ENGINEERING Agriculture

Engineering Journals

RESEARCH ARTICLE

2027 / Volume 14 / Issue 3 / 27738

An innovative vegetable-flower-oil canola (*Brassica napus*) cropping system increases crop yields and economic returns, while reducing environmental impact in the Erhai Lake Basin

Jiangtao WANG*[1,2,3], Shuntao ZHANG*[1,3,4], Jing YANG[3,5], Kang WANG[1,3,6], Feiyu YING[1,3], Jianwei LU[7], Hans LAMBERS[1,8], Wen-Feng CONG (✉)[1,3,9]

1 State Key Laboratory of Nutrient Use and Management, Key Laboratory of Plant-Soil Interactions (Ministry of Education), College of Resources and Environmental Sciences, National Academy of Agriculture Green Development, China Agricultural University, Beijing 100193, China.
2 College of Agriculture, Henan University of Science and Technology, Luoyang 471000, China.
3 Erhai Academy of Agriculture Green Development, Dali 671008, China.
4 College of Resources and Environment, Henan Agricultural University, Zhengzhou 450046, China.
5 Yunnan University Resource Plant Research Institute, Kunming 650504, China.
6 School of Chemistry and Chemical Engineering, Dezhou University, Dezhou 253023, China.
7 College of Resources and Environment, Huazhong Agricultural University, Wuhan 430070, China.
8 School of Biological Sciences and Institute of Agriculture, University of Western Australia, Perth, WA6009, Australia.
9 College of Resources and Environmental Sciences, Yunnan Agricultural University, Kunming 650201, China.

*These authors contribute equally to the work

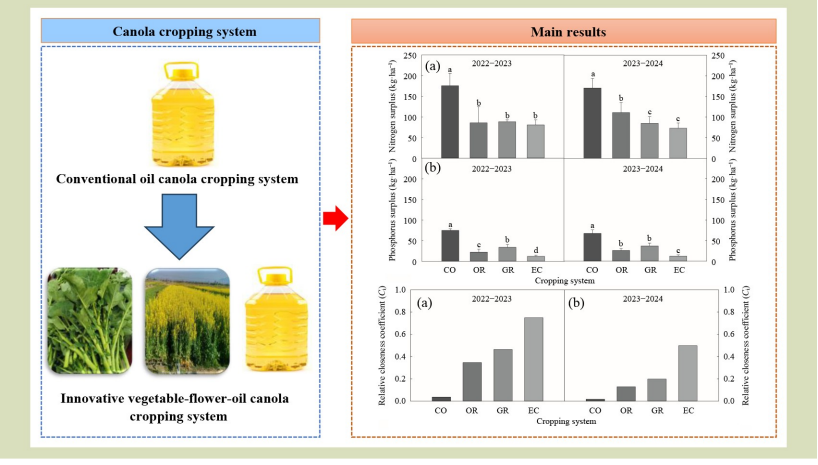
KEYWORDS

Canola system, economic benefits, Erhai Lake Basin, soil nutrient surplus

HIGHLIGHTS

- An ecological vegetable-flower-oil canola system enables multifunctional production and landscape services in vulnerable lake basins.
- Entropy-weighted TOPSIS modeling objectively identified this system as optimal for balancing green production and high-value outcomes.
- This system cuts N surplus by up to 57% and P surplus by up to 84%, while substantially increasing net profit.
- It enhances floral traits, increasing flower abundance by up to 342% and extending blooming by 3–10 days to support agritourism.
- This integrated system provides a scalable solution for sustainable agricultural

GRAPHICAL ABSTRACT



intensification in ecologically sensitive regions worldwide.

Received February 24, 2026;
Accepted July 13, 2026.

Correspondence: wenfeng.cong@cau.edu.cn

ABSTRACT

The Erhai Lake Basin is subject to severe eutrophication from agricultural nutrient losses, and current canola farming in the region fails to balance environmental protection, yield and economic benefits. To address the central challenge of reconciling green production with high-value output, an innovative vegetable-flower-oil canola system was developed. A field experiment evaluated five canola cropping systems: control (CK), conventional organic (CO), organic optimization (OR), green production (GR) and ecological (EC). Key indicators for assessing green production and economic performance including yields, floral traits, N, P and irrigation water use efficiencies (NUE, PUE and IWUE, respectively), soil N and P surpluses, and economic performance were measured. The entropy-weighted TOPSIS model enabled objective multi-criteria evaluation. Results ranked systems by relative closeness (C_i): EC exhibited the highest C_i (0.50–0.75), with the full ranking: EC > GR > OR > CO. EC significantly outperformed CO: it increased net benefit by 42.7 thousand yuan·ha^{-1}, reduced soil N and P surpluses (54.1%–57.2% and 81.6%–84.0%, respectively), improved NUE (62.7%–112%) and PUE (306%–392%), enhanced IWUE by 181.50%, and boosted yields. EC enhanced floral traits (138%–342% more flowers, 3–10 days longer flowering), supporting agritourism. The EC system meets the dual goals of green production and high-value output while offering agritourism value, providing sustainable solutions for agricultural green development in vulnerable lake basins.

© The Author(s) 2027. Published by Higher Education Press. This is an open access article under the CC BY license (http://creativecommons.org/licenses/by/4.0)

1 Introduction

The Erhai Lake Basin, Yunnan Province, China serves as a critical ecological barrier for plateau freshwater ecosystems and a core zone for national agricultural green development[1,2]. As the second-largest plateau freshwater lake in Yunnan, Erhai Lake regulates the regional climate, maintains biodiversity, and supports the livelihoods of over 800,000 residents[3,4]. Characterized by a low-latitude plateau subtropical southwest monsoon climate, the Basin receives an annual average precipitation of 1048 mm, with 90% concentrated in the wet season (May–October) and only 10% in the dry season (November–April), a distributional unevenness that poses major challenges to agricultural water management[5,6]. Against this climatic and ecological backdrop, agriculture, which contributes over 35% of the regional GDP, has long been a key sector in the Basin. However, its unsustainable agricultural practices now threaten the ecological security of Erhai Lake[7].

In recent decades, the expansion of water- and fertilizer-intensive cash crops, particularly garlic, has intensified agricultural non-point source pollution in the Basin. Garlic is extensively cultivated in the Basin, generating an annual output value of 3.0 billion yuan and a farmer income of 150–300 thousand yuan·ha^{-1}[2]. Notably, garlic production is extremely resource-intensive: it requires more than 500 kL·ha^{-1} of irrigation water and 450 kg·ha^{-1} of total nitrogen annually, which is 2–3 times higher than that of other local food crops[8]. Excessive water and fertilizer application has caused severe soil degradation, including compaction and acidification, as well as substantial losses of N and P[9–11]. Specifically, Zou et al.[7] reported that garlic cultivation accounts for 74% of total N and 68% of total P emissions from the agricultural sector of the Basin, with annual losses of 126 and 28 kg·ha^{-1}, respectively, to Erhai Lake. Consequently, persistent eutrophication has occurred, with water quality deteriorating from Class II to Class III (as defined in the Surface Water Quality Standard of China) in some parts of the Lake, threatening both drinking water safety and the sustainability of local tourism[12].

To address this crisis, local authorities have implemented strict policies, including banning garlic cultivation in the core protection zone of the Basin and promoting the use of organic fertilizers since 2019[13,14]. To complement these policies, canola (*Brassica napus*) has emerged as a promising alternative crop, with unique adaptability to the conditions in the Basin: (1) its growth period (November–April) aligns with the dry season, avoiding water competition with summer crops and thriving in the 5–15 °C low-temperature environment to produce high-quality seeds[15]; (2) it has lower resource demand compared with garlic, requiring 60% less irrigation water and a total N input of ⩽300 kg·ha^{-1}[16]; and (3) it improves soil quality: long-term canola cultivation increases soil organic matter content by 12%–15% and reduces soil bulk density by 8%–10%[15], thereby mitigating garlic-induced soil degradation.

Nevertheless, current canola cultivation in the Basin has three critical bottlenecks. The first is single-purpose utilization with over 90% of canola grown solely for oil production, overlooking the economic value of its edible young stems and ornamental flowers. This results in low farmer income (15 thousand yuan·ha^{-1}), which is < 50% of the income from the former garlic cultivation period[17]. The second is inefficient fertilizer management with winter low temperatures limiting the soil organic matter mineralization rate (15%–20%)[2], leading to insufficient available N despite high soil organic matter (72.6 g·kg^{-1}) and total N levels (4.0 g·kg^{-1}). To compensate, farmers apply excessive organic fertilizers, with N input reaching up to 310 kg·ha^{-1} in a conventional organic system, ultimately causing severe soil N and P surpluses (176 and 75 kg·ha^{-1}, respectively) and associated environmental risks[7]. The third is low water use efficiency with 80% of canola fields needing flood irrigation, resulting in an irrigation water use efficiency (IWUE) of only 0.8–1.2 kg·kL^{-1}. This not only wastes scarce dry-season water but also accelerates nutrient leaching[8].

While the oil-vegetable dual-use canola model has boosted economic benefits by 30%–40% in the Yangtze River Basin compared with single-purpose canola cultivation[18–20], existing studies focus primarily on mild-climate plain regions and fail to account for adaptation to plateau lake basins, particularly the integration of canola-flower tourism value into a multipurpose vegetable-flower-oil system. Notably, the Erhai Lake Basin is a world-renowned tourist destination, where its vibrant spring flower landscapes serve as a primary driver of tourism, attracting millions of visitors and generating substantial annual revenue[2,5]. Leveraging this tourism potential, a multipurpose vegetable-flower-oil canola system, combining edible young stems, ornamental flowers and oil seeds, thus has the potential to synergize ecological, economic and social benefits[21,22].

Against this backdrop, this study aimed to address the challenges of canola cultivation in the Erhai Lake Basin, a world-famous tourist destination, and establish a green, high-value cropping system that also aligns with local agritourism needs. Based on three core technical improvements, including the selection of the multipurpose cultivar Yunyouza No. 15 for both yield and floral performance, fertilizer optimization using organic-inorganic blends or mineral fertilizers to replace pure organic fertilizers, and water-saving irrigation with drip irrigation instead of flood irrigation, this study further integrated the mechanical direct seeding of supporting technologies adapted to different planting scales.

A field experiment was conducted from 2022 to 2024 to assess five canola cropping systems designated as: control (CK), conventional organic (CO), organic optimization (OR), green product (GR) and ecological (EC). Key indicators were measured to evaluate system performance, including young stem and seed yields (for production value), floral traits (flower number and flowering duration, which are needed for supporting agritourism), nitrogen and phosphorus-use efficiency (NUE and PUE, respectively), IWUE, soil N and P surpluses (for environmental protection), and economic benefits. The entropy-weighted TOPSIS method was applied to comprehensively evaluate performance (focused on yield, economic and environmental metrics) and screen the optimal system for large-scale promotion.

This study not only provides technical support for the agricultural green transformation of the Erhai Lake Basin but also offers a solution to synergize crop production with local agritourism, serving as a reference for agricultural ecosystems in similar plateau lake regions worldwide.

