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COMPREHENSIVE STATISTICAL AND OPTIMISATION ANALYSES FOR CROP NUTRITIONAL QUALITY IN LOCALLY GROWN VEGETABLES CULTIVATED BY AGRA CANAL WATER

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ABSTRACT
Irrigation is the backbone of agricultural activities. The Agra Canal, which originates from the Yamuna River, provides essential water for vegetable cultivation; however, its quality may impact the nutritional profile of the crops. This study presents a comparative analysis of the nutritional value of spinach, radish, and tomato, grown under different irrigation regimes:100% groundwater (GW), mixed water (50% GW + 50% CW), 100% CW (canal water), and canal-side conditions. Standard analytical protocols (SOP/FL-04, IS 7219; IS 1656, and IS 4684) were employed to quantify the energy, protein, carbohydrate, and fat content of the harvested vegetables. In the series of essential minerals, zinc (Zn) and iron (Fe) were analysed. Spinach irrigated with 100% GW recorded the highest energy (28.7 kcal/100g) and protein (2.8 g/100g) content, while those grown with 100% CW showed notably lower energy levels (14.91). Radish and tomato samples exhibited minor variations in energy content across treatments, although radish protein content was highest with 10% GW. A mix of GW and CW generally yielded intermediate to improved nutritional outcomes, particularly for tomatoes, where the highest energy value (19.78 kcal/100g) was observed. The highest Fe content was found in canal-side-harvested vegetables, followed by 100% CW, and Zn was found in 100% CW. All the results were analysed by Q-Q plots, Pareto plots, and Box plots, which show the significance of the results. All the values fell within the FSSI parameters. The results show that the type of water source affects the nutritional quality of crops. It emphasises the need for integrated water management strategies to improve food quality and promote sustainable agriculture in the region.

KEYWORDS: Nutritional values, irrigation, water management, Agra canal, food quality.

1. INTRODUCTION
Agriculture and irrigation are critical to sustaining agricultural productivity, especially in regions with variable rainfall. The Agra Canal is a lifeline for agriculture in the Faridabad and Palwal districts of Haryana. However, the quality of irrigation water can significantly impact the nutritional value of the crops grown (Singh et al., 2021). The agricultural sector's reliance on irrigation water underscores its pivotal role in determining the suitability and success of crop cultivation. Factors such as water quality, soil type, salt tolerance of plants, climate, and drainage collectively influence the appropriateness of irrigation water in agriculture (Nagaraju et al., 2016; Bijekar et al., 2022). Water resources and crop production are crucial steps in the economy of any country (Döndü et al., 2022). This research aims to provide a comparative analysis of the nutritional value of vegetables irrigated with water from the Agra Canal (Kumari et al., 2024b). The Agra Canal, originating from the Yamuna River, traverses through various regions before reaching Faridabad. Along its course, the canal water can accumulate various pollutants and nutrients, which may impact soil quality and, consequently, crop growth (Verma et al., 2022). The study focuses on Tomato (*Solanum lycopersicum*), Radish (*Raphanus sativus*), and Spinach (*Spinacia oleracea*) plants, aiming to unravel the intricate connections between water quality, plant health, and their subsequent influence on nutritional value and mineral content in the edible parts of the crops (Patel et al., 2019). Understanding the nutritional profile of these vegetables is crucial, not only for consumer health but also for agricultural practices and policies (Dobosy et al., 2020). This study addresses the nutritional content, including macro- and micronutrients, of vegetables grown with Agra Canal water compared with those grown with other water sources (Fig. 1) as well as with FSSI parameters. By analysing parameters such as protein content, vitamin levels, and mineral concentrations, the research provides insights into the benefits and potential risks of using canal water for irrigation (Kumari et al., 2024a). Previous studies have not shown that crop yields vary with differences in irrigation water quality. Still, there is a paucity of specific data on the nutritional value of crops under different water-quality conditions. This research fills this gap by systematically comparing the dietary values of locally grown vegetables.

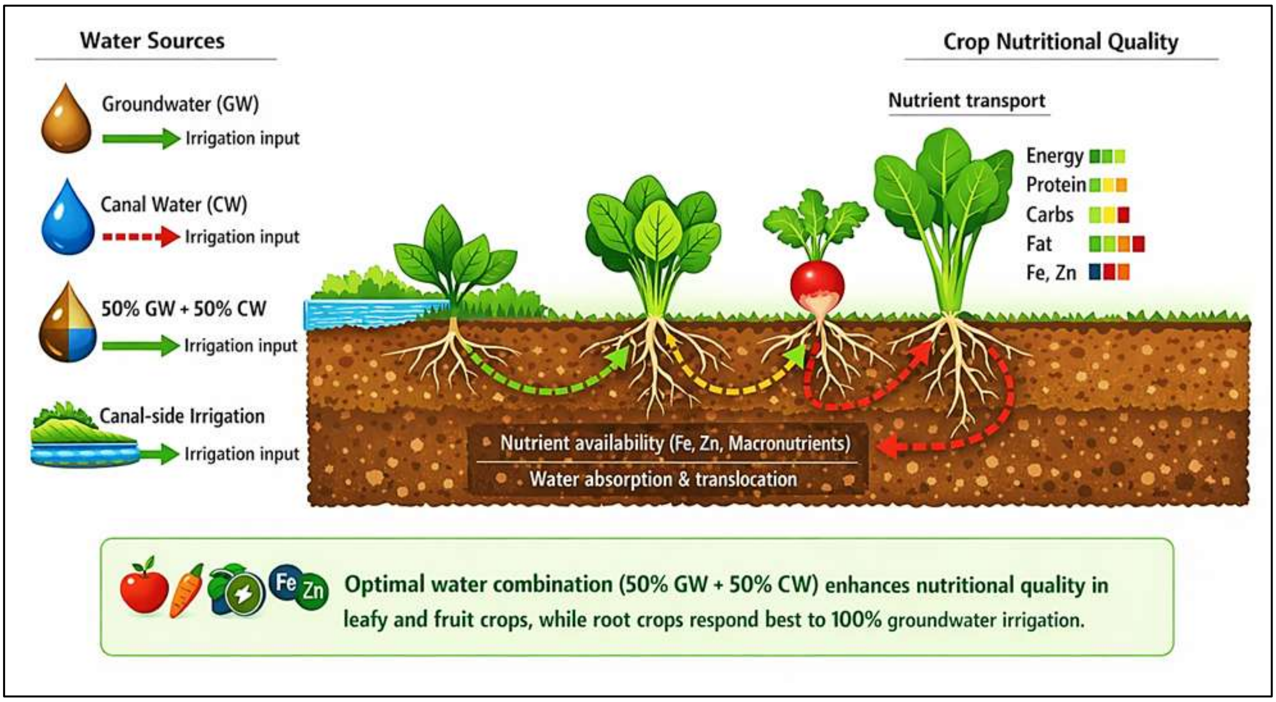


Figure 1: Conceptual diagram illustrating the influence of different irrigation water sources on vegetable nutritional quality.

