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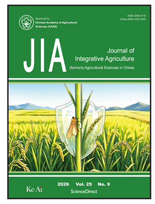

RESEARCH ARTICLE

Integrative fertilizer nitrogen management mitigates nitrogen leaching and gray water footprint in a subtropical vegetable rotation system

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Highlights

- Annual N leaching in subtropical open-field vegetable fields averaged 251 kg ha^{-1}, representing 29% of applied N fertilizer.
- Optimizing rate and timing of N fertilizers reduced N leaching by 68%.
- Nitrification inhibitor reduced N leaching and gray water footprint more effectively than controlled-release urea or mixed organic-inorganic fertilizers.
- Integrative "4R" N stewardship produced more vegetables with less N leaching.

Abstract

Nitrogen (N) leaching is a major pathway of N loss in subtropical crop production systems, contributing to groundwater pollution and thus posing serious threats to human health. However, the characteristics of annual N leaching in subtropical open-field vegetable systems and the effectiveness of integrative N fertilization management practices in reducing N leaching remain poorly understood. In this study, two plot-based field experiments were conducted with open-field Chinese cabbage–pepper rotation system in subtropical Southwest China to quantify annual N leaching and evaluate the effectiveness of integrated N fertilization management practices. Experiment 1 compared five N fertilizer application rates using conventional urea, while Experiment 2 compared different N sources including conventional urea, organic fertilizer, nitrification inhibitor-based fertilizer, and controlled-release urea which were all applied at the optimized N rate. Results showed that the annual N leaching under farmers' N practice (FNP) was 251 kg N ha^{-1}, with contributions of 55, 31, and 14% from the pepper season, Chinese cabbage season, and fallow period, respectively. Total N leaching increased exponentially with N rate. The seasonal N leaching factor was 32% for pepper and 17% for Chinese cabbage in the FNP treatment, respectively. Compared to FNP, optimizing N rate based on crop requirement and soil supply significantly reduced N leaching by 68% and gray water footprint by 66−75%, while improving N use efficiency (NUE) from 35 to 54%. In Experiment 2, mixing organic and inorganic fertilizers, applying nitrification inhibitor, and using controlled-release urea further reduced annual N leaching by 27, 54, and 25%, respectively, compared to conventional urea. These practices also improved crop yields by 2−11% and NUE by 10−13%, and lowered gray water footprint by 28−58%. In summary, integrative N stewardship practices, particularly use of nitrification inhibitors under optimized N rates, effectively reduced N leaching while achieving high NUE and vegetable yields, providing a promising strategy for sustainable subtropical vegetable production.

Keywords: enhanced efficiency fertilizer, leaching factor, marketable yield, nitrogen balance, nitrogen rate, nitrogen use efficiency

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1. Introduction

Vegetables generally contain high levels of essential nutrients and play a crucial role in human diet and nutrition (Willett *et al.* 2019). However, intensive vegetable production often involves excessive nitrogen (N) fertilizer application (Wang *et al.* 2021). Due to their shallow root systems and limited nutrient and water absorption capacity, vegetables are prone to leaving substantial residual mineral N (N_{min}, the sum of NH_4^+ and NO_3^-) in the soil profile (Tei *et al.* 2020; Zhang Q *et al.* 2020; Zhou *et al.* 2022). In tropical/subtropical regions with heavy precipitation or irrigation, residual N_{min} is highly susceptible to leaching, especially in vegetable production systems that typically receive high N fertilizer inputs (Min *et al.* 2012; Zhang *et al.* 2017). Nitrogen leaching leads to soil fertility depletion and groundwater contamination, posing serious threats to human health and agricultural sustainability (Ying *et al.* 2020; Wang *et al.* 2023; Tian *et al.* 2024; Xu *et al.* 2024). The gray water footprint (GWF) is a reference indicator of groundwater contamination and refers to the water amount required to dilute pollutants from N fertilizer application during crop production (Hoekstra *et al.* 2011; Zhang Y *et al.* 2020). Previous studies have demonstrated that crop production systems in tropical/subtropical regions of China exhibit higher gray water footprints compared to temperate regions (Zhang Y *et al.* 2020; Yao *et al.* 2021). Therefore, optimizing N fertilizer management to reduce N leaching losses and gray water footprints in tropical and subtropical vegetable systems is more urgent.

Effective N management requires mechanistic understanding of plant–soil N pathways to balance agricultural productivity and water protection (Sainju 2017; Yin *et al.* 2021; Luo *et al.* 2023). Nitrogen balance analysis serves as a critical tool for assessing fertilizer application efficiency, enabling systematic quantification of N inputs and outputs, crop uptake efficiency, and soil N accumulation and loss patterns, thereby providing a scientific basis for developing effective mitigation strategies (Min *et al.* 2011; Zhou *et al.* 2016; Sainju 2017). Previous N balance studies across diverse tropical/subtropical agricultural systems, such as cereal (Zhou *et al.* 2016), citrus (Luo *et al.* 2023), sugarcane (Yang *et al.* 2024), and greenhouse vegetable (Min *et al.* 2011) production systems, have consistently established leaching as the predominant N loss pathway, representing 54−86% of N losses and corresponding to 18−44% of fertilizer-N inputs. Unlike greenhouse vegetable production systems, open-field vegetable systems are directly exposed to natural environments, making their soil N dynamics more susceptible to climatic factors such as rainfall and temperature variations (Wang *et al.* 2018). However, systematic investigations into N budgets in tropical/subtropical open-field vegetable production systems remain scarce. Additionally, most existing studies on N leaching have focused on single growing seasons (Zhang *et al.* 2017), and comprehensive evaluations of N leaching dynamics in open-field vegetable production systems are limited.

Implementing knowledge-based N management practices to meet crop N needs is essential for boosting vegetable yields while reducing N leaching (Xia *et al.* 2017; Zhang F *et al.* 2022). Methods such as soil test of residual N_{min} and N-Expert fertilization strategies align fertilizer application with soil nutrient supply and crop requirements, thereby enhancing fertilizer use efficiency and minimizing losses (Tei *et al.* 2020; Zhang *et al.* 2021; Zhang J *et al.* 2022). In recent years, enhanced-efficiency fertilizers (EEFs), such as controlled-release N fertilizers and stabilized N fertilizers containing nitrification inhibitors (NIs), have also emerged as effective strategies for increasing vegetable yields while reducing N losses (Souza *et al.* 2021; Pan *et al.* 2024; You *et al.* 2024). A meta-analysis found that compared to conventional urea, nitrification inhibitors (NIs) and polymer-coated urea (PCU) reduced NO_3^- leaching losses by 31 and 29%, respectively (Pan *et al.* 2024). Additionally, combining organic and inorganic fertilizers has further benefits, such as improving soil structure, water retention, and nutrient availability (Li *et al.* 2024; Wang J *et al.* 2024). Zhou *et al.* (2019) reported that combining organic and inorganic fertilizers reduced N leaching by 34−45% compared to inorganic fertilizers alone. However, some studies suggest that organic fertilizers may increase leaching of dissolved organic N (DON), which is often overlooked in high-fertilizer-input intensive vegetable production systems (Fan *et al.* 2024; Wang and Li 2024). Furthermore, existing studies typically focus on the effects of individual management practices on N leaching (Yao *et al.* 2021), while often fail to address the persistent high levels of N leaching in vegetable systems. Integrated approaches that combine optimized N rates with EEFs represent a more comprehensive approach to mitigating N leaching (Zhang *et al.* 2017).

Southwest China is a prominent vegetable-producing region with open-field farming accounts for 92% of the cultivation area (MARA 2015). The region features a typical subtropical climate with warm temperatures and abundant but unevenly distributed rainfall. Therefore, this study aims to investigate and mitigate N leaching throughout the year in subtropical regions, using a typical open-field vegetable rotation system in Southwest China as a case study. We addressed the following questions: (1) What are the characteristics of N leaching in typical open-field vegetable systems in Southwest China over the course of a rotation year? (2) Can integrative fertilizer N management effectively reduce N leaching in these systems? This study is expected to provide a reliable scientific basis for intensive vegetable production systems in tropical and subtropical regions to improve N use efficiency (NUE), sustain high vegetable yields, and minimize environmental pollution.

2. Materials and methods

2.1. Experimental site

We conducted two plot-based field experiments at the Hechuan Base of Southwest University (30°0´N, 106°7´E), in Chongqing, China, as part of a long-term study initiated in 2018. The region featured a subtropical rain-fed cropping system with a typical rotation of Chinese cabbage (*Brassica rapa* L. var. pekinensis) and pepper (*Capsicum annuum* L.). Chinese cabbage was grown from October to January of the following year, while pepper was grown from April to

September. The experiments spanned two rotation cycles from 2020 to 2022. During this period, the average seasonal temperature was 12°C for Chinese cabbage and 27°C for pepper, with corresponding precipitation levels of 137 and 518 mm, respectively (Appendix A). Initial soil (0–20 cm) properties were 0.50 g kg^{-1} total Kjeldahl N, 2.06 mg kg^{-1} NH_4^+ (extracted by $CaCl_2$), 4.89 mg kg^{-1} NO_3^- (extracted by $CaCl_2$), 5.34 g C kg^{-1} SOC, and a pH (H_2O) of 5.7.

