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Dynamics of growth, yield and quality traits of Mustard Greens (*Brassica juncea* L.) under the using of nutrient-rich irrigation water resources

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ABSTRACT

Irrigation water is increasingly recognized as a potential nutrient source in intensive vegetable systems, particularly in peri-urban areas influenced by organic and wastewater inputs. This study evaluated the effects of organic-rich irrigation water on yield and quality of mustard greens (*Brassica juncea* L.) grown on Red River alluvial soil, and quantified its contribution to nitrogen supply. A greenhouse experiment using a randomized complete block design with three replications and four treatments compared Cau Bay canal water, treated domestic wastewater, and groundwater, with and without chemical fertilization, across three cropping seasons. Organic-rich irrigation significantly improved plant growth and yield compared with unfertilized groundwater, supplying approximately 19–22 kg N ha^{-1} per crop season (27.5–31.0% of the recommended nitrogen rate). Yield increased by 30–70%, although maximum productivity still depended on mineral fertilization. Nitrate accumulation rose consistently with nitrogen availability and was strongly associated with yield and root traits, indicating that nitrogen supply simultaneously enhances productivity and nitrate storage. Multivariate analysis showed that growth, yield, and nitrate accumulation aligned along a common gradient governed by nitrogen availability, revealing a system-level trade-off between productivity and product quality. These results demonstrated that irrigation water functions not only as a water source but also as an active nutrient carrier influencing crop performance and nutrient dynamics. Integrating irrigation water quality into fertilization strategies is therefore essential to improve resource use efficiency while mitigating risks of nitrate accumulation, food safety concerns, and environmental impacts.

Keywords: irrigation water quality, growth, mustard greens, nitrate accumulation, Red River alluvial soil, yield.

INTRODUCTION

Irrigation water quality is increasingly recognized as a critical determinant of crop productivity, nutrient cycling, and food safety in intensive vegetable production systems, particularly in peri-urban environments where water resources are exposed to anthropogenic pressures. In such systems, irrigation water is not only a carrier of water but also a vector of nutrients, organic matter, and potential contaminants, thereby directly influencing plant growth, soil processes, and product quality (Qadir et al., 2010; Ait-Mouheb et al., 2018). The dual role of irrigation water as both a resource and a risk factor presents a complex challenge for sustainable agricultural management.

The reuse of nutrient-rich water sources, including wastewater and polluted surface water, has been widely reported to enhance crop productivity due to the continuous supply of nitrogen (N), phosphorus (P), and organic compounds (Pedrero et al., 2010; Chen et al., 2013). However, excessive nitrogen availability can lead to nitrate (NO_3^-) accumulation in plant tissues, particularly in leafy vegetables, where rapid biomass growth often exceeds the plant's nitrate assimilation capacity (Santamaria, 2020; Zhou et al., 2022). This imbalance between nitrate uptake and reduction is a well-documented physiological constraint that links nitrogen supply directly with both yield formation and product quality. As a result, increasing nitrogen inputs, whether from fertilizers or irrigation water, may induce a trade-off between productivity and food safety.

Leafy vegetables such as mustard greens (*Brassica juncea* L.) have a short growth period and high nutrient demand, particularly nitrogen, which makes them sensitive to nutrient availability in soil and irrigation water. Several studies have reported improved growth and soil fertility when vegetables were irrigated with wastewater due to continuous nutrient inputs and enhanced soil biological activity (Yang et al., 2015; da Silva et al., 2023). In addition, reclaimed water irrigation has been shown to influence soil microbial processes and nutrient cycling, thereby affecting crop productivity and soil health (Chen et al., 2015). However, excessive nutrient supply may also increase the risk of nitrate accumulation in plant tissues and environmental pollution, indicating the need for appropriate management of irrigation water quality.

The Red River alluvial soil region is one of the main vegetable production areas in northern Vietnam, where farmers commonly use different irrigation water sources, including canal water, treated domestic wastewater, and groundwater. Although these water sources are widely used, quantitative information on their nutrient contribution to crop growth and their potential to substitute for chemical fertilizers under alluvial soil conditions is still limited. Most previous studies have mainly focused on water quality assessment or contamination risks, while fewer studies have evaluated the agronomic value of irrigation water nutrients in vegetable production systems. This lack of information makes it difficult to develop appropriate irrigation and fertilizer management strategies that optimize nutrient use efficiency and production sustainability.

Root system architecture plays a key role in mediating this process by regulating nutrient uptake efficiency. Traits such as root length, density, and branching determine the plant's ability to access nutrients from both soil and irrigation water (Lyu et al., 2021). Moreover, interactions between root development and nutrient availability are further influenced by soil properties and organic matter inputs, which can enhance microbial activity and nutrient mineralization (Levy, 2011; Colla et al., 2018). These interactions highlight the importance of considering the soil–plant–water continuum when evaluating irrigation water effects on crop performance.

In Vietnam, irrigation water and environmental quality are commonly assessed using national technical regulations, including QCVN 08:2023/BTNMT for surface water quality and QCVN 03:2023/BTNMT for soil quality. At the international level, wastewater reuse in agriculture is increasingly guided by risk-based management approaches. For example, Regulation (EU) 2020/741 establishes minimum requirements for reclaimed water quality, monitoring, and risk management for safe agricultural irrigation. These frameworks also highlight the potential of reclaimed water to contribute to circular economy objectives through water and nutrient recovery. However, limited studies have quantitatively evaluated the contribution of irrigation water to crop nutrient supply and its effects on crop performance under local conditions. Therefore, assessing irrigation water quality together with nutrient inputs and crop response is essential for sustainable agricultural water reuse.

Multivariate statistical techniques, such as principal component analysis (PCA) and cluster analysis, provide powerful tools to evaluate these complex relationships by identifying key factors controlling plant response and revealing patterns among variables (Abdi and Williams, 2010; Jolliffe and Cadima, 2016). Recent studies have successfully applied PCA to assess nutrient dynamics and plant responses under different irrigation and fertilization regimes, demonstrating its usefulness in environmental and agricultural research (García-García et al., 2021; Sun et al., 2023).