2. MATERIAL AND METHODOLOGY

2.1 Sampling Site

The study was conducted in the Agra Canal-irrigated area of Faridabad, Haryana, India. There are two subdivisions within the district of Faridabad (Faridabad and Ballabhgarh block) (Choudhary et al., 2022). The length of the Agra Canal is 140 miles (230 km)-lock length is 120 feet, lock width 20 feet (6.1m), maximum height above sea level 659 feet (201m). The Agra Canal runs from Delhi to Agra. The climate of the Faridabad district is hot, semiarid, and tropical, characterised by arid air conditions except during the monsoon season. Different crops are grown in the Faridabad district, including gram, pulses, jowar, bajra, rice, and wheat. (Choudhary et al., 2022). It is well defined in three seasons: April through the end of June marks the beginning of the sweltering summer months, and July through September is the rainy season. Winter lasts from November through February. For the experimental setup, water and soil samples were collected from the agricultural site in Faridabad (S3) (28°14'49.7"N 77°21'09.5" E) (Fig. 2). The soil predominantly consists of sandy loam and clayey components.

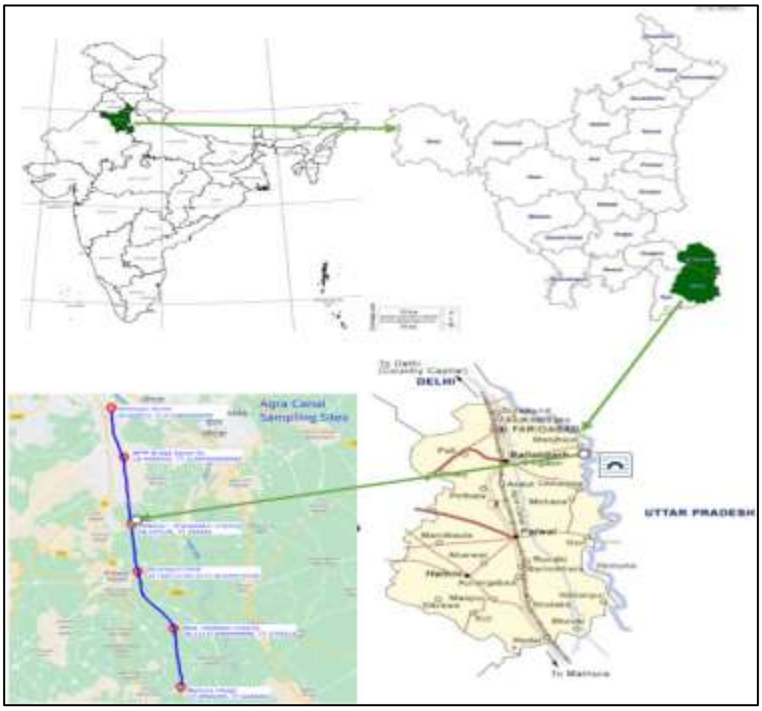


Figure 2: Study area showing the Agra Canal-irrigated Faridabad district, Haryana, India.

2.2 Water and Soil Sampling

Ground and canal water were collected from location S3. Groundwater was collected from a hand pump near the canal. After 15 minutes of running, the hand-pumped water was collected in a plastic one-litre bottle. For canal water sampling, the composite samples were collected from the left, right, and mid-stream in high-grade plastic bottles. For soil Sampling, points were selected at 50 m and 100 m from the canal on both sides (left and right). Samples were collected 20 inches deep from each sub-site, removing pebbles and debris by hand and placing soil in clean, labelled polythene bags with a zip-lock (Kazerooni et al., 2017), marking the location and date, noting coordinates, and recording climatic conditions (Patel et al., 2019). Upon reaching the laboratory, the soil was air-dried, ground, sieved with a 2 mm sieve, and stored at room temperature. (Mahmood et al., 2020). Soil samples weighing 1 g each underwent digestion with a 15 mL mixture of HNO_3, H_2SO_4, and $HClO_4$ in a 5:1:1 ratio at 80°C until a transparent solution was obtained. The USEPA 3050B digestion method was used for metal digestion (Islam et al., 2014; Kama et al., 2023). Inductively Coupled Plasma Mass Spectrometry (ICP-MS) (Agilent 7700X) (Fig.3) was used to determine the concentrations of heavy metals in the soil. (Kumari et al., 2024b; Singh et al., 2020).

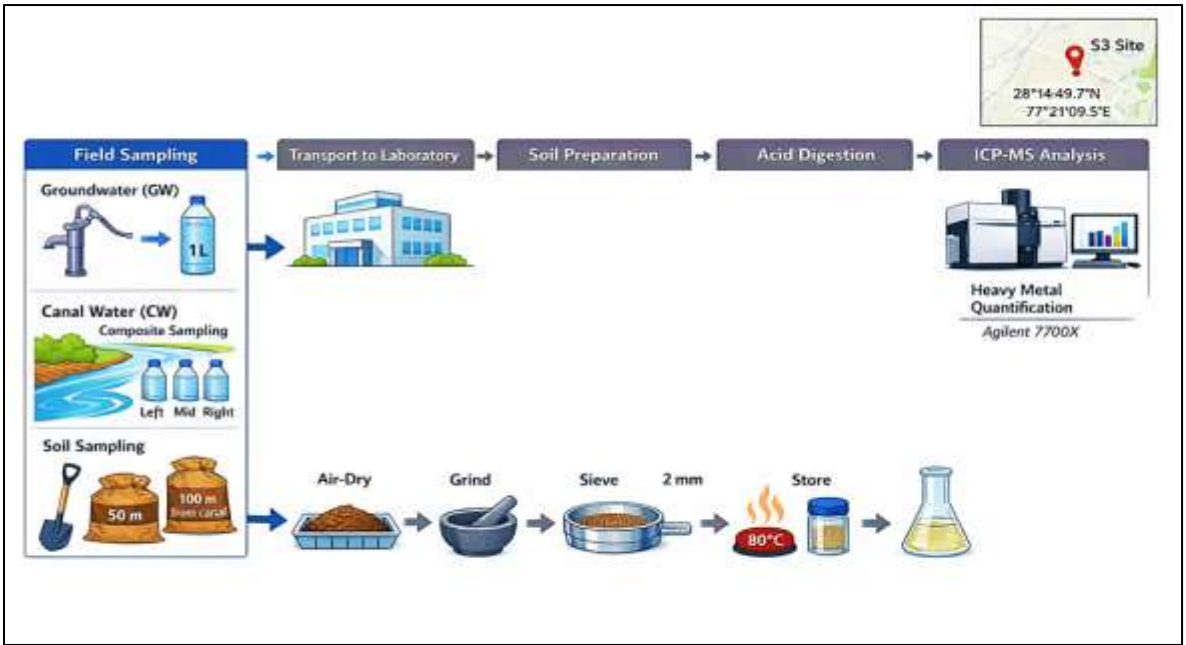


Figure 3: Workflow for Collection and Analysis of Water and Soil Samples for Heavy Metals

2.3 Experimental Design

For the experiment, three veggies were selected: spinach (leafy), tomato (fruit), and radish (root) (Hassan et al., 2024). The soil was collected from the same farm where the soil samples were taken, prepared, and organised in triplicate during the second week of September 2022. Groundwater and canal water for irrigation were also used from the same site (S3). Five kilograms of soil were measured using a digital balance, sterilised in an oven, and placed in 12-inch pots. Irrigation was applied to each pot as required (Petrou et al., 2020). CW and GW were collected from S3. The first set of pots was irrigated with 100% GW, the second with 50% GW + 50% CW, and the third with 100% CW Irrigate the plants at regular intervals (Kumari et al., 2024a). Plant measurements were taken to assess total yield (Rahil et al., 2013), and the number of germinating seeds, vegetative growth, flowers, fruit, and yield (Fig. 4B). The pots were kept on the Floor terrace of RPS Palms, Sector 88, Greater Faridabad, Haryana, India (Fig. 4A) (Kumari et al., 2024b).