2 Materials and methods

2.1 Experimental site

This experiment was conducted from November 2022 to April

2024 at the core experimental station of the Erhai Academy of Agriculture Green Development (eAGD), located in Gusheng Village, Wanqiao Town, Dali City, Yunnan Province (within the Erhai Lake Basin). The experimental site was equipped with a functional irrigation system, enabling precise control of flood and drip irrigation treatments and thus eliminating interference from uneven natural water availability. The study region features a typical low-latitude plateau subtropical southwest monsoon climate, an altitude of 980 m, a mean annual temperature of 14.6 °C, and a mean annual precipitation of 1048 mm. During the 2022–2024 canola growing season (November–April), mean temperatures and monthly total precipitation was shown in Fig.1. No extreme frost events occurred during this period, which is consistent with the typical dry-season conditions of the Erhai Lake Basin.

The soil at the experimental site is classified locally as dark brown soil. Prior to canola sowing (October 2022), soil samples from the 0–20 cm layer were collected using an S-shaped sampling method: 5–6 individual samples were collected across the field and mixed thoroughly to form a single composite sample for subsequent analysis. Key physical and chemical properties of the soil were: soil pH 7.2, soil organic matter content 72.6 $g \cdot kg^{-1}$, total N 4.0 $g \cdot kg^{-1}$, alkali-hydrolyzable N 453.5 $mg \cdot kg^{-1}$, available P 182.2 $mg \cdot kg^{-1}$, and available K 85.6 $mg \cdot kg^{-1}$. The previous crop was rice, which was harvested in October 2022. This rice-canola rotation is the most common cropping system in the Erhai Lake Basin, a practice that avoids potential residual effects from fertilizers or crop residues of the previous season.

2.2 Experimental design

Five canola cropping systems were evaluated, including CK, CO, OR, GR and EC. The canola cultivar used was Yunyouza No. 15, a multipurpose cultivar well-adapted to the conditions in the Basin, supporting utilization the vegetable-flower-oil elements (i.e., edible young stems, ornamental flowers and oilseeds), which aligned with the core objectives of our study. A randomized complete block design was adopted, with each treatment having 3–4 replicates. Each experimental plot covered 210 m^2 (7 m × 30 m) and was separated by 0.3-m wide ridges to prevent cross-contamination of irrigation water and fertilizers. Details of sowing and field management are as follows:

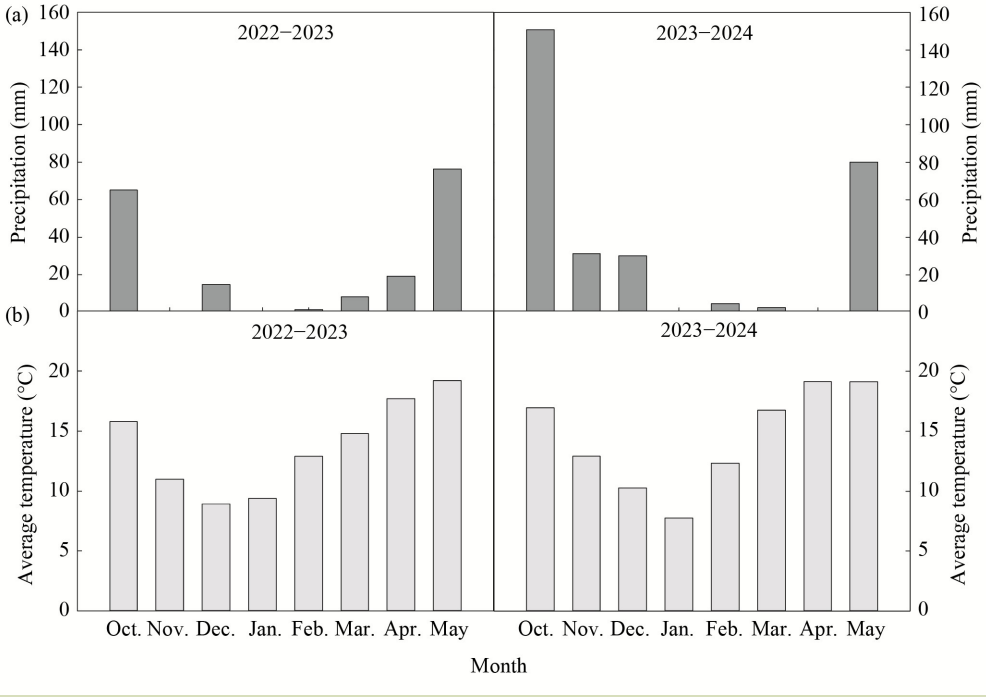


Fig. 1 Monthly total precipitation (a) and average temperature (b) at the study site in 2022–2024.

2.2.1 Sowing methods and timing

CK and CO were established by broadcast sowing on 10 November 2022 and 15 November 2023, with a seeding rate of 6.0 kg·ha^{-1}. OR, GR, and EC were conducted in a wide-narrow row configuration (25–45–25 cm): sown on 10 November 2022 and 15 November 2023, with a seeding rate of 4.5 kg·ha^{-1}.

2.2.2 Harvest management

All treatments were harvested for seeds on 30 April 2023 and 27 April 2024. Young stem harvests differed by establishment method: In 2022–2023, CO had no harvests of young stems, while the other treatments had one harvest. In 2023–2024, EC had two harvests, and the other treatments had one harvest. After each young stem harvest, 4–5 lower leaves were retained to ensure subsequent plant growth and development.

2.2.3 Water and pest management

2.2.3.1 Irrigation

CK and CO used flood irrigation (total irrigation volume: 2610 kL·ha^{-1} during the growing season), consistent with local conventional practices. OR, GR and EC used drip irrigation (total irrigation volume: 1710 kL·ha^{-1}) combined with fertigation, to precisely regulate water and nutrient supply (aligning with the water-saving objectives of our study).

2.2.3.2 Pest control

CK and CO followed local standard practices: 10% imidacloprid wettable powder at 20 g·ha^{-1} for aphid control and 75% chlorothalonil wettable powder at 300 g·ha^{-1} for sclerotinia prevention. OR, GR and EC used environmentally-friendly pest management: 0.3% matrine aqueous solution at 500 mL·ha^{-1} for aphids, *Bacillus thuringiensis* wettable powder at 150 g·ha^{-1} for cabbage loopers.

2.2.4 Fertilizer management

All treatments (except CK) had a basal and a supplementary (5-leaf stage) fertilizer applications. The specific protocols for each treatment were as follows.

CK: no fertilizer application.

CO: total NPK input of 311, 81.8 and 208 kg·ha^{-1}, respectively, with basal NPK application of 180, 52 and 126 kg·ha^{-1}, respectively, applied as organic fertilizer (2.74% N, 0.48% P and 1.48% K; Yunnan Yunye Fertilizer Co., Ltd. (Kunming, China)) at 3.75 t·ha^{-1} and microbial fertilizer (NPK of 3.46%, 1.52% and 3.13%, respectively; Yunnan Yunye Fertilizer Co., Ltd.) at 2.25 t·ha^{-1}, and supplementary application (5-leaf stage) of organic water-soluble fertilizer (NPK of 61.5, 14.0 and 39.0 g·L^{-1}, respectively; Yunnan Yunye Fertilizer Co., Ltd.) supplying NPK of 73.5, 17.0 and 47.3 kg·ha^{-1}, respectively.

OR: total NPK input of 270, 42.6 and 93.4 kg·ha^{-1}, respectively, with basal NPK application of 180, 21.6 and 36.1 kg·ha^{-1}, respectively, applied as oil cake organic fertilizer (NPK of 5.54%, 0.65% and 1.12%, respectively; Yunnan Yunye Fertilizer Co., Ltd.), and supplementary application of organic water-soluble fertilizer (NPK of 61.5, 14.0 and 39.0 g·L^{-1}, respectively; Yunnan Yunye Fertilizer Co., Ltd.) supplying NPK of 45.0, 10.5 and 28.6 kg·ha^{-1}, respectively.

GR: a system using organic-inorganic blended fertilizer (with ⩾50% N from the organic fertilizers) designed for green production with total NPK of 270, 58.3 and 117 kg·ha^{-1}, respectively, with a basal NPK application of 180, 42.6 and 74.7 kg·ha^{-1}, respectively, applied as green intelligent organic-inorganic compound fertilizer (NPK of 7.5%, 1.8% and 3.11%, respectively; Yuntianhua Co. (Kunming, China)) at 2.4 t·ha^{-1}, and supplementary application of urea supplying 22.5 kg·ha^{-1} N plus organic water-soluble fertilizer (NPK of 61.5, 14.0 and 39.0 g·L^{-1}, respectively; Yunnan Yunye Fertilizer Co., Ltd.) supplying NPK of 7.5, 5.2 and 13.7 kg·ha^{-1}, respectively.

EC: a low-input system using mineral fertilizers, designed to minimize environmental risk while maintaining yield with total NPK input of 270, 32.7 and 74.7 kg·ha^{-1}, respectively, with a basal NPK application of 180, 32.7 and 62.3 kg·ha^{-1}, respectively, applied as compound fertilizer (NPK of 15.0%, 6.6% and 12.5%, respectively) at 500 kg·ha^{-1}), urea at 228 kg·ha^{-1} and boron fertilizer at 15 kg·ha^{-1}, and supplementary application of urea supplying 45 kg N·ha^{-1}.

Summary information on total nutrient inputs (NPK), fertilizer types (e.g., organic fertilizer and microbial fertilizer for CO, canola meal for OR, organic-inorganic blends for GR and bulk blended fertilizers for EC) and other field management practices for each treatment is given in Table 1.

2.2.5 Experimental design changes over two seasons

To systematically evaluate the multipurpose vegetable-flower-

Table 1 Summary of management under different cropping system treatments for canola cv Yunyouza No. 15

Cropping system designation	Seeding method	Total NPK applied ($kg \cdot ha^{-1}$)	Fertilizer type	Irrigation method	Irrigation quantity ($kL \cdot ha^{-1}$)
Control (CK)	Broadcast	0, 0 and 0	None	Flood	2610
Conventional organic (CO)	Broadcast	311, 81.8 and 208	Organic fertilizer and microbial fertilizer	Flood	2610
Organic optimization (OR)	Direct	270, 42.6 and 93.4	Canola meal	Drip	1710
Green production (GR)	Direct	270, 58.3 and 117	Organic-inorganic fertilizer (with ⩾ 50% N in the organic source)	Drip	1710
Ecological (EC)	Direct	270, 32.7 and 74.7	Bulk blended fertilizer	Drip	1710

oil canola system under realistic production conditions, the experimental protocol was progressively refined from the first to the second growing season. In 2022–2023, the primary objective was to establish a baseline assessment: treatments CK and CO followed standard seed-only management without young stem harvesting, representing the common local practices. Meanwhile, the optimized treatments (OR, GR and EC) were harvested once for young stems to test the basic feasibility of multifunctional production. In 2023–2024, based on the encouraging results obtained from the first year, the protocol was advanced to fully capture the vegetable-flower-oil potential of the system. Specifically, (1) young stem harvesting was extended to all five treatments (including CK and CO) to enable a more equitable comparison of multifunctional performance; (2) the EC treatment was allowed to receive two harvests to explore the upper limit of vegetable yield without compromising subsequent seed production; and (3) IWUE was not determined in the second year because the water content of fresh young stems was not measured at harvest (as described above for dry-weight conversion). This stepwise, adaptive design reflects a reasoned optimization of the experimental protocol rather than an inconsistency and provides a robust basis for evaluating system performance across contrasting harvest regimes.

