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Agronomic and environmental evaluation of integrated nutrient management for cabbage production in high-altitude regions

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KEYWORDS

High-altitude regions, highland cabbage, carbon footprint, nitrogen footprint, integrated soil-crop system management

HIGHLIGHTS

- Global warming drives alpine farming expansion, raising C/N emission risks.
- ISSM boosts high-altitude cabbage yield, cuts C/N environmental footprints.
- ISSM yields 95.6 Mg·ha^{-1}, cutting Nr loss 26%, GHG 23%, EP 35% vs FP.
- ISSM offers a scalable framework for sustainable alpine vegetable production.

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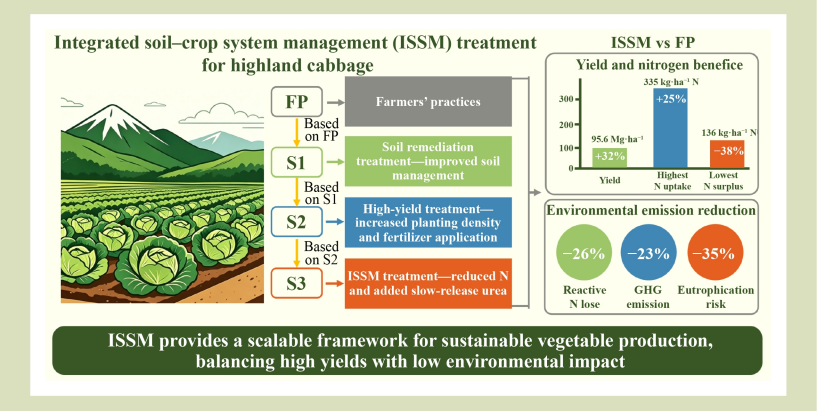
GRAPHICAL ABSTRACT



ABSTRACT

Global warming has driven the expansion of cultivated land into high-altitude regions, making mountainous regions important sources of vegetable production. Crop cultivation in southwest China high-altitude regions has encountered various challenges, such as reactive nitrogen loss and greenhouse gas emissions. We report the results of a field experiment using an integrated soil-crop system management (ISSM) approach to improve the yield of highland cabbage and reduce the carbon and nitrogen footprints in southwest China. The treatments included farmers' practices (FP), soil remediation (S1), high yield (S2), and ISSM (S3) strategies targeting nutrient inputs, crop management, and soil management. Based on field measurements, the ISSM treatment had the highest yield (95.6 Mg·ha^{-1}), aboveground N uptake (335 kg·ha^{-1} N), and lowest N surplus (136 kg·ha^{-1} N). Life cycle assessment further revealed that, compared with FP, ISSM significantly reduced reactive

nitrogen losses by 26%, greenhouse gas emissions by 23%, and eutrophication potential by 35%. These results demonstrate the potential of ISSM in improving the environmental performance of sustainable nitrogen management in high-elevation vegetable production. The findings enhance our understanding of sustainable agricultural practices in high-altitude ecosystems and provide a scalable framework for improving vegetable production systems in similar regions.

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1 Introduction

Global warming has driven the expansion of cultivated land into high-altitude regions[1]. Highland vegetables are adapted to cool climatic conditions and serve as the primary source of vegetables in China's high-altitude regions[2,3]. However, prolonged cultivation and excessive use of chemical fertilizers in such regions have led to a continuous decline in soil quality, particularly in essential base cations such as Ca^{2+} and Mg^{2+}, as well as a range of environmental issues, including reactive nitrogen loss, greenhouse gas emissions, eutrophication, and soil erosion[4,5]. Therefore, addressing these challenges is crucial for ensuring the sustainable development of highland vegetable agriculture in high-altitude regions of China.

Although environmental cost assessments of vegetable production systems have received increasing attention, particularly in low-altitude regions (<1000 m) and greenhouse-based systems[6–8], research has remained disproportionately focused on these settings. Further, even though numerous studies have quantified the impacts of fertilizer usage[9], fertilizer types[10], management practices[11] and greenhouse settings[12] limited research has investigated resource inputs and environmental costs in high-altitude vegetable production systems. Significant differences in climate, soil properties, and farm management between high- and low-altitude regions are likely to result in divergent yield patterns and environmental outcomes[1,13]. To systematically evaluate these environment-related trade-offs, life cycle assessment (LCA) provides a standardized framework (ISO 14040:2006) for quantifying the environmental impacts across all stages of crop production. In agricultural research, LCA has been extensively applied to inventory resource inputs and pollutant outputs, converting them into aggregated indicators such as greenhouse gas emissions, nitrogen losses, and eutrophication potential via established characterization factors[8,14]. Consequently, resource inputs and environmental footprints in high-altitude vegetable production remain underexplored, particularly the integrated metrics derived from LCA, highlighting a critical knowledge gap in achieving sustainability in mountain agriculture.

Previous studies have shown that vegetable production has significant potential to enhance yield, reduce fertilizer applications, and lower greenhouse gas emissions. Compared with conventional farming practices, the implementation of an integrated knowledge and product strategy (IKPS) in China's vegetable production systems has resulted in a 38% reduction in nitrogen fertilizer use, a 65% decrease in nitrogen surplus, and a 28% decline in greenhouse gas emissions, while simultaneously increasing crop yields by 17%[15]. In addition, our previous study found that open-field highland pepper production can achieve higher yields while offering the potential reducing fertilizer application and associated emissions[11]. However, the extent of yield improvement and emission reduction remains insufficiently validated through empirical studies. Given the ecological fragility of highland regions and the limited availability of relevant research, it is imperative to develop targeted strategies to verify and optimize open-field vegetable production systems in these regions.

Integrated soil-crop system management (ISSM) involves optimizing the crop production system through considerations such as variety, density, and sowing date, with the aim of maximizing resource utilization and increasing crop yields. This is an important approach that can simultaneously achieve significant improvements in crop yield and nutrient management efficiency[16]. Wang et al. successfully implemented ISSM in pepper[17] and tomato[18] production systems, achieving notable increases in yield and reduced environmental impacts. The core components of the ISSM include the optimization of crop varieties, planting density, sowing dates, fertilizer types and application rates, irrigation practices, and integrated pest, disease, and weed management

practices that enhance crop adaptability to local conditions and unlock yield potential [19–21]. Vegetable production systems differ markedly from other cropping systems in terms of growth characteristics, field management requirements, and cultivation environments. However, the application of ISSM in high-altitude vegetable production systems has rarely been examined previously.