2.4 Vegetable Harvesting and Analysis

The events observed from germination to harvest were recorded, including the number of germinating seeds, sapling growth, vegetative growth, and seedling health at various stages. All vegetables were harvested at optimal maturity, around 45 days for spinach and 60 days for radishes. The experiment was extended for 100 days for tomatoes, and other researchers observed a similar period Hassan et al., 2024). Vegetables were watered as required. After maturation, cut the spinach by hand, harvest it twice, uproot the radish, analyse the radish yield, and pluck the Tomato fruit by hand to evaluate the total yield. Samples were then identified, packed into sterile polythene bags, and sent to the lab, where they were washed with tap water, then with double-distilled water. The samples were oven-dried at 60°C until a constant weight was obtained and ground for further analysis (Patel et al., 2019;Mahmood et al., 2020). To homogenise the dried samples, they were crushed and powdered. Then, 15 ml of a tri-acid mixture (HNO_3, H_2SO_4, and $HClO_4$) was added in a 5:1:1 ratio (totalling 15 ml) at 80°C until a transparent solution was obtained (Gaurav et al., 2018). After cooling, the digested samples were filtered through the Whatman No. 42 filter paper. The ICP-MS Agilent 7500 was utilised to determine the concentrations of minerals in vegetables (Alkhatib et al., 2022;Islam et al., 2014). Analysis of energy, protein, carbohydrates, and fat was done using SOP/FL-04, IS 7219, IS: 1656, and IS: 4684, in that order.

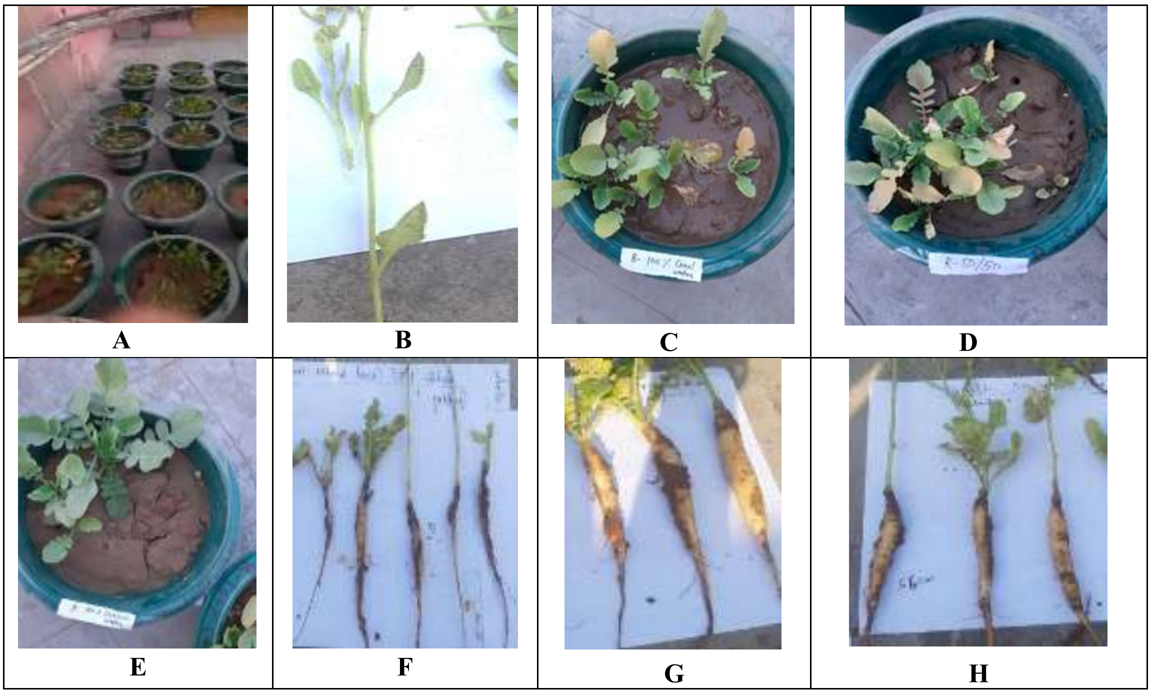


Figure 4. Experimental pot setup and harvested vegetables under different irrigation regimes**.** (A) Overall pot setup showing spinach, radish, and tomato growth; (B) Spinach twigs; (C) Radish pot irrigated with 100% groundwater (GW); (D) Radish pot irrigated with mixed water (50% GW + 50% canal water, CW); (E) Radish pot irrigated with 100% CW; (F) Harvested radish from 100% CW treatment; (G) Harvested radish from 100% GW treatment; (H) Harvested radish from mixed water (GW+CW) treatment. The figure illustrates growth variations and yield outcomes across irrigation treatments.

3.1 Analysis of Nutritional Content in Vegetables Irrigated by Different Sources.

3.1.1 Energy (kcal/100g)

The study examined the energy content per 100 grams of spinach, radish, and tomato under different water ratios. In Spinach, the pattern was 100% GW > 50% GW + 50% CW > Canal Side > 100% CW, in Radish: 50% GW + 50% CW > 100% GW > 100% CW > Canal Side, and in tomato: 50% GW + 50% CW > 100% CW > 100% GW > Canal Side, obtained in whole. For spinach, the highest energy content was observed with 100% GW, averaging 28.7 ± 1.01 kcal/100g. When supplied with a mixed 50% GW + 50% CW, the energy content remained relatively stable, averaging 28.57 ± 7.07 kcal/100g. However, a notable decrease in energy content was observed when spinach was grown with 100% CW, with a mean of 14.91 ± 1.6 kcal/100g. Along the canal side, the energy content was measured at 25.46 ± 1.59 kcal/100g (Table 1), indicating a moderate level compared to other water compositions. Similarly, the energy content showed only marginal differences across water ratios in radish samples. When cultivated with 100% GW, the average energy content was 16.86 ± 5.72 kcal/100g; it was relatively consistent with a 50% GW and 50% CW mixture, which averaged 16.9 ± 4.8 kcal/100g. Likewise, the energy content of 100% CW was 16.6 ± 4.3 kcal/100g. Along the canal side, radish showed an energy content of 16.32 ± 1.64, indicating minimal variance compared to other water compositions, as shown in the Q-Q plots (Fig. 9A).