2.2. Experimental design and field management

Experiment 1 (Exp 1) consisted of five treatments: 1) CK: no N application; 2) OPT-CU: optimal N rate; 3) OPT*70%: 70% of the optimal N rate; 4) OPT*130%: 130% of the optimal N rate; and 5) FNP: farmers' N fertilizer practice, based on a survey of 366 vegetable farmers in Southwest China. Conventional urea was used in all treatments. The optimal N rates for both crops were calculated using a root-zone N management strategy by subtracting the mineral N content in the soil (0–20 cm) from the calculated crop N requirement based on target yields (Zhang *et al.* 2012, 2023; Chen and Lu 2015). These target values were derived from literature analyses and expert recommendations, corresponding to yield targets of 120 t ha^{-1} for Chinese cabbage and 35 t ha^{-1} for pepper (Zhang *et al.* 2009; Chen and Lu 2015). Furthermore, fertilizer application timing was determined based on N uptake patterns for each crop (Zhang *et al.* 2009; Chen and Lu 2015). The specific N rates for the OPT*70%, OPT-CU, OPT*130%, and FNP treatments were 175, 250, 325, and 450 kg N ha^{-1} in the Chinese cabbage season, and 175, 250, 325, and 400 kg N ha^{-1} in the pepper season, respectively (Appendices B and C).

Experiment 2 (Exp 2) consisted of five treatments including a non-fertilized control (CK, 0 kg N ha^{-1}), and four fertilizer sources, each applied at the optimal N rate of 250 kg N ha^{-1} for both the Chinese cabbage and pepper seasons. The four sources included: 1) conventional urea (CU); 2) a combination of conventional urea and commercial food waste-derived organic fertilizer (manufactured by Sichuan Goldenway Biotech Co., Ltd., with C, N, P_2O_5 and K_2O contents of 46%, 1.69%, 0.65% and 0.46%) at a 7:3 ratio (OIF); 3) nitrification inhibitor-based EEF (ENTEC®26, 18.5% NH_4^+-N and 7.5% NO_3^--N with 0.15% DMPP; BASF, Ludwigshafen, Germany) (NI); and 4) a combination of conventional urea and polymer-coated urea (45% N, with a nutrient release cycle of 90 days; MOITH New Fertilizer Co., Ltd., Anhui, China) at a 3:7 ratio (CRU).

Phosphorus and potassium fertilizers were applied as superphosphate and potassium sulfate in both experiments, with the specific rates for each treatment and growing stage outlined in Appendices B and C. For the OPT-OIF treatment in Exp 2, organic fertilizers were spread on the surface and incorporated into soil at approximately 15 cm before transplanting. Other fertilizers were applied in 10–15 cm deep holes near the crops and covered with soil.

Treatment plots, measuring 5.6 m×8.3 m each, were set up in a randomized complete block design with four replicates. The Chinese cabbage variety used was Fengkang 70, and the pepper variety was Xinxiang 8. Seedlings of Chinese cabbage and pepper were first raised in a nursery medium and then transplanted into the field. The row spacing was 0.4 m for Chinese cabbage and 0.6 m for pepper, with a within-row plant spacing of 0.4 m for both crops. The experimental site is a rain-fed field, receiving only minimal irrigation during transplanting. However, due to drought conditions in the summer of 2022, supplemental irrigation of 15–20 mm per week (totaling 120 mm) was provided during July and August to support pepper growth. Field management practices such as weed management and disease control followed local standards for high-yielding vegetable systems.

2.3. Sampling and laboratory analysis

Vegetable yield and N uptake During harvest, the vegetable marketable yields were determined for pepper based on fresh weigh of 24 pepper plants or for Chinese cabbage based on that of the above-ground leaves of 18 plants in the center row of each plot. Additionally, four representative plants from each plot were selected for further nutrient analysis. Pepper plants were segmented into roots, stems, leaves, and fruits, while Chinese cabbage plants were separated into roots and above-ground parts. After washing, the samples were oven-dried at 75°C until reaching a constant weight, then ground into powder for total N concentration analysis using the Kjeldahl method. The total N uptake for each crop was determined by multiplying the dry matter weight of each plant part by its corresponding N concentration, summing these values, and then extrapolating the results to estimate the N uptake per hectare.

Lysimeters and leachates *In-situ* lysimeters were installed at 60 cm depth of subsoil in each plot one year before the experiment to ensure proper integration with the soil. Each installation consisted of a lysimeter pan and a leachate collection system (Appendix D). During installing, the soil from each 20 cm soil layer was removed separately and backfilled at the same depth to maintain the original stratification. The lysimeter pan (120 cm long, 40 cm wide, and 10 cm high) was open at the top and covered with two layers of fine nylon mesh, followed by a 5 cm of fine quartz sand (1–2 mm) and then a 5 cm of coarse quartz sand (3–5 mm) at the bottom. Leachate was usually collected after cumulative rainfall reached 80 mm. At each sampling, the leachate in the collection container was pumped using a lifting pipeline and vacuum pump. The volume of each sample was measured, and a 100 mL sample of leachate was then collected and stored at −20°C for further analysis. The total N, NO_3^-, and NH_4^+ concentrations of each leachate sample were then determined using an AA3 continuous flow analyzer. DON was calculated by subtracting NO_3^-, and NH_4^+ from total N. The area-scaled seasonal N leaching was calculated based on the volume and N concentration of each leachate during the vegetable growing period.

The area-scaled seasonal N leaching factor (SNLF) was calculated as follows:

$$SNLF=(NL_N-NL_{CK})/N\times100\%$$

where NL_N and NL_{CK} are the seasonal N leaching (kg N ha^{-1}) from N addition treatments and control, respectively; N is the N fertilizer application rate (kg N ha^{-1}).

Area-scaled annual N leaching loss (ANL) was calculated as the sum of the N leaching from each growing season and the fallow period over the crop rotation cycle.

The gray water footprint per unit yield (GWFp, m^3 Mg^{-1}) quantifies N leaching relative to vegetable marketable yield (Zhang Y *et al.* 2020), calculated as:

$GWF_p=L/(C_{max}-C_{nat})/Y$

where L is the total NO_3^- leaching (kg N ha^{-1}); C_{max} is the maximum allowable NO_3^- concentration in ambient water (11.3 mg N L^{-1}, as per the *Guideline for Drinking-Water Quality* (WHO 2011); C_{nat} is the natural concentration of NO_3^- in the water body (2 mg N L^{-1}, based on China's Quality Standards for Ground Water) (GB/T 14848-2017 2017); and Y represents vegetable marketable yield (Mg ha^{-1}).

Soil N_{min} concentrations Soil samples were collected from the 0–60 cm depth, and subdivided into 0–20, 20–40, and 40–60 cm layers before transplanting and after harvesting vegetables during each vegetable season. Fresh soil sample was sieved to pass a 5 mm sieve and then extracted with a 0.01 mol L^{-1} $CaCl_2$ solution. The concentrations of NH_4^+ and NO_3^- in the extracts were then determined using an AA3 continuous flow analyzer.

N budget The N balance was calculated as the difference between total N inputs and outputs. Inputs included fertilizer application, atmospheric deposition, irrigation, substrate, and non-symbiotic N_2 fixation. Outputs accounted for crop N uptake, N leaching, NH_3 volatilization, and emissions of N_2O, NO, and N_2. Atmospheric deposition was based on Liu *et al.* (2024). Substrate-derived N referred to the N contained in the growth medium attached to the roots of Chinese cabbage and pepper seedlings at transplantation (Zhang *et al.* 2017). For these non-leguminous crops, N fixation was estimated at 15 kg N ha^{-1} (Liu *et al.* 2008). N input from irrigation was calculated by multiplying the total irrigation volume by the mean N concentration of the water. N_2O emissions and NH_3 volatilization were quantified by static opaque chambers and venting methods, respectively (Zhang *et al.* 2023; Zhang 2025). Although high-frequency fluxes were monitored during the growing seasons, this study focused on the seasonal cumulative losses, which were integrated into the N budget to provide a comprehensive evaluation of N dynamics. NO emissions were estimated based on Han *et al.* (2024), and N_2 emissions were calculated as 7 times the direct N_2O emissions (Butterbach-Bahl *et al.* 2011).

The apparent N surplus was defined as the difference between the total N input into the soil and the amount of N uptake by the crops during the entire rotation period (Di *et al.* 2024). It was calculated as follows:

Apparent N surplus (kg N ha^{-1})=Total N input (N from fertilizer+N from deposition+N from irrigation+N from substrate+N from non-symbiotic N_2 fixation)–Crop N uptake at harvest

Apparent NUE for the annual crop rotation was calculated as follows (Fu *et al.* 2023):

Apparent NUE=$(AN_N-AN_{CK})/N\times100\%$

where AN_N and AN_{CK} are the annual N uptake in Chinese cabbage and pepper (kg N ha^{-1}) from N addition treatments and control, respectively. N is the annual N fertilizer application rate (kg N ha^{-1}).

2.4. Statistical analysis

Statistical analyses were performed using the SPSS version 20.0 (SPSS Inc., Chicago, IL, USA). In both Experiments, the main and interactive effects of N treatment and year on vegetable yield and N leaching were evaluated using a two-way ANOVA. When significant effects were detected, Duncan's test was applied to compare treatment means. Statistical significance was set at $P<0.05$. Partial least squares path modeling (PLS-PM) was performed using the R package "plspm" to evaluate the relationships among N fertilizer management practices, seasonal precipitation, soil residual N_{min}, leachate N concentration, leachate volume, seasonal total N leaching, crop N uptake, and vegetable yield. The fitness of generated models was evaluated using the goodness-of-fit index (GOF), with higher values indicating better model performance.