2.3 Measurements and methods

2.3.1 Basic soil physicochemical properties

Prior to canola basal fertilizer application, soil samples from the 0–20 cm plow layer were collected via stratified S-shaped sampling: 5–6 representative points were selected, subsamples mixed into a composite sample, then air-dried, ground, and sieved (2 mm) to remove debris (e.g., plant roots and stones) for analysis.

Soil pH was determined in a 1:2.5 (w/v, soil: deionized water) suspension using a glass electrode[23]. Soil organic matter (SOM) was analyzed via potassium dichromate external heating oxidation[23], with a 1.1 correction factor for organic carbon-to-SOM conversion. Total nitrogen was measured by semi-micro Kjeldahl method[23]: samples digested with concentrated H_2SO_4 and $CuSO_4$-K_2SO_4 catalyst, then distilled and titrated with standard HCl.

Alkali-hydrolyzable nitrogen was determined via alkali diffusion[23]: soil incubated with 1.0 $mol \cdot L^{-1}$ NaOH, released NH_3 absorbed by boric acid, and titrated with standard H_2SO_4. Available phosphorus was extracted with 0.5 $mol \cdot L^{-1}$ $NaHCO_3$ (pH 8.5) and quantified via molybdenum-antimony colorimetry (UV-1800, Shimadzu, Kyoto, Japan) at 700 nm[23]. Available potassium was extracted with 1.0 $mol \cdot L^{-1}$ CH_3COONH_4 (pH 7.0) and determined by flame photometry[23]. All methods followed Soil Agricultural Chemistry Analysis for consistency[23].

2.3.2 Young stem yield and components

During the budding-bolting stage (canola plant height of 35–40 cm), the upper edible segment of the main stem (15–25 cm in length) was harvested using specialized pruning shears. For each plant, 4–5 lower leaves were retained to promote lateral branch regrowth and ensure subsequent vegetative and reproductive development. For each treatment, three replicate sampling subplots (7.5 m^2 each, randomly assigned within the main plot) were established to determine young stem traits and yield.

Immediately postharvest, fresh young stems were measured for the following traits: stem diameter measured at the midpoint of

the harvested segment using a digital caliper (precision: 0.01 mm), number of attached leaves per stem; single-stem fresh weight determined using an electronic balance (precision: 0.01 g), and stem length measured using a ruler (1 mm precision).

Young stem yield (kg·ha^{-1}) was calculated by scaling the total fresh weight of harvested stems from the sampling subplots to per-ha basis, accounting for the ratio of the sampling subplot area to the total main plot area.

2.3.3 Canola seed yield and yield components

At physiological maturity, canola seed yield and yield components were determined for each experimental plot.

2.3.3.1 Yield component analysis

Ten representative plants were randomly sampled from each plot to measure the following traits: total number of branches per plant, total number of pods per plant, number of grains per pod and 1000-grain weight.

For 1000-grain weight determination, seeds from the sampled plants were air-dried to a constant moisture content. After counting 1000 intact seeds with a seed counter and the seeds were weighed using an electronic balance (0.01 g precision).

2.3.3.2 Plot-level seed yield

A representative 10 m^2 sampling subplot was randomly established in each main plot. All canola plants within this subplot were harvested, threshed, and the seeds were cleaned, air-dried and weighed. Plot-level seed yield was then scaled to per-ha basis (kg·ha^{-1}).

2.3.4 Nitrogen and phosphorus use efficiency

NUE and PUE were calculated using the difference in aboveground crop nutrient accumulation between fertilized and non-fertilized (control) treatments. Detailed procedures for determining key parameters are outlined below.

2.3.4.1 Aboveground crop nutrient accumulation determination

At canola physiological maturity, aboveground nutrient (N and P) accumulation was measured for each treatment. At canola physiological maturity, 10 representative canola plants were randomly selected from each main plot. These plants were used to determine both yield components and aboveground nutrient accumulation. After harvest, they were manually separated into three components: stems, pod shells and seeds. These components were oven-dried at 75 °C to a constant weight, then ground and passed through a 0.25 mm sieve for nutrient analysis.

Total N content of each plant component was determined via the semi-micro Kjeldahl method (consistent the soil TN analysis described above). Total P content was measured via the molybdenum yellow colorimetric method. Both methods followed protocols in Soil Agricultural Chemistry Analysis[23] to ensure consistency with soil nutrient analysis procedures. Aboveground nutrient (N and P) accumulation (kg·ha^{-1}) for each treatment was calculated as the sum of nutrient uptake by all plant components: this was computed by multiplying the dry weight of each component (stems, pod shells and seeds) by its corresponding nutrient (N and P) content, then scaling the total to a per-ha basis.

2.3.4.2 NUE and PUE calculation

NUE and PUE were computed using the following formulas:

$$UE = \frac{U_X - U_0}{F_X} \times 100\% \quad (1)$$

where, UE is either NUE or PUE depending on N or P, with U_X being total aboveground N or P accumulation (kg·ha^{-1}), U_0 is the total aboveground N or P accumulation (kg·ha^{-1}) of canola in the non-fertilized control (CK, no N input), and F_X is the total N or P input from applied fertilizers in each treatment as detailed in Table 1.

2.3.5 Irrigation water use efficiency

IWUE (kg·kL^{-1}) was calculated to evaluate water use efficiency for canola production. The method was adapted from Ünlü et al.[24] to match the multipurpose vegetable-flower-oil canola system of this study (accounting for both young stem and seed yields, with consistent dry weight metrics to avoid moisture interference). As the water content of the young stems was not determined in the second year, the water use efficiency data for that year are unavailable.

2.3.5.1 IWUE calculation formula

IWUE (kg·kL^{-1}) was computed as follows, with total economic

yield integrates dry weights of both products to standardize the yield metric:

$$\text{IWUE} = \frac{Y_{\text{total}}}{I} \quad (2)$$

where, Y_{total} is the total economic yield of canola (kg·ha^{-1}), defined as the sum of dry young stem yield and dry seed yield, and I is the total irrigation amount applied per ha during the entire canola growing season (November 2022 to April 2023, kL·ha^{-1}).

Dry young stem yield was determined by fresh young stem sampling with a representative subsample of approximately 200 g taken from each fresh sample, killed at 105 °C for 30 min, then oven-dried at 75 °C to constant weight. Dry weight was scaled to per-ha yield based on the fresh-to-dry weight ratio of the subsample.

This dry-weight integration aligns with the focus of our study on a multipurpose system, as it eliminates yield bias from variable moisture content in fresh young stems, ensuring accurate IWUE comparison across treatments.

2.3.5.2 Total irrigation amount determination

Irrigation amount was measured differently based on the irrigation method, ensuring accuracy for each treatment: For flood irrigation treatments (CK and CO), the irrigation volume was measured by a pre-calibrated water meter installed at the inlet of each border plot. The total water volume recorded for each plot was subsequently converted to per-ha equivalent. Drip irrigation (OR, GR and EC): A flow meter was installed at the inlet of the drip irrigation system in each plot to record irrigation volume in real time. Specific total irrigation amounts for each treatment are provided in Table 1: 2610 kL·ha^{-1} for flood irrigation (CK, CO) and 1710 kL·ha^{-1} for drip irrigation (OR, GR and EC).

2.3.6 Apparent nitrogen and phosphorus balance

The apparent N and P balance was calculated to evaluate the potential environmental risk of nutrient surpluses in farmland under different cropping systems. This analysis focused on two core factors, fertilizer nutrient input and crop nutrient removal, while non-harvest losses (e.g., leaching, volatilization and runoff) were temporarily ignored. This approach prioritized clarifying the basic nutrient balance between input and crop uptake, which is foundational for optimizing local fertilizer application practices.

The apparent N and P balances (kg·ha^{-1}) was computed as the difference between total fertilizer nutrient input and aboveground crop nutrient accumulation (the main nutrient removal pathway via harvesting). The formulas are as follows:

$$\begin{aligned}&\text{Apparent N or P balances} = \text{Total fertilizer N or P input}\\&-\text{Canola aboveground N or P accumulation}\end{aligned} \quad (3)$$

$$\begin{aligned}&\text{Canola aboveground N or P accumulation}\\&=(\text{Stem biomass}\times\text{Stem N or P content})+\\&(\text{Pod shell biomass}\times\text{Pod shell N or P content})\\&+(\text{Seed biomass}\times\text{Seed N or P content})\end{aligned} \quad (4)$$

Total fertilizer N and P inputs were calculated based on three factors for each treatment: fertilizer type, application rate (kg·ha^{-1}) and nutrient content (%) (detailed in Table 1). The specific calculation was:

$$\begin{aligned}&\text{Total N or P input} = \text{Fertilizer application rate}\\&\times\text{Fertilizer N or P content}\end{aligned} \quad (5)$$

The aboveground biomass and N and P contents were determination by the same protocol as the aboveground nutrient accumulation analysis given above.

At canola physiological maturity, 10 representative canola plants were randomly selected from each main plot. These plants were separated into stems, pod shells and seeds, then oven-dried at 75 °C to constant weight (biomass was converted to kg·ha^{-1}). Dried samples were ground, passed through a 0.25 mm sieve and digested via H_2SO_4-H_2O_2 wet digestion. Total N content was measured using the semi-micro Kjeldahl method and total P content via the molybdenum yellow colorimetric method, both following protocols in Soil Agricultural Chemistry Analysis[23], ensuring consistency with other nutrient-related measurements in this study.

Positive apparent N or P balances indicate nutrient surpluses (implying potential risk of environmental loss, e.g., N or P leaching to water bodies). Negative values indicate nutrient deficit (indicating possible depletion of soil nutrients).

2.3.7 Economic benefits

Economic benefits were calculated to quantify the profitability of the multipurpose vegetable-flower-oil canola system. All

economic data were collected based on local agricultural production practices in the Erhai Lake Basin (2022–2024), with raw values in the local currency (yuan).

Economic benefits (yuan·ha^{-1}) were computed as:

$$\text{Economic benefits} = (\text{Young stem output value} + \text{Canola seed output value}) - \text{Total production cost} \quad (6)$$

Young stem output value (yuan·ha^{-1}) was calculated as:

$$\text{Young stem output value} = \text{Fresh young stem yield} \times \text{Local average market price} \quad (7)$$

Fresh young stem yield (kg·ha^{-1}) was determined as above. Local average market price was deemed to be 5.5 yuan·kg^{-1} (based on agricultural product market data from Dali City).

Canola seed output value was calculated as canola seed output value = dry seed yield (kg·ha^{-1}) × local average purchasing price. Dry seed yield was determined as above. Local average purchasing price was deemed to be 7.0 yuan·kg^{-1} (sourced from the Yunnan Provincial Grain and Oil Association (Kunming, China)).

Total production costs included seeds (seedlings), fertilizers, pesticides, plastic films, drip irrigation tape, labor costs and agricultural machinery costs. Total production cost included all direct and indirect costs, varying by treatment based on management practices.

2.3.8 Flowering traits (flowering days and flower quantity)

Flowering traits were measured to evaluate the ornamental value of canola flowers, a key component of the vegetable-flower-oil system, with relevance to potential agritourism integration, aligning with the tourism-driven agricultural development needs in the Erhai Lake Basin.

