



Irrigation Water Quality Assessment of Agra Canal's Haryana Stretch in India: Insights and Implications

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Abstract

The study presents a comprehensive assessment of the water sustainability of the irrigation system and the ecosystem based on a detailed analysis of the Agra Canal's water quality. A survey involving farmers and local communities was conducted using questionnaires, followed by the collection of water samples from six points during the summer, monsoon, and winter seasons. The samples were analysed for hydrochemical parameters, including pH, EC, Na⁺, K⁺, Ca²⁺, Mg²⁺, SO₄²⁻, Cl⁻, HCO₃⁻, CO₃²⁻, NO₂⁻, boron, and heavy metals (Fe, Cu, Zn, Pb, Ni, Cr, Cd, and As). Water quality indices, such as the Sodium Absorption Ratio (SAR), Residual Sodium Carbonate (RSC), Kelly Index (KI), Permeability Index (PI), Sodium Percentage (Na%), and Magnesium Ratio (MR), were also evaluated and compared to FAO and CGWB CPCB (2000) standards. The results indicated that all parameters were within the permissible limits. SAR and RSC for 100% of samples were categorised as excellent; Na% fell within the good to medium category; PI was within the Class 2 category; MR values were < 50; and KI was also < 1 for 100% of samples, confirming the suitability of canal water for irrigation. Heavy metals were also within the FAO limits. These findings provide valuable insight for decision-makers and agricultural stakeholders to develop sustainable irrigation practices. However, further research is recommended to determine the cause of the degradation in crop quality observed with Agra Canal Water irrigation.

Keywords: water resources, water quality index, Irrigation Standards, Hydrochemical Parameters, Agra Canal

1. Introduction

Water resources are diminishing alarmingly, especially in densely populated South Asian countries like India. Water is the most crucial natural resource for a state, government, and humanity. (Döndü et al., 2022). Indian society is grappling with a crucial environmental issue, as its population is growing rapidly and alarmingly. (D. Singh & Satija, 2018). The Agra Canal, a vital lifeline for agricultural practices from Faridabad to Agra, has been plagued by escalating pollution stemming from urbanisation, industrialisation, and agricultural runoff. The importance of assessing water quality in this context is underscored by studies showing the detrimental effects of water pollution on soil quality and crop yields. Thus, conducting a thorough evaluation of water quality parameters along the Agra Canal is imperative for devising informed strategies to sustain agricultural practices, such as pH, Electrical conductivity (EC), Total dissolved solids (TDS), Total Hardness (TH), Chemical oxygen demand (COD), anions such as Bicarbonate (HCO₃⁻), Chloride (Cl⁻), Nitrate, (NO₃⁻), Sulfate (SO₄²⁻), and cations; Calcium, (Ca⁺²), Magnesium, (Mg⁺²), Sodium (Na⁺), Potassium, (K⁺) and Boron (B) and trace metals were utilised in water pollution research. Various Water Quality Indexes (WQI) were analysed by calculating cation and anion concentration, including SAR, RSC, KI, PI, Na%, and MR. (Gibrilla et al., 2011). WQI has emerged as a valuable tool for integrating multiple parameters into a unified framework, offering a holistic understanding of water quality. In a water quality monitoring program, data from various locations generates voluminous information, which complicates categorising water quality. The Central Pollution Control Board (CPCB) and the Central Ground Water Board (CGWB) present the criteria for assessing the suitability of irrigation water in India. As human impact on water bodies increases, evaluating water quality has become essential to protect agricultural and environmental interests. The current research aims to comprehensively assess the Agra Canal's WQI and compare these findings with the established WQI standards; this comparative analysis is crucial for determining the suitability of water for irrigation, thereby bridging the gap between water quality assessment and practical agricultural applications.