3. Results

3.1. Marketable vegetable yield

In Exp 1, the marketable yields of Chinese cabbage and pepper showed no significant differences among the OPT-CU, OPT*130%, and FNP treatments. However, all three treatments resulted in significantly higher yields compared to both the CK and OPT*70% treatments (Fig. 1-A and B). Chinese cabbage yield exhibited no significant interannual variation, but pepper yield was significantly influenced by climatic conditions across years. In 2022, elevated temperatures and prolonged drought during the late growth stage of pepper reduced marketable pepper yield by 22% relative to the 2021 growing season (Appendix E).

In Exp 2, compared to the OPT-CU treatment, the OPT-OIF and OPT-CRU treatments significantly increased the marketable yield of Chinese cabbage by 11 and 10%, respectively, while the OPT-NI treatment resulted in a numerical increase of 2% (Fig. 1-C). For pepper, compared to the OPT-CU treatment, the OPT-NI and OPT-CRU treatments increased the marketable yield by 7 and 11%, respectively. Additionally, there was no significant difference in the marketable pepper yield between OPT-OIF and OPT-CU treatments (Fig. 1-D).

3.2. Characteristics of N leaching

Dynamics of NH_4^+, NO_3^-, and DON concentrations in the leachate Overall, NH_4^+, NO_3^-, and DON concentrations in leachate fluctuated with time from 2020 to 2022, ranging from 0.02–2.34, 0.68–70.0, and 0.04–9.41 mg N L^{-1}, respectively (Fig. 2). In Exp 1, the mean concentrations of NH_4^+, NO_3^-, and DON in leachate in the FNP treatment were 0.78, 42.9, and 5.88 mg N L^{-1}, respectively, significantly higher than those in the other treatments (Fig. 2; Appendix F).

In Exp 2, the mean concentrations of NH_4^+ and NO_3^- in leachate from the OPT-CU treatment were 13–127% higher than those from the OPT-OIF, OPT-NI, and OPT-CRU treatments. In contrast, the concentration of DON in leachate from the OPT-OIF treatment was 25–165% higher than in the OPT-CU, OPT-NI, and OPT-CRU treatments (Fig. 2; Appendix F).

Total N leaching for a rotation cycle In Exp 1, total N

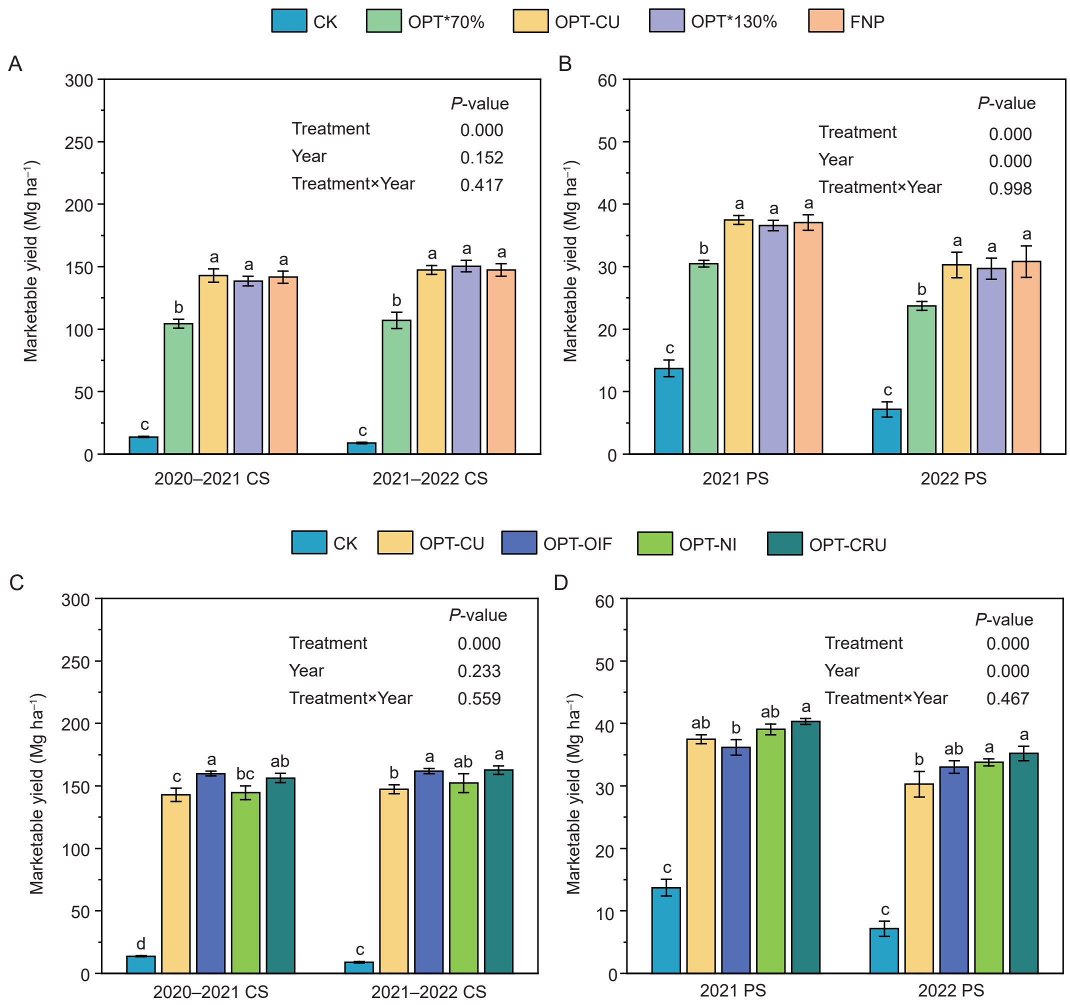

Fig. 1 Marketable yield of Chinese cabbage (A and C) and pepper (B and D) under different N fertilizer treatments during 2020–2022. A and B, different N rate treatments; C and D, different N source treatments. CS, Chinese cabbage season; PS, pepper season; CK, no N; OPT*70%, 70% of optimal N rate; OPT-CU, optimal N rate; OPT*130%, 130% of optimal N rate; FNP, farmers' N fertilizer practice; OPT-OIF, optimal N rate (30% organic fertilizer and 70% conventional urea); OPT-NI, optimal N rate (ENTEC®26); OPT-CRU, optimal N rate (70% controlled-release urea and 30% conventional urea). Statistical differences among treatments within the same year are indicated by different lowercase letters (P<0.05). Error bars represent mean±SE (n=4).

leaching was significantly affected by treatment and year, and their interactions (Fig. 3; Appendix G). The mean total N leaching across the 2-year rotation cycle in FNP treatment was 251 kg N ha^{-1} yr^{-1}, with the pepper season, Chinese cabbage season, and fallow period contributing 55, 31, and 14% of the total, respectively (Fig. 3). Compared to FNP, the OPT-CU treatment significantly reduced total N leaching by 68% over the rotation year, 65% during the pepper season, and 74% during the Chinese cabbage season (Fig. 3-A and B). Total N leaching was lower in the second rotation year due to high temperatures and drought during the 2022 pepper season (Fig. 3; Appendix G).

In Exp 2, compared to conventional urea, a combined use of organic fertilizer with urea, or use of polymer-coated urea significantly reduced N leaching by 18–28% in the pepper season, and by 25–46% in the Chinese cabbage season, resulting in an overall reduction of N leaching by 23–30% across the rotation cycle (Fig. 3-C and D). More evident reduction was observed in the nitrification inhibitor treatment, where N leaching was reduced by 53–57, 40–57, and 51–56% for the pepper season, Chinese cabbage season, and overall rotation cycle, respectively (Fig. 3-C and D).

Leaching losses of NH_4^+, NO_3^-, and DON During both the Chinese cabbage and pepper growing seasons across the two experiments, NO_3^- was the dominant form of N leaching, accounting for 74–93% of the total, followed by DON (4.6–22%) and NH_4^+ (0.4–14%) (Fig. 4). In Exp 1, the maximum total N leaching was observed in the FNP treatment, being 77 kg N ha^{-1} in Chinese cabbage season and 138 kg N ha^{-1} in pepper season, respectively (Fig. 4-A). Compared with the FNP, the OPT-CU treatment significantly reduced NO_3^- and DON leaching by 75 and 78% during the Chinese cabbage season, and by 65 and 63% during the pepper season, without significantly affecting NH_4^+ leaching (Fig. 4-A).