Brassica oleracea (var. *capitata* L.), commonly known as cabbage, is an important high-altitude vegetable crop in China and worldwide. In southwestern China, vegetable cultivation in high-altitude regions faces multiple challenges, including substantial nitrogen loss, greenhouse gas emissions and water eutrophication. Given these issues and the current lack of effective and sustainable management strategies in high-altitude agricultural systems, this study aims to: (1) enhance crop yield in high-altitude vegetable production by optimizing fertilization strategies among lead farmers (top 25%), implementing ISSM, and refining planting density, fertilization methods and nutrient sources, soil remediation techniques, and other key agronomic practices based on local survey data; and (2) quantify the potential of ISSM to reduce carbon (C) and nitrogen (N) footprints as well as eutrophication potential, while simultaneously improving crop productivity. The findings of this study are expected to enhance our understanding of sustainable agricultural practices in high-altitude regions and provide a model for optimizing vegetable production systems in similar regions.

2 Materials and methods

2.1 Experimental setup

2.1.1 Survey data

The study area is located on Fairy Mountain, Wulong District, Chongqing City, China, with geographical coordinates of 106.13°E and 30.01°N. This region is traditionally used for the cultivation of highland vegetables and falls within the subtropical humid monsoon climate zone. It has an elevation of 1350 m, an average annual temperature of 18.03 °C, and an annual precipitation of 1149 mm. This study comprised of two components. The first component involved conducting a questionnaire survey among 80 representative cabbage growers at elevations ranging from 1100 m to 1400 m on the Fairy Mountain. The survey collected data on altitude, yield, planting density, and inputs such as organic fertilizers, chemical fertilizers, plastic mulch, and pesticide. A total of 66 valid responses were received.

The average yield and planting density of all surveyed farmers were 57 Mg·ha^{-1} and 37443 plants ha^{-1}, respectively, and the chemical fertilizer application rates were 420 kg·ha^{-1} N and 297 kg·ha^{-1} P_2O_5 and 223 kg·ha^{-1} K_2O, respectively. The average yield and planting density of the top 25% of farmers were 88 Mg·ha^{-1} and 42044 plants ha^{-1}, respectively, and the chemical fertilizer application rates were 481 kg·ha^{-1} N, 359 kg·ha^{-1} P_2O_5 and 219 kg·ha^{-1} K_2O, respectively (Table 1). Although the top 25% of farmers applied a greater amount of organic fertilizer than the average farmer, the overall proportion of total fertilizer use remained low, indicating a significant shortage of organic fertilizers in the region. These survey results were used as a reference for planting density and fertilization recommendations for households with average and high-yields.

2.1.2 Field experiments based on the survey data

A plot-based field experiment was conducted during the 2020–2022 growing seasons in the Wulong District (altitude of 1200 m) of Chongqing City, China. The growing period for each cabbage season was approximately 110–120 days. The soil in the experimental area was yellow and derived from

Table 1 Cabbage yield, planting density, and fertilizer management based on a questionnaire survey

Farmer	Yield (Mg·ha^{-1})	Planting density (plants ha^{-1})	Total fertilizer (kg·ha^{-1})			Chemical fertilizer (kg·ha^{-1})			Organic fertilizer (kg·ha^{-1})		
			N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
Average across all farmers	57	37443	485	320	274	420	297	223	65	23	51
Top 25%	88	42044	566	430	287	481	359	219	85	71	68

Note: Top 25% referred to the farmers whose yield ranks in the top 25%.

limestone weathering. It was weakly developed and exhibited distinct aluminum enrichment characteristics. The pH of the plow layer (0–20 cm) was 5.3, with an organic matter content of 23.4 g·kg^{-1}, available phosphorus of 32 mg·kg^{-1}, and available potassium of 89 mg·kg^{-1}. The cabbage cultivar used was 'Fengyuan 911', a locally promoted, high-yielding variety. Notably, the experimental field had been under continuous cabbage monoculture without crop rotation for six years prior to the experiment, reflecting local intensive farming practices and providing a relevant context for investigating soil degradation. The experimental design included four management treatments, as shown in Table 2, with each replicate performed in triplicate. Each plot had an area of 4 m × 5 m. The plots were arranged in a randomized complete block design with a protective row surrounding the experimental area.

2.1.3 The specific treatment schemes

FP: Farming practice, fertilization, and field management based on the average of a previous survey of 66 households. Fresh chicken manure was used as an organic fertilizer. The planting density was 37500 plants ha^{-1}. Chemical fertilizers were applied at 420 kg·ha^{-1} N, 300 kg·ha^{-1} P_2O_5 and 225 kg·ha^{-1} K_2O, and organic fertilizers at 65 kg·ha^{-1} N, 23 kg·ha^{-1} P_2O_5 and 51 kg·ha^{-1} K_2O, based on the average values from all surveyed farmers.

Strategy 1 (S1, Soil remediation treatment): This single-factor treatment was designed to improve soil management. We identified poor soil management and soil-borne diseases, particularly those arising from continuous cropping and the application of uncomposted organic fertilizers, such as fresh chicken manure, as the primary constraints in regional vegetable production systems. To address these issues, calcium cyanamide has been applied as a soil disinfectant, and plastic film mulching has been used to elevate soil temperature, thereby suppressing pathogen populations and improving overall soil health[17,22]. Concurrently, composted organic fertilizers (mushroom residue and cow manure) were substituted with fresh chicken manure to mitigate improper

Table 2 Soil, crop, and nutrient management practices in the four treatments

Input	Treatment			
	FP	S1	S2	S3
Total fertilizer (kg·ha^{-1})				
N	485	497	576	471
P_2O_5	323	323	402	222
K_2O	276	283	395	402
Compound fertilizer (kg·ha^{-1})				
N	420	420	480	375
P_2O_5	300	300	360	180
K_2O	225	225	218	225
Organic fertilizer (kg·ha^{-1})				
N	65	77	96	96
P_2O_5	23	23	42	42
K_2O	51	58	177	177
Pesticide (kg·ha^{-1})	1.4	1.4	1.4	1.4
Mulch film (kg·ha^{-1})	10.35	10.35	10.35	10.35
Electricity (kWh·ha^{-1})	0	0	0	0
Labor (capita day ha^{-1})	297	297	297	297
Fuel consumption (kg·ha^{-1})	25.3	25.3	25.3	25.3

Note: FP was the farmers' practices treatment; S1 was the soil remediation treatment; S2 was the high-yield treatment; S3 was the ISSM treatment.

fertilization practices and enhance the availability of organic nutrients (Table S1). The planting density was 37500 plants ha^{-1}. Other fertilization and field management practices were consistent with FP.