2. Materials And Methodology

Table 1: The Sampling sites of the Agra canal in Faridabad and Palwal district of Haryana

Sampling site (S)	Location Name	District	Activity	Coordinates
S1	Meethapur Border	Faridabad	Urban site	(28°29'45.2"N 77°18'57.4" E)
S2	BPTP Brize Sector 81 crossing	Faridabad	Urban site	(28°23'22.7"N 77°20'19.4" E)

S3	Fatehpur-Prahladpur crossing	Faridabad	Agricultural site	(28°14'49.7"N 77°21'09.5" E)
S4	Basant Garh Palwal	Palwal	Agricultural site	(28°08'40.2"N 77°21'48.1" E)
S5	Bela-Ajijabad crossing	Palwal	Agricultural site	(28°01'20.4"N 77°25'48.4" E)
S6	Bansva village	Palwal	Agricultural site	(27°53'48.6"N 77°26'34.3" E)

2.1 Water Sampling and Analysis

Samples were collected in the summer, monsoon, and winter seasons from August 2021 to May 2023. (Kumari et al., 2024a). Sampling and Handling have been performed in accordance with BIS (1999) and APHA (1999) standards. All the containers were washed with detergent, followed by water, a diluted solution of HNO₃, and then distilled water. Grab samples were collected from the left, middle, and right streams of the canal in polyethene bottles and analysed in the morning. The closed bottle was dipped in the canal to a depth of 15-25 cm, opened, washed twice with canal water, and then filled. The 2-litre bottle was filled for general parameters. The one-litre bottle for heavy metals was spiked with 1ml of concentrated HNO₃, and pH, EC, and TDS were analysed on the spot for general information but are not mentioned in the article. PH was measured with a Digital PH meter (H196107), and EC was measured with an EC meter-3 (Alobaidy et al., 2010). A TDS meter-3 measured TDS. All the samples are preserved in the ice box. Samples were stored at 4°C in the laboratory refrigerator. The analysis was conducted in an ISO 9001:2015-certified laboratory, and the mean value was reported in the results. Na⁺ and K⁺ were determined using a flame photometer, and NO₃⁻ and SO₄⁻² were measured using a UV-visible spectrophotometer. Furthermore, Ca²⁺, Mg²⁺, and Hardness were measured by titrating an EDTA solution. In determining CO₃⁻², HCO₃⁻³ was determined by potentiometric titration, and for Cl⁻, argentometric titration was applied. COD was analysed using the reflux method per BIS (Indian Standards, 2006). Heavy metals Fe, Cu, Zn, Pb, Ni, Cr, Cd, and As were analysed by an inductively coupled plasma-optical emission spectrometer (ICPMS- Agilent Tech. 7700x) (Kumari et al., 2024b). SAR and Na% were determined to study the sodium hazard in irrigation water. Other indices such as RSC, PI, MR, and KI were used to determine the irrigation water quality (G. Singh et al., 2022), using the standards of the Food and Agriculture Organization (FAO) of the United Nations, the CGWB, and the CPCB (2000) to categorise surface water into different irrigation quality standards (G. Singh et al., 2022). The following formula was used to calculate SAR, RSC, Na%, PI, MR, and KI (Table 2).