Flowering duration was defined as the period from 30% initial flowering (≥ 3 open flowers per plant across 30% of the plants in the plot) to 90% flower senescence (petals fallen and no remaining ornamental value). Observations were conducted every 2 days from early February 2023 (first flower appearance) until full senescence. For each plot, three representative 1 m^2 sampling subplots were established; within each subplot, the number of flowering and senesced plants was counted to determine the timestamps of 30% initial flowering and 90% senescence. Flowering duration (day) was calculated as the interval between these two timestamps.

Floral abundance, a critical determinant of landscape appeal for tourism, was estimated as flower quantity (flowers ha^{-1}). Direct flower counting at peak bloom was logistically impractical for a large-scale field experiment. Therefore, the total number of siliques per plant was used as a robust proxy for flower number, based on the established on a one-flower-one-silique relationship in oilseed rape, provided that post-anthesis abortion was negligible in our study conditions.

At physiological maturity, for each of the three replicate plots per treatment, ten representative plants were randomly selected. The total number of pods on each plant was counted. The mean number of pods per plant was calculated for each replicate plot.

Flower quantity (flowers ha^{-1}) was then estimated as:

$$\text{Flower quantity} = \text{Mean pods number per plant} \times \text{Actual plant density per hectare} \quad (8)$$

2.3.9 Evaluation of green and high-value canola cropping system based on the entropy-weighted TOPSIS model

2.3.9.1 Selection of green and high-value evaluation indicators for canola cropping system

To develop canola cropping systems integrating green production and high value, a scientific and systematic indicator system was established to comprehensively evaluate the performance of four cropping system categories (CO, OR, GR and EC). This evaluation adhered to the principles of systematicity (covering core dimensions of green production and economic value), operability (all indicators quantifiable via prior measurements) and objectivity (avoiding subjective weighting bias), aligning with the dual goals of the multipurpose vegetable-flower-oil canola system.

A two-tiered indicator system was constructed to reflect the dual objectives of green (resource efficiency + environmental safety) and high value (economic profitability + output efficiency) for canola cropping systems. Details of the indicator system (including primary indicators, secondary indicators, indicator numbers, and indicator types [positive/negative]) are given in Table 2.

2.3.9.2 Determination of indicator weights for green and high-value evaluation of canola cropping systems

To ensure the objectivity of comprehensive evaluation (for

reliable comparisons of four cropping systems), the entropy weight method was adopted to assign weights to 13 evaluation indicators (Table 2). This method avoids subjective bias from artificial weighting, a key advantage for multidimensional green-production plus high-value evaluation, especially for balancing dimensional differences between indicators, for example, resource efficiency indices such as IWUE (kg·kL^{-1}) and economic indices like economic benefits (yuan·ha^{-1}).

The calculation followed four steps: (1) standardization of raw data (to eliminate interference from inconsistent dimensions and indicator attribute orientations); (2) calculation of indicator proportion (to reflect sample importance within each indicator); (3) computation of indicator entropy (to quantify information disorder, where lower entropy indicates stronger discrimination); and (4) derivation of entropy weights (to reflect the relative contribution of each indicator to comprehensive evaluation). Detailed calculation formulas, symbol definitions and parameter settings (e.g., constant ε to avoid calculation errors) are provided in supplementary materials.

2.3.9.3 Construction and application of the TOPSIS model

TOPSIS[25], a widely used multi-criteria decision-making method, was combined with the entropy weight method (as given above) to rank the four cropping systems. This integration avoided subjective weighting bias, ensuring balanced evaluation of dual objectives: green production (e.g., resource efficiency and reduced nutrient surpluses) and high value (e.g., dual yields of young stems/seeds and economic benefits), core goals of the vegetable-flower-oil canola system. Model application included three key steps (adapted from Duan et al.[26]; detailed calculation formulas and symbol definitions for each step, including relative closeness (C_i), are provided in supplementary materials): (1) weighted standardization by applying entropy weights to standardized indicator data to form a weighted matrix, reflecting the contribution of each indicator to comprehensive evaluation; (2) reference solution definition by determining the ideal solution (maximum value of each weighted indicator) and negative-ideal solution (minimum value of each weighted indicator) as performance benchmarks; and (3) C_i determined by computing Euclidean distances between each management practice and the two reference solutions, then deriving C_i (on 0–1 scale) with a higher C_i indicating closer proximity to the ideal solution, representing better comprehensive performance.

2.4 Statistical analyses

All experimental data (e.g., yield, nutrient efficiency, economic benefits and flowering traits) were analyzed using SPSS Statistics 17.0 (SPSS Inc., Chicago, IL, USA). One-way ANOVA was performed, with LSD post-hoc tests for multiple

Table 2 Evaluation indicators for green and high-value objective

Primary indicator	Secondary indicator	Indicator No.	Indicator type
Green	Irrigation water use efficiency	1	Positive
	Nitrogen use efficiency	2	Positive
	Phosphorus use efficiency	3	Positive
	Apparent N surplus	4	Negative
	Apparent P surplus	5	Negative
High value	Fresh young stem (bolt) yield	6	Positive
	Dry seed yield	7	Positive
	Young stem (bolt) output value	8	Positive
	Seed output value	9	Positive
	Total output value	10	Positive
	Total production cost	11	Negative
	Economic benefits	12	Positive
	Input-output ratio	13	Positive

comparisons at $P < 0.05$. Entropy weights of the 13 evaluation indicators (Table 2) and TOPSIS-based C_i were calculated using Microsoft Excel (Microsoft Corporation, Redmond, WA, USA). All figures (for visualizing core results, e.g., treatment differences in nutrient use efficiency or economic benefits) were generated using SigmaPlot 12.5 (Systat Software, San Jose, CA, USA).

3 Results

3.1 Young stem yield under different cropping systems

In the first year (2022–2023), CK and CO focused solely on seed production without young stem harvesting. The optimized systems (OR, GR, and EC) were designed for vegetable-oil dual use, and all treatments were direct-seeded. Among them, EC achieved the highest young stem yield (3140 kg·ha^{-1}), significantly higher than OR (1220 kg·ha^{-1}) and GR (1930 kg·ha^{-1}) ($P < 0.05$). The increase was 159% compared to OR and 63.3% compared to GR.

In the second year (2023–2024), EC was harvested twice, while all other treatments (CK, CO, OR and GR) were harvested once. EC produced the highest young stem yield (6910 kg·ha^{-1}), far exceeding the other treatments, which ranged from 896 (CK) to 1500 (GR) kg·ha^{-1} (Table 3).

In both years, EC gave the highest single young stem weight and young stem diameter among all treatments (e.g., 27.5 g and 9.3 mm in 2022–2023; 35.4 g and 10.1 mm in 2023–2024), which likely contributed to its superior yield.

3.2 Growth period and phenological characteristics of canola under different cropping systems

Phenological dynamics of canola across five management patterns (CK, CO, OR, GR and EC) are given in Table 4, with obvious phenological variations between growing seasons and treatments.

In the 2022–2023 season, CK and CO were sown on 15 November without stem picking. CK growth finished in 147 days whereas CO had uniformly delayed phenological stages and a 156-day growth cycle. OR, GR and EC were direct-seeded on 10 November and allowed stem harvesting; OR had the longest growth cycle (167 days), and GR and EC had identical phenological schedules and a 161-day growth cycle, with distinctly longer flowering duration than CO. In contrast, all treatments were sown uniformly on 1 November in 2023–2024. CK had the shortest growth cycle (135 days). CO, OR and GR had identical 140-day growth cycles and no stem picking operations. Only EC supported two rounds of stem picking, featuring the earliest budding date (15 January), a slightly prolonged 143-day full growth cycle, and the longest flowering window of all treatments.

This phenological divergence supported the multipurpose vegetable-flower-oil goal: systems with stem picking (OR, GR and EC in 2022–2023; solely EC in 2023–2024) reached early

Table 3 Young stem yield components of different canola cropping systems

Year	Cropping system treatment	Seeding or planting method	Single young stem weight (g)	Young stem length (cm)	Young stem diameter (mm)	Number of leaves	Picking yield (kg·ha^{-1})
2022–2023	OR	D	23.5 b	35.7 a	7.7 b	2.4 b	1220 b
	GR	D	34.2 a	34.1 a	10.1 a	4.1 a	1930 ab
	EC	D	27.5 ab	31.6 a	9.3 a	3.9 a	3140 a
2023–2024	CK	B	14.6 c	15.8 a	3.7 b	3.1 b	896 b
	CO	B	14.3 c	17.9 a	4.0 b	3.0 b	990 b
	OR	D	17.3 c	20.8 a	4.9 b	4.9 b	984 b
	GR	D	22.6 b	21.4 a	6.0 b	5.3 a	1500 b
	EC	D	35.4 a	23.6 a	10.1 a	5.2 a	6910 a

Note: Data are means ($n = 4$). Means with the same letters in each column are not significantly different ($P < 0.05$). CK, no fertilizer application; OR, organic optimization; GR, green production; EC, ecological; B, broadcast sowing; and D, direct seeding.

Table 4 Growth period under different canola cropping system treatments

Year	Cropping system treatment	Sowing date	Budding stage	Picking first time	Picking Second time	Early flowering	Full bloom	Final flowering period	Horn period	Whole growth period (day)
2022–2023	CK	11/15	2/17	/	/	2/18	3/2	3/10	4/11	147
	CO	11/15	2/25	/	/	3/1	3/15	3/26	4/22	156
	OR	11/10	2/18	/	2/20	2/21	3/10	3/28	4/26	167
	GR	11/10	2/8	/	2/10	2/12	2/27	3/12	4/20	161
	EC	11/10	2/7	/	2/10	2/12	2/27	3/12	4/20	161
2023–2024	CK	11/1	2/4	/	2/10	2/12	2/27	3/5	3/15	135
	CO	11/1	2/5	/	2/10	2/16	2/25	3/8	3/20	140
	OR	11/1	2/2	/	2/10	2/15	2/25	3/8	3/20	140
	GR	11/1	1/30	/	2/10	2/14	2/22	3/10	3/20	140
	EC	11/1	1/15	1/20	2/10	2/12	2/22	3/14	3/23	143

Note: CK, no fertilizer application; CO, conventional organic; OR, organic optimization; GR, green production; and EC, ecological.

budding to enable young stem harvest for vegetable yield without disrupting subsequent reproductive development; GR and EC gave extended flowering periods, which facilitates dry matter accumulation for seed and oil production, and extends floral viewing time to raise agritourism value. EC with optimized nutrient management comprehensively balanced stem harvest potential, prolonged flowering performance and moderate growth cycle length, matching the dual demands for the Erhai Lake Basin of ecological conservation and diversified economic benefits.

3.3 Canola seed yield under different cropping systems

Seed yield and yield components of canola under five cropping patterns (CK, CO, OR, GR and EC) are listed in Table 5, with significant inter-treatment differences ($P < 0.05$).

In both growing seasons, EC produced the maximum seed yield of 4720 kg·ha^{-1} (2022–2023) and 4830 kg·ha^{-1} (2023–2024), significantly exceeding CO (at 2800 and 1150 kg·ha^{-1}, respectively). GR was second in yield, followed by OR, and CK yielded the lowest in both years.

Yield component disparities drove these output gaps. EC had the greatest total pod number per plant and grains per pod in both seasons. GR and OR also had more branches, pods per plant and grains per pod than CO and CK. However, the 1000-grain weight varied significantly among treatments in 2022–2023 (with CO being the highest) but showed no significant differences in 2023–2024. Optimized nutrient regimes of OR, GR and EC boosted branch formation, pod set and grain count per pod, serving as the core drivers of yield elevation. EC provided the most robust yield-building traits and peak seed output over the two seasons.