Despite increasing interest in wastewater reuse and irrigation water quality, there is still a lack of integrated studies that quantify nutrient inputs from irrigation water and link them directly with plant growth responses, yield formation, and nitrate accumulation under local agronomic conditions. In particular, evidence from Southeast Asian alluvial soil systems remains scarce, even though such systems are highly vulnerable to water quality fluctuations and nutrient loading. Therefore, this study aimed to evaluate the effects of irrigation water sources of contrasting quality on growth, root development, physiological traits, yield, and nitrate accumulation of mustard greens (*Brassica juncea* L.) cultivated on Red River alluvial soil in Hanoi, Vietnam. In addition, the study quantified nitrogen input from irrigation water and assessed its contribution to fertilizer substitution. By integrating nutrient input analysis with plant response and multivariate approaches, this research provides new insights into the role of irrigation water as an active component of nutrient flow in agroecosystems, supporting the development of more sustainable irrigation-fertilizer management strategies.

MATERIALS AND METHODS

Materials

Mustard greens cultivar PD518 (*Brassica juncea* L.), supplied by Phu Dien Seeds Company, was used as the experimental plant material. The soil used for the greenhouse experiments was collected from the Trau Quy field, Gia Lam district, Hanoi. The soil was air-dried, and stones, roots, and plant residues were removed before adjusting moisture content to approximately 15%.

The main physicochemical properties of the experimental soil are presented in Table 1. Heavy metal concentrations were below the permissible limits according to QCVN 03:2023/BTNMT (Ministry of Natural Resources and Environment, 2023a). Water samples were collected from each irrigation source three times per cropping season. The analyzed parameters included pH, DO, TSS, NH_4^+, NO_3^-, NO_2^-, PO_4^{3-}, COD, BOD_5, and *coliform*. The analytical results were compared with QCVN 08:2023/BTNMT and relevant water reuse guidance.

Table 1. Physicochemical properties of the experimental soil used in the greenhouse study

Parameter	Unit	Value
Clay	% (w/w)	26.00
Silt	% (w/w)	55.88
Sand	% (w/w)	18.12
Soil texture	–	Medium-textured
Field capacity	% (v/v)	44.10
Bulk density	g cm^{-3}	1.00
pH (KCl)	–	6.40
Cation exchange capacity (CEC)	cmol(+) kg^{-1}	17.80
Organic matter (OM)	% (w/w)	2.53
Available P_2O_5	mg 100 g^{-1} soil	9.40
Available K_2O	mg 100 g^{-1} soil	20.10
Available N	mg 100 g^{-1} soil	10.50

The irrigation sources included water from the Cau Bay River (a branch of the Bac Hung Hai irrigation system, Hanoi, Vietnam), treated domestic wastewater meeting discharge standards from the wastewater treatment facility of the Vietnam National University of Agriculture, Hanoi, Vietnam, and groundwater (well water) from the Trau Quy area, Gia Lam district, Hanoi.

Methods

The pot experiment was arranged in a net house at the experimental field of the Faculty of Agronomy, Vietnam National University of Agriculture, located at coordinates 21°00′00″ N - 106°55′54″ E. The study was conducted over three cropping seasons (Season 1: November -December 2023, Season 2: January-February 2024, and Season 3: March - April 2024). The experiment consisted of four irrigation treatments: CT1 - irrigation with water from the Cau Bay River irrigation system without chemical fertilizer; CT2 - irrigation with treated domestic wastewater meeting discharge standards without chemical fertilizer; CT3 - irrigation with groundwater without chemical fertilizer; and CT4 - irrigation with groundwater with chemical fertilizer application. Experimental pots were arranged in a randomized complete block design with three replications, each replication consisting of one pot measuring 68 × 42 × 19.5 cm (length × width × height), with a surface area of 0.2856 m² per pot.

The experiment was conducted on a basal fertilizer background calculated per hectare: 15 tons of organic cow manure applied to all treatments, and for the treatment with chemical fertilizer, a rate of 70 kg N + 50 kg P_2O_5 + 36 kg K_2O was applied (Nguyen Cam Long, 2014). Fertilizers used included urea (46% N), superphosphate (17% P_2O_5), and potassium chloride (60% K_2O). The entire amounts of organic and chemical fertilizers were mixed thoroughly with dry soil and placed into the pots one day before sowing.

Measured parameters

Growth parameters included plant height (cm), measured from the base to the highest leaf tip; plant height was measured from the plant base to the tip of the highest leaf and then recorded at four-day intervals until harvest; number of leaves (counting all fully developed leaves at harvest); root length, number of primary roots, and fresh root weight measured after harvest. Physiological parameters including SPAD index (used as an indicator of relative leaf chlorophyll content, was measured by SPAD - 502 chlorophyll meter (Konica-Minolta 502, Japan), measurements were taken on fully expanded leaves, and the average value was used for analysis; dry matter accumulation was determined after oven-drying plant samples to constant weight (g plant^{-1}) was measured at the end of each season.

Yield and quality parameters included fresh weight; individual yield (g plant^{-1}), determined by weighing each plant in the experimental unit at 28 days after sowing for mustard greens; and actual yield (g pot^{-1}), calculated as the total harvested biomass per pot; brix content was measured from fresh leaf juice using a digital refractometer and expressed as %; nitrate content (NO_3^-) (mg kg^{-1} FW (Fresh weight)) was analyzed according to ISO 14256-2:2020 using UV-Vis spectrophotometry and expressed as mg kg^{-1} fresh weight. All quality analyses were performed according to relevant Vietnamese standard methods (TCVN).

Water quality was analyzed following APHA standard methods for parameters (pH, N,P, BOD_5, COD, TSS, *coliform*) Soil samples were collected before the experiment and analyzed for physicochemical parameters followwing ISO standards.

Nitrogen substitution ratio: The contribution of irrigation water to crop nitrogen requirements was evaluated using the nitrogen substitution ratio:

$$N_{substitution} (\%) = N_{irrigation}/N_{recommended} \times 100 \quad (1)$$

where: $N_{irrigation}$ is the nitrogen input through irrigation water (kg N ha^{-1} crop^{-1}), and $N_{recommended}$ is the recommended nitrogen fertilizer rate (70 kg N ha^{-1}).