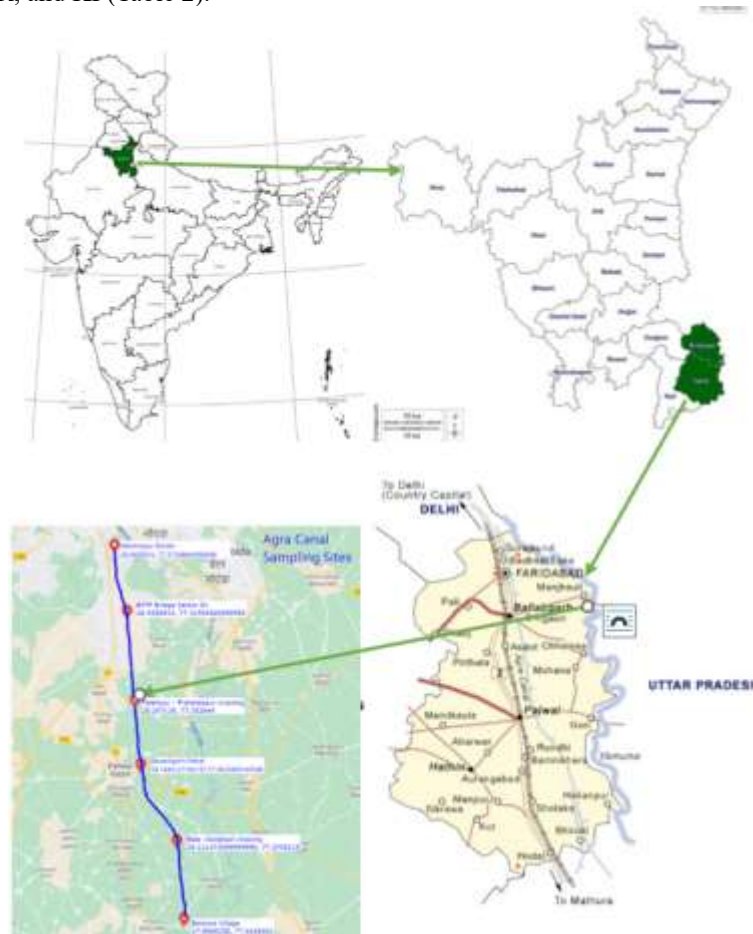


Figure 1: The Sampling sites with coordinates. (Kumari et al., 2024b, 2025).

Table 2 Irrigation Water Quality Indices calculation formulae

Parameter	Formula	References
SAR	$\frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$	(Aly, Al-Omran, and Alharby, 2015; Nagaraju, Muralidhar, and Sreedhar, 2016)
KI	$\frac{Na^+}{(Ca^{2+} + Mg^{2+})}$	(Aly et al., 2015; El-Amier et al., 2021)
PI	$\left\{ \frac{Na^+ + \sqrt{HCO_3^-}}{Ca^{2+} + Mg^{2+} + Na^+} \right\} \times 100$	(El-Amier et al., 2021)
RSC	$(CO_3^{2-} + HCO_3^-) - (Ca^{2+} + Mg^{2+})$	(Batayneh, 2011; El-Amier et al., 2021)
Na%	$\left\{ \frac{(Na^+ + K^+)}{(Ca^{2+} + Mg^{2+} + Na^+ + K^+)} \right\} \times 100$	(El-Amier et al., 2021)
MR	$\frac{Mg^+}{Ca^{2+} + Mg^{2+}} \times 100$	(El-Amier et al., 2021; Kumari & Rai, 2020)

Unit: (HCO_3^- , Ca^{2+} , Mg^{2+} , Na^+ , K^+) in Millimole/litre (Me/l), (Murthy Arignar Anna, 2010; G. Singh et al., 2022).