Strategy 2 (S2, High-yield treatment): This treatment refined S1 by applying commercial liquid organic fertilizer as a top-dressing and increasing the chemical fertilizer to match the top 25% of surveyed farmers. As a top-dressing fertilizers, liquid organic fertilizer enriched with beneficial microorganisms can effectively suppress soil-borne pathogens, mitigate root and stem diseases in vegetables, and enhance root development. The planting density was 42000 plants ha^{-1}. Chemical fertilizers were applied at 480 kg·ha^{-1} N, 360 kg·ha^{-1} P_2O_5, and 225 kg·ha^{-1} K_2O, and organic fertilizers at 96 kg·ha^{-1} N, 42 kg·ha^{-1} P_2O_5, and 177 kg·ha^{-1} K_2O, based on the top 25% values from surveyed farmers. Other fertilization and field management practices were consistent with FP.

Strategy 3 (S3, ISSM treatment): Chemical N fertilizer was reduced by 21.8% relative to the S2 treatment, and replaced with 600 kg·ha^{-1} slow-release urea, 225 kg·ha^{-1} superphosphate, and 75 kg·ha^{-1} potassium sulfate, at a planting density of 42000 plants ha^{-1}. Other fertilization and field management practices were consistent with FP.

The detailed fertilizer application rates, nutrient compositions, and management practices of all experimental treatments are presented in Table 2, Table S1 and Table S2.

2.2 Data analysis

2.2.1 Yield analysis

Cabbage heads were harvested at physiological maturity. Yield was determined using the field-weighting method. The heads were first subjected to standard commercial trimming (removal of the outer leaves and roots) before measurement. The fresh matter yield of each plot was recorded immediately after harvesting and trimming and then converted to Megagram per hectare (Mg·ha^{-1}). All reported yield data refer to fresh weight.

2.2.2 Nitrogen balance analysis

The total nitrogen uptake in the aboveground biomass was determined using the Kjeldahl method[19–21]. Dried and ground plant samples were digested, and the N concentrations were analyzed. Total N uptake was calculated by multiplying the N concentration by the corresponding dry biomass weight for each plot. The nitrogen balance was calculated as follows:

$$N_{surplus} = N_{input} - N_{uptake} \quad (1)$$

where $N_{balance}$ is measured in kg·ha^{-1} N, N_{input} represents the amount of organic and inorganic nitrogen fertilizers used, and N_{uptake} represents the total nitrogen accumulated in the aboveground cabbage biomass at harvest.

2.2.3 Environmental impact analysis

The LCA method was used to assess the environmental impact of the entire crop production process, from seeding to harvesting. This entire process includes input stages (fertilizer production and transportation and other input production and transportation stages) and agricultural operation stages (fertilizer application and other inputs used in agricultural fields). The main environmental impact evaluation indicators included reactive nitrogen loss caused by fertilizer input, greenhouse gas emissions, eutrophication potential, and acidification potential.

2.2.4 Reactive nitrogen loss

Reactive nitrogen loss emissions refer to the total amount of reactive nitrogen emitted into the environment during the crop life cycle, including nitrous oxide emissions during nitrogen fertilizer application in farmlands, ammonia volatilization, nitrate leaching, and NO_x and NH_4-N emissions generated during fertilizer production and transportation.

Reactive nitrogen emissions during nitrogen fertilization

$$Nr - AFS = N_2O + NH_3 + NO^-_{3\,leaching} \quad (2)$$

where N_2O, NH_3, and $NO^-_{3\,leaching}$ represent the amount of N_2O emissions, NH_3 volatilization, and nitrate leaching losses directly generated by the application of nitrogen fertilizers in agricultural systems per unit (per hectare or per unit of yield). The emission factors of N_2O, NH_3, and $NO_3^-{}_{leaching}$ for N fertilizer application at the arable farming stage are listed in Table S3.

Other sources of reactive nitrogen loss emissions (Nr−AMS) include the production and transportation processes of fertilizers, pesticides, and other inputs, as well as mechanical fuel emissions and energy used for irrigation during the field cultivation process. This equation is expressed as:

$$Nr-AMS = N_{input} \times EFN + P_{input} \times EFP + K_{input} \times EFK + Pest_{input} \times EF_{pest} + Fuel_{input} \times EF_{fuel} + Electricity_{input} \times EF_{electricity} \quad (3)$$

where N_{input} represents the amount of nitrogen fertilizer applied (kg·ha^{-1} N), EF_N represents the N fertilizer emission factor, the mass of reactive nitrogen (kg) generated per kg of N fertilizer during production and transportation; P_{input} represents the amount of phosphate fertilizer applied (kg·ha^{-1} P_2O_5), EF_P represents the P fertilizer emission factor, the mass of reactive nitrogen (kg) generated per kg P_2O_5 during production and transportation; K_{input} represents the amount of potash fertilizer applied (kg·ha^{-1} K_2O), EF_K represents the K fertilizer emission factor, the mass of reactive nitrogen (kg) generated per kg K_2O during production and transportation; $Pest_{input}$ represents the amount of pesticide applied (kg·ha^{-1}), EF_{pest} represents the pest emission factor, the mass of reactive nitrogen (kg) generated per kg pesticide during production and transportation; $Fuel_{input}$ represents the amount of diesel used (kg·ha^{-1}), EF_{fuel} represents the fuel emission factor, the mass of reactive nitrogen (kg) generated per kg diesel during production, transportation, and application; and $Electricity_{input}$ represents the amount of electricity used (kWh·ha^{-1}), $EF_{electricity}$ represents the electricity emission factor, which is the mass of reactive nitrogen (kg) generated per kilowatt-hour of electricity during production and transportation. The corresponding emission factors for the reactive nitrogen emission of agricultural inputs are listed in Table S4.

The global warming potential (GWP) is a metric that compares the greenhouse gas emissions of various gases, typically using CO_2 as a reference. It was measured in kg CO_2-eq. Emissions of CH_4 and N_2O were converted to CO_2-eq using conversion coefficients of 21 and 298, respectively[23]. Greenhouse gas emissions from crop production systems mainly originate from fertilizers, pesticides, and infrastructure materials used during production and transportation of crops. These emissions are also caused by the direct application of nitrogen fertilizers, resulting in N_2O emissions, as well as indirect N_2O emissions resulting from NO_3^- leaching and NH_3 emissions. The equations used for these calculations are as follows:

$$GWP = \sum AMSCO_2 + Total\ N_2O \times 44/28 \times 298 \quad (4)$$

$$Total\ N_2O = N_2O_{direct} + 1\% \times NH_3 + 2.5\% \times NO^-_{3\ leaching} \quad (5)$$

where GWP represents the greenhouse gas emissions generated by the production of one unit of crop input, measured in kg·t^{-1} CO_2-eq. $AMSCO_2$ represents CO_2 emissions from the production and transportation of agricultural inputs (such as nitrogen, phosphorus, and potassium fertilizers, pesticides, fuel, steel, and plastic film) during the agricultural input stage. Total N_2O represents the total N_2O emissions generated during the agricultural operation process, including direct emissions from nitrogen fertilizer application and indirect emissions resulting from NH_3 volatilization and NO_3^- leaching. N_2O_{direct}, NH_3, and $NO_3^-{}_{leaching}$ represent the calculated N_2O emissions, NH_3 volatilization, and $NO_3^-{}_{leaching}$ losses, respectively. Here, 44/28 is the conversion coefficient for N to N_2O, and 298 is the conversion factor for 1 kg of N_2O, which is equivalent to the CO_2 greenhouse gas effect. The corresponding emission factors for the greenhouse gas emission of agricultural inputs are listed in Table S4.