In the case of tomatoes, the highest energy content was observed with a 50% GW + 50% CW, with a mean value of 19.78 ± 6.97 kcal/100g. When supplied with 100% GW, the energy content was slightly lower at 17.9 ± 2.62 kcal/100g. A comparable energy level was found with 100% CW, yielding a mean energy value of 17.92 ± 2.06 kcal/100g (fig 4A). Along the canal side, tomatoes exhibited an energy content of 16.86 ± 4.9 kcal/100 g, suggesting a moderate level like that of 100% GW. These findings indicate that the water composition of these vegetables can influence their energy content, with implications for agricultural practices and food quality. In spinach, the highest energy was detected in 100% GW and 50% GW + 50% CW. In radish, similar energy across all treatments. 100% CW generally lowers the energy content in spinach and tomato (Fig.5). A boxplot, also called a box-and-whisker plot, is a graphical display of the spread and distribution of a dataset. It summarises the data using five key numbers, often called the five-number summary (Figure 8A). The interaction between irrigation treatments can significantly affect leaf area and total plant fresh weight in tomatoes (Trotta et al., 2024).

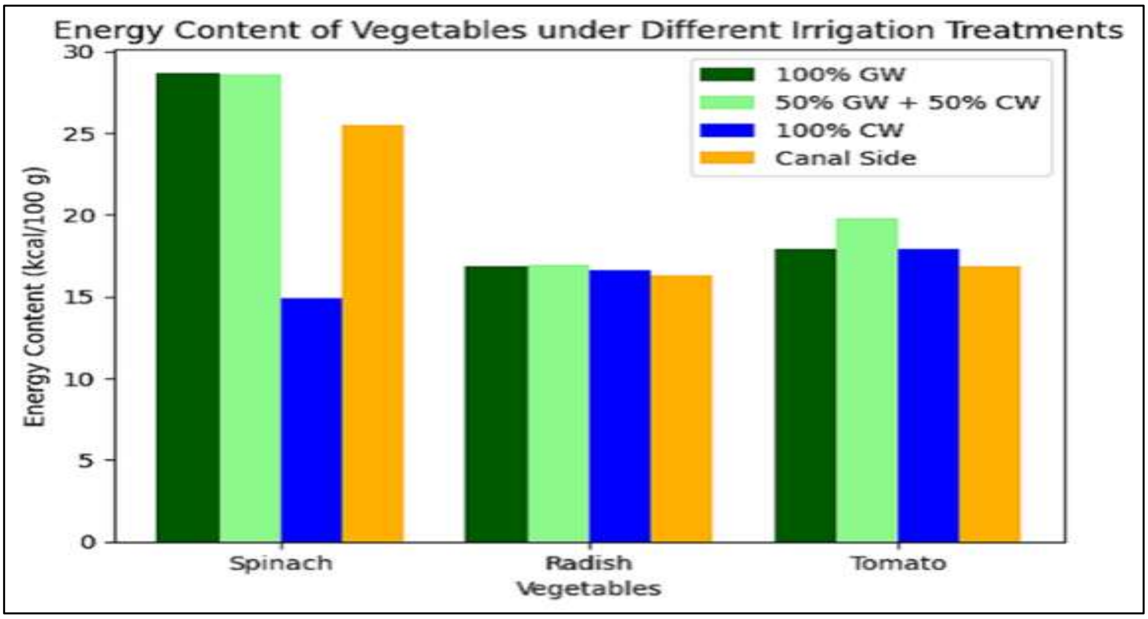


Figure:5 Energy content (kcal/100 g) of spinach, radish, and tomato under four irrigation regimes: 100% GW, mixed water (50% GW + 50% CW), 100% CW, and canal-side conditions.

Table 1 Nutritional and Mineral Values in Vegetables (Spinach, Radish, and Tomato)

S. No.	Parameters	water Ratio	Spinach	Radish	Tomato	WHO/FAO	IS
1	Energy	100% GW	28.7 ± 1.01	16.86 ± 5.72	17.9 ± 2.62	NA	NA
		50% GW + 50% CW	28.57 ± 7.07	16.9 ± 4.8	19.78 ± 6.97		
		100% CW	14.91 ± 1.6	16.6 ± 4.3	17.92 ± 2.06		
		Canal Side	25.46 ± 1.59	16.32 ± 1.64	16.86 ± 4.9		
2	Protein	100% GW	2.8 ± 0.67	0.69 ± 0	0.68 ± 0.16	NA	NA
		50% GW + 50% CW	2.6 ± 0.99	0.6 ± 0.23	0.72 ± 0.02		
		100% CW	2.71 ± 0.31	0.39 ± 0	0.71 ± 0.16		
		Canal Side	2.49 ± 0.61	0.51 ± 0.01	0.7 ± 0.16		
3	Carbohydrate	100% GW	3.7 ± 0.09	3.3 ± 1.34	3.4 ± 0.76	NA	NA
		50% GW + 50% CW	3.8 ± 1.3	3.2 ± 0.8	4 ± 0.13		
		100% CW	3.2 ± 0.37	3.1 ± 1.17	3.5 ± 1.33		
		Canal Side	3.2 ± 0.12	3.3 ± 0.05	3.2 ± 0.57		
4	Fat	100% GW	0.3 ± 0.1	0.1 ± 0.03	0.11 ± 0.03	NA	NA
		50% GW + 50% CW	0.33 ± 0.03	0.11 ± 0.02	0.1 ± 0.01		
		100% CW	0.31 ± 0.04	0.16 ± 0.03	0.12 ± 0.04		
		Canal Side	0.3 ± 0.09	0.12 ± 0.02	0.14 ± 0.05		
5	Iron (as Fe)	100% GW	34.25 ± 11.38	38.39 ± 7.46	38.42 ± 14.38	425	425
		50% GW + 50% CW	38.93 ± 13.03	40.53 ± 13.18	40.56 ± 7.92		
		100% CW	42.15 ± 11.14	54.4 ± 0.86	52.1 ± 20.46		
		Canal Side	19.46 ± 2.78	37.56 ± 9.22	54.43 ± 14.18		
6	Zinc (as Zn)	100% GW	1.28 ± 0.28	1.63 ± 0.39	1.21 ± 0.17	60.00	50.00
		50% GW + 50% CW	1.98 ± 0.55	1.74 ± 0.33	1.62 ± 0.56		
		100% CW	2.97 ± 0.44	2.64 ± 0.11	2.73 ± 0.69		
		Canal Side	2.23 ± 0.61	1.56 ± 0.56	1.29 ± 0.13		

(Ayers et al., 1985; Singh et al., 2021)

3.1.2 Protein

The sequence of parameters across various water ratios irrigated plants was in spinach - 100% GW > 100% CW > 50% GW + 50% CW > Canal Side. In radish, it was 100% GW > 50% GW + 50% CW > Canal Side > 100% CW, Tomato 50% GW + 50% CW > 100% CW > Canal Side > 100% GW. Spinach irrigated with 100% GW exhibited a protein content of 2.8g/100g. In comparison, spinach with a 50% CW and 50% GW mix showed a slightly higher protein content of 3.2 g/100g. Spinach irrigated with 100% CW obtained a protein content of 2.71 g/100g, while spinach grown on the canal side had a protein content of 2.49 g/100g. A Q–Q Plot (Quantile–Quantile Plot) is also presented for all values, a graphical tool used to determine whether values followed a particular theoretical distribution (Fig. 3B). For radishes, those irrigated with 100% GW had a protein content of 0.69 g/100g. The radishes irrigated 50% GW + 50% CW had a slightly lower protein content of 0.6g/100g. Radishes irrigated with 100% CW exhibited a further reduction in protein content, measuring 0.39 g/100g. Radishes grown in canal-side fields had a protein content of 0.51g. For tomatoes, those cultivated with 100% GW had a protein content of 0.68g/100g. The 50-50 ratio of GW + CW irrigated tomatoes showed a slightly higher protein content of 0.72 g/100g. Tomatoes irrigated with 100% CW had a protein content of 0.71 g/100g. Additionally, tomatoes grown along canals had a protein content of 0.70 g/100 g; protein values were not obtained in a definite water ratio (Fig. 6).