3. Results And Discussion

3.1. A comparative Assessment of Hydrochemical characteristics of Agra Canal water with FAO and CGWB CPCB (2000).

During the summer, the pH ranged from 7.335 to 7.550, with a mean value of 7.425 ± 0.102 . During the rainy season, pH ranged from 7.190 to 7.275, with a mean of 7.24 ± 0.084 . In the winter, the pH ranged from 7.435 to 7.660, with a mean value of 7.522 ± 0.178 . Per FAO standards, the normal pH range for irrigation water is 6.5-8.4 (Alobaidy et al., 2010; Kambire et al., 2022; Riaz et al., 2018). The recorded pH values in all seasons are well within the FAO limits (Table 2). The pH outside the normal range might be suitable for irrigation (Jeong et al., 2016). In summer, the EC ranged from 1923.500 to 2517.500 $\mu\text{s/cm}$, with a mean value of $2266.500 \pm 215.118 \mu\text{s/cm}$. During the monsoon season, conductivity ranged from 690.100 to 733.945 $\mu\text{s/cm}$, with a mean of $711.994 \pm 223.293 \mu\text{s/cm}$. EC ranged from 875.300 to 1025.050 $\mu\text{s/cm}$ in winter, with a mean value of $965.075 \pm 146.906 \mu\text{s/cm}$. All values were within the FAO permissible limit of 3000 $\mu\text{s/cm}$. In all seasons, 100% of the samples fall into the slightly to moderately category (Table 3). According to CGWB & CPCB (2000), 50% of water samples were in the medium category in summer, and 50% were in the bad category. In the monsoon season, 50% of the samples were in the sound range, and 50% were within the medium range. In winter, 100% of the samples were within the medium category, showing suitability for irrigation water. These results show variations in EC, reflecting the salt concentration in water samples across different seasons. Other researchers also reported similar results, with EC values ranging from 553 to 3020 $\mu\text{s/cm}$ in summer and from 290.5 to 1425 $\mu\text{s/cm}$ in winter. The high EC primarily results from the disposal of industrial process waste, a prevalent practice in this region. EC levels rise during the summer due to effluent discharge from small-scale industries and salt disintegration. However, during the monsoon season, dilution reduces EC several times in winter (G. Singh et al., 2020). As the EC of the water increases, the Mg/Ca ratio also tends to rise (Raychaudhuri et al., 2014). However, the mixed-type water with high EC in India (2) was considered of good quality for irrigation (Islam & Mostafa, 2022). In Summer, the HCO_3^- ranged from 348.5 to 404.0 mg/L, with a mean value of $372.625 \pm 31.514 \text{ mg/L}$. During the monsoon season, HCO_3^- ranged from 248.350 to 277.050 mg/L, with a mean of $264.248 \pm 95.138 \text{ mg/L}$. In winter, the HCO_3^- ranged from 188.335 to 329.115 mg/L, with a mean value of $284.595 \pm 59.133 \text{ mg/L}$. All values were within the FAO-permissible limits (610). Seasonal variation is shown in Fig. 2A. Carbonate was nil throughout the research, possibly due to the non-availability of the source.

Table 3: Statistical Analysis of Agra Canal Irrigation Parameters and Comparison with FAO Permissible Limits.

Parameter	Season	Mean	SD	Min	Max	Skew	Kurt	FAO Norms
pH	Summer	7.425	0.102	7.335	7.550	0.696	-1.478	6.5–8.4
	Monsoon	7.240	0.084	7.190	7.275	-0.775	-1.017	
	Winter	7.522	0.178	7.435	7.660	0.949	-1.083	
EC ($\mu\text{S/cm}$)	Summer	2266.500	215.118	1923.500	2517.500	-0.756	-0.134	3000
	Monsoon	711.994	223.293	690.100	733.945	0.241	-1.855	
	Winter	965.075	146.906	875.300	1025.050	-0.871	0.377	
TDS (mg/L)	Summer	1047.333	111.101	942.500	1144.500	-0.287	-0.795	2000
	Monsoon	462.150	130.788	438.725	491.335	0.577	-0.274	
	Winter	698.640	184.702	596.000	799.500	0.047	-0.792	

Total Hardness (mg/L)	Summer	592.489	114.567	424.505	713.370	-0.569	-1.423	600
	Monsoon	201.579	83.502	187.500	209.650	-1.039	0.476	
	Winter	266.658	57.361	178.400	319.000	-0.926	-0.027	
COD (mg/L)	Summer	53.195	7.304	50.065	61.485	1.852	3.260	250
	Monsoon	37.775	6.764	33.950	41.250	-0.125	-1.529	
	Winter	49.899	9.743	42.800	64.730	1.736	3.426	