In Exp 2, the OPT-OIF, OPT-NI, and OPT-CRU treatments significantly reduced NO_3^- leaching by 47, 52, and 28% during the Chinese cabbage season, and by 28, 56, and 26% in the pepper season, respectively, compared to the OPT-CU treatment (Fig. 4-B). However, DON leaching was 35% to 2-fold higher in the OPT-OIF treatment than in the other

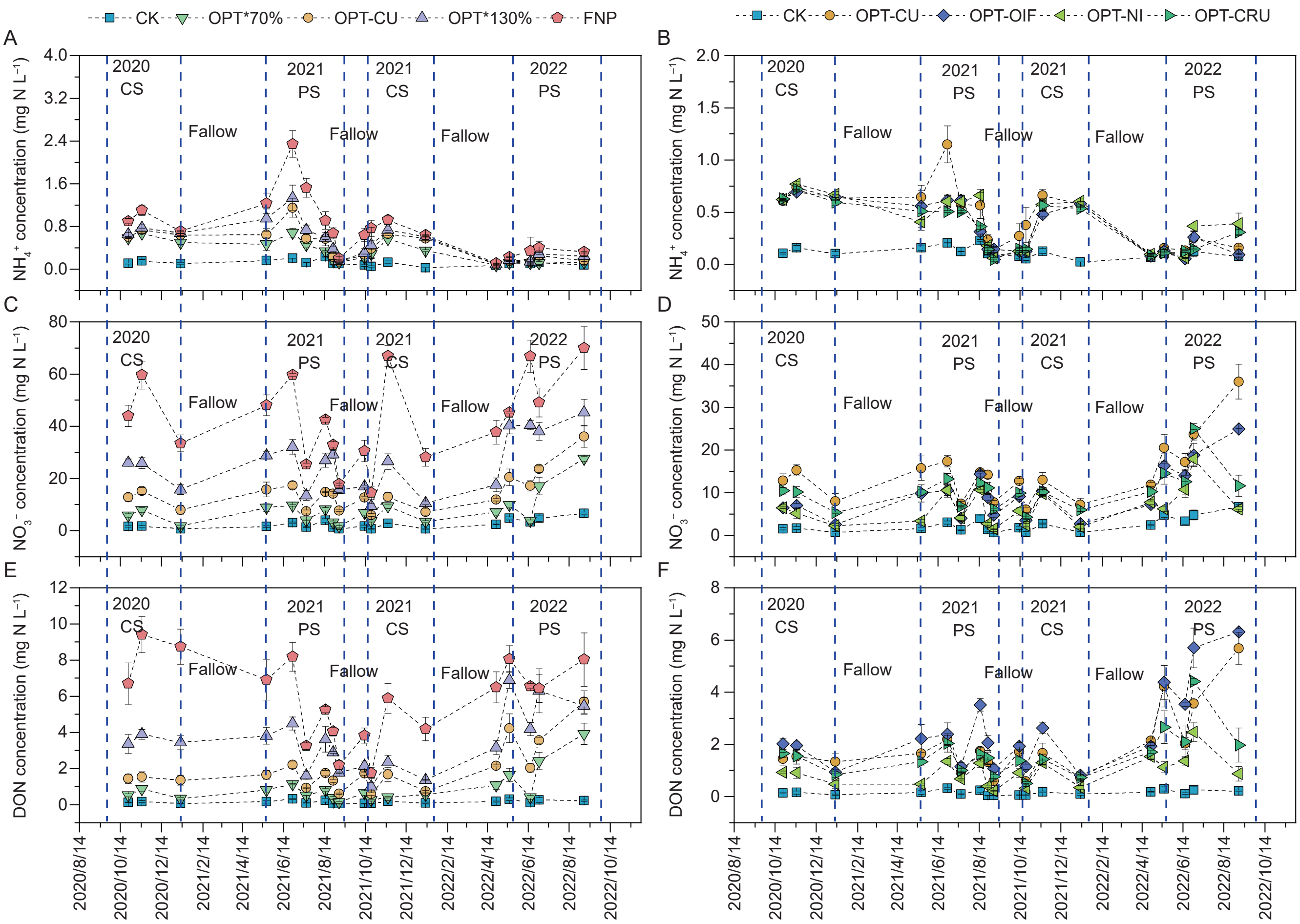

Fig. 2 Concentrations of NH_4^+ (A and B), NO_3^- (C and D), and dissolved organic N (DON, E and F) in leachate under different N fertilizer treatments during 2020–2022. CS, Chinese cabbage season; PS, pepper season; CK, no N; OPT*70%, 70% of optimal N rate; OPT-CU, optimal N rate; OPT*130%, 130% of optimal N rate; FNP, farmers' N fertilizer practice; OPT-OIF, optimal N rate (30% organic fertilizer and 70% conventional urea); OPT-NI, optimal N rate (ENTEC®26); OPT-CRU, optimal N rate (70% controlled-release urea and 30% conventional urea). Error bars represent ±SE (*n*=4).

treatments, and there was no significant difference in NH_4^+ leaching among the N fertilized treatments (Fig. 4-B).

Seasonal N leaching factors In Exp 1, N leaching factor was significantly affected by treatment and year, but not by their interactions. N leaching factor increased with increasing N fertilizer application in both Chinese cabbage and pepper seasons (Fig. 5-A and B). In both seasons, the FNP treatment had the highest N leaching factors, being 17% during the Chinese cabbage season and 32% during the pepper season, respectively. Compared to the FNP, the OPT-CU significantly reduced N leaching factor by 58% during the Chinese cabbage season and 51% during the pepper season, respectively (Fig. 5-A and B). Significant interannual variations in N leaching factor were observed, with 2020 Chinese cabbage and 2021 pepper seasons showing 23 and 12% increases over 2021 Chinese cabbage and 2022 pepper growing seasons, respectively (Appendix E).

In Exp 2, the OPT-OIF, OPT-NI, and OPT-CRU treatments further significantly decreased N leaching factor by 44, 57, and 30% during the Chinese cabbage season, and by 25, 66, and 30% during the pepper season, respectively, compared to the OPT-CU treatment (Fig. 5-C and D).

Gray water footprint In Exp 1, the gray water footprint during both Chinese cabbage and pepper seasons increased with higher N fertilizer application rates (Fig. 6-A and B). The FNP treatment had the highest gray water footprint of 49 m^3 Mg^{-1} in the Chinese cabbage and 375 m^3 Mg^{-1} in the pepper seasons, respectively. The OPT-CU treatment substantially reduced the gray water footprint by 75% during the Chinese cabbage season and 66% during the pepper season (Fig. 6-A and B).

In Exp 2, the OPT-OIF, OPT-NI, and OPT-CRU treatments further reduced gray water footprints compared to OPT-CU treatment, with decreases of 53, 55, 35% during the Chinese cabbage season, and 28, 58, 32% during the pepper season, respectively (Fig. 6-C and D). It was noted that the OPT-NI treatment had the lowest gray water footprint, especially in the pepper season.

3.3. Residual soil NH_4^+ and NO_3^-

In Exp 1, soil residual NH_4^+ and NO_3^- concentrations increased with higher N fertilizer rates, but decreased with increasing soil depth (Fig. 7-A and C). The FNP treatments had the highest NO_3^- concentrations at harvest across all crop

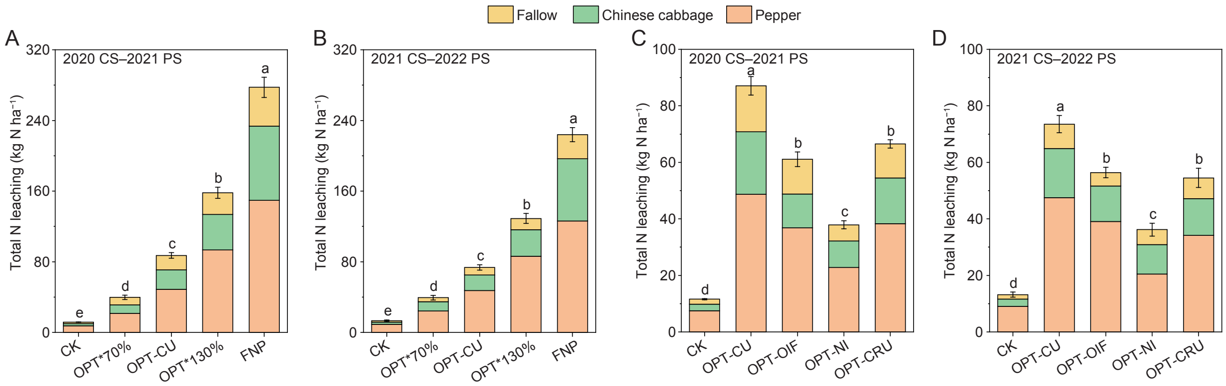

Fig. 3 Total N leaching during Chinese cabbage season, pepper season, and fallow period in 2020–2021 (A and C) and 2021–2022 (B and D) rotations for different N fertilizer treatments. CS, Chinese cabbage season; PS, pepper season; CK, no N; OPT*70%, 70% of optimal N rate; OPT-CU, optimal N rate; OPT*130%, 130% of optimal N rate; FNP, farmers' N fertilizer practice; OPT-OIF, optimal N rate (30% organic fertilizer and 70% conventional urea); OPT-NI, optimal N rate (ENTEC®26); OPT-CRU, optimal N rate (70% controlled-release urea and 30% conventional urea). Statistical differences among treatments within the same year are indicated by different lowercase letters (P<0.05). Error bars represent mean±SE (n=4).