Statistical analysis

Data were processed using Microsoft Excel and Minitab 16 software to calculate basic statistical parameters. Analysis of variance (ANOVA) was performed to evaluate the significance and reliability of treatment effects using Tukey's test at a 5% significance level. Principal component analysis (PCA) was conducted using a correlation matrix to reduce data dimensionality and identify key variables driving variation among treatments. Principal components with eigenvalues greater than 1 were retained, and score plots and biplots were used to interpret the multivariate structure and relationships among variables.

RESULTS

Irrigation water quality and nutrient input

Water quality was analyzed three times per cropping season, and Table 2 presents the average values across three seasons for the different irrigation water sources. The analytical results showed that nitrogen concentrations in Cau Bay River water were 3–10 times higher than the limits specified in QCVN 08:2023/BTNMT - Vietnamese national technical regulation on surface water quality (Ministry of Natural Resources and Environment, 2023b). This water source was contaminated with organic matter and did not meet the irrigation water quality requirements (Class B). Treated domestic wastewater still contained nitrogen, phosphorus, BOD, and COD levels approximately 1.5–2 times higher than the permissible limits. In contrast, groundwater generally met the quality requirements for vegetable irrigation (Table 2).

The chemical characteristics of irrigation water sources differed considerably among treatments (Table 2). Canal water from the Cau Bay River contained higher concentrations of nitrogen and organic matter compared with groundwater, with NH_4^+ concentrations exceeding the permissible limits by several times. Treated domestic wastewater also contained relatively high concentrations of nutrients (N and P) and organic matter (BOD, COD), although lower than canal water. In contrast, groundwater generally met irrigation water quality standards and contained minimal nutrient concentrations. In addition, coliform counts were highest in Cau Bay River water and treated wastewater, suggesting potential microbiological contamination.

The total irrigation water applied and the corresponding total nitrogen input, calculated based on the average nitrogen concentration in irrigation water, were presented in the Table 3. The

Table 2. Irrigation water quality used in the experiment

No.	Parameter	Unit	Cau Bay River water	Treated domestic wastewater	Groundwater	Reference QCVN 08:2023/BTNMT
1	pH	-	7.1–7.4	7.1–7.3	6.8–6.9	6.5–8.5
2	DO	mg L^{-1}	4.1–4.5	4.5–5.1	4.1–4.3	≥ 5.0
3	TSS	mg L^{-1}	147.2–189.0	19–26	53.6–61.8	≤ 100
4	NH_4^+	mg L^{-1}	1.5–1.9	0.46–0.48	0.3–0.4	0.3
5	NO_3^-	mg L^{-1}	5.3–6.7	1.2–1.4	0.2–0.3	10
6	NO_2^-	mg L^{-1}	0.1–0.4	0.02–0.04	0.01	0.05
7	PO_4^{3-}	mg L^{-1}	1.5–1.7	1.6–1.9	0.1–0.3	≤ 0.3
8	COD	mg L^{-1}	140–142	27–30	10–12	≤ 15
9	BOD_5	mg L^{-1}	75–79	14–16	6–7	≤ 6
10	*Coliform*	MPN 100 mL^{-1}	8400–9100	6800–7200	3100–3600	≤ 5000

total irrigation volume of 72.5 L pot^{-1} $season^{-1}$ was calculated from the irrigation schedule applied during the 28-day growing period. Irrigation was adjusted to maintain soil moisture near the crop water requirement and to avoid water stress. The same irrigation volume was applied to all treatments to ensure that differences among treatments were mainly attributable to water quality and nutrient composition rather than water quantity. Based on the irrigation volume applied during the experiment, the estimated nitrogen inputs from irrigation water varied substantially among treatments (Table 3). Canal water supplied approximately 21.7 kg N ha^{-1} per crop, followed by treated wastewater with 19.26 kg N ha^{-1}, while groundwater contributed only 2.10 kg N ha^{-1}. When expressed relative to the recommended nitrogen application rate, the nitrogen supplied through Cau Bay River water and treated wastewater accounted for 31.0% and 27.5%, respectively, while groundwater contributed only a minor fraction (3.0%). These results highlight the substantial role of nutrient-rich irrigation water as an additional source of nitrogen for crop production. These results indicate that irrigation water served as an additional nutrient source, particularly for canal water and treated wastewater treatments.

Effects of irrigation water sources on plant growth

Irrigation water sources significantly affected the growth of mustard greens across the three cropping seasons. Plant height generally followed the trend CT4 (groundwater with fertilizer) ≥ CT2 (treated wastewater) ≥ CT1 (canal water) > CT3 (groundwater without fertilizer). In most cases, plants irrigated with groundwater without fertilizer (CT3) exhibited the lowest growth performance. Treatments receiving nutrient inputs either from irrigation water (CT1 and CT2) or from chemical fertilizer (CT4) produced taller plants and more leaves compared with CT3 (Table 4). Plant height showed clear differences among treatments, particularly in the second and third seasons. The highest values were consistently recorded in the treatment combining groundwater irrigation with chemical fertilization, while the lowest values were observed under groundwater irrigation without fertilization. The difference between these treatments reached approximately 40–60% depending on the season and was statistically significant. Irrigation with Cau Bay River water and treated wastewater without fertilizer resulted in intermediate plant height, generally 10–30% higher than groundwater without fertilizer, although these differences were

Table 3. Irrigation water volume and total nitrogen applied in the experiment

Treatment	Total irrigation water per pot (L pot^{-1} $season^{-1}$)	Total nitrogen based on average concentration and irrigation volume (g pot^{-1} $season^{-1}$)	N input (kg N ha^{-1} $crop^{-1}$)	N substitution (%)
Cau Bay River water	72.5	0.62	21.70	31.0
Treated wastewater	72.5	0.55	19.26	27.5
Groundwater	72.5	0.06	2.10	3.0

Table 4. Effects of irrigation water quality on plant height and leaf number of mustard greens

Treatment	Plant height (cm)			Number of leaves (leaves plant⁻¹)		
	Season 1	Season 2	Season 3	Season 1	Season 2	Season 3
CT1	17.9ᵃ	11.5ᵇ	13.9ᵇ	5.3ᵇ	5.9ᵃ	5.1ᵃ
CT2	17.7ᵃ	12.0ᵇ	17.7ᵃ	5.2ᵇ	5.5ᵃ	5.2ᵃ
CT3	11.5ᵇ	10.2ᵇ	11.5ᵇ	5.7ᵃᵇ	5.3ᵃ	5.7ᵃ
CT4	17.5ᵃ	16.7ᵃ	17.5ᵃ	6.1ᵃ	5.8ᵃ	6.1ᵃ

Note: mean values within the same column followed by the same letter are not significantly different at the 95% confidence level. Different letters indicate significant differences ($p < 0.05$). CT1 – irrigation with Cau Bay River water without chemical fertilizer; CT2 – irrigation with treated domestic wastewater (meeting discharge standards) without chemical fertilizer; CT3 – irrigation with groundwater without chemical fertilizer; CT4 – irrigation with groundwater with chemical fertilizer application.

not always statistically significant. Across seasons, plant height tended to decrease under non-fertilized conditions, especially when groundwater was used, indicating limited nutrient availability. In contrast, the fertilized treatment maintained relatively stable and higher growth performance, suggesting that external nutrient supply played a key role in sustaining plant development.