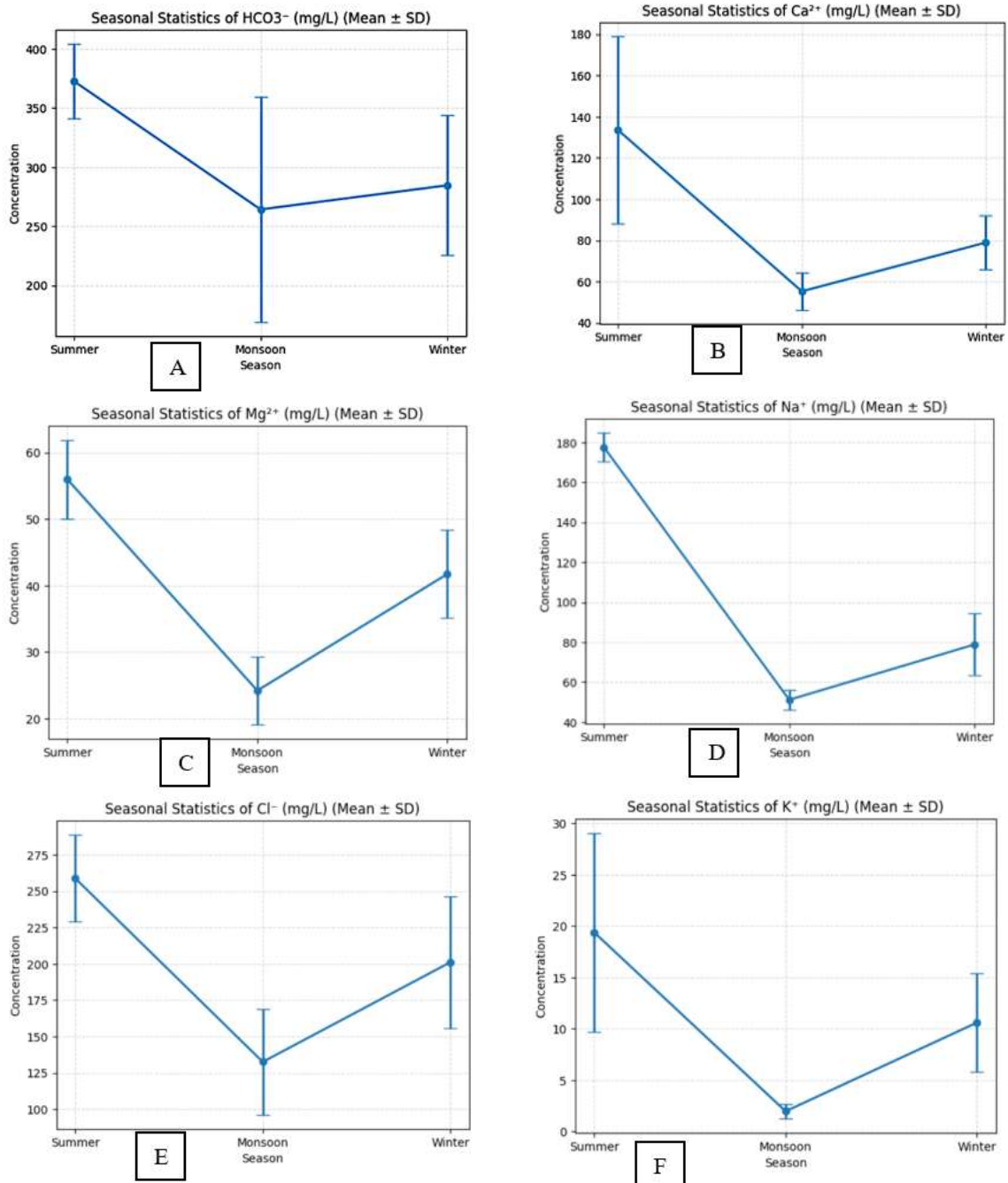


Figure 2 (A, B, C, D, E, F) Seasonal Variation of different ionic concentrations in the water of the Agra Canal