3.4 Floral traits (flower quantity and flowering duration) of canola: implications for agritourism potential

CO was used as a reference treatment, with significant differences in floral traits observed for EC (Fig. 2). For flower quantity, EC exceeded CO by 134%–342%. Regarding flowering duration, CO had 21–25 days flowering period, whereas EC extended this by 3–10 days to 28–31 days. Notably, the green high-value EC system not only increased flower quantity compared to CO but also prolonged flowering duration, two key traits enhancing agritourism potential. Abundant flowers and a longer ornamental period can attract more agritourism visitors, creating an income stream beyond vegetable-oil production and supporting the sustainability of the system in the Erhai Lake Basin.

3.5 Nitrogen-use efficiency, phosphorus-use efficiency, and irrigation water use efficiency under different cropping systems

CO had the lowest NUE, PUE and IWUE, probably due to

Table 5 Seed yield components of different canola cropping systems

Year	Cropping system treatment	Plant density ($\times 10^4$ plants ha^{-1})	Total number of branches per plant	Total number of pods per plant	Number of grains per pod	1000-grain weight (g)	Seeds yield (kg·ha^{-1})
2022–2023	CK	28.7 b	0.1 b	9.8 b	10.7 c	3.17 b	296 d
	CO	38.5 a	2.4 b	59.4 b	15.2 b	3.73 a	2800 c
	OR	29.0 b	9.2 a	201 a	21.3 a	3.43 ab	3210 bc
	GR	22.1 c	10.6 a	191 a	21.4 a	3.16 b	4060 ab
	EC	31.5 ab	12.0 a	230 a	22.9 a	3.22 ab	4720 a
2023–2024	CK	57.3 c	5.4 b	87.2 c	14.2 a	3.09 a	755 c
	CO	55.3 c	6.7 b	118 bc	16.5 a	3.21 a	1150 bc
	OR	94.7 ab	6.0 b	118 bc	18.6 a	3.29 a	2170 bc
	GR	116 a	7.2 b	151 b	18.1 a	3.30 a	3380 b
	EC	76.3 b	13.5 a	327 a	19.3 a	3.30 a	4830 a

Note: Data are means (n = 4). Means with the same letters in each column are not significantly different (P < 0.05). CK, no fertilizer application; CO, conventional organic; OR, organic optimization; GR, green production; and EC, ecological.

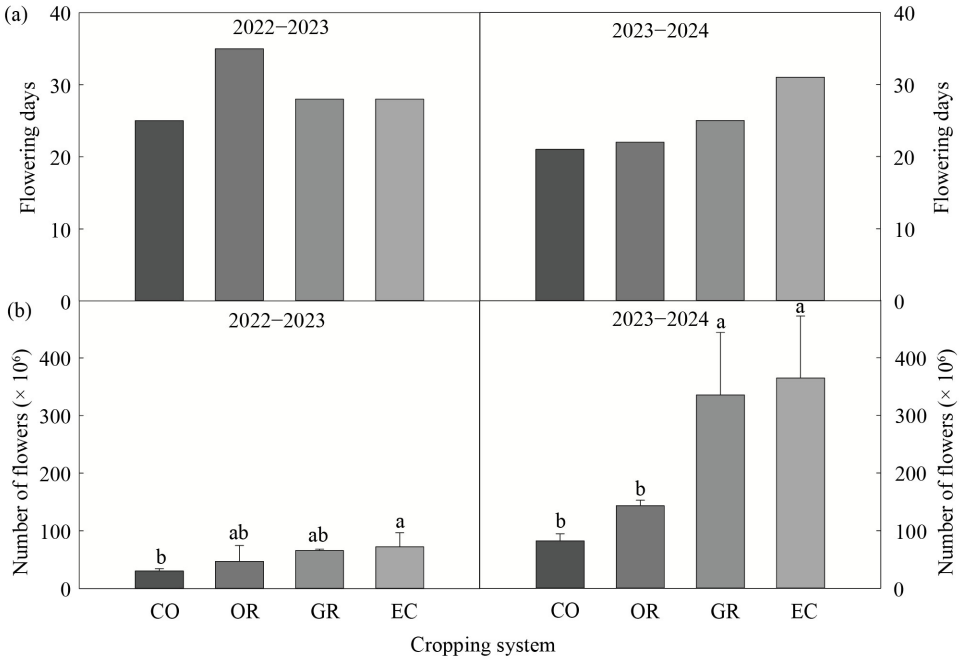


Fig. 2 Flowering days (a) and number of flowers (b) under different canola cropping system treatments. The data of number of flowers are means (n = 4). Means with the same letters in each subfigure are not significantly different (P < 0.05). CO, conventional organic; OR, organic optimization; GR, green production; and EC, ecological.

excessive organic fertilizer input and inefficient flood irrigation (Fig. 3). Optimized direct-seeded treatments (GR and EC) gave significant efficiency improvements compared to CO (P < 0.05). The NUE of GR and EC were 55.7%–112% and

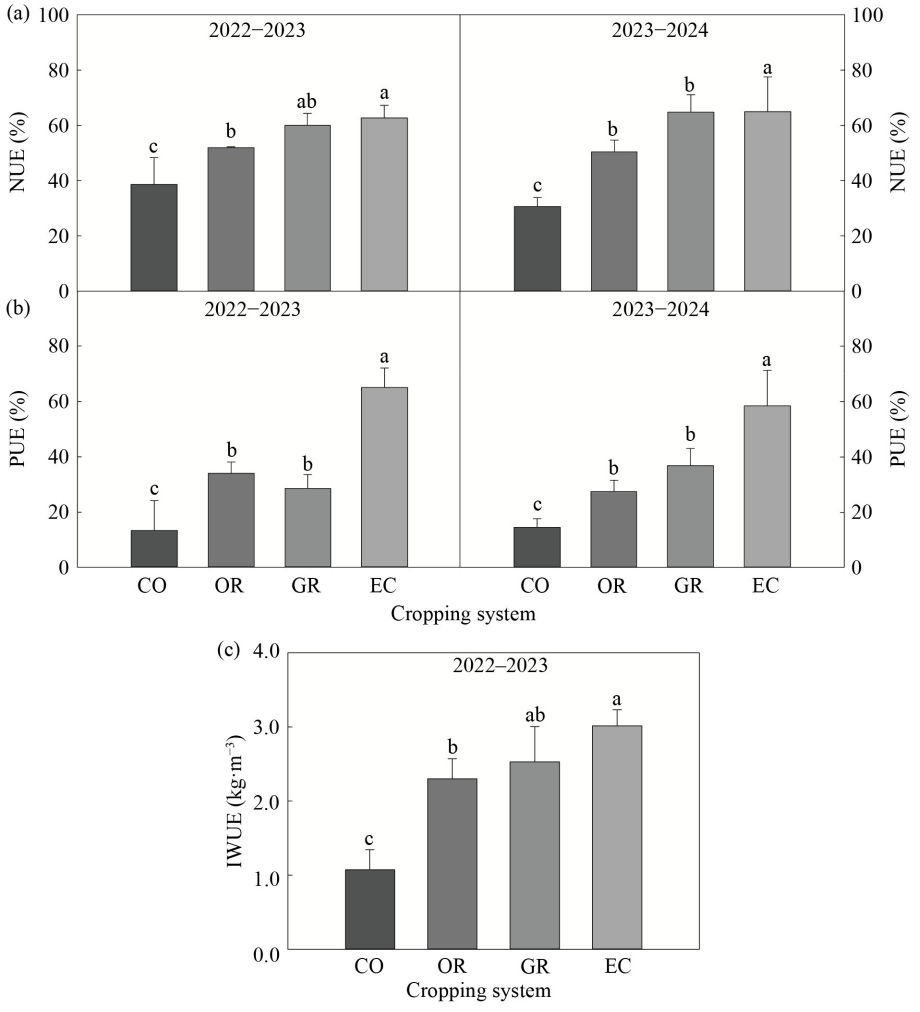


Fig. 3 NUE (a), PUE (b), and IWUE (c) under different cropping system treatments. The data are means with n = 3 for NUE and PUE and n = 4 for IWUE. Means with the same letters in each subfigure are not significantly different (P < 0.05). NUE, nitrogen-use efficiency; PUE, phosphorus-use efficiency; IWUE, irrigation water use efficiency; CO, conventional organic; OR, organic optimization; GR, green production; and EC, ecological.

62.7%–112% higher than CO, respectively (Fig. 3(a)). Compared to CO, GR and EC gave clear increases in PUE, reaching 116%–156% and 305%–392%, respectively, (Fig. 3(b)). The IWUE of GR and EC increased by 134% and 182% compared to CO (Fig. 3(c)), reflecting the water-saving provided by drip irrigation. Overall, EC had the highest PUE and IWUE of all treatments, demonstrating the synergistic effect of direct seeding, optimized fertilizer management and drip irrigation on enhancing resource use efficiency.

3.6 Nitrogen and phosphorus surpluses under different cropping system treatments

CO had the highest N and P surpluses (Fig. 4), primarily due to excessive organic fertilizer input. In the cool winter conditions of Erhai Lake Basin, organic fertilizers have low nutrient release efficiency, leading to unused nutrients accumulating in soil as surpluses. Optimized direct-seeded treatments (GR and EC) had significant surplus reductions compared to CO (P < 0.05): The N surplus of GR and EC were 49.7%–50.2% and 54.1%–57.2% lower than CO, respectively (Fig. 4(a)); Relative

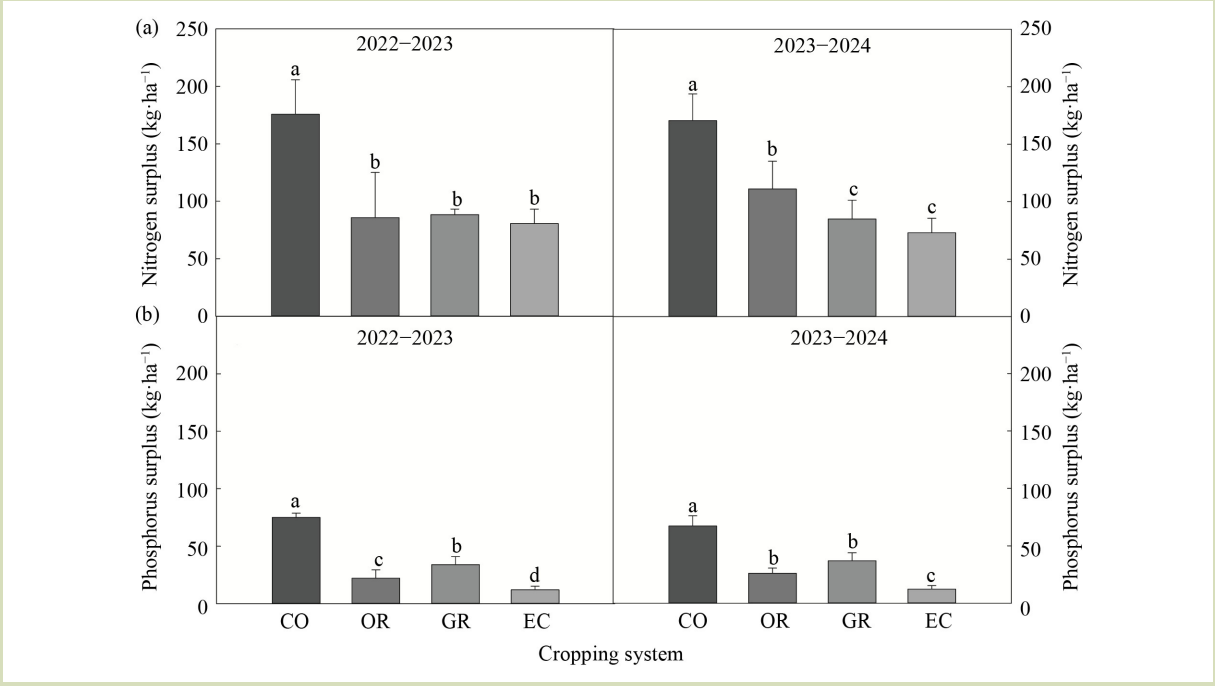


Fig. 4 Nitrogen (a) and phosphorus (b) surpluses under different cropping system treatments. Data are means (n = 3). Means with the same letters in each subfigure are not significantly different (P < 0.05). CO, conventional organic; OR, organic optimization; GR, green production; and EC, ecological.

to CO, GR and EC gave substantial reductions in P surpluses of 44.8%–54.7% and 81.6%–84.0%, respectively, underscoring the efficacy of their P input management strategies (Fig. 4(b)). Overall, EC has the lowest N and P surpluses, demonstrating that the EC could effectively mitigate nutrient surplus risks in the Erhai Lake Basin.