The number of leaves showed less pronounced variation compared to plant height. Although the fertilized treatment generally produced the highest leaf number, the differences among treatments were relatively small and often not statistically significant. However, groundwater without fertilization tended to result in the lowest leaf number, with reductions of approximately 10-20% compared to the highest treatment (Table 4).

Effects on root characteristics

Fresh root weight showed relatively limited variation among treatments, and differences were generally not statistically significant across seasons. Although the fertilized treatment tended to produce slightly higher values, the overall variation remained small, suggesting that root biomass was less sensitive to differences in irrigation water quality compared to above-ground growth (Table 5). In contrast, root length exhibited a more noticeable response to irrigation treatments. The highest values were generally observed in the fertilized treatment, while lower values were recorded under groundwater irrigation without fertilization. The increase in root length under fertilized conditions reached approximately 20–40%, although differences were not consistently statistically significant across all seasons. Irrigation with Cau Bay River water and treated wastewater resulted in intermediate values, indicating a partial improvement in root development compared to nutrient-limited conditions.

The number of main roots showed clearer differences among treatments. The fertilized treatment consistently produced the highest number of roots, with increases of approximately 30–80% compared to the lowest treatment, and these differences were statistically significant in several cases. In contrast, groundwater without fertilization resulted in the lowest root number, reflecting restricted root development under low nutrient availability. Treatments receiving nutrient-rich irrigation water showed moderate values, higher than groundwater without fertilizer but lower than the fertilized treatment.

Effects on physiological and quality traits

The effects of irrigation water quality on physiological and quality traits of mustard greens are

Table 5. Effects of irrigation water quality on root characteristics of of mustard greens

Treatment	Fresh root weight (g pot⁻¹)			Longest root length (cm)			Number of main roots plant⁻¹		
	Season 1	Season 2	Season 3	Season 1	Season 2	Season 3	Season 1	Season 2	Season 3
CT1	0.2ᵃ	0.2ᵃ	0.2ᵃ	5.7ᵃ	5.1ᵃ	5.5ᵃ	2.8ᵇ	1.2ᵃ	1.2ᵃ
CT2	0.2ᵃ	0.1ᵃ	0.2ᵃ	5.5ᵃ	6.0ᵃ	5.5ᵃ	2.3ᵇ	1.1ᵃ	1.1ᵃᵇ
CT3	0.1ᵃ	0.4ᵃ	0.1ᵃ	4.5ᵃ	6.1ᵃ	4.5ᵃ	2.9ᵇ	1.0ᵃ	1.0ᵇ
CT4	0.2ᵃ	0.3ᵃ	0.2ᵃ	5.4ᵃ	7.2ᵃ	5.6ᵃ	4.2ᵃ	1.3ᵃ	1.2ᵃᵇ

presented in Tables 6 and 7. Dry matter showed significant variation among treatments in most seasons. The highest values were generally observed in the treatment combining groundwater irrigation with chemical fertilization, while the lowest values occurred under groundwater irrigation without fertilization. The difference between these treatments reached up to approximately 50–100% depending on the season, and was statistically significant. Treatments irrigated with Cau Bay River water and treated wastewater without fertilizer produced intermediate values, indicating that nutrient-rich irrigation water partially compensated for the absence of mineral fertilizer.

In contrast, SPAD values exhibited limited variation among treatments. Differences were mostly not statistically significant, except in the later season where the fertilized treatment showed a significantly higher chlorophyll content. This increase was approximately 20–30% compared to the lowest treatment, suggesting enhanced nitrogen assimilation under combined nutrient supply.

Quality traits showed clearer responses to irrigation treatments. Brix content varied moderately across treatments, with the highest values typically recorded in the fertilized treatment and the lowest under groundwater without fertilizer. The relative increase in Brix content ranged from approximately 15–40%, although differences were not always statistically significant across all seasons.

Nitrate accumulation exhibited the most pronounced differences among treatments. The highest nitrate levels were consistently found in the fertilized treatment, exceeding those of other treatments by approximately 2–3 times, with statistically significant differences observed in all seasons. In contrast, the lowest nitrate accumulation occurred under groundwater irrigation without fertilization. Treatments irrigated with Cau Bay River water and treated wastewater showed intermediate nitrate levels, generally 20–50% higher than groundwater without fertilizer, but significantly lower than the fertilized treatment.

Across seasons, nitrate accumulation showed a decreasing trend in non-fertilized treatments, while remaining consistently high under fertilized conditions. These differences were statistically significant and highlight the strong influence of external nitrogen inputs on nitrate accumulation.

Effects on yield and productivity

Yield parameters were significantly affected by irrigation treatments across all cropping seasons (Table 8). The fertilized treatment (CT4)

Table 6. Effects of irrigation water quality on physiological of mustard greens

Treatment	Dry matter (g plant^{-1})			SPAD		
	Season 1	Season 2	Season 3	Season 1	Season 2	Season 3
CT1	0.4^{a}	0.1^{b}	0.2^{a}	20.9^{a}	19.6^{a}	21.2^{a}
CT2	0.3^{a}	0.2^{b}	0.2^{a}	20.1^{a}	20.6^{a}	21.0^{a}
CT3	0.2^{b}	0.1^{b}	0.1^{a}	17.8^{a}	19.5^{a}	21.5^{a}
CT4	0.3^{a}	0.3^{a}	0.2^{a}	19.0^{a}	19.8^{a}	26.4^{b}

Note: mean values within the same column followed by the same letter are not significantly different at the 95% confidence level; different letters indicate significant differences.