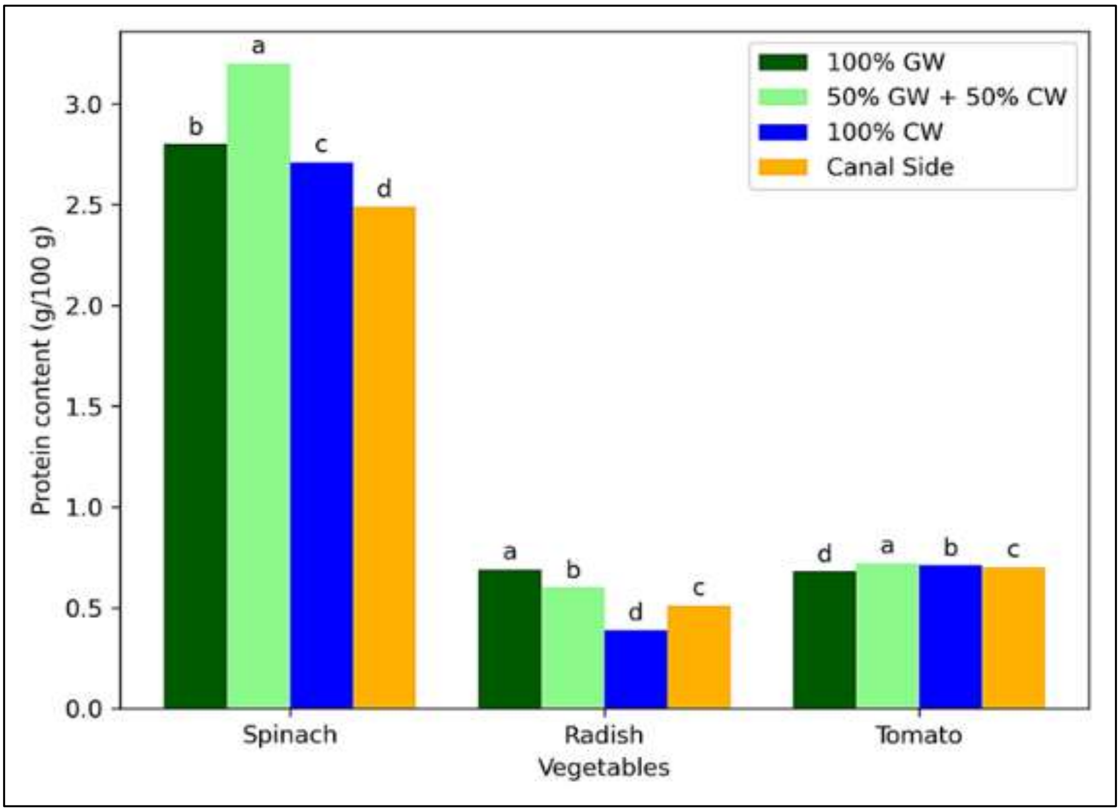


Figure:6 Protein content (g/100 g) of spinach, radish, and tomato grown under four irrigation regimes: 100% GW, mixed water (50% GW + 50% CW), 100% CW, and canal-side conditions.

Other researchers observed a trend in leaf protein content across all investigated varieties, in the following order: M. rubra > M. nigra > M. alba (Iqbal et al., 2012). The protein content in the edible parts of vegetables grown in sewage, canal, and tubewell water has also been reported by other researchers (Naz et al., 2018). Protein contents were significantly higher ($p \geq 0.05$) in okra, tomato, and spinach when grown with sewage water, followed by those irrigated with canal water. Lower protein content values were recorded in these vegetables grown with tubewell water. While four vegetables (cauliflower) and one root vegetable (carrot) had higher protein content when grown with tubewell water, they also had higher protein content when grown with CW. Significantly lower protein content was recorded when these vegetables (cauliflower and carrot) were raised with sewage water. (Naz et al., 2018). Spinach has much higher protein than radish and tomato under all treatments. Lowest radish protein seen with 100% CW. The water source has a lesser effect on tomato protein content.

Table 2: Statistical analysis of the analysed values of grown vegetables (Spinach, Radish, and Tomato)

	Energy	Protein	Carbohydrate	Fat	Iron (Fe)	Zinc (Zn)
Valid	12	12	12	12	12	12
Missing	0	0	0	0	0	0
Median	17.40	0.705	3.300	0.130	39.73	1.680

Mean	19.73	1.300	3.408	0.183	40.93	1.906
Std. Error of Mean	1.423	0.290	0.082	0.028	2.785	0.175
Std. Deviation	4.929	1.004	0.284	0.095	9.648	0.606
95% CI Std.Dev. Lower	3.491	0.711	0.201	0.067	6.834	0.429
95% CI Std. Dev. Upper	8.368	1.705	0.483	0.162	16.38	1.028
Minimum	14.91	0.390	3.100	0.100	19.46	1.210
Maximum	28.70	2.800	4.000	0.330	54.43	2.973
25th percentile	16.80	0.660	3.200	0.110	38.18	1.492
50th percentile	17.40	0.705	3.300	0.130	39.73	1.680
75th percentile	21.20	2.518	3.550	0.300	44.64	2.330

3.1.3 Carbohydrate

Spinach irrigated with 100% GW exhibited a carbohydrate content of 3.7 g/100g, while the 50% CW and 50% GW mix showed a slightly higher carbohydrate content of 3.8 g/100g. Spinach irrigated with 100% CW displayed a carbohydrate content of 3.1 g/100g, and spinach grown on the canal side had a carbohydrate content of 3.2 g/100g. In spinach, the pattern obtained was (50% GW + 50% CW > 100% GW > 100% CW / Canal Side). For radishes, those irrigated with 100% GW showed a carbohydrate content of 3.3 g/100 g, and the mix of 50% canal and 50% groundwater displayed a carbohydrate content of 3.2 g/100 g. Radishes irrigated with 100% canal water exhibited a carbohydrate content of 3.1 g/100g, while radishes grown in canal-side fields had a carbohydrate content of 3.3 g/100g.