3.7 Production cost, output value and economic benefit under different canola cropping systems

CO was used as the economic baseline, with significant differences in total production cost, total output value, economic benefit and input-output ratio across treatments (Table 6). For total production cost, GR and EC reduced costs by 6.11% and 33.3%–40.8% compared to CO, respectively, attributed to optimized low-cost fertilizers and reduced labor input for direct seeding. In terms of total output value, GR and EC were 99.3%–135% and 157%–433% higher than CO, respectively, benefiting from young stem harvest and higher seed yield. Regarding economic benefit and input-output ratio, GR and EC increased economic benefit by 19.7–21.2 thousand yuan·ha^{-1} and 42.7–67.2 thousand yuan·ha^{-1} compared with CO, respectively. Notably, EC had the lowest production cost, achieved an economic benefit of 33.0–51.3 thousand yuan, and possessed the highest input-output ratio.

3.8 Dynamic shifts in indicator weight distributions between two growing seasons

This study aimed to screen the optimal canola cropping system balancing green production (low nutrient surplus, high resource use efficiency) and high-value multipurpose output (high yield and economic returns). Thirteen evaluation indicators were established for the 2022–2023 season, while 12 indicators were used for 2023–2024 (indicator 1 IWUE was excluded in the second year, Table 7). The entropy weight method was employed to calculate objective indicator weights to avoid subjective bias, and the TOPSIS model was further applied to quantify the comprehensive performance of each cropping system for multi-criteria optimization.

Indicator weight structures varied distinctly between the two

Table 6 Production costs, output value and economic benefits under different canola cropping system treatments

Year	Treatment	Total production cost (yuan·ha^{-1})	Young stem output value (yuan·ha^{-1})	Seed output value (yuan·ha^{-1})	Total output value (yuan·ha^{-1})	Economic benefits (yuan·ha^{-1})	Ratio of output to input
2022–2023	CO	29,245	0	19,576	19,576	–9669	0.67
	OR	32,291	6682	22,464	29,146	–3145	0.90
	GR	27,458	10,586	28,422	39,008	11,550	1.42
	EC	17,307	17,291	33,013	50,304	32,998	2.91
2023–2024	CO	29,245	5444	7836	13,281	–15,965	0.45
	OR	32,291	5410	14,756	20,167	–12,124	0.62
	GR	27,458	8236	22,982	31,218	3760	1.14
	EC	19,507	38,015	32,821	70,836	51,328	3.63

Note: Total production costs include seeds (seedlings), fertilizers, pesticides, plastic films, drip irrigation tape, labor costs and agricultural machinery costs. The average price of young stem was 5.5 yuan·kg^{-1}. The average price of canola seed was 7.0 yuan·kg^{-1}. CO, conventional organic; OR, organic optimization; GR, green production; and EC, ecological. Local market prices (e.g., 5.5 yuan·kg^{-1} for fresh young stems) were average values in 2023 and 2024, sourced from the Dali Agricultural Product Market, to minimize the impact of short-term price fluctuations.

Table 7 Entropy weights and weights of each indicator

Year	Indicator No.												
	1	2	3	4	5	6	7	8	9	10	11	12	13
2022–2023	0.0682	0.0687	0.0741	0.0988	0.0794	0.0708	0.0745	0.0727	0.0808	0.0754	0.0676	0.0863	0.0828
2023–2024	–	0.0446	0.0570	0.0788	0.0621	0.1552	0.0569	0.1552	0.0569	0.0841	0.0432	0.0985	0.1075

Note: Indicators: 1, IWUE; 2, NUE; 3, PUE; 4, N surplus; 5, P surplus; 6, young stem yield; 7, seeds yield; 8, young stem output value; 9, seed output value; 10, total output value; 11, total production cost; 12, economic benefits; and 13, Ratio of output to input.

growing seasons. In 2022–2023, N surplus (Indicator 4, 0.0988) obtained the highest weight, followed by economic benefit (Indicator 12, 0.0863) and input-output ratio (Indicator 13, 0.0828). Resource efficiency indices (NUE, PUE and IWUE) and yield/output indicators occupied moderate, evenly distributed weights. In 2023–2024, young stem yield (Indicator 6) and young stem output value (Indicator 8) tied for the maximum weight (0.155 each), vastly surpassing other metrics; input-output ratio (Indicator 13, 0.1075) and economic benefit (Indicator 12, 0.0985) also had prominent weights.

Across both years, nutrient surpluses, crop yield, output value, economic profit and input-output efficiency formed the core evaluation dimensions. The weight divergence reflected shifting priority constraints seasonally. The first year placed stronger emphasis on nitrogen environmental risk whereas the second year prioritized young stem vegetable production capacity. Overall, this weighting framework accurately fits the dual demands in the Erhai Lake Basin of watershed ecological conservation and stable income growth for local farmers.

3.9 Recommendation of the optimal canola cropping system based on the entropy weight-TOPSIS model

After determining entropy weights and normalizing indicator values to eliminate dimensional discrepancies, we applied the TOPSIS model to compute C_i in the range 0–1, with larger values denoting superior comprehensive performance, for each cropping system in the two growing seasons.

For 2022–2023, the C_i ranking from high to low was EC (0.7498) > GR (0.4645) > OR (0.3470) > CO (0.0366). In 2023–2024, the order remained consistent with EC (0.4989) > GR (0.1983) > OR (0.1291) > CO (0.0176) (Fig. 5). In both years, EC had the highest C_i by a substantial margin, followed by GR and OR. CO had the weakest comprehensive performance with far lower C_i values.

This two-year ranking verified that EC best balanced green production and high multipurpose economic output, with GR

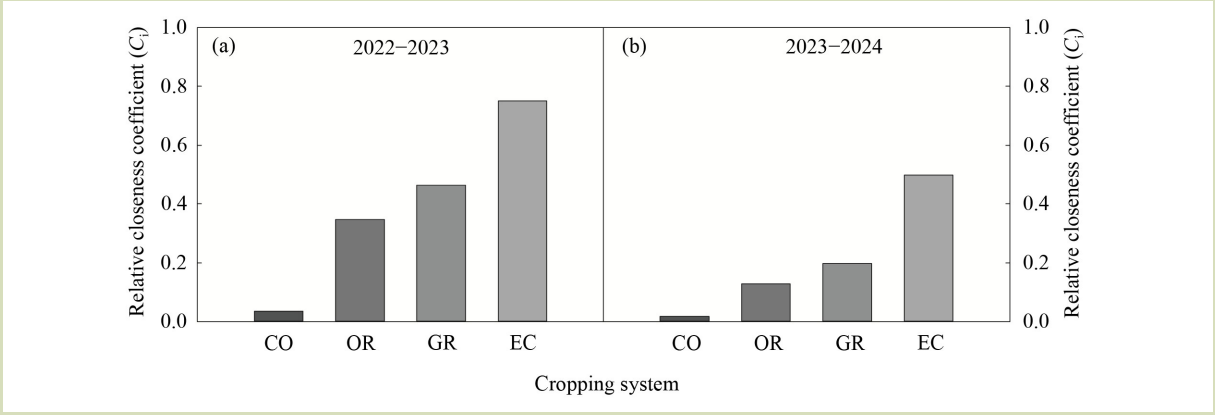


Fig. 5 Relative closeness (C_i) of different canola cropping system treatments in 2022–2023 (a) and 2023–2024 (b). CO, conventional organic; OR, organic optimization; GR, green production; and EC, ecological.

and OR as suboptimal alternatives, while CO lagged greatly in integrated eco-economic benefits. Aligned with demands in the Erhai Lake Basin for mechanized large-scale planting and smallholder cost control, the EC system delivers multiple core merits: reduced N and P surpluses, elevated resource use efficiency, moderate production expenditure and superior input-output efficiency. Its highest TOPSIS score in the two years confirms it has the optimal integrated green high-value capacity, making it the priority cropping system for regional scaled extension.

3.10 Emission reduction and value-added potential of the green high-value canola system in the Erhai Lake Basin

To quantify the practical application potential of EC, we estimated its environmental and economic benefits based on the current canola planting area in the Basin and experimental data (Table 8). Compared to CO system, EC significantly reduced soil N and P surpluses by 54.1%–57.2% and 81.5%–84.0%, respectively. This reduction directly mitigates the risk of agricultural non-point source pollution in Erhai Lake, supporting the water environmental protection strategy in the Basin. Economically, replacing CO with EC across the planting area of the Basin could generate total additional benefits of 50.2–79.1 million yuan. This demonstrates the potential of the system to boost farmer income while adhering to green production principles. The dual benefits of environmental protection and economic growth confirm that EC is a potentially sustainable cropping system worthy of large-scale promotion in the Erhai Lake Basin.

4 Discussion

The Erhai Lake Basin faces a critical trade-off between agricultural economic benefits and ecological security. While garlic cultivation exacerbates eutrophication[2,7], conventional organic canola (CO) fails to balance yield, profitability and

Table 8 Expected emission reduction and value addition of different canola cropping system treatments (all with a planting area of 1175 ha)

Year	Cropping system treatment	Nitrogen surplus (t)	Phosphorus surplus (t)	Total economic benefits (×10^6 yuan)
2022–2023	CO	206	88.1	–11.4
	EC	94.7	14.1	38.8
2023–2024	CO	200	79.0	–18.8
	EC	85.8	14.6	60.3

Note: CO, conventional organic; and EC, ecological.

nutrient loss control. To address this, we developed a multipurpose vegetable-flower-oil canola system and conducted two years of field experiments using a stepwise, adaptive design. In the first year (2022–2023), CK and CO followed standard seed-only practice (no young stem harvest), while OR, GR and EC were harvested once to test basic multifunctional feasibility. In the second year (2023–2024), based on promising first-year results, we advanced the evaluation by extending young stem harvest to all treatments (including CK and CO) and allowing EC to be harvested twice, so as to fully explore the upper limit of the system. Additionally, IWUE was not determined in the second year because the water content of young stems was not measured at harvest. Consequently, the TOPSIS model used 13 indicators for 2022–2023 and 12 indicators (IWUE excluded) for 2023–2024 (Table 7). These differences reflect a reasoned, progressive refinement of the experimental protocol rather than any flaw in design. Importantly, despite the variation in harvest regimes and indicator sets, the EC system consistently ranked first in comprehensive performance across both years (Fig. 5), with C_i of 0.50–0.75. This cross-year consistency strongly supports the robustness of our conclusions.