2.2.5 Eutrophication effect

Eutrophication potential (EP), generally using PO_4 as a reference, with a unit of kg PO_4-eq per unit. The substances that cause the eutrophication effect mainly include $AMSPO_4$, NH_3, NO_x, NO_3^-, NH_4^+-N, and P_{input}. The conversion coefficients to PO_4 equivalent are 0.33, 0.13, 0.42, 0.33, 0.022, and 3.06, respectively[2,24].

$$EP = \sum AMSPO_4 + 0.33 \times NH_3 \times 17/14 + 0.42 \times NO^-_{3\ leaching} + 0.2\% \times P_{input} \quad (6)$$

Where EP represents the eutrophication effect generated by the production of one unit of crop input, measured in kg PO_4-eq per unit. $AMSPO_4$ represents PO_4 emissions from the production and transportation of agricultural inputs (such as nitrogen, phosphorus, and potassium fertilizers, pesticides, fuel, electricity, steel, and plastic film) during the agricultural input stage. NH_3 and $NO_3^-{}_{leaching}$ represent the calculated NH_3 volatilization and NO_3^- leaching losses, respectively. 17/14 is the conversion coefficient for N to NH_3, and 0.33 is the conversion factor for 1 kg of NH_3, equivalent to the PO_4 eutrophication effect. 0.42 is the conversion factor for leaching 1 kg of NO_3^- leaching equivalent to the PO_4 eutrophication effect. P_{input} represents the total input of phosphate fertilizer[25]. The corresponding emission factors for the water eutrophication emission of agricultural inputs are listed in Table S4.

2.3 Statistical analysis

Calculations of the output, resource inputs, nitrogen balance, reactive nitrogen emissions, greenhouse gas emissions, and EP were performed using Microsoft Excel 2020. Because agricultural performance is significantly influenced by inter-annual climatic variations, data from the 2020–2021 and 2021–2022 seasons were analyzed separately. For each growing season, a one-way analysis of variance (ANOVA) was applied, with treatment as the sole fixed factor, to assess the significant differences among the dependent variables. Prior to ANOVA, the normality of the residuals was tested using the Shapiro-Wilk test, and the homogeneity of variance was assessed using Levene's test. All data met the assumptions for parametric analyses ($p > 0.05$). SigmaPlot (version 14.0; Systat Software Inc., San Jose, California, USA) was used for all statistical analysis. Treatment means were compared using the least significant difference (LSD) test at a significance level of 5%. Pearson's correlation coefficients were used to evaluate the influence of fertilizer application rate and planting density on crop yield, carbon footprint, nitrogen footprint, and EP using Origin version 2019b.

3 Results

3.1 Yields

Total cabbage yields of FP, S1, S2, and S3 were 80.5 ± 3.89, 97.3 ± 6.08, 99.0 ± 21.33, and 107.1 ± 13.08 Mg·ha^{-1}, respectively (Fig. 1(a)). Compared to FP, S1, S2, and S3 increased the yield by 21%, 23%, and 33% in 2020–2021, respectively. In 2021–2022, the total yields of FP, S1, S2, and S3 were 64.14 ± 1.66, 77.81 ± 6.81, 82.87 ± 5.15, and 84.15 ± 3.91 Mg·ha^{-1}, respectively (Fig. 1(b)). Compared to FP, S1, S2, and S3 increased the yield by 21%, 29%, and 31% respectively in 2021–2022. The yields varied significantly among the treatments in both seasons, with the S3 treatment consistently producing the highest yield.

3.2 Nitrogen surplus

Based on the nitrogen balance of cabbage production under the different treatments during the 2020–2021 season, the nitrogen surpluses of FP, S1, S2, and S3 were 184, 133, 206, and 71 kg·ha^{-1} N, respectively (Table 3). The total nitrogen inputs for the different treatments were 485, 497, 576, and 471 kg·ha^{-1} N, respectively (Table 3). Compared with FP, S1 and S2 increased the total nitrogen input by 2%–19% (Table 3). In terms of nitrogen uptake, compared to FP, S1 and S2 increased the uptake by 21% and 23%, respectively. Compared with FP, S3 decreased the total nitrogen input by 3% and nitrogen uptake by 33% (Table 3). Based on the nitrogen balance of the different cabbage during the 2021–2022 season, the nitrogen surpluses of FP, S1, S2, and S3 were 253, 216, 276, and 167 kg·ha^{-1} N, respectively (Table 3). The total nitrogen input remained unchanged compared with that of FP. Compared with FP, S1 and S2 increased nitrogen uptake by 21% and 29%, respectively, whereas S3 increased nitrogen uptake by 31%

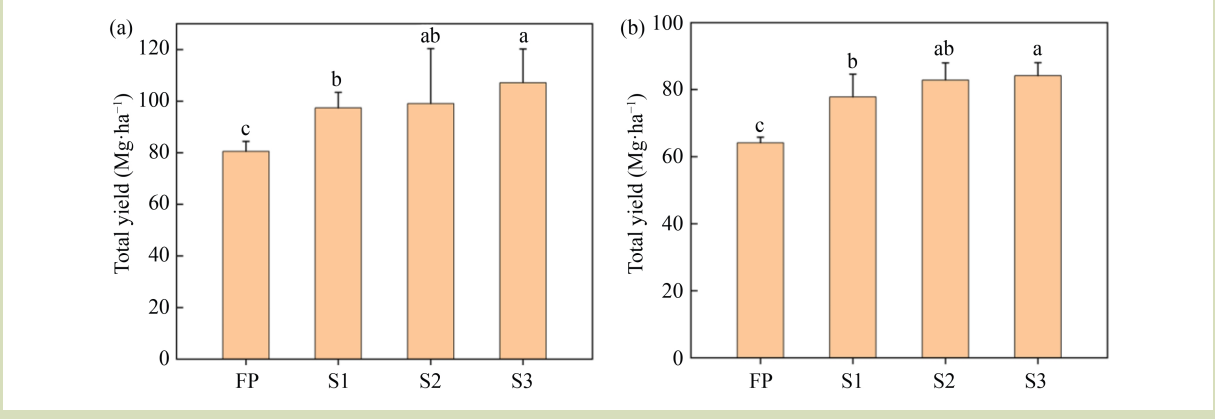

Fig. 1 Total yields of highland cabbage in the four treatments during 2020–2021 (a) and 2021–2022 (b). FP was the farmers' practices treatment; S1 was the soil remediation treatment; S2 was the high-yield treatment; S3 was the ISSM treatment. Different lowercase letters indicate significant differences between treatments means ($p < 0.05$), $n = 3$.