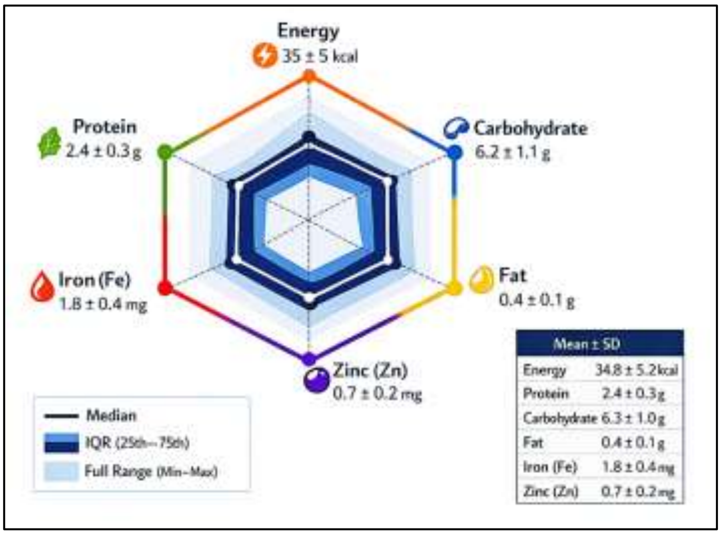


Figure:7 Nutritional profile of vegetables grown under different water treatments.

The pattern was100% GW & Canal Side > 50% GW + 50% CW > 100% CW growth yield obtained, which was analyzed by Q-Q plots (Fig.9C). Researchers used sewage water to obtain higher yields since sewage water contains many organic nutrients. Sewage enhances the production of vegetables (Hussain et al., 2019), excluding root crops, because of the abundance of organic matter.

In the case of tomatoes, those cultivated with 100% GW had a carbohydrate content of 3.40 g/100g. The 50-50 ratio of CW and GW-irrigated tomatoes showed a slightly higher carbohydrate content of 4.00 g/100 g. Tomatoes irrigated with 100% CW had a carbohydrate content of 3.50 g/100 g, and tomatoes grown on canal sides had a carbohydrate content of 3.2 g/100g. In tomato, the pattern was (50% GW + 50% CW > 100%CW > 100% GW > Canal Side) obtained (Fig.8C). All the statistical analyses of all the vegetables are shown in Figure 7.

Energy (A)	**Protein (B)**

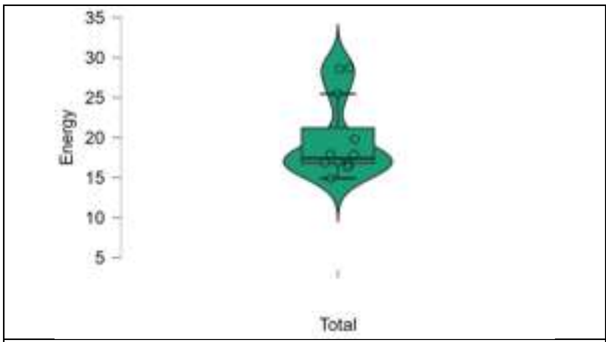
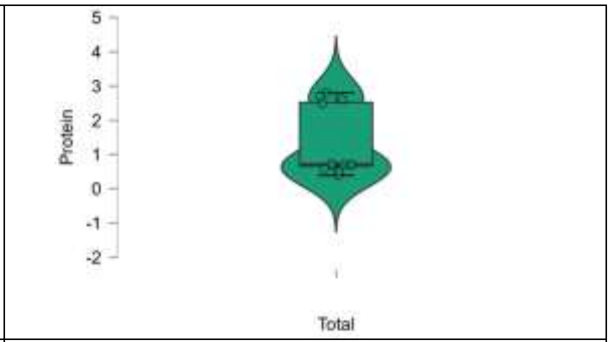
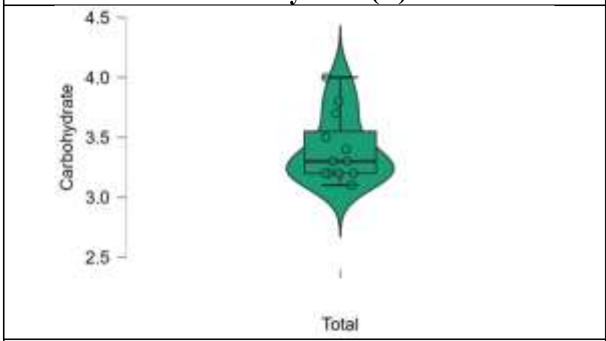
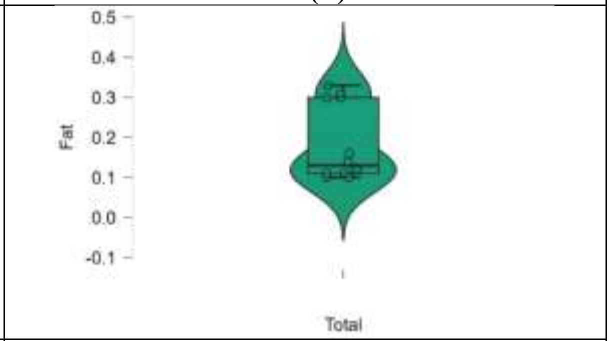
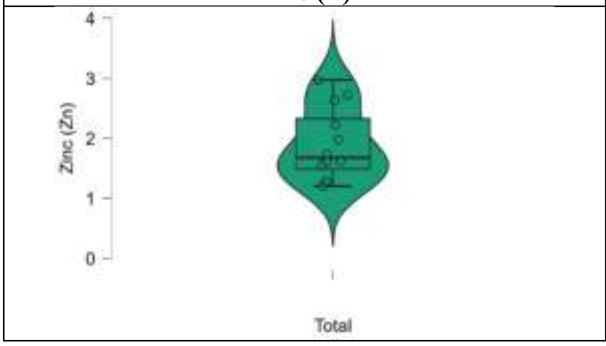
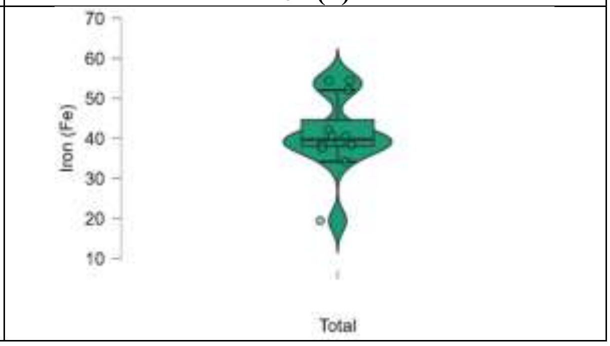
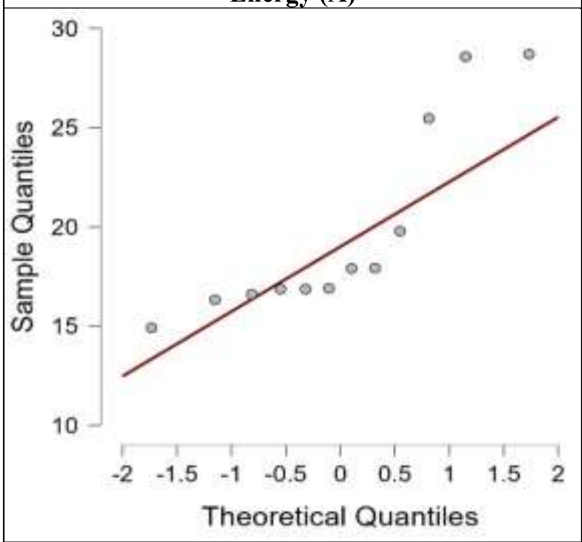
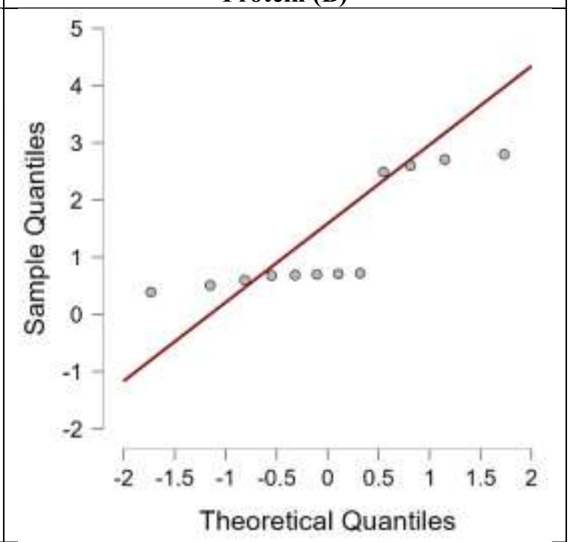
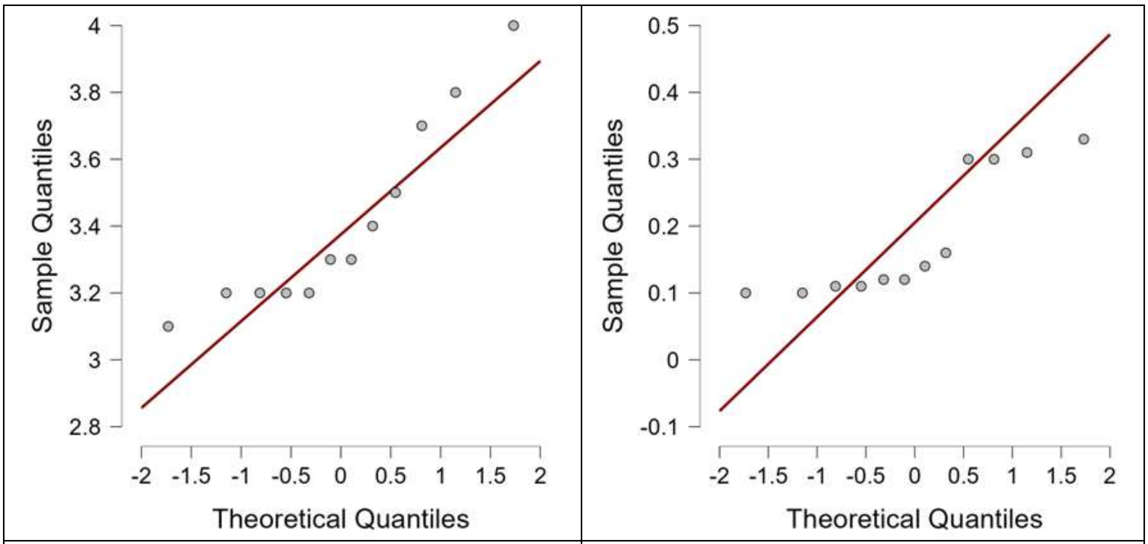
	