4.1 Multifunctional yield synergy: balancing vegetable, oil and floral value

The optimized direct-seeded systems, OR, GR and EC, overcome the single-output limitation of CO by enabling coordinated production of young stems, seeds and ornamental flowers. In 2022–2023, where CK and CO had no stem harvest (representing standard practice), EC achieved the highest young stem yield (3140 kg·ha^{-1}) among the harvested treatments, significantly exceeding OR (1220 kg·ha^{-1}) and GR (1930 kg·ha^{-1}) (Table 3). In 2023–2024, after extending young stem harvesting to all treatments for a more equitable comparison, EC with two harvests produced a substantially higher yield (6910 kg·ha^{-1}) than single-harvest treatments (896–1500 kg·ha^{-1}) (Table 3). Notably, despite multiple harvests, EC maintained the highest seed yield in both years (4720 and 4830 kg·ha^{-1}, respectively), exceeding CO (2797 and 1150 kg·ha^{-1}) (Table 5). This synergy, contrary to concerns that stem removal might reduce seed yield[27], is attributed to optimized nutrient management. While CO relied on low-efficiency organic fertilizers that mineralize slowly in cool winters (< 20% mineralization rate)[2], EC used readily available mineral fertilizers (Table 1). This ensured timely nutrient supply during peak demand, sustaining pod development post-harvest[28–30] and improving key yield components, such as more branches and grains per pod (Table 5).

Beyond dual-purpose yields, the EC system significantly enhanced floral tourism value. Compared to CO, EC increased flower abundance by 138%–342% and extended the flowering duration by 3–10 days (Fig. 2). These improvements, observed even in the second year when all treatments were harvested, are attributed to optimized plant density in EC[31,32] and precise drip fertigation[33,34], which supported sustained floral bud differentiation[35]. Thus, EC emerges as a multifunctional solution integrating production, ecology and tourism.

4.2 Resource use efficiency and nutrient surpluses control: the core of green production

Given the policy priority to mitigate non-point source pollution in the Basin[13], high nutrient and water use efficiency, and low environmental surplus are key metrics. Among all treatments, the EC system excelled, achieving the most balanced high-efficiency, low-surplus performance.

In 2022–2023, EC gave markedly superior resource use efficiency compared to CO. It increased NUE by 62.7%–112%, PUE by 306%–392%, and IWUE by 182% (Fig. 3). This synergistic enhancement stems from three integrated innovations. First, optimized fertilizer application with readily available mineral fertilizers circumvented the slow mineralization issue of organic fertilizers in cool winters[36]. Second, drip irrigation reduced total irrigation volume by 34.5% compared to flood irrigation in CO (Table 1), minimizing water waste[37,38] and nutrient leaching[8]. Third, high seed yield in EC ensured maximal nutrient uptake per unit of input. Although IWUE was not measured in 2023–2024 (due to the absence of young stem water content data), the consistent superiority of EC in NUE, PUE, yield and nutrient surpluses across both years strongly indicates its sustained water-saving advantage.

Consequently, EC achieved substantial reductions in nutrient surpluses in both years. Compared to CO, EC reduced N surplus by 54.1%–57.2% and P surplus by 81.6%–84.0% (Fig. 4). This distinct advantage, particularly the lower P surplus compared to GR (which uses organic-inorganic blends), stems from the higher immediate availability of mineral fertilizers in EC, avoiding soil immobilization

associated with organic components[17,39]. Scaling up EC across the 1175 ha of canola (Table 8) in the Basin would cut N surplus by 113 t and P surplus by 69.2 t annually, directly mitigating eutrophication risk[7,40,41].

4.3 Economic viability and comprehensive ranking: guiding farmer adoption

Farmer adoption hinges on economic profitability and operational simplicity[2,42,43]. Using an entropy-weighted TOPSIS model, we evaluated systems with 13 indicators (2022–2023) and 12 indicators (2023–2024, IWUE excluded because young stem water content was not determined) (Table 7). Despite the difference in indicator sets arising from this missing measurement, EC consistently ranked as the optimal system, with the highest C_i of 0.50–0.75 (Fig. 5), followed by GR and OR, while CO ranked last. This consistency across two years with different harvest regimes and indicator sets strongly validates the robustness of the superiority of EC.

From a cost perspective, EC gave the lowest total production cost (17.3–19.5 thousand yuan·ha^{-1}, Table 6), 33.3%–40.8% lower than CO. This cost advantage originates from the use of low-cost bulk mineral fertilizers (Table 1) and the elimination of unnecessary inputs. In terms of economic returns, EC achieved a net benefit of 33.0–51.3 thousand yuan·ha^{-1} (Table 6), contrasting sharply with the economic loss under CO of 9.7–16.0 thousand yuan·ha^{-1}. Although GR also achieved positive returns (3.8–11.6 thousand yuan·ha^{-1}), net benefit of EC was 135%–426% higher. Also, input-output ratio of EC (2.91–3.63, Table 6) substantially exceeded that of GR (1.14–1.42). Notably, in the second year when all treatments were harvested, two harvests in EC further amplified its economic advantage (net benefit of 51.3 vs. 3.76 thousand yuan·ha^{-1} for GR), demonstrating that the dual-harvest design did not compromise but rather enhanced profitability. The TOPSIS model, by integrating multidimensional metrics across both years, provides a robust, farmer-centered rationale for promoting EC as the optimal cropping system.

4.4 Regional adaptability and sustainable development implications

The agricultural landscape of the Erhai Lake Basin is diverse, necessitating tailored cropping systems. EC has strong regional adaptability, particularly for large-scale promotion in main canola-growing areas. Its key advantages, low production cost, high input-output ratio and compatibility with mechanical seeding, align with the needs of large-scale farmers and cooperatives. In addition, significantly enhanced floral traits in EC (Fig. 2) unlock considerable agritourism potential. As quantified above, replacing CO with EC across 1175 ha of the Basin would transform an annual economic loss into a substantial gain of 50.2–79.1 million yuan, while reducing N and P surpluses by about 113 and 69.2 t·yr^{-1}, respectively. This aligns directly with the Three Prohibitions and Four Promotions policy for the Basin[13], positioning EC as a win-win solution for farm income, tourism revenue and Erhai Lake water quality.

4.5 Study limitations and future research directions

Several limitations should be acknowledged. First, the experimental protocol evolved between the two seasons: 2022–2023 did not include young stem harvest for CK and CO (serving as standard controls), whereas 2023–2024 extended harvest to all treatments to enable a fuller assessment of multifunctional performance, with EC receiving two harvests. This stepwise design was intentional, following the logic of adaptive system optimization (as given above); however, it does limit direct statistical comparison of young stem yields across the two years. Second, IWUE could not be calculated for 2023–2024 because the water content of fresh young stems, a necessary parameter for dry-weight conversion, was not measured at harvest. This resulted in an imbalance in the TOPSIS indicator sets (13 vs. 12 indicators). Nevertheless, the fact that EC attained the highest C_i in both years, under different harvest regimes and with slightly different indicator sets, demonstrates that its superiority is not an artifact of a single-year design. Third, the study covered only two growing seasons without extreme weather events, limiting insight into the resilience of EC under climatic stress. Future research should prioritize multi-year trials examining the performance of EC under cold snaps and droughts[44,45]. Also, nutrient surplus calculations were based on input-uptake balances; follow-up work should employ isotope tracing or lysimeter experiments to quantify leaching and volatilization more precisely[46]. Finally, investigating the performance of EC within the dominant canola-rice rotation[47] and its long-term effects on soil carbon sequestration would enhance understanding of its sustainability benefits[48–50]. Despite these limitations, the EC system demonstrates a robust integration of multifunctional yield, high resource efficiency, and economic

viability, offering a sustainable solution for balancing agricultural production and ecological protection in the Erhai Lake Basin and beyond.

5 Conclusions

This study established a multipurpose vegetable-flower-oil canola system for the Erhai Lake Basin. The ecological (EC) system was consistently ranked as the optimal solution by entropy-weighted TOPSIS evaluation. For farmers, EC offers low cost, high input-output efficiency, and mechanical compatibility. For policy makers, adopting EC across the Basin would reduce nutrient surpluses while increasing economic returns. For other plateau lake regions, this model provides a transferable paradigm for sustainable agriculture.

Supplementary materials

The online version of this article at https://doi.org/10.15302/J-FASE-2027738 contains supplementary materials.

Acknowledgements

This study was supported by the Major Science and Technology Project of Yunnan Province, China (202202AE090034) and projects of Science and Technology Department of Yunnan Province, China (202304BQ040005 and 202305AF150055). During the preparation of this work, the authors used AI-assisted tools for language polishing. All content was reviewed and finalized by the authors, who take full responsibility for the published work.

Compliance with ethics guidelines

Jiangtao Wang, Shuntao Zhang, Jing Yang, Kang Wang, Feiyu Ying, Jianwei Lu, Hans Lambers, and Wenfeng Cong declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

REFERENCES

1. Sharpley A, Tunney H. Phosphorus research strategies to meet agricultural and environmental challenges of the 21st Century. *Journal of Environmental Quality*, 2000, **29**(1): 176–181
2. Hou Y, Xu W, Cong W F, Jin K M, Xu J L, Ying H, Wang S R, Sheng H, Yang L Z, Ma W Q, Oenema O, Zhao Z X, Zhang F S. Agricultural green development in the Erhai Lake Basin—the way forward. *Frontiers of Agricultural Science and Engineering*, 2023, **10**(4): 510–517
3. Chen K, Duan L Z, Liu Q, Zhang Y, Zhang X N, Liu F W, Zhang H C. Spatiotemporal changes in water quality parameters and the eutrophication in Lake Erhai of Southwest China. *Water*, 2022, **14**(21): 3398
4. Tian Y S, Shen J, Feng J M, Wang T T, Jiao Y M, Wang X Z. Research advancements on agricultural non-point source pollution in major lake and reservoir watersheds of China: status, sources, monitoring, and prospects. *Ecological Indicators*, 2025, **178**: 113981
5. Yuan Z, Xu J J, Meng X Y, Wang Y Q, Yan B, Hong X F. Impact of climate variability on blue and green water flows in the Erhai Lake Basin of Southwest China. *Water*, 2019, **11**(3): 424
6. An G Y, Guo Z C, Ye P. Climatic changes and impacts on water quality of Erhai Lake in Dali area, Yunnan province over the period from 1989 to 2019. *Geoscience*, 2022, **36**(2): 406–417 (in Chinese)
7. Zou T T, Meng F L, Zhou J C, Ying H, Liu X J, Hou Y, Zhao Z X, Zhang F S, Xu W. Quantifying nitrogen and phosphorus losses from crop and livestock production and mitigation potentials in Erhai Lake Basin, China. *Agricultural Systems*, 2023, **211**: 103745
8. Yang M, Zhang B C, Gu S X, Han H H, Gao R, Cui Y L. Different water-fertilizer control patterns of garlic and its effect on water saving and emission reduction in the Lake Erhai watershed. *China Rural Water and Hydropower*, 2022, (9): 55–60 (in Chinese)
9. Lian Q Y, Yao L G, Uddin Ahmad Z, Lei X B, Islam F, Zappi M E, Gang D D. Nonpoint source pollution. *Water Environment Research*, 2019, **91**(10): 1114–1128
10. Liu P C, Lei B K, Zhai L M, Ni X Y, Luo X H, Hu W L, Liu H B. Effects of nitrogen managements on growth of garlic and risk of nitrogen loss in field of Erhai Lake Basin, China. *Journal of Agro-Environment Science*, 2011, **30**(7): 1364–1370