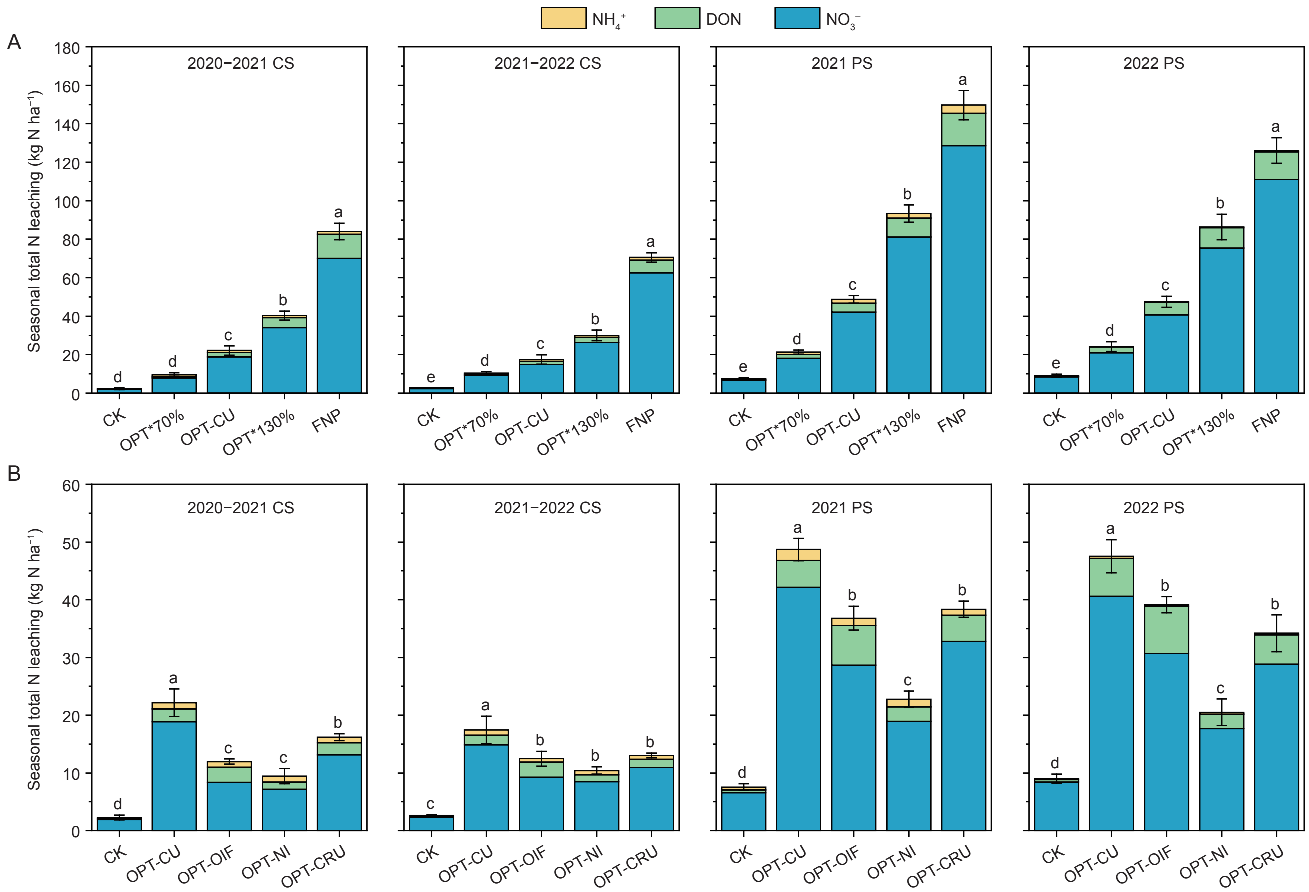

Fig. 4 Seasonal total N leaching under different N fertilizer treatments during the growing seasons of Chinese cabbage and pepper. A, N leaching of different N rate treatments; B, N leaching of different N source treatments. CS, Chinese cabbage season; PS, pepper season; CK, no N; OPT*70%, 70% of optimal N rate; OPT-CU, optimal N rate; OPT*130%, 130% of optimal N rate; FNP, farmers' N fertilizer practice; OPT-OIF, optimal N rate (30% organic fertilizer and 70% conventional urea); OPT-NI, optimal N rate (ENTEC®26); OPT-CRU, optimal N rate (70% controlled-release urea and 30% conventional urea). Statistical differences among treatments within the same year are indicated by different lowercase letters (P<0.05). Error bars represent mean±SE (n=4).

seasons and soil layers. The average NO_3^- concentrations in the 0–20, 20–40, and 40–60 cm soil layers under the FNP treatment were 23.8, 14.7, and 12.4 mg N kg^{-1}, respectively, higher than those of the OPT-CU treatment by 9.7, 3.8, and 3.2 mg N kg^{-1}, respectively (Fig. 7-A and C).

In Exp 2, during both vegetable seasons, the OPT-NI

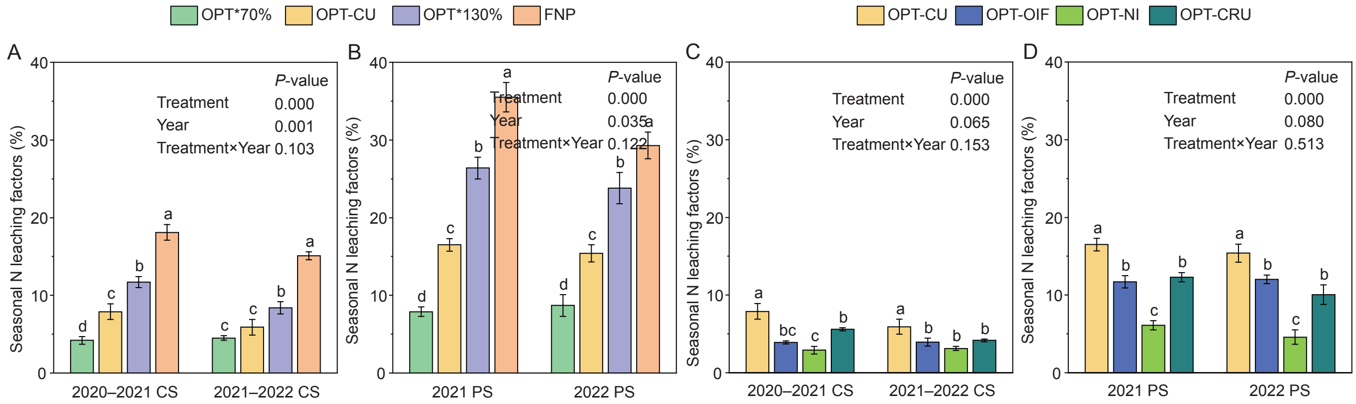

Fig. 5 Seasonal N leaching factors under different N fertilizer treatments during the growing seasons of Chinese cabbage (A and C) and pepper (B and D). CS, Chinese cabbage season; PS, pepper season; CK, no N; OPT*70%, 70% of optimal N rate; OPT-CU, optimal N rate; OPT*130%, 130% of optimal N rate; FNP, farmers' N fertilizer practice; OPT-OIF, optimal N rate (30% organic fertilizer and 70% conventional urea); OPT-NI, optimal N rate (ENTEC®26); OPT-CRU, optimal N rate (70% controlled-release urea and 30% conventional urea). Statistical differences among treatments within the same year are indicated by different lowercase letters (P<0.05). Error bars represent mean±SE (n=4).

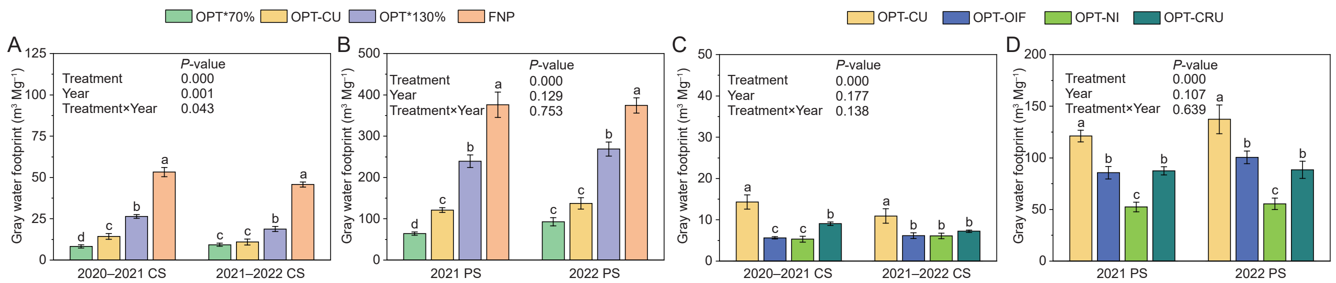

Fig. 6 Gray water footprint of different N fertilizer treatments during the growing seasons of Chinese cabbage (A and C) and pepper (B and D). A and B, gray water footprint of different N rate treatments; C and D, gray water footprint of different N source treatments. CS, Chinese cabbage season; PS, pepper season; CK, no N; OPT*70%, 70% of optimal N rate; OPT-CU, optimal N rate; OPT*130%, 130% of optimal N rate; FNP, farmers' N fertilizer practice; OPT-OIF, optimal N rate (30% organic fertilizer and 70% conventional urea); OPT-NI, optimal N rate (ENTEC®26); OPT-CRU, optimal N rate (70% controlled-release urea and 30% conventional urea). Statistical differences among treatments within the same year are indicated by different lowercase letters (P<0.05). Error bars represent mean±SE (n=4).

treatment had higher soil NH_4^+ concentrations but lower NO_3^- concentrations compared to the OPT-CU treatment, especially in the 0–20 cm soil layer (Fig. 7-B and D).