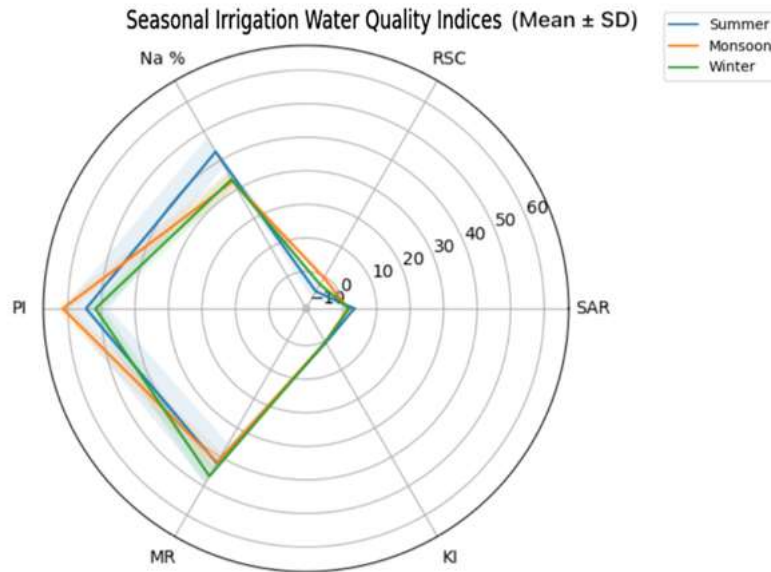


Figure 3: Seasonal Variation of Water Quality Indices of Agra Canal Water

The unit for EC is $\mu\text{s}/\text{cm}$. SAR, RSC, Na%, PI, MR, and KI are represented in me/L , while all other measurements are in mg/L (except pH). NA (Not given the direct value). (Ayers et al., 1985; Jahin et al., 2020; Mandal et al., 2019; Murthy Arignar Anna, 2010; Nagaraju et al., 2016; G. Singh et al., 2022).

The Total Hardness in summer ranged from 424.505 to 713.370 mg/L , with a mean value of 592.489 ± 114.567 mg/L . The monsoon season varied from 187.500 to 209.650 mg/L , with a mean value of 201.579 ± 83.502 mg/L . In winter, it ranged from 178.4 to 319.0 mg/L , with a mean value of 266.658 ± 57.361 mg/L . In summer, 100% of samples fall within the Very hard range; in monsoon, samples fall in the moderately hard (50%) to hard (50%) category; in winter, 66.7% of samples fall within the hard category, and 41.7% within the very hard category. However, the acceptable limit is 600 (Kothari et al., 2021). The high TH may be due to the addition of effluents from industries and to wastewater and sewage dumping from surrounding areas. In the Kali River, TH values varied from 117 to 332.8 mg/L in summer but from 93.6 to 288 mg/L in winter. In the Summer Season, Ca^{+2} concentration ranges from 92.715 to 153.845 mg/L with a mean of 133.605 ± 45.520 . The Monsoon Season varies from 50.150 to 63.365 mg/L with a mean of 55.294 ± 9.035 . In the Winter Season, Ca^{+2} concentration ranges from 68.80 to 85.94 mg/L (Fig. 2 B) with a mean of 78.982 ± 13.008 ; this elevated level is due to the convergence of agricultural runoff and industrial effluents. Similar values reported by other researchers ranged from 14.1 to 85.0 mg/L (G. Singh et al., 2022); all values were within the permissible limits of the FAO (400 mg/L). Na^{+} concentration ranged from 171.500 to 186.500 mg/L during the summer, with a mean value of 177.667 ± 7.299 mg/L . During the rainy season, the concentration ranged from 46.360 to 57.560 mg/L (Fig. 2D) with a mean of 51.194 ± 5.027 mg/L . In the winter, it ranged from 61.550 to 91.400 mg/L , with a mean of 78.889 ± 15.521 mg/L . All values were within the FAO-permissible limits (920 mg/L), indicating that the water is suitable for irrigation. Na^{+} is possibly due to the influx of sewage and industrial discharges. A similar Na^{+} range was observed by others, 0.0 to 55.2 mg/L from Udham Singh Nagar, Uttarakhand (K. K. Singh et al., 2020). In the Kali River, the Na^{+} content of water samples ranges from 52 to 213 mg/L and from 42.8 to 201.5 mg/L during summer and winter, respectively (G. Singh et al., 2020).

The concentration of chloride (Cl^{-}) varied throughout the seasons. In summer, it ranged