Carbohydrate (C)	**Fat (D)**
	
Zinc (E)	**Iron (F)**
	

Figure 8: Boxplots of nutritional (Energy, Protein, Carbohydrate, Fat, Fe, and Zn) contents in different water ratios.

Energy (A)	**Protein (B)**
	
Carbohydrate (C)	**Fat (D)**



Zinc (E)	Iron (F)

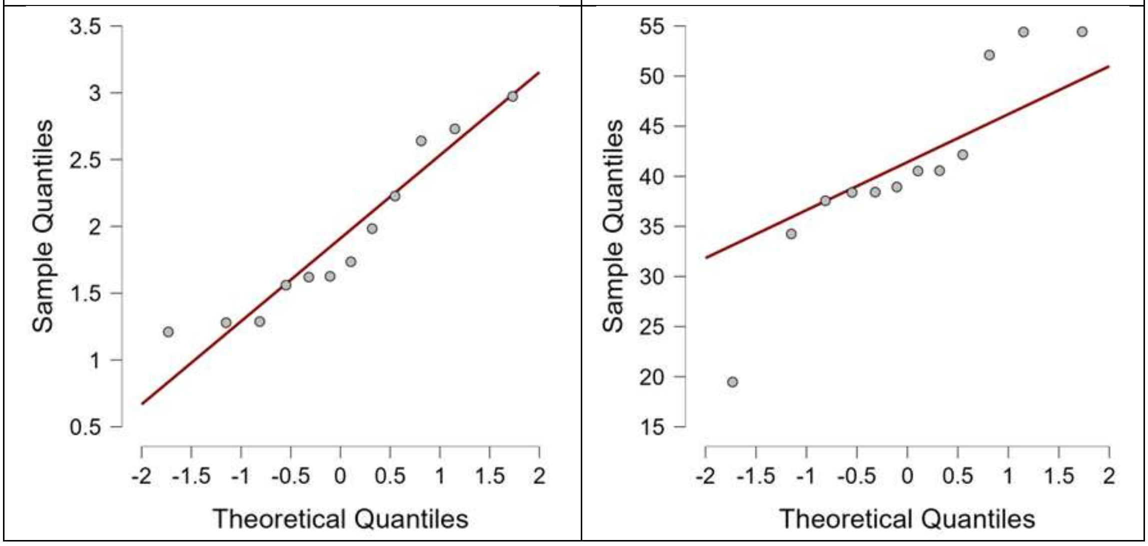


Figure 9 Q-Q Plots of nutritional (Energy, Protein, Carbohydrate, Fat, Fe, and Zn) contents in different water ratios

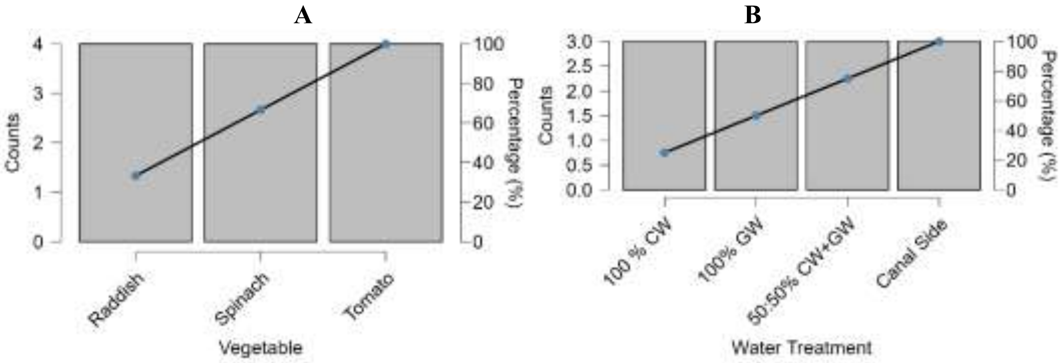


Figure:10 (A) Pareto Plots of all vegetables (spinach, radish, and tomato) and different water ratios (10 B).