3.4. N balance

In the Chinese cabbage–pepper rotation system, N fertilizer was the major contributor to N input in the N fertilized treatments, accounting for 85–93% of the total N input (Tables 1 and 2). Other sources of N inputs included deposited N (2–5%), irrigated N (1%), substrate N (2–5%), and non-symbiotic N_2 fixation (2–4%). Plant N uptake and N leaching were the major pathways of N output, accounting for 51–85% and 8–33% of total, respectively (Tables 1 and 2).

In Exp 1, total N uptake by Chinese cabbage and pepper was comparable between the FNP (384 kg N ha^{-1}) and OPT-CU (350 kg N ha^{-1}) treatments (Table 1). The apparent N surplus in the FNP treatment was 527 kg N ha^{-1}, 1.5 times greater than the OPT-CU treatment (Table 1). In addition, the OPT-CU treatment increased the annual NUE from 35% to 54% compared to the FNP treatment. N leaching was the main pathway for N output in the FNP treatment, accounting for 33% of the N output, 68% of the N losses, and 29% of the N fertilizer input (Table 1). For other N application treatments, N leaching accounted for 51–64% of the N losses and 11–22% of the N fertilizer inputs.

In Exp 2, the OPT-OIF, OPT-NI, and OPT-CRU treatments reduced apparent N surplus by 12–17% and increased NUE by 10–13% compared to the OPT-CU treatment (Table 2).

3.5. Influencing factors

In Exp 1, for both pepper and Chinese cabbage seasons, total N leaching increased exponentially with N fertilizer rate (R^2=0.95 for both crops, P<0.01) and N surplus (R^2=0.82–0.95, P<0.01) (Fig. 8-A and B). Similarly, the gray water footprint exhibited an exponential increase with N fertilizer rate (R^2=0.91–0.94, P<0.01) (Fig. 8-C). The PLS-PM analysis indicated that the N fertilizer rate indirectly influenced seasonal total N leaching by significantly increasing soil N_{min} and leachate N concentration (Fig. 9-A). Seasonal precipitation also significantly increased both leachate volume and N concentration, collectively contributing to seasonal total N leaching. Together, these factors accounted for 89% of the observed variation in seasonal N leaching. Additionally, both N fertilizer rate and precipitation related positively with plant N uptake and vegetable yield, whereas soil residual N_{min} and seasonal N leaching losses related negatively with marketable yield (Fig. 9-A).

In Exp 2, the N fertilizer source negatively affected soil N_{min} but positively affected leachate N concentration (Fig. 9-B). Seasonal precipitation significantly and positively impacted leachate volume and leachate N concentration, ultimately driving seasonal total N leaching. These factors accounted for 86% of the variation in seasonal total N leaching. Additionally, vegetable yields were positively related to precipitation. Instead, seasonal N leaching was negatively related to plant N uptake and yield (Fig. 9-B).

4. Discussion

4.1. Leaching is the primary N loss pathway in the subtropical open-field vegetable rotation system

Our study confirmed that the subtropical open-field Chinese cabbage–pepper rotation system is characterized by excessive N fertilizer input, resulting in significant N loss and low NUE. Nitrogen fertilizer inputs in these systems substantially exceeded crop reequipments, with input values being 2.2 times crop N uptake (384 kg N ha^{-1}). This imbalance further led to substantial apparent N surplus (527 kg N ha^{-1}) and a low NUE (35%) (Table 1). This NUE is lower than other systems such as the wheat–maize rotation system (50%) in North China Plain (Zhou *et al.* 2016), and the international reference NUE (50–90%) (Oenema *et al.* 2015). Therefore, optimizing N fertilizer management in

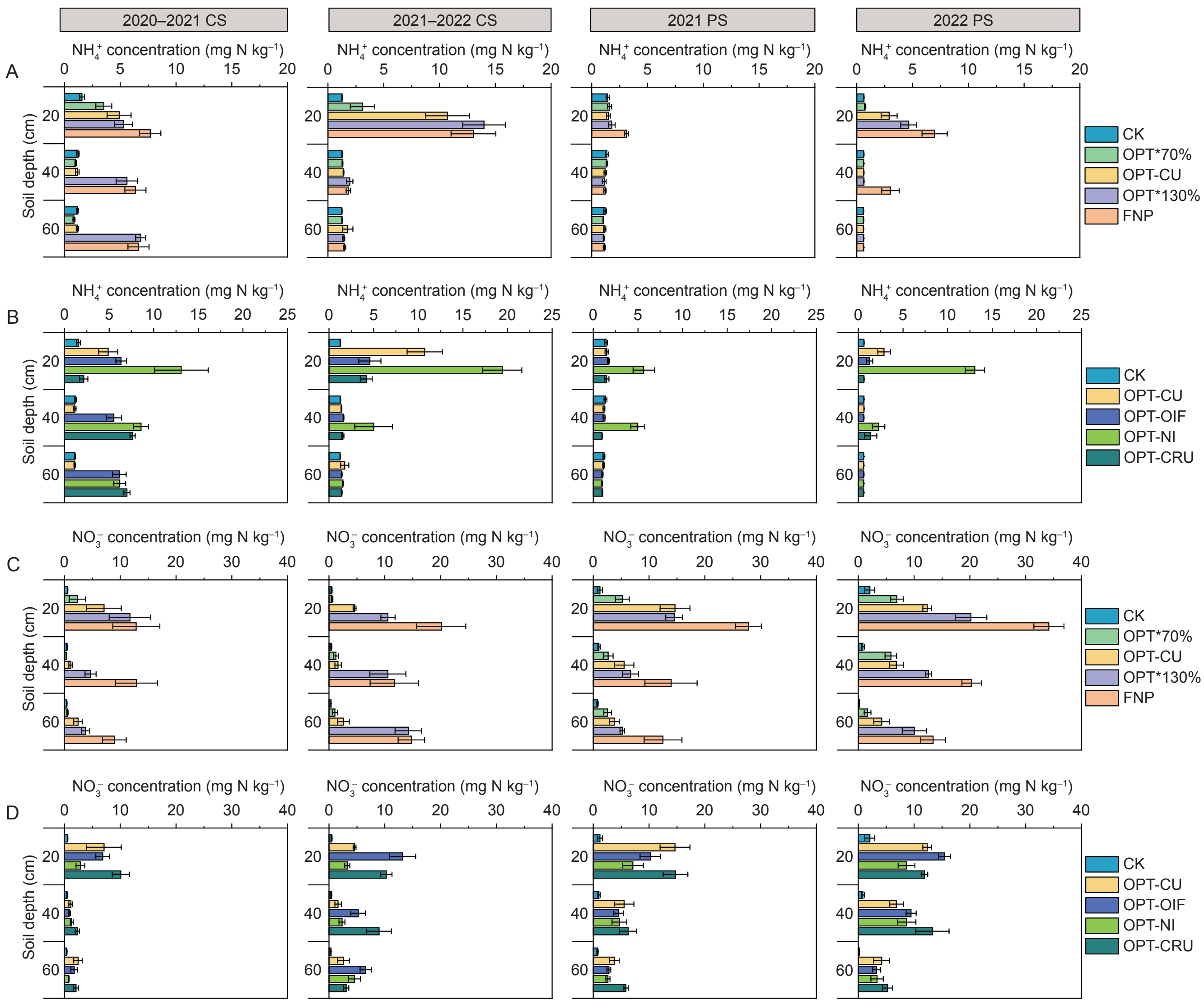

Fig. 7 NH_4^+ (A and B) and NO_3^- (C and D) concentrations in the 0–60 cm soil layer at the harvest stage of Chinese cabbage and pepper under different N fertilizer treatments during 2020–2022. A and C, NH_4^+ and NO_3^- concentrations under different N rate treatments; B and D, NH_4^+ and NO_3^- concentrations under different N source treatments. CS, Chinese cabbage season; PS, pepper season; CK, no N; OPT*70%, 70% of optimal N rate; OPT-CU, optimal N rate; OPT*130%, 130% of optimal N rate; FNP, farmers' N fertilizer practice; OPT-OIF, optimal N rate (30% organic fertilizer and 70% conventional urea); OPT-NI, optimal N rate (ENTEC®26); OPT-CRU, optimal N rate (70% controlled-release urea and 30% conventional urea). Error bars represent mean±SE (*n*=4).

Table 1 N inputs and outputs in Chinese cabbage–pepper rotation system under different N rate treatments (two-year average values)

Treatment[1)]	N input (kg N ha^{-1})					N output (kg N ha^{-1})						N balance (kg N ha^{-1})	N surplus (kg N ha^{-1})	Annual N use efficiency (%)
	Fertilizer	Atmospheric deposition	Irrigation	Substrate	N_2 fixation	Crop uptake	NH_3 volatilization	N_2O emission	NO emission	N_2 emission	N leaching			
CK	0	22	4.9	20	15	83	3.5	0.3	0.5	2.1	12	−40	−21	–
OPT*70%	350	22	4.9	20	15	238	22	1.5	3.5	10	39	97	174	44
OPT-CU	500	22	4.9	20	15	350	34	2.4	4.8	17	80	73	211	54
OPT*130%	650	22	4.9	20	15	369	49	3.3	6.1	23	144	118	343	44
FNP	850	22	4.9	20	15	384	69	4.9	7.8	34	251	161	527	35

[1)] CK, no N; OPT*70%, 70% of optimal N rate; OPT-CU, optimal N rate; OPT*130%, 130% of optimal N rate; FNP, farmers' N fertilizer practice.

