce N loss[64–70]. A seven-year N fertilizer reduction experiment in the northern slope region of the Qinling Mountains showed that, compared with normal N fertilization (900 kg·ha^{-1}·yr^{-1} N) practiced by farmers, no adverse effects were found on the yield and quality of kiwifruit, with a 25% reduction in the N application rate in 2012–2014 and reaching 45% in 2014–2019; however, it increased economic benefits for farmers and reduced nitrate accumulation in soil [71,72]. Reducing N fertilizer by 40% significantly reduced nitrate accumulation in the 0–1 m of soil and increased NUE in apple planting regions in Bohai Bay[33]. Obviously, an appropriate reduction in N fertilizer rate in OVFs can still guarantee crop

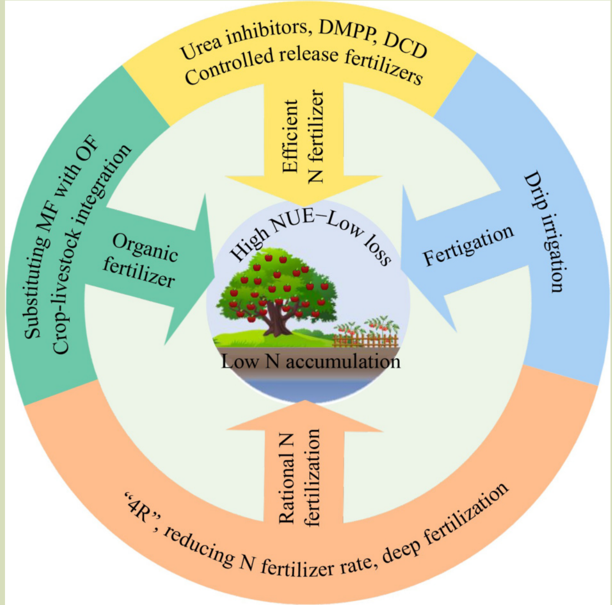


Fig. 3 Practices to reduce N loss and increase NUE for orchard-vegetable systems. MF and OF represent mineral N fertilizer and organic N fertilizer, respectively.

yields while also reducing N fertilizer loss. Although N reduction is the most effective way to reduce N loss in OVFs, the effects of continuous N fertilizer reduction need to be further studied to ensure that production will not decrease.

5.2 Substituting mineral N fertilizers with organic fertilizers

Compared with mineral N fertilizer, partial replacement of mineral N fertilizer with organic fertilizer (30%–60%) significantly reduces N_2O emissions, NH_3 volatilization, and N leaching[73]. A meta-analysis indicated that reasonable substitution of organic fertilizer for mineral fertilizer (ratio of organic fertilizer less than 70%) increases vegetable yields and reduces reactive N emissions[42]. There are many kinds of organic fertilizers applied for OVFs in China. Estimations of the N supply characteristics of organic fertilizer effectively and the proportion of different organic fertilizers to mineral N fertilizer in different OVFs are urgently needed.

The separation of cropping and livestock production makes the supply of organic fertilizers to OVFs challenging. Therefore, investigation of how to promote the regional N cycle and reduce N fertilizer application by integrating crop and livestock systems is needed. Other options include planting cover crops in orchards and returning crop straw to OVFs.

5.3 Replacing flood irrigation with fertigation

Commonly-practiced flood irrigation with excessive N fertilizer application is the main cause of N leaching loss in agricultural systems[74,75]. Fertigation can match the demand of crops for water and N in the growing season and effectively reduce N accumulation and loss[76]. Compared with flood irrigation, drip irrigation not only reduces the input of water and N but also significantly reduces nitrate accumulation in soil and the emission of N_2O and N leaching loss and increases NUE[77–79]. The key technologies and measures for the comprehensive regulation of water and N in OVFs in the different regions of China need to be studied.

5.4 Developing high efficiency N fertilization systems

Developing high efficiency N fertilization systems that can synchronize fertilizer and soil N supply and plant N demand is another way to increase NUE and reduce its loss, including controlled release fertilizers and mixing N fertilizers with different inhibitors. Urea inhibitors and nitrification inhibitors (Dicyandiamide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP)) can prolong the conversion time of ammonium N to nitrate N, increase the amount of ammonium N and amide N absorbed by crops, inhibit nitrification and nitrate leaching, and ultimately improve NUE and reduce N loss. Compared with urea alone, the application of urease inhibitor decreases NH_3 volatilization, nitrate leaching and N_2O emission[80,81]. The application of nitrification inhibition significantly reduces nitrate leaching and N_2O emissions from vegetable fields[33,70,82]. In addition, the application of DMPP can reduce N runoff loss for sloping orchards by reducing the nitrification of inorganic N[83]. Notably, the beneficial effect of nitrification inhibitors to mitigate N_2O emission can be undermined by an increase in NH_3 volatilization[84,85]. Therefore, the development of high efficiency N fertilization systems could be a key way to decrease N fertilizer losses, but the trade-off of different N loss pathways should be given more attention.

6 CONCLUSIONS

More than 30% of China's annual N fertilizer application is to OVFs. The long-term excessive application of N fertilizer has led to OVFs as hotspots of both N surplus and N loss. Nitrate accumulation in the soil profile is the main fate of surplus N in OVFs in northern China and has led to increased groundwater pollution. Considering the range of climates, soils and management practices in OVFs in China, more studies are needed to clarify the main fates of N fertilizer in the different systems. Reducing the N rate in fields with excessive application is the most direct and effective way to reduce N loss and increase NUE. Other measures include substituting mineral N fertilizers with organic fertilizers, replacing flood irrigation with fertigation, using a controlled release N fertilizer, and mixing mineral N fertilizers with urease inhibitors and nitrification inhibitors.

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Compliance with ethics guidelines

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