3.1.4 Fat

Spinach irrigated with 100% GW exhibited a fat content of 0.3 g/100g, while the 50% GW+ 50% CW mix showed a slightly higher fat content of 0.33g. Spinach irrigated with 100% CW displayed a fat content of 0.31g, and spinach grown on the canal side had a fat content of 0.30g/100g. Spinach follows the trend: 50% GW + 50% CW > 100% CW > 100% GW / Canal Side. For radishes, those irrigated with 100% GW showed a fat content of 0.10g, and the mix of 50% CW + 50% GW displayed a fat content of 0.11g. Radishes irrigated with 100% CW exhibited a higher fat content of 0.16 g/100g, while radishes grown in canal-side fields had a fat content of 0.12g. The pattern is- Canal Side > 100% CW > 100% GW > 50% GW + 50% CW. (Q-Q plots shown in Fig.9D). In the case of tomatoes, those cultivated with 100% GW had a fat content of 0.11g. The 50%GW +50% CW blend showed a similar fat content of 0.10g. Tomatoes irrigated with 100% CW had a fat content of 0.12g, and tomatoes grown on canal sides displayed a slightly higher fat content of 0.14g. Tomato shows the pattern highest to lowest - Canal Side >100% CW > 100% GW > 50% GW + 50% CW (Fig.8D). Radish shows a slight increase in fat with 100% CW—no significant effect of different water ratios on fat content.

3.1.5 Fe as a mineral

In Spinach, Iron content ranged from 19.46 mg/kg (Canal Side) to 42.15 mg/kg (100% CW). Spinach irrigated with 100% CW showed the highest Fe concentration, with a notable increase compared to GW irrigation. The lowest Fe level was recorded in spinach grown near the canal side, possibly due to differences in soil characteristics or uptake efficiency. In radish, the Fe content in radish was relatively consistent across most water treatments, with values ranging from 37.56 mg/kg (Canal Side) to 54.40 mg/kg (100% CW). The highest radish concentration was observed with 100% CW, suggesting enhanced metal mobility or uptake under this irrigation regime. Among the three vegetables, tomato exhibited the highest Fe levels, with those grown on canal-side land (54.43 ± 14.18 mg/kg) being the highest. It may indicate a higher tendency for bioaccumulation in fruit-bearing crops when exposed to iron-rich irrigation sources. (Q-Q plots shown in Fig.9F). Highest iron accumulation in tomato and radish with 100% CW is shown by Pareto chart (Fig.10A, B). Spinach has the highest iron content (100% CW), but the canal side shows a drop in iron content. Canal-side spinach shows a drastic drop in Fe (Fig.9F). It is an essential nutrient for human health, and consuming vegetables with such Fe concentrations is generally considered beneficial for meeting dietary requirements. Black pepper had the most significant Fe content, at 9.29 ± 1.72, followed by green chili and branded chili powder, with concentrations of 35.46 ±3.94 and 34.02 ± 3.18, respectively (Islam et al., 2023), and similar values of Fe were also obtained from Saudi Arabia (31.96–543.2) (Ali & Al-Qahtani, 2012). Other studies showed that the maximum accumulation of Fe was found in Rohinullah vegetable samples, the order being 105-210 in beetroot > 71-110 in turnip > 55-97 in radish> 25-40 in carrot (Khalid Iqbala et al., 2009).

3.1.6 Zn as a mineral

Zn is an essential micronutrient required for both plant metabolism and human health; however, elevated levels can be phytotoxic and harmful to consumers if concentrations exceed recommended dietary limits. Zn concentration in spinach increased with the proportion of canal water used. The lowest Zn content was observed in samples irrigated with 100% GW (1.28 ± 0.28 mg/kg). In comparison, the highest was recorded under 100% CW (2.97 ± 0.44 mg/kg) (Table 2), indicating no immediate health risk from Zn accumulation in spinach. The Zn content in radish ranged from 1.56 ± 0.56 mg/kg (Canal Side) to 2.64 ± 0.11 mg/kg (100% CW), (Fig.2). In tomatoes, the Zn concentration ranged from 1.21 ± 0.17 mg/kg (100% GW) to 2.73 ± 0.69 mg/kg (100% CW) (Q-Q plots shown in Fig.9E). While the accumulation trend was like that of spinach and radish, tomato showed slightly higher variability under CW treatment, possibly due to differences in fruit physiology or soil-water interaction at the root zone. A consistent pattern is observed across all vegetable types. The highest Zn values in all crops were associated with 100% CW, confirming the presence of Zn in CW, likely derived from agricultural runoff, industrial effluents, or soil leaching. Spinach accumulates more Zn than radish or tomato overall. A similar range of Zn was obtained by other researchers from Hisar, which was in the range of 1.56–23.76 mg kg-1(Garg et al., 2014). Similar results were obtained from Soudi Arebia Zn (8.27–71.77 lg/mg) (Ali & Al-Qahtani, 2012), Zn ranged between 9-110 mg/kg in all the Rohinullah vegetable samples (Khalid Iqbala et al., 2009).

3.1.7 WHO/FAO Recommendations and FSSAI & Indian Standards (IS)

FSSAI does not set a maximum or minimum standard value for total carbohydrates for general foods, but mandates that total carbohydrates be declared on the Nutrition Information panel of packaged foods, along with energy, protein, fats, sugars, etc. Recommended Dietary Allowances (RDAs) specify the daily nutrient requirements for different age groups, but not per-vegetable standards. The RDA is ~12–15 mg/Kg (adults, varies by sex/age/pregnancy). Zinc ranges 8–12 mg/day (FSSAI & IS). For raw/fresh vegetables and fruits, regulatory focus is on contaminant safety, not minimum nutritional content. For enriched or fortified foods, minimum and maximum allowable levels are established (excluding naturally occurring nutrients in fresh produce). Zn is 10-15 mg/kg, as per the FSSI norms (Food Safety and Standards (Fortification of Foods) Regulations, 2018).

4. CONCLUSION

The findings of this study underscore the significant influence of irrigation water sources on the nutritional quality of vegetables grown in Faridabad. For spinach, irrigation with 100% GW resulted in the highest energy (28.7 kcal/100g) and protein (2.8 g/100g) levels, whereas irrigation with 100% CW led to a notable reduction in energy content. In contrast, a mixture of 50% GW + 50% CW generally yielded intermediate nutritional values and, in the case of tomatoes, even the highest energy content (19.78 kcal/100g). Radish samples showed minor variation across treatments, with protein content highest in 100% GW. The data indicate that the exclusive use of CW may diminish specific nutritional parameters, particularly in spinach. In contrast, a combined irrigation approach (50% GW + 50% CW) can optimise nutrient content in tomatoes. The observed variations in carbohydrate and fat content further suggest that the composition of irrigation water subtly affects the overall nutritional profile of the produce. These results underscore the importance of meticulous water management and indicate that integrating GW with CW could be a beneficial strategy to improve crop nutritional quality, thereby supporting improved agricultural outcomes and public health. In summary, this study evaluates the nutritional quality of vegetables irrigated with Agra Canal water, contributing to a broader understanding of the relationship between irrigation water sources and crop nutrition.

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