Table 2 N inputs and outputs in Chinese cabbage–pepper rotation system under different N source treatments (two-year average values)

Treatment[1)]	N input (kg N ha^{-1})					N output (kg N ha^{-1})						N balance (kg N ha^{-1})	N surplus (kg N ha^{-1})	Annual N use efficiency (%)
	Fertilizer	Atmospheric deposition	Irrigation	Substrate	N_2 fixation	Crop uptake	NH_3 volatilization	N_2O emission	NO emission	N_2 emission	N leaching			
CK	0	22	4.9	20	15	83	3.5	0.3	0.5	2.1	12	−40	−21	–
OPT-CU	500	22	4.9	20	15	350	34	2.4	4.8	17	80	73	211	54
OPT-OIF	500	22	4.9	20	15	376	27	2.2	4.8	15	59	78	186	59
OPT-NI	500	22	4.9	20	15	379	16	1.1	3.6	7.9	37	117	183	59
OPT-CRU	500	22	4.9	20	15	386	17	1.6	3.6	12	60	82	176	61

[1)] CK, no N; OPT-CU, optimal N rate (conventional urea); OPT-OIF, optimal N rate (30% organic fertilizer and 70% conventional urea); OPT-NI, optimal N rate (ENTEC®26); OPT-CRU, optimal N rate (70% controlled-release urea and 30% conventional urea).

these systems to enhance N uptake, minimize N losses, and improve NUE is a critical challenge.

In this study, N leaching was the primary pathway of N loss, accounting for 68% of the annual N loss under conventional fertilizer practices (Table 1). Annual N leaching in subtropical open-field vegetable systems averaged 251 kg N ha^{-1}. This value is comparable to leaching rates observed in subtropical greenhouse vegetable systems with high irrigation and N inputs (Min *et al.* 2012), and aligns with findings from other open-field vegetable systems in central subtropical China under similar conditions of high rainfall and fertilization (Cui 2012). In contrast, this value significantly exceeds N leaching from the subtropical wheat–maize rotation systems (Zhou *et al.* 2016), citrus orchard systems (Luo *et al.* 2023), and temperate vegetable systems (Fan *et al.* 2024; Sun *et al.* 2024). These results confirm that subtropical open-field vegetable systems are hotspots for N leaching. The elevated N leaching levels were primarily driven by the synergistic effects of heavy rainfall events, excessive N inputs, shallow rooting systems characteristic of vegetable crops, and the region's highly permeable soils (Zhang *et al.* 2017; Yao *et al.* 2021). In addition, we observed significant seasonal variations in N leaching throughout the year, with the highest leaching occurred during the high-temperature and heavy rainfall pepper season, accounting for 54–69% of the annual leaching (Fig. 3). The N leaching factor under the FNP treatment reached 32% in the pepper season, which was 1.9 times higher than both the concurrent Chinese cabbage season (17%) and global vegetable system averages (17%) (Wang *et al.* 2025). This highlights the pepper season is a critical period for controlling N leaching. Sufficient water availability during the pepper season resulted in saturated water conditions in the soil profile, which could have facilitated NO_3^- movement to deeper layers (Zhang *et al.* 2017).

The study also confirmed that NO_3^- was the predominant form of N leaching, accounting for 74–93% of the total, while NH_4^+ contributed minor fractions (Fig. 4). Due to the strong nitrification capacity of subtropical vegetable field soils, NH_4^+ is rapidly converted to NO_3^-, which is highly mobile due to its negative charge and low soil adsorption. This makes NO_3^- susceptible to leaching under rainfall or irrigation, resulting in elevated NO_3^- concentrations in groundwater (Lu *et al.* 2018; Wang *et al.* 2019; Elrys *et al.* 2023). In contrast, NH_4^+ leaching remained stable owing to its stronger adsorption and limited mobility, rendering it less responsive to reduced fertilizer inputs. These findings indicate that mitigating N leaching in such systems depends primarily on controlling nitrification and the fate of NO_3^-. Notably, the average NO_3^- concentration in the leachate from conventional N application reached 43 mg N L^{-1}, exceeding the World Health Organization's drinking water threshold (10 mg N L^{-1}) (WHO 2011), posing health risks to local residents. Therefore, effective measures are urgently needed to mitigate N loss, particularly NO_3^- leaching, from subtropical open-field vegetable systems to ensure public health.

4.2. Optimization of N fertilizer management could reduce N leaching and gray water footprint while improving NUE

Optimizing rate and timing of N fertilizer application based

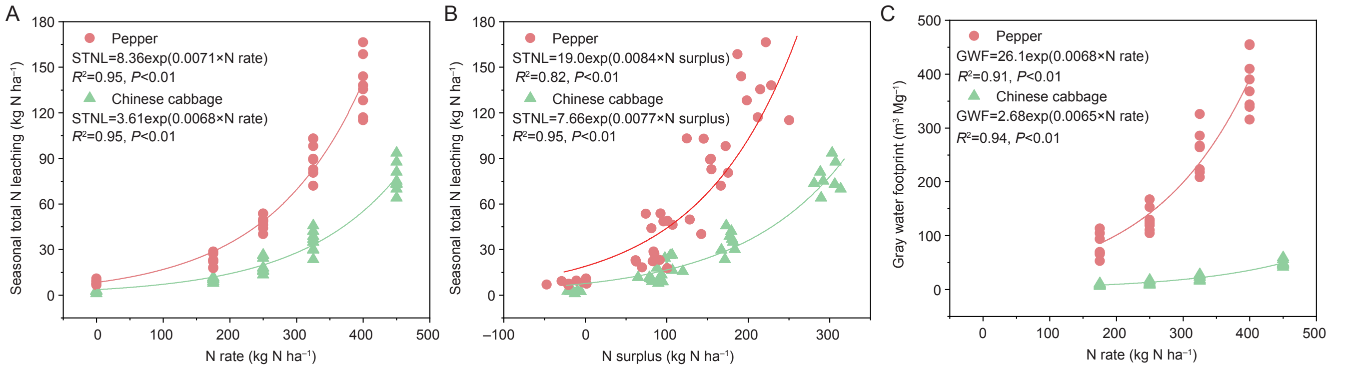

Fig. 8 Seasonal total N leaching in response to N fertilizer rate (A) and N surplus (B), and gray water footprint in response to N fertilizer rate (C) during the growing seasons of Chinese cabbage and pepper. STNL, seasonal total N leaching; GWF, gray water footprint.

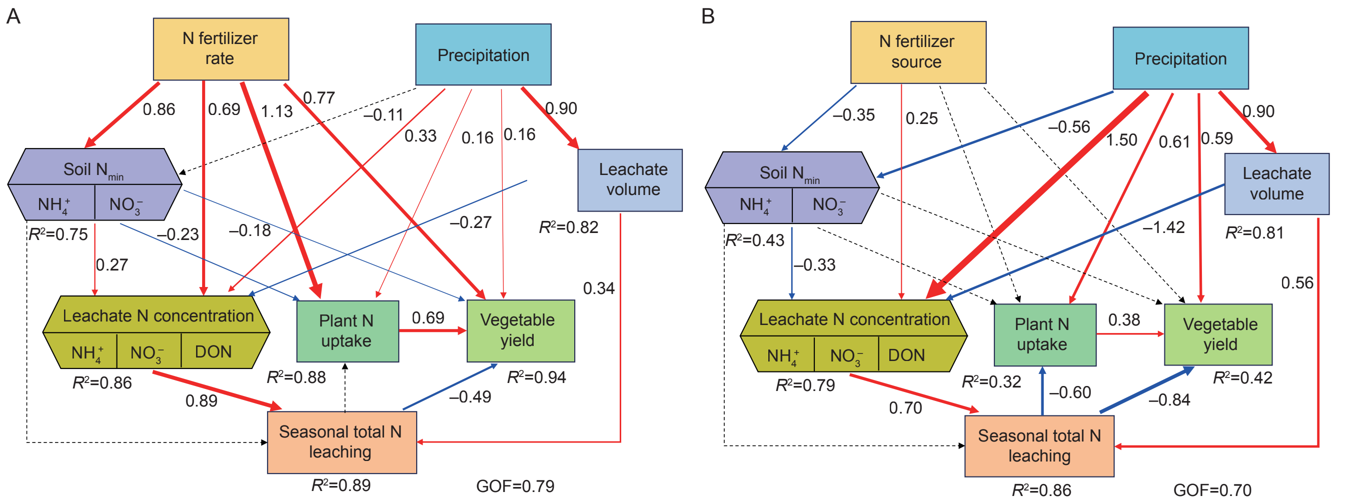

Fig. 9 Partial least squares path modelling for Experiment 1 (A) and Experiment 2 (B). N_{min}, mineral N; DON, dissolved organic N; GOF, goodness-of-fit index. The numbers beside the arrows indicate the standardized path coefficients, and the width of the arrows reflects the coefficient strength. Solid red and blue arrows indicate significant positive and negative effects (P<0.05), respectively, while black dashed arrows denote non-significant paths (P>0.05).