Table 3 Nitrogen surplus of the four treatments of cabbage production during the 2020–2022 season

Inventory	2020–2021				2021–2022				Average value			
	FP	S1	S2	S3	FP	S1	S2	S3	FP	S1	S2	S3
Total fertilizer (kg·ha^{-1} N)	485	497	576	471	485	497	576	471	485	497	576	471
N fertilizer (kg·ha^{-1} N)	420	420	480	375	420	420	480	375	420	420	480	375
Organic fertilizer (kg·ha^{-1} N)	65	77	96	96	65	77	96	96	65	77	96	96
N uptake (kg·ha^{-1})	301 ± 15 c	364 ± 23 b	370 ± 79 ab	400 ± 48 a	232 ± 60 c	281 ± 24 b	300 ± 18 ab	304 ± 14 a	267	267	323	335
N surplus (kg·ha^{-1} N)	184 ± 16 ab	133 ± 25 b	206 ± 78 a	71 ± 46 c	253 ± 71 ab	216 ± 27 b	276 ± 16 a	167 ± 12 c	218	231	253	136

Note: FP was the farmers' practices treatment; S1 was the soil remediation treatment; S2 was the high-yield treatment; S3 was the ISSM treatment. Both were calculated from the three plot replicates per treatment (n = 3). Significance letters derive from one-way ANOVA with LSD tests (p < 0.05).

(Table 3). The average N uptake (335 kg·ha^{-1} N) of S3 was the highest, whereas the average N surplus (136 kg·ha^{-1} N) was the lowest during both the 2020–2021 and 2021–2022 seasons. These results indicate that the lowest accumulation of N in the soil was observed in the S3 treatment compared to the FP, S1, and S2 treatments.

3.3 Reactive nitrogen loss

It can be seen from the figure that the average reactive nitrogen loss of FP, S1, S2, and S3 during the 2020–2021 season was 1.22, 1.05, 1.36, and 0.89 kg·t^{-1} N, respectively (Fig. 2(a)). Compared with the FP treatment, S2 showed 11% increase, whereas S1 and S3 showed decreases of 14% and 27%, respectively. During the 2021–2022 season, the average reactive nitrogen losses in FP, S1, S2, and S3 were 1.53, 1.31, 1.62, and 1.14 kg·t^{-1} N, respectively (Fig. 2(b)). Compared with the FP treatment, reactive nitrogen losses decreased by 14% and 26% for S1 and S3, respectively, whereas S2 showed a 6% increase. Among these sources, nitrate leaching accounts for 82%–89% of the reactive nitrogen loss during the agricultural input stage.

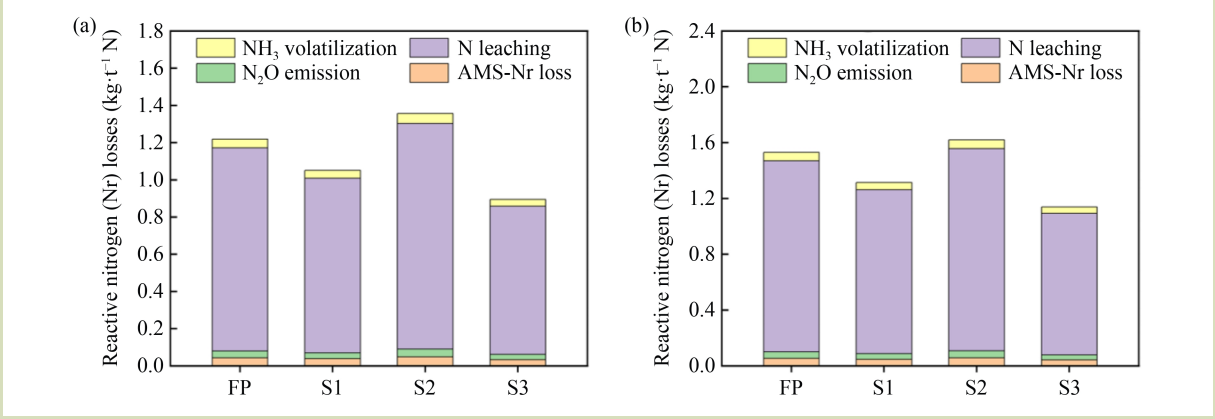

Fig. 2 Reactive N losses of different cabbage production treatments at each input step during the 2020–2021 (a) and 2021–2022 (b). FP was the farmers' practices treatment; S1 was the soil remediation treatment; S2 was the high-yield treatment; S3 was the ISSM treatment. AMS-Nr loss is the total Nr loss from the production and transportation of steel, plastic, fertilizers, pesticides, diesel and electricity; N_2O emission is the N_2O emission from inorganic and organic N fertilizer following application; N leaching represents the N leaching from inorganic and organic N fertilizer following their application; NH_3 volatilization represents the NH_3 volatilization losses from inorganic and organic N fertilizer following application.

3.4 Greenhouse gas emissions

The greenhouse gas emissions of FP, S1, S2, and S3 during the 2020–2021 season were 84.9, 75.3, 94.9, and 64.9 kg·t^{-1} CO_2-eq, respectively (Fig. 3). Compared with the FP treatment, S1 and S3 reduced greenhouse gas emissions by 11% and 24%, respectively, whereas S2 increased emissions by 12%. Compared with the FP treatment, the greenhouse gas emissions of S1 and S3 decreased. During the 2021–2022 season, the greenhouse gas emissions of FP, S1, S2, and S3 were 106.6, 94.2, 113.4, and 82.7 kg·t^{-1} CO_2-eq, respectively (Fig. 3). Compared with the FP treatment, S1 and S3 reduced greenhouse gas emissions by 12% and 22%, respectively, whereas S2 increased emissions by 6%. Fertilizer contributed to most greenhouse gas emissions in all treatments.

3.5 Eutrophication effect

The eutrophication values of FP, S1, S2, and S3 during the 2020–2021 season were 0.88, 0.75, 0.95, and 0.57 kg·t^{-1} PO_4-eq, respectively (Fig. 4). Compared with FP treatment, S1 and S3 decreased eutrophication by 15% and 36%, respectively, whereas S2 increased eutrophication by 7% (Fig. 4). During the 2021–2022 season, the eutrophication values of FP, S1, S2, and S3 were 1.11, 0.94, 1.13, 0.72 kg·t^{-1} PO_4-eq, respectively (Fig. 4). Compared with FP treatment, S1 and S3 reduced eutrophication by 15% and 35%, respectively, whereas S2 increased eutrophication by 2% (Fig. 4). Fertilizer contributed the most to eutrophication in all treatments during both seasons.