Table 7. Effects of irrigation water quality on quality parameters of mustard greens

Treatment	Brix content (%)			Nitrate content (mg kg^{-1}FW)		
	Season 1	Season 2	Season 3	Season 1	Season 2	Season 3
CT1	4.1^{a}	4.7^{a}	4.7^{a}	275.0^{c}	305.0^{c}	198.0^{b}
CT2	3.5^{b}	4.3^{a}	5.0^{a}	297.0^{b}	317.0^{b}	132.3^{c}
CT3	2.9^{c}	5.0^{a}	4.6^{a}	200.3^{d}	172.3^{d}	107.0^{d}
CT4	4.3^{a}	5.2^{a}	4.6^{a}	740.7^{a}	614.0^{a}	542.4^{a}
Standards according to Vietnamese standard (Decision No. 99/2008/QĐ-BNN)				500 mg kg^{-1}		
WHO standards				300 mg kg^{-1}		

Note: mean values within the same column followed by the same letter are not significantly different at the 95% confidence level; different letters indicate significant differences.

Table 8. Effects of irrigation water quality on yield parameters of mustard greens

Treatment	Individual yield (g plant^{-1})			Actual yield (g pot^{-1})		
	Season 1	Season 2	Season 3	Season 1	Season 2	Season 3
CT1	3.5^{a}	1.4^{b}	1.6^{b}	231.1^{a}	76.5^{ab}	74.0^{bc}
CT2	3.4^{a}	1.6^{b}	2.4^{ab}	181.2^{ab}	57.9^{b}	87.9^{b}
CT3	1.6^{b}	1.3^{b}	1.6^{b}	97.7^{c}	50.4^{b}	67.2^{c}
CT4	4.0^{a}	4.7^{a}	3.9^{a}	161.8^{bc}	110.4^{a}	175.7^{a}

Note: mean values within the same column followed by the same letter are not significantly different at the 95% confidence level; different letters indicate significant differences.

consistently produced the highest individual yield and total fresh biomass per pot, whereas groundwater irrigation without fertilization (CT3) resulted in the lowest values. The differences between CT4 and CT3 ranged from approximately 80–150% and were statistically significant in all seasons.

Treatments irrigated with canal water (CT1) and treated domestic wastewater (CT2) generally produced higher yields than CT3, with increases of approximately 30–70%, although these differences were not always statistically significant. Across seasons, the overall yield ranking was generally CT4 > CT2 > CT1 > CT3. In several cases, yields obtained under CT1 were comparable to those observed under fertilized conditions, indicating the positive contribution of nutrients supplied through irrigation water.

Yield tended to decline over time under non-fertilized treatments, particularly under groundwater irrigation, while CT4 maintained relatively stable productivity throughout the experiment. These results indicate that irrigation water quality and associated nutrient inputs had a clear influence on crop productivity.

The Pearson correlation matrix among growth traits, root characteristics, yield parameters, and nitrate accumulation is presented in Table 9. Nitrate accumulation showed strong positive correlations with yield-related parameters, particularly total yield ($r = 0.80–0.95$, $p < 0.01$) and individual yield ($r = 0.70-0.90$, $p < 0.01$). Significant positive correlations were also observed between nitrate accumulation and root traits, including root number ($r = 0.80–0.93$, $p < 0.01$) and root length ($r = 0.60-0.75$, $p < 0.01$). In contrast, the relationship between nitrate accumulation and root biomass was weaker ($r = 0.30–0.50$).

Plant height was strongly correlated with yield ($r = 0.75–0.90$, $p < 0.01$), whereas the correlation between leaf number and yield was weaker ($r = 0.20–0.50$) and not consistently significant across all cases. Positive correlations were generally observed among growth traits, root development, and yield parameters, indicating close associations among these variables under different irrigation treatments.

Multivariate analysis of growth, yield, and nitrate accumulation (PCA)

PCA was performed to evaluate the relationships among growth traits, root characteristics, yield parameters, physiological traits, and nitrate accumulation under different irrigation water treatments (Figures 1 and 2). The first two principal components explained a substantial proportion of the total variance in the dataset. PC1 was mainly associated with growth and yield-related variables, whereas PC2 was more closely related to physiological and quality traits.

The score plot (Figure 1- left) separated the treatments according to irrigation water quality and fertilization status. The fertilized treatment (CT4) was located in the positive region of PC1 and was associated with higher growth and yield parameters. In contrast, groundwater without fertilization (CT3) was distributed in the negative region of PC1. Treatments irrigated with Cau Bay canal water (CT1) and treated wastewater (CT2) were positioned between CT3 and CT4, indicating intermediate responses.

The biplot (Figure 1- right) showed that yield parameters and growth traits were closely aligned in the same direction. Nitrate accumulation was also oriented similarly to growth and yield variables. Root traits, particularly root number and root length, were positioned close to yield and nitrate variables. In contrast, Brix was oriented in a different direction from nitrate-related variables.

Overall, the PCA results revealed clear separation among irrigation treatments and showed close associations among growth traits, root development, yield parameters, and nitrate accumulation. The hierarchical cluster dendrogram revealed

Table 9. Pearson correlation matrix among growth, yield and root traits of mustard greens under different irrigation water quality