(in Chinese)
11. Zou T, Zhang X, Davidson E A. Global trends of cropland phosphorus use and sustainability challenges. *Nature*, 2022, **611**(7934): 81–87
12. Tang Q X, Ren T Z, Lei B K, Zhai L M, Hu W L, Zhang J Z, Lin T, Liu H B. Characteristics of nitrogen and phosphorus loss in various crop rotation systems in northern watershed of Erhai Lake. *Journal of Plant Nutrition and Fertilizers*, 2011, **17**(3): 608–615 (in Chinese)
13. Xu W, Zhang J, Yang L Z, Liu X J, Zhang F S. Strengthening non-point source pollution control to promote agricultural green development. *Frontiers of Agricultural Science and Engineering*, 2023, **10**(4): 503–509
14. Uddin M K, Saha B K, Wong V N L, Patti A F. Organo-mineral fertilizer to sustain soil health and crop yield for reducing environmental impact: a comprehensive review. *European Journal of Agronomy*, 2025, **162**: 127433
15. Wan C, Ma Y J, Zhang K Q, Wang F, Shen S Z. Effects of different organic fertilizer substitutions on soil physical and chemical properties and rapeseed yield in Erhai Lake basin, China. *Journal of Agro-Environment Science*, 2021, **40**(11): 2494–2502 (in Chinese)
16. Wang K, Yang J, Yue P L, Wang R, Wang J T, Zhang S T, Lu J W, Cong W F. Effects of plucking times on yield, quality, and comprehensive benefits of flowering stalk and rapeseed of oilseed-vegetable dual-purpose rape (*Brassica napus*) cultivated in Erhai Lake Basin. *Chinese Journal of Oil Crop Sciences*, 2025, **47**(2): 413–420 (in Chinese)
17. Gao Y J, Zhang S T, Wang J T, Wang K, Zhang J P, Lu J W, Cong W F. Fertilization pattern and nitrogen fertilizer operation on yield and quality of rapeseed with dual-use of vegetable and oil in the Erhai Lake Basin. *Chinese Journal of Oil Crop Sciences*, 2025, **47**(3): 754–767 (in Chinese)
18. Fu D H, Jiang L Y, Mason A S, Xiao M L, Zhu L R, Li L Z, Zhou Q H, Shen C J, Huang C H. Research progress and strategies for multifunctional rapeseed: a case study of China. *Journal of Integrative Agriculture*, 2016, **15**(8): 1673–1684
19. Zhang Z, Yin Y, Liu F, Wang J J, Fu T D. Current situation and development countermeasures of Chinese rapeseed multifunctional development and utilization. *Chinese Journal of Oil Crop Sciences*, 2018, **40**(5): 618–623 (in Chinese)
20. Yu Y, He Y, Zou X Y, Zhou M R, Zhang F G, Zhu Z H, Zhou K J. Status and prospects for development and utilization of double-low rapeseed (*Brassica napus*) for oil-vegetable-dual-purpose. *Chinese Journal of Oil Crop Sciences*, 2022, **44**(5): 921–929 (in Chinese)
21. Krishna D K, Verma R K, Sahoo A K, Kumbhare N V. Agri-tourism: an approach to sustainable rural development. *Rashtriya Krishi*, 2018, **13**(2): 87–89
22. Krishna D K, Kumbhare N V, Sharma D K, Kumar P, Bhowmik A. Facilitating factors for a successful agri-tourism venture: a principal component analysis. *Indian Journal of Extension Education*, 2020, **56**(2): 18–21
23. Bao S D. Soil and Agricultural Chemistry Analysis. 3rd ed. Beijing: *China Agriculture Press*, 2000 (in Chinese)
24. Ünlü M, Kanber R, Koç D L, Tekin S, Kapur B. Effects of deficit irrigation on the yield and yield components of drip irrigated cotton in a Mediterranean environment. *Agricultural Water Management*, 2011, **98**(4): 597–605
25. Hwang C L, Yoon K. Methods for multiple attribute decision making. In: Hwang C L, Yoon K, eds. Multiple Attribute Decision Making: Methods and Applications A State-of-the-Art Survey. Berlin, Heidelberg: *Springer*, 1981, 58–191
26. Duan K L, Niu Z R, Cui L. Analysis of water resources carrying capacity and obstacle factors in Gansu section of the Wei River basin using combined weighting TOPSIS model. *Scientific Reports*, 2025, **15**(1): 12775
27. Zhang Z J, Mao L L, Zhong L, Li Y J, Ming R. Effect of different branches removing methods of vegetable rape on yield, rapeseed and economic effect. *Southwest China Journal of Agricultural Sciences*, 2017, **30**(4): 734–738 (in Chinese)
28. Chirinda N, Olesen J E, Porter J R, Schjønning P. Soil properties, crop production and greenhouse gas emissions from organic and inorganic fertilizer-based arable cropping systems. *Agriculture, Ecosystems & Environment*, 2010, **139**(4): 584–594
29. Neely C B, Walsh C, Davis J B, Hunt C, Brown J. Investigation of early planted winter canola as a dual-purpose crop for silage and seed production. *Agronomy Journal*, 2015, **107**(5): 1905–1914
30. Li Z J, Shah F, Xiong L, Wu W. Enhancing rapeseed yield and lodging resistance through combined inorganic nitrogen and long-term organic fertilizer application. *European Journal of Agronomy*, 2024, **159**: 127286
31. Li X Y, Zuo Q S, Chang H B, Bai G P, Kuai J, Zhou G S. Higher density planting benefits mechanical harvesting of rapeseed in the Yangtze River Basin of China. *Field Crops Research*, 2018, **218**: 97–105
32. Tao Y, Li Z J, Shah F, Wu W. Optimizing biomass allocation for optimum balance of seed yield and lodging resistance in rapeseed. *Field Crops Research*, 2024, **316**: 109493
33. Adamsen F J, Coffelt T A. Planting date effects on flowering, seed yield, and oil content of rape and crambe cultivars. *Industrial Crops and Products*, 2005, **21**(3): 293–307
34. Aiken R, Baltensperger D, Krall J, Pavlista A, Johnson J. Planting methods affect emergence, flowering and yield of spring oilseed crops in the U.S. central high plains. *Industrial Crops and Products*, 2015, **69**: 273–277
35. Lilley J M, Flohr B M, Whish J P M, Farre I, Kirkegaard J A. Defining optimal sowing and flowering periods for canola in Australia. *Field Crops Research*, 2019, **235**: 118–128
36. Macholdt J, Piepho H P, Honermeier B. Mineral NPK and

manure fertilisation affecting the yield stability of winter wheat: results from a long-term field experiment. *European Journal of Agronomy*, 2019, **102**: 14–22

37. Wang J T, Du G F, Tian J S, Zhang Y L, Jiang C D, Zhang W F. Effect of irrigation methods on root growth, root-shoot ratio and yield components of cotton by regulating the growth redundancy of root and shoot. *Agricultural Water Management*, 2020, **234**: 106120
38. Wang J T, Du G F, Tian J S, Jiang C D, Zhang Y L, Zhang W F. Mulched drip irrigation increases cotton yield and water use efficiency via improving fine root plasticity. *Agricultural Water Management*, 2021, **255**: 106992
39. Liu E K, Yan C R, Mei X R, He W Q, Bing S H, Ding L P, Liu Q, Liu S, Fan T L. Long-term effect of chemical fertilizer, straw, and manure on soil chemical and biological properties in northwest China. *Geoderma*, 2010, **158**(3–4): 173–180
40. Sharpley A N. Rainfall frequency and nitrogen and phosphorus runoff from soil amended with poultry litter. *Journal of Environmental Quality*, 1997, **26**(4): 1127–1132
41. McDowell R W, Sharpley A N. Variation of phosphorus leached from Pennsylvanian soils amended with manures, composts or inorganic fertilizer. *Agriculture, Ecosystems & Environment*, 2004, **102**(1): 17–27
42. Luo L G, Qin L H, Wang Y, Wang Q. Environmentally-friendly agricultural practices and their acceptance by smallholder farmers in China—a case study in Xinxiang County, Henan Province. *Science of the Total Environment*, 2016, **571**: 737–743
43. Rodthong W, Kuwornu J K M, Datta A, Anal A K, Tsusaka T W. Factors influencing the intensity of adoption of the roundtable on sustainable palm oil practices by smallholder farmers in Thailand. *Environmental Management*, 2020, **66**(3): 377–394
44. Pullens J W M, Sharif B, Trnka M, Balek J, Semenov M A, Olesen J E. Risk factors for European winter oilseed rape production under climate change. *Agricultural and Forest Meteorology*, 2019, **272–273**: 30–39
45. Novikova L Y, Bulakh P P, Nekrasov A Y, Seferova I V. Soybean response to weather and climate conditions in the Krasnodar and Primorye territories of Russia over the past decades. *Agronomy*, 2020, **10**(9): 1278
46. Wenninger J, Beza D T, Uhlenbrook S. Experimental investigations of water fluxes within the soil–vegetation–atmosphere system: stable isotope mass-balance approach to partition evaporation and transpiration. *Physics and Chemistry of the Earth, Parts A/B/C*, 2010, **35**(13–14): 565–570
47. Huang J D, Cao X Y, Kuai J, Cheng H, Zuo Q S, Du H, Peng S B, Huang J L, Deng N Y. Evaluation of production capacity for rice-rapeseed cropping system in China. *Field Crops Research*, 2023, **293**: 108842
48. Li T T, Zhang Y L, Bei S K, Li X L, Reinsch S, Zhang H Y, Zhang J L. Contrasting impacts of manure and inorganic fertilizer applications for nine years on soil organic carbon and its labile fractions in bulk soil and soil aggregates. *CATENA*, 2020, **194**: 104739
49. Zhang S T, Ren T, Cong W F, Fang Y T, Zhu J, Zhao J, Cong R H, Li X K, Lu J W. Oilseed rape-rice rotation with recommended fertilization and straw returning enhances soil organic carbon sequestration through influencing macroaggregates and molecular complexity. *Agriculture, Ecosystems & Environment*, 2024, **367**: 108960
50. Wang N, Ai Z P, Zhang Q Y, Leng P F, Qiao Y F, Li Z, Tian C, Shi X J, Cheng H F, Chen G, Li F D. The variations of wheat-maize production, soil organic carbon, and carbon footprints: insights from a 20–year on-farm observational experiment in the North China Plain. *Frontiers in Plant Science*, 2025, **16**: 1547431