4 Discussion

4.1 The potential for increasing vegetable production with ISSM in high-altitude regions

Analysis of the survey data showed that the yield of the top 25% of farmers was 54% higher than the average (Table 1). This yield gap is primarily attributable to increased planting density (12% higher), greater use of chemical fertilizers (13% increase), and a substantially higher application of organic fertilizers (61% increase). Despite the notable increase in organic fertilizer use among high-performing farmers, organic inputs accounted for only 17% of total fertilizer application. Consequently, organic fertilizer utilization in this region remains insufficient, falling significantly below the recommended substitution rate of 30%[26]. Key factors

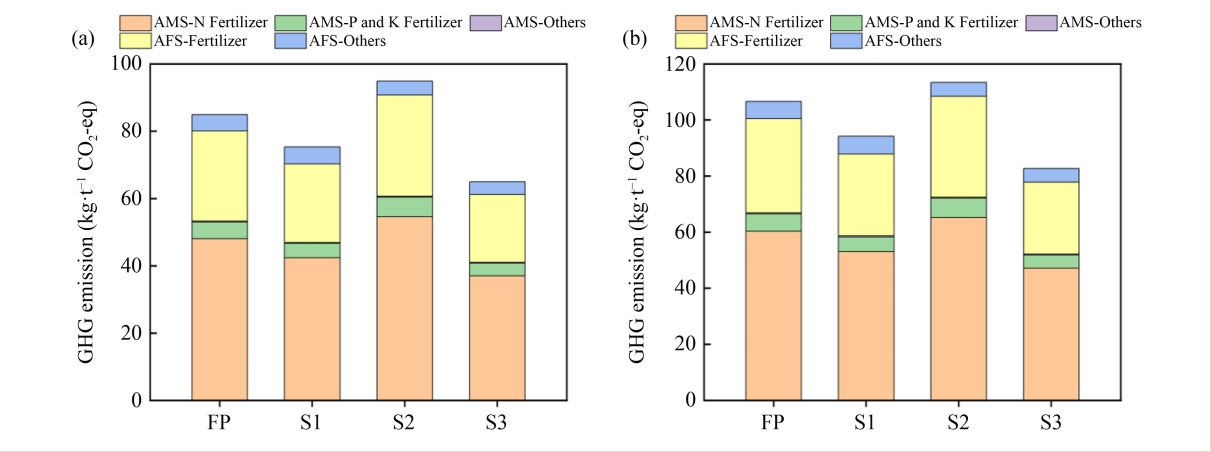

Fig. 3 Global warming potentials of different cabbage production treatments at each input step during 2020–2021 (a) and 2021–2022 (b). FP was the farmers' practices treatment; S1 was the soil remediation treatment; S2 was the high-yield treatment; S3 was the ISSM treatment. Each environmental impact includes impacts originating in the agricultural materials stage (AMS) and in the arable farming stage (AFS). AMS includes the production and transportation of fertilizers, pesticides, diesel and polyethylene. AFS includes the application of fertilizer, polyethylene and pesticides, the use of diesel for machinery, and field management labor input. Colors indicate the relative contributions of different components. The bar heights and totals remain unchanged when the AMS-Others component is excluded from the visual representation.

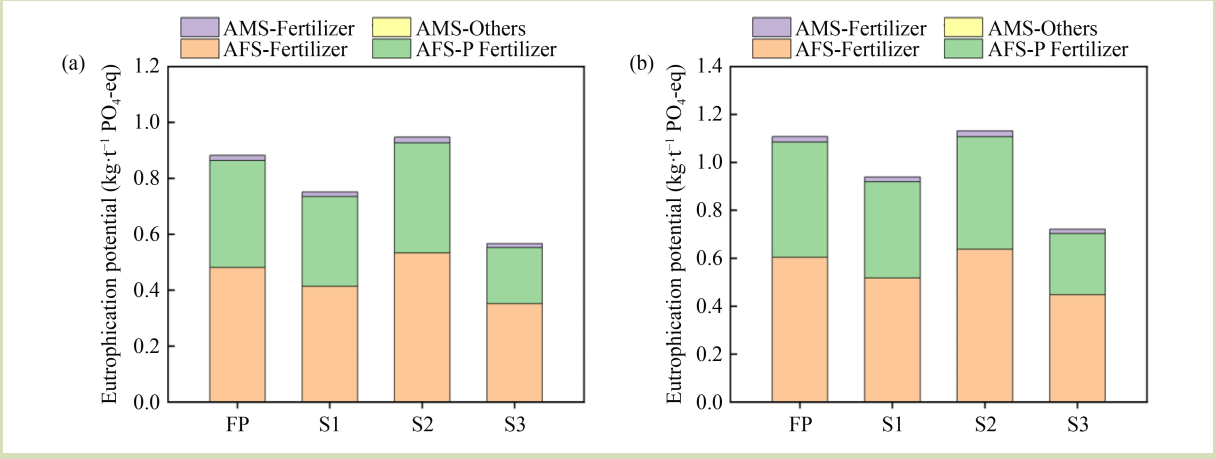

Fig. 4 Eutrophication potential of different cabbage production treatments at each input step during 2020–2021 (a) and 2021–2022 (b). FP is the farmers' practices treatment; S1 is the soil remediation treatment 1; S2 is the high-yield treatment; S3 is the ISSM treatment. Each environmental impact includes impacts originating in the agricultural materials stage (AMS) and in the arable farming stage (AFS). AMS includes the production and transportation of fertilizers, pesticides, diesel and polyethylene. AFS includes the application of fertilizer, polyethylene and pesticides, the use of diesel for machinery, and field management labor input. Colors indicate the relative contributions of different components. The bar heights and totals remain unchanged when the AMS-Others component is excluded from the visual representation.

contributing to this shortfall include the region's underdeveloped livestock sector, inadequate transportation infrastructure, and relatively high cost of commercial organic fertilizers. Liu et al. found that organic substitution increased vegetable yields by 23%–33% in intensive greenhouse production systems[26]. Wu et al. also found that replacing 15%, 30%, 45%, and 100% of chemical fertilizers with organic fertilizers increased annual yields by 9.7%–37.6%, respectively[27]. Pearson's correlation analysis revealed that the strongest positive correlations with yield were for planting density (0.52), P fertilizer (0.27), organic fertilizer (0.26), and chemical fertilizer (0.25). This result indicates that appropriately increasing planting density and applying N/P fertilizers are the main factors driving the increased vegetable yields. Multiple studies have shown that planting density significantly affects vegetable crop growth, yield, and resource use efficiency[28]. This relationship is nonlinear and depends on factors such as crop type, environment, and management practices[29].