Season 1	PH	LN	LRL	FRW	NMR	DM	Brix	NO_3^-	IY	AY
PH	1									
LN	-0.14	1								
LRL	0.73*	-0.02	1							
FRW	0.63*	-0.31	0.80**	1						
NMR	0.12	0.85***	0.19	0.00	1					
DM	0.81**	-0.29	0.77**	0.69**	-0.10	1				
Brix	0.79**	0.12	0.54*	0.42	0.37	0.75**	1			
NO_3^-	0.42	0.67*	0.25	0.10	0.71**	0.24	0.69**	1		
IY	0.91***	0.13	0.79*	0.68*	0.39	0.73*	0.81**	0.60*	1	
AY	0.81**	-0.35	0.58*	0.46	-0.17	0.79*	0.68*	0.06	0.64*	1
Season 2	PH	LN	LRL	FRW	NMR	DM	Brix	NO_3^-	IY	AY
PH	1									
LN	0.46	1								
LRL	0.56*	0.13	1							
FRW	0.18	-0.04	0.01	1						
NMR	0.85**	0.63*	0.61*	0.11	1					
DM	0.82*	0.40	0.58*	0.08	0.72*	1				
Brix	0.23	-0.06	0.53	-0.18	0.32	0.38	1			
NO_3^-	0.79*	0.38	0.42	-0.04	0.69*	0.92***	0.22	1		
IY	0.93*	0.39	0.63*	0.26	0.82*	0.87**	0.29	0.84**	1	
AY	0.46	0.31	0.30	-0.08	0.57*	0.76*	0.36	0.85***	0.62*	1
Season 3	PH	LN	LRL	FRW	NMR	DM	Brix	NO_3^-	IY	AY
PH	1									
LN	0.09	1								
LRL	0.66*	0.05	1							
FRW	0.68*	-0.10	0.79*	1						
NMR	0.11	0.15	0.07	-0.13	1					
DM	0.63*	0.21	0.17	0.15	0.69*	1				
Brix	0.27	-0.09	0.20	0.17	0.32	0.29	1			
NO_3^-	0.34	0.56*	0.22	-0.04	0.70*	0.55*	0.20	1		
IY	0.54*	0.61*	0.38	0.25	0.61*	0.69*	0.42	0.85***	1	
AY	0.42	0.57*	0.21	0.02	0.67*	0.61*	0.25	0.95***	0.89***	1

Note: *,**, *** – correlation is significant at the 0.05, 0.01, 0.001 level (2-tailed). PH – plant height, LN – number of leaves (leaves $plant^{-1}$), LRL – longest root length (cm); FRW – fresh root weight (g pot^{-1}), NMR – number of main roots $plant^{-1}$, DM – dry matter, Brix – Bix content, NO_3^- – nitrate accumulation, IY – individual yield, AY – actual yield.

clear groupings among the measured parameters across the three cropping seasons (Figure 2). Most growth and yield variables were grouped within the same cluster, indicating close relationships among vegetative development, biomass accumulation, and productivity. Nitrate accumulation was also located near this cluster, showing a similar response pattern to growth and yield parameters under different irrigation treatments.

Root-related traits were generally associated with the productivity cluster, although their relative positions varied slightly among seasons. Root number and root length tended to show closer associations with yield and nitrate accumulation than root fresh weight. Meanwhile, quality-related traits such as Brix were separated from the main growth–yield cluster and formed a more distinct group.

Although some minor seasonal variation was observed, the overall clustering pattern remained relatively stable throughout the experiment. The dendrogram consistently showed close

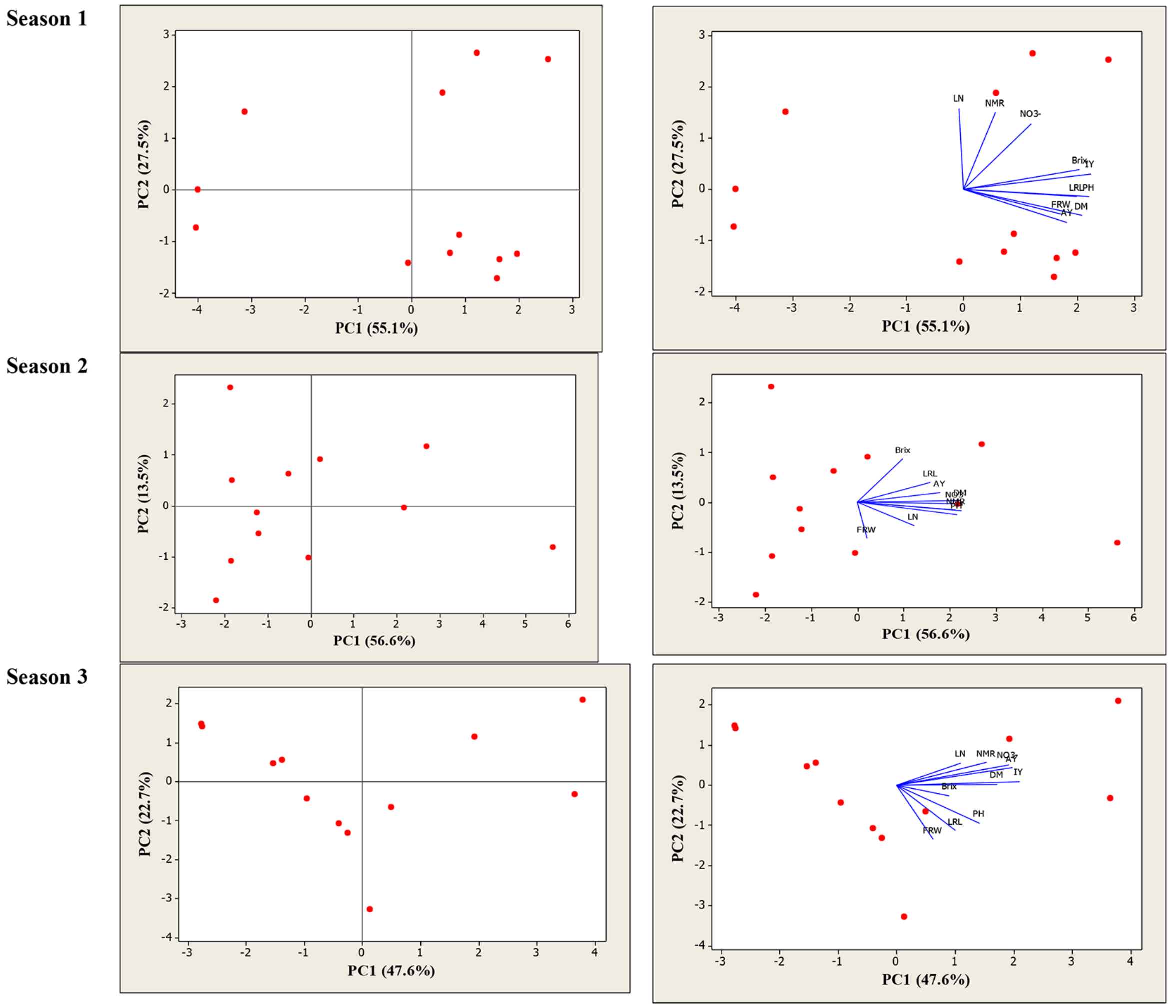

Figure 1. Principal component analysis (PCA) of measured variables of mustard greens under different irrigation water quality – score plot (left) and biplot (right) of three seasons. PH: Plant height, LN: Number of leaves (leaves plant^{-1}), LRL – longest root length (cm); FRW – fresh root weight (g pot^{-1}), NMR – number of main roots plant^{-1}, DM – dry matter, Brix – Bix content, NO_3^- – nitrate accumulation, IY – individual yield, AY – actual yield

relationships among growth traits, root development, yield, and nitrate accumulation under different irrigation water conditions.