on crop growth characteristics and N demand patterns is an effective strategy to reduce N leaching in vegetable systems (Wang *et al.* 2019; Tei *et al.* 2020; Zhou *et al.* 2022; Wen *et al.* 2024). Total N leaching and gray water footprint increased exponentially with higher N fertilizer application rates during both the pepper and Chinese cabbage seasons (Fig. 8), consistent with previous findings (Chen *et al.* 2014; Qasim *et al.* 2021; Yao *et al.* 2021; Zhang *et al.* 2021). These results demonstrate that the potential risk of N leaching to aquatic systems escalates rapidly under high N application rates (Yao *et al.* 2021). The OPT-CU treatment significantly reduced total N leaching by 62–75% compared to the FNP treatment (Fig. 3). Such a substantial reduction can be attributed to several factors. First, compared to the FNP treatment, the OPT-CU treatment optimized the total N fertilizer rate and the timing of N fertilizer application based on the target vegetable yield and N requirements. For example, during the pepper season, farmers typically apply 70% of the total N fertilizer as a basal fertilizer. However, the low N demand in the seedling stage resulted in high soil N availability, which combined with high rainfall during this period and led to significant N leaching, accounting for 35% of the total seasonal N leaching (Appendix H). The OPT-CU treatment substantially lowered N fertilizer rates used as basal fertilizer and thus reduced both the absolute leaching and the percentage from the seedling stage to the overall leaching loss (Appendix C). Second, N fertilizer in the OPT-CU treatment was split-applied as two applications at the mid- and full-fruiting stages, ensuring sufficient N supply throughout the growth period of peppers. By reducing the overall N input and splitting applications, the OPT-CU treatment limited the accumulation of NH_4^+ substrate available for nitrification during high-risk periods, thereby curtailing the subsequent generation and leaching of NO_3^-. The retained N pool aligned N fertilizer supply with crop N requirement at various growth stages, thereby reducing N leaching, enhancing NUE, and sustaining vegetable yields. The gray water footprint serves as a comprehensive indicator that reflects both N leaching levels and crop production efficiency (Hoekstra *et al.* 2011; Zhang Y *et al.* 2020). Notably, the optimized N fertilization achieved a 66–75%

reduction in gray water footprint for vegetable production in this region (Fig. 6), surpassing the 56% national average reduction (Zhang Y *et al.* 2020). This underscores the critical importance of tailored N management in mitigating N leaching losses and enhancing water security for subtropical vegetable systems.

Previous studies have shown that optimizing N fertilizer source can further reduce N leaching and improve crop yield (Bai *et al.* 2020; Min *et al.* 2021; Hina 2024; Pan *et al.* 2024). In this study, combined application of organic and inorganic fertilizers, use of stable N fertilizers containing nitrification inhibitors, and application of controlled-release urea further reduced N leaching and gray water footprints while improving NUE and vegetable yield, compared to application of conventional urea at the same optimal N fertilizer rate. However, the three strategies demonstrated varying effectiveness in reducing N leaching. Use of CRU significantly reduced seasonal N leaching losses by 21–28% compared to conventional urea (Fig. 4), consistent with previous findings (Pan *et al.* 2024). The N release rate of CRU depends on soil moisture and temperature (Yang *et al.* 2021). Compared to conventional urea, the slow release of N from CRU could promote effective N uptake by crops, improve NUE, and reduce N accumulation in the soil, slowing nitrification process (Kanter and Searchinger 2018).

The mixed application of organic and inorganic fertilizers significantly reduced seasonal NO_3^- leaching by 24–56% compared to conventional urea (Fig. 4), which is in agreement with previous findings from greenhouse vegetable systems (Quan *et al.* 2015; Wang S *et al.* 2024). Gradual decomposition of organic fertilizers can provide continuous N supply to the crop while improving soil structure and its ability to retain water and nutrients (Wei *et al.* 2021; Li *et al.* 2024). However, the same practice led to a 16–54% increase in seasonal DON leaching. This rise may be associated with the input of soluble organic compounds derived from organic fertilizer, which can elevate the pool of leachable organic N (Quan *et al.* 2015). The increased DON losses highlight a potential environmental trade-off, as DON can contribute to groundwater contamination and serve as a precursor for harmful disinfection by-products during drinking water treatment (Hao *et al.* 2024). Therefore, while mixed fertilization offers clear benefits in reducing NO_3^- leaching, strategies to mitigate concomitant DON losses should be considered in future nutrient management plans.

Use of NIs was most effective and significantly reduced seasonal N leaching by 40–57% and gray water footprint by 55–58% compared to conventional urea (Fig. 4). NIs inhibit the activity of ammonia monooxygenase, slowing nitrification rate and reducing soil NO_3^- availability, which further reduces NO_3^- leaching (Kanter and Searchinger 2018; Souza *et al.* 2021). Although NIs could lead to enhanced NH_4^+ availability in the soil, NH_4^+ binds to the negative charge on the soil surface and is less likely to move through the soil layer and will be retained more in the soil (Zhang C *et al.* 2022). Therefore, the implementation of an integrated 4R strategy, by use of NIs with the optimized application rate and timing of N fertilizer can better meet crop N demand, improve vegetable yield and NUE, while reducing N leaching loss and gray water footprint. This approach is essential for sustainable vegetable production in subtropical regions.

4.3. Implications for N fertilization management in vegetable systems

Achieving high crop yields and high NUE while reducing environmental pollution is one of the core challenges for intensive agriculture worldwide (Foley *et al.* 2011; Zhang *et al.* 2015). Sustainable N fertilization management is essential for achieving sustainable agriculture and ensuring food security (Zhang F *et al.* 2022; Zhang *et al.* 2024). In this study, we proposed an integrative N fertilization management based on the 4R principles to provide fundamental insights into sustainable vegetable production. First, to address the common issues of N fertilizer over-application or inappropriate timing in traditional practices in the region, we recommend optimizing N fertilizer rates based on crop demand. This includes adjusting the ratio of basal fertilizer to top-dressing fertilizer and avoiding excessive N inputs during the early growth stages when crop demand is relatively low. Second, given the high rainfall in this region, we recommend using nitrification inhibitors, controlled-release urea, or a combination of organic and inorganic fertilizers. These integrated management practices enhanced NUE and vegetable yields while reducing N leaching, N_2O emissions and NH_3 volatilization (Table 2). This study serves as a valuable reference for the development of efficient, sustainable, and environmentally friendly vegetable production systems in subtropical regions.

Furthermore, diversifying crop rotations may further enhance NUE and reduce environmental impacts. Specifically, employing crop rotations with N-fixing legumes or cultivating green manure during fallow periods would directly reduce the reliance on synthetic N fertilizer in subsequent seasons (Ma *et al.* 2025). Future research should explore such alternative rotations to expand the agronomic representativeness and practical applicability of sustainable N management strategies in subtropical vegetable systems.

4.4. Limitations and prospects

This study demonstrates that integrative N management can reduce N leaching and the gray water footprint while sustaining yields in subtropical vegetable systems. Nevertheless, some limitations remain. The climatic anomalies may have influenced soil N dynamics and leaching. For example, drought conditions observed in 2022 can reduce N uptake by crops, alter soil microbial activity, and affect the timing and extent of N leaching. Longer-term, multi-year monitoring is needed to capture interannual variability and improve the robustness of conclusions. Furthermore, to improve the completeness of the N budgets, we also estimated NO and N_2 emissions based on peer-reviewed literature. However, these emissions can vary substantially with climate and soil conditions. Additional unaccounted pathways, including surface runoff, soil erosion during heavy rainfall, and microbial mineralization-immobilization cycles, may also contribute significantly to N dynamics, particularly in warm, moist, and fertilized soils. Future research should incorporate more comprehensive monitoring to better quantify these processes and further enhance the accuracy and completeness of N budget assessments.

5. Conclusion

This study reported that annual N leaching in the Chinese cabbage–pepper rotation system under conventional management reached 251 kg N ha^{-1}, indicating high N leaching in subtropical region. Seasonal N leaching factor under the FNP treatment was 32% for pepper and 17% for Chinese cabbage, respectively, with the pepper season accounting for the majority of the loss. This highlights the pepper season as a critical period for mitigating N leaching. The OPT-CU treatment significantly reduced annual N leaching by 68%, increased NUE to 54%, and maintained vegetable marketable yields compared to the FNP treatment. Additionally, it reduced gray water footprint by 66−75%, indicating a substantial decrease in water pollution potential. Furthermore, our results demonstrated that combining organic and inorganic fertilizers, using nitrification inhibitor-based stable N fertilizers, and applying controlled-release urea further reduced N leaching by 25−54% compared to conventional urea. These measures also increased crop yields by 2−11% and NUE by 10−13%, while reducing gray water footprint by 28−58%. These findings underscore the potential of integrated 4R principles to mitigate N leaching while enhancing vegetable yields. In conclusion, our research provides effective strategies for improving N fertilizer management in subtropical vegetable production systems, contributing to reduced water pollution and more sustainable agriculture.

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Declaration of competing interest

The authors declare that they have no conflict of interest.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the authors used ChatGPT 4.0 to assist in improving the clarity and readability of the language. All content generated was carefully reviewed and revised by the authors as necessary, and the authors take full responsibility for the final content of the article.

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