Analysis of the experimental data showed that organic fertilizer and planting density were important factors affecting the vegetable yield. The application of S1, S2, and S3 with additional organic fertilizer increased vegetable yields by 21% to 33% (Fig. 1). Similarly, the S2 and S3 treatments, with increased planting density, led to a 23%–33% increase in vegetable yield. Pearson's correlation analysis (Fig. 5(b)) showed that soil remediation (0.64) and planting density (0.52) had the strongest positive correlations with yield, followed by slow-release (0.40), organic (0.24), and N (0.24) fertilizer. Cultivating cabbage in the same field for over six years has caused continuous cropping obstacles, making soil remediation essential. Calcium cyanamide sterilizes the soil and adjusts its pH[30]. Organic fertilizers such as cow dung and mushroom residue, along with commercial liquid formulations, have high carbon-to-nitrogen ratios that effectively increase soil organic matter. Slow-release fertilizers regulate nutrient release to match crop demand during growth, improve nutrient-use efficiency, and increase yield[31]. Wang et al.[18] and Liu et al.[32] confirmed that slow- and controlled-release fertilizers can effectively increase the yields of peppers and tomatoes. Notably, while lowland studies in southwestern China suggest optimal N rates of ~250 kg·ha^{-1} N for cabbage production[33], our high-altitude system required substantially higher inputs (~485 kg·ha^{-1} N) to overcome colder temperatures and shorter growing seasons, underscoring the unique nutrient demands of upland ecosystems. Therefore, enhancing the production potential of vegetables using ISSM in high-altitude regions mainly involves appropriately increasing planting density and

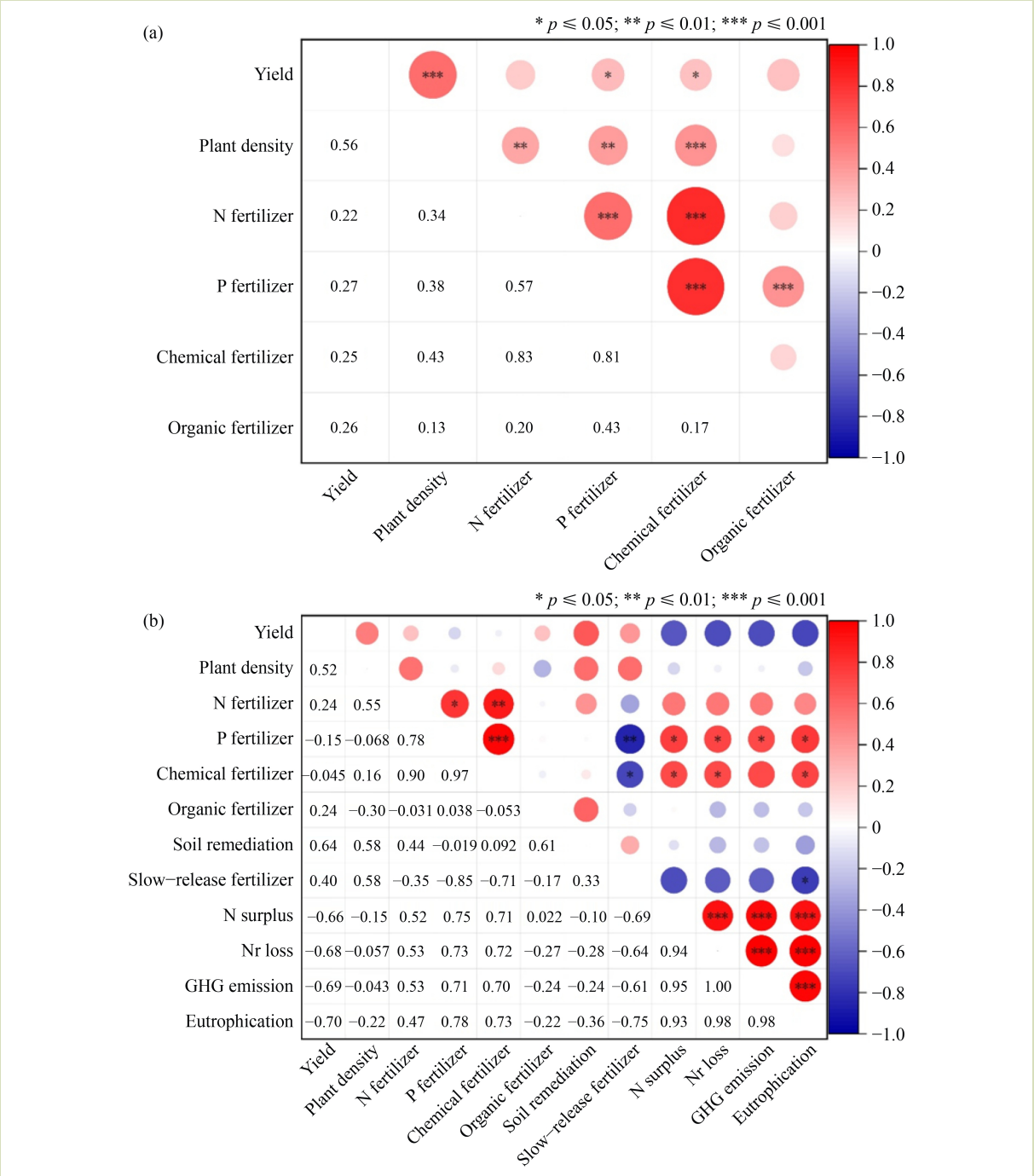

Fig. 5 Heatmap of Pearson's correlation coefficients between farm agronomic management practices and environmental costs (including yield, plant density, N fertilizer, P fertilizer, N surplus, chemical fertilizer, organic fertilizer, Nr loss, GHG emissions, and eutrophication potential). Results are derived from (a) survey data (n = 66 farmers) and (b) experimental data (treatment means, n = 3 replicates). Asterisks (*, **, and ***) indicate significant correlations at $p \leqslant 0.05$, $\leqslant 0.01$, and $\leqslant 0.001$, respectively. Note: Correlations in panel (b) are based on treatment means and are intended to illustrate mechanistic associations among variables. Due to limited replication, these coefficients should be interpreted conceptually to complement the statistical significance of treatment effects established via one-way ANOVA.

applying organic fertilizers, soil remediation, and slow-release fertilizers.