DISCUSSION

Irrigation water as a nutrient source

The present study demonstrated that irrigation water quality had a direct influence on mustard green productivity through differences in nutrient supply. Canal water and treated domestic wastewater provided measurable nitrogen inputs, supplying approximately 19–22 kg N ha^{-1} per crop, equivalent to nearly one-third of the recommended nitrogen rate. This additional nutrient contribution explains the higher growth and yield observed under CT1 and CT2 compared with groundwater irrigation without fertilization. Similar findings have been reported in reclaimed water systems, where irrigation water contributes substantial nutrient inputs and partially reduces fertilizer demand (Cirelli et al., 2021; da Silva et al., 2023).

The beneficial effect of nutrient-rich irrigation water is closely related to the presence of dissolved nitrogen, phosphorus, and organic matter. Recent studies have shown that wastewater-derived nutrients can improve soil fertility, stimulate microbial activity, and increase nutrient availability for crops (Li et al., 2022; Zhang et al., 2024). In leafy vegetables, these effects are often expressed through enhanced vegetative growth and biomass accumulation because nitrogen availability strongly regulates leaf expansion and photosynthetic activity (Colla et al., 2021).

Season 1

Season 2

Season 3

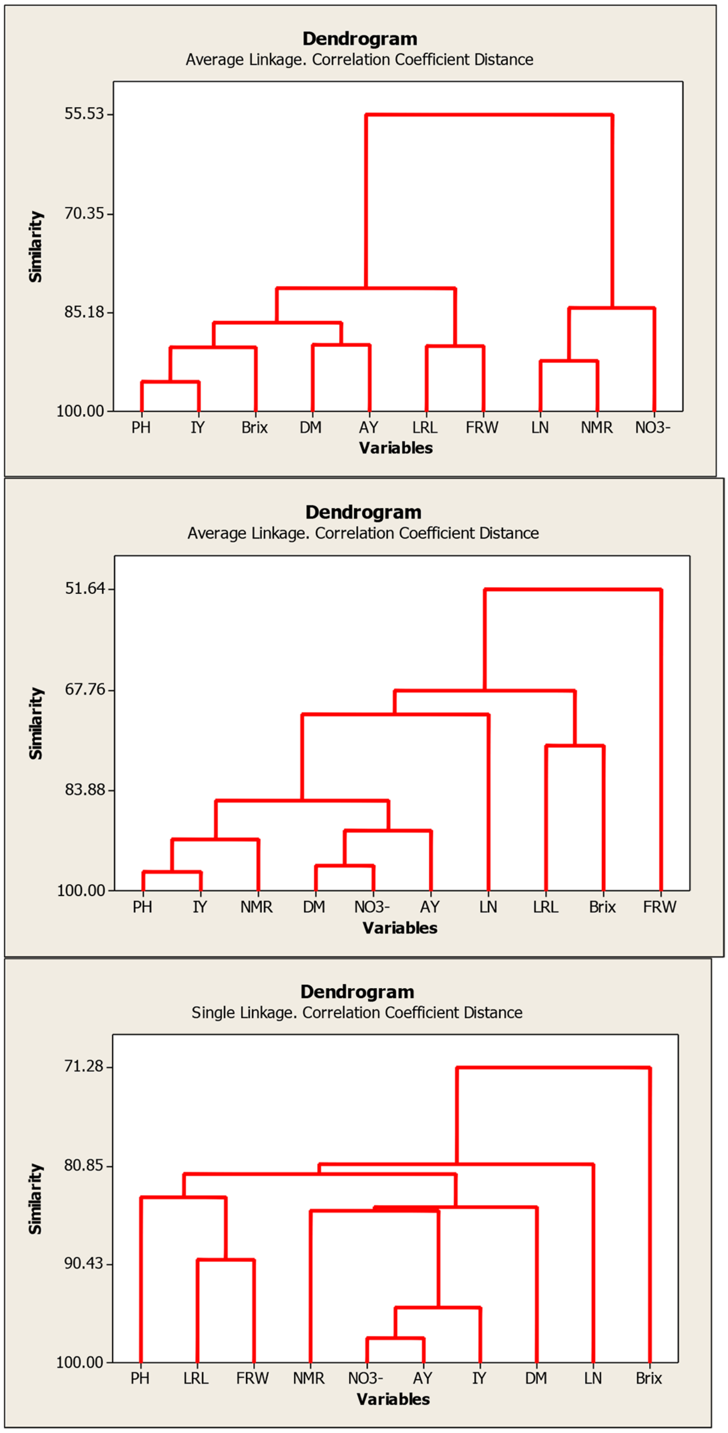

Figure 2. Cluster dendrogram of mustard greens parameters of three seasons. PH: Plant height, LN: Number of leaves (leaves plant^{-1}), LRL: Longest root length (cm); FRW: Fresh root weight (g pot^{-1}), NMR: Number of main roots plant^{-1}, DM: Dry matter, Brix: Bix content, NO_3^-: Nitrate accumulation, IY: Individual yield, AY: Actual yield.

Fertilizer substitution potential under nutrient-rich irrigation

Although nutrient-rich irrigation water improved crop performance, the highest yield was consistently obtained under mineral fertilization. This indicates that nutrients supplied through irrigation water were supplementary rather than sufficient to fully satisfy crop demand. Similar observations were reported by Pedrero et al. (2021), who found that reclaimed wastewater could partially substitute mineral fertilizers but could not completely replace nitrogen application under intensive vegetable production systems.