4.2 Environmental mitigation potential of ISSM and agriculture sustainability in high-altitude vegetable production

Compared with FP, ISSM treatment significantly reduced the loss of reactive nitrogen by approximately 26%, greenhouse gas emissions by 23%, and the potential value of eutrophication effects by 35% (Figs. 2–4). The primary driver of these differences is the variation in both the yield and fertilizer input. First, the amount of fertilizer, especially nitrogen fertilizer, was the main contributing factor to the environmental costs, which is consistent with previous research results[8,14]. N_2O emissions, nitrate leaching, and ammonia volatilization caused by nitrogen fertilizer application during the farming stage are the main factors contributing to environmental costs. Notably, S2 significantly increased the loss of reactive nitrogen by approximately 8%, greenhouse gas emissions by 9%, and the potential value of eutrophication effects by 4%, owing to the increased use of chemical compound fertilizers. Furthermore, Pearson's correlation analysis revealed that environmental costs (including N surplus, Nr loss, GHG emissions, and EP) were significantly and positively correlated with N, P, and chemical fertilizers (Fig. 5(b)). However, they were significantly negatively correlated with the yield and controlled-release fertilizers. Consistent with the observation that high-altitude pepper production often incurs higher environmental costs despite lower yields than lowland counterparts[13], our results confirm that conventional high-altitude cabbage practices face a "high-input, low-efficiency" dilemma. Environmental costs can be reduced by applying enhanced-efficiency fertilizers, such as nitrification inhibitors and slow-release fertilizers, thereby lowering nitrous oxide emissions, ammonia volatilization, and nitrate leaching during the farming stage[31,34,35]. Improving the production of fertilizers and other production materials can significantly reduce environmental costs, particularly greenhouse gas emissions and energy consumption. For example, Zhang et al. found that improving the production process of nitrogen fertilizers can significantly reduce nitrogen-related greenhouse gas emissions by 20%–63% (approximately 102–357 Tg of greenhouse gas emissions)[36]. Wang et al. also utilized the ISSM method to increase tomato fruit yield by 37.3%, while reducing the N footprint by 52% and carbon footprint by 46%[18]. According to ISSM theory, the potential for environmental mitigation depends primarily on reducing the application of chemical fertilizers, particularly nitrogen-based fertilizers, through the adoption of organic fertilizers, slow- and controlled-release fertilizers, and other effective agricultural management practices, thereby enhancing agricultural sustainability in high-altitude vegetable production.

4.3 Policy implication and popularization of ISSM for vegetable production in high-altitude regions

Based on regional and vegetable production characteristics, this study designed an ISSM model for vegetable production systems in China through comprehensive measures, such as optimizing soil management, crop population design, and nutrient management. Owing to years of excessive fertilization of intensive vegetable production systems in China, soil acidification and continuous soil cropping obstacles are prominent issues. Therefore, soil remediation measures, such as soil amendments and bio-organic fertilizers, were adopted in this production system, which differs from the ISSM in grain production systems. Unlike grain crops, vegetables lack effective crop growth models[16,37]. Therefore, in contrast to the ISSM models for grain production, this approach uses the maximum yield that farmers can achieve through yield difference analysis to construct a high-yield vegetable production system. Because small-scale farmers in China face numerous constraints, implementing comprehensive knowledge training is difficult. Therefore, to optimize nutrient management, this study employed root-layer nutrient regulation technology. Nutrient regulation throughout the cabbage growth period relies on stage-specific fertilizer types: slow-release fertilizer during seedling cultivation, formula fertilizer in the early stage, and water-soluble fertilizer in the middle and late stages. This can help farmers quickly improve their fertilization management skills, which is also different from the ISSM in grain production systems. Consistent with previous research on grain crops[21,32], the results of the two-year field experiment showed that the ISSM based on soil-crop system integration can achieve high yields while significantly reducing environmental costs in vegetable production. This not only meets farmers' demands for increased yield but also aligns with the government's environmental emission reduction policies, contributing to practical, social, and environmental benefits. This study also provides an important reference for the sustainable development of vegetable production systems in the future.

This study has several limitations. First, the findings are derived from a two-year field experiment conducted exclusively in a single high-altitude region using cabbage as the test crop; thus, their generalizability across diverse agroecological contexts, including varying climatic years, geographic locations, and vegetable species, requires further empirical validation. Second, the life cycle assessment relies predominantly on regionally reported or literature-based emission coefficients rather than direct, site-specific measurements of nitrogen losses and greenhouse gas emissions. This reliance may propagate uncertainty into the quantification of carbon, nitrogen, and eutrophication footprints. To enhance robustness, future LCA efforts should integrate field-measured flux data for model calibration and outcome validation. Third, the absence of well-validated, vegetable-specific crop growth models, together with the lack of quantitative analyses addressing economic costs, farmers' adoption barriers, and long-term policy implications, limits the holistic evaluation of ISSM strategies. Advancing ISSM implementation therefore necessitates interdisciplinary integration of process-based crop simulation, rigorous cost-benefit analysis, and representative socioeconomic surveys.

The ISSM approach to high-altitude vegetable production requires careful analysis because of the unique ecological and farming characteristics of this region. The following suggestions are proposed:

(1) Improve the yield and quality. ISSM practices, such as replacing 30% of chemical nitrogen with organic fertilizers, optimizing planting density, and integrating pest management, can significantly enhance vegetable yields and safety.

(2) Protect the environment and address climate change issues. By reducing chemical inputs, ISSM lowers nitrate leaching and water pollution. The using of slow- or controlled-release fertilizers improves nutrient efficiency and reduces greenhouse gas emissions (e.g., N_2O and CH_4), supporting low-carbon, eco-friendly farming.

(3) Promoting technological innovation and knowledge transfer. Successful ISSM adoption depends on training farmers in precision fertilization, organic-fertilizer use, and pest management.

(4) Support standardized production and boost market competitiveness. The ISSM-produced vegetables, known for their quality and sustainability, can benefit from policy-backed green and organic certifications, branding, and value addition.

5 Conclusions

We propose an ISSM strategy that translates regional ecological constraints and vegetable-specific physiology into three levers: soil conditioning, population design, and nutrient synchrony. Two years of field trials demonstrated that this ISSM package increased cabbage yield by 32%, while simultaneously reducing reactive nitrogen losses by 26%, greenhouse gas emissions by 23%, and EP by 35%. The observed yield improvement can be attributed to the increased planting density and the partial substitution of chemical nitrogen with organic and slow-release nitrogen sources. The environmental benefits primarily stem from reduced N_2O, NH_3, and NO_3^- fluxes resulting from optimized nitrogen fertilizer application. Therefore, the ISSM presents a scalable and practical strategy for achieving enhanced productivity, climate change mitigation, and improved water quality in small-scale vegetable production systems in China's high-altitude regions.

Supplementary materials

The online version of this article at http://doi.org/10.15302/J-FASE-2027741 contains supplementary materials (Tables S1–S4).

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Compliance with ethics guidelines

Yan Wang, Yang Cheng, Linxin Sun, Xin Zhang, Youyue Zhao, Mengni He, Xing Feng, Jing Liu, Anle Chen, Lingyun Chen, and Tao Liang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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