The relatively high productivity obtained under canal water and treated wastewater irrigation nevertheless demonstrates the practical value of nutrient recovery through irrigation reuse. In peri-urban agricultural regions, where nutrient-rich surface water is widely available, incorporating irrigation-derived nutrients into fertilizer planning may reduce fertilizer consumption and improve nutrient use efficiency. Recent studies have emphasized that integrating water quality into nutrient management strategies is an important component of circular agriculture and sustainable resource management (Garrido-Baserba et al., 2022; Melo et al., 2024).

Root development and nutrient uptake responses

Root system responses observed in this study suggest that root architecture played an important role in nutrient acquisition under different irrigation conditions. Root number and root length showed stronger relationships with yield and nitrate accumulation than root fresh weight, indicating that root structural traits may contribute more to nutrient uptake efficiency than root biomass alone. Similar responses have been described in recent studies on nitrogen acquisition, where fine root development and root branching enhanced nutrient capture under heterogeneous nutrient supply conditions (Lyu et al., 2021; Sun et al., 2023).

Organic-rich irrigation water may also influence rhizosphere processes by increasing microbial activity and nutrient mineralization. Enhanced root proliferation under nutrient-rich conditions has been associated with increased availability of soluble nitrogen and improved nutrient mobility in the soil solution (Wang et al., 2022). This mechanism may partly explain the closer association between root traits and productivity observed in the present study.

Physiological responses and biomass accumulation

The physiological responses further reflected differences in nutrient availability among irrigation treatments. Dry matter accumulation varied considerably among treatments, whereas SPAD values remained relatively stable across seasons. This pattern suggests that chlorophyll content was maintained within a relatively narrow range despite differences in nutrient supply, while biomass accumulation responded more strongly to nitrogen availability. Comparable results were reported by Colla et al. (2021), who observed that leafy vegetables may maintain chlorophyll stability under moderate nitrogen variation while exhibiting substantial differences in biomass production.

The stable SPAD values observed in this study may indicate that the nitrogen supply provided by irrigation water was sufficient to maintain leaf chlorophyll synthesis but not necessarily optimal for maximum biomass accumulation. Such physiological buffering has also been reported under reclaimed water irrigation systems where moderate nutrient enrichment supports photosynthetic function without proportionally increasing dry matter production (Renna et al., 2022).

Nitrate accumulation and the productivity–quality relationship

Nitrate accumulation was strongly associated with plant growth and yield, indicating that nitrogen availability simultaneously promoted productivity and nitrate storage in plant tissues. Positive correlations between nitrate and yield parameters are commonly observed in leafy vegetables because nitrate uptake often exceeds assimilation capacity under high nitrogen supply (Santamaria, 2020; Zhou et al., 2022). In fast-growing leafy crops, nitrate reductase activity may become insufficient to fully convert absorbed nitrate into amino acids and proteins, resulting in nitrate accumulation in edible tissues.

The close relationship between nitrate accumulation and root traits further suggests that enhanced root development increased nitrogen uptake efficiency under nutrient-rich irrigation conditions. Similar relationships have been reported in leafy vegetables under high nitrogen availability, where enhanced nitrogen uptake promoted both biomass accumulation and nitrate accumulation in edible tissues (Santamaria, 2020; Zhou et al., 2022).

In contrast, quality-related traits such as Brix tended to show weaker or negative relationships with nitrate accumulation. This pattern may reflect a shift in carbon–nitrogen balance, where increased nitrogen availability promotes vegetative growth at the expense of soluble carbohydrate accumulation. Similar trade-offs between productivity and quality have been reported in lettuce, spinach, and mustard greens under excessive nitrogen supply (Kyriacou et al., 2021; Renna et al., 2022).

Interpretation of multivariate analysis

The PCA and cluster analyses provided an integrated view of the relationships among growth, yield, root development, and nitrate accumulation. Growth and yield variables were closely grouped with nitrate accumulation, indicating that these parameters responded similarly to irrigation water quality and nutrient availability. Treatments irrigated with nutrient-rich water occupied intermediate positions between unfertilized groundwater and mineral fertilization, reflecting their partial contribution to crop nutrient supply (Figures 1, 2). The alignment of nitrate with productivity-related variables suggests that nitrate accumulation was not an isolated response but part of a broader nutrient-driven growth pattern. Similar PCA patterns have been reported in recent studies evaluating nutrient dynamics in vegetable systems, where nitrogen availability was identified as the dominant factor controlling both productivity and nitrate accumulation (García-García et al., 2021; Sun et al., 2023).

Cluster analysis further confirmed these relationships by separating productivity-related variables from quality traits. The relatively stable clustering structure across seasons indicates that the interactions among growth, yield, and nitrate accumulation remained consistent despite seasonal variation. This stability suggests that irrigation water quality exerts a persistent effect on nutrient dynamics within the soil–plant system.

Environmental implications and management considerations

From an ecological engineering perspective, the reuse of nutrient-rich irrigation water represents both an opportunity and a management challenge. On one hand, irrigation water can contribute to nutrient recycling and reduce dependence on synthetic fertilizers. On the other hand, continuous nutrient loading may increase nitrate accumulation and potentially affect soil and water quality if nutrient inputs exceed crop demand. Similar concerns have been highlighted in recent studies on wastewater reuse and nutrient recovery systems (Garrido-Baserba et al., 2022; Melo et al., 2024).

The results of this study therefore support the integration of irrigation water quality into fertilizer management strategies. Rather than considering irrigation water solely as a source of water, nutrient contributions from irrigation should be included in nutrient budgeting and fertilizer recommendations. Such an approach is consistent with current circular economy and sustainable agriculture frameworks promoted in both European and international water reuse policies.

CONCLUSIONS

Irrigation water quality significantly affected the growth, yield, and nitrate accumulation of mustard greens cultivated on alluvial soil. Canal water and treated domestic wastewater supplied approximately 19–22 kg N ha^{-1} per crop, equivalent to nearly 30% of the recommended nitrogen rate, and substantially improved productivity compared with unfertilized groundwater irrigation, although they did not fully replace mineral fertilization. Nitrate accumulation increased together with plant growth, yield, and root development, indicating that nitrogen availability was the main factor regulating both productivity and nitrate storage in plant tissues. These findings demonstrate that irrigation water should be considered not only as a water source but also as a component of nutrient management, with important implications for fertilizer optimization, food safety, and sustainable agricultural water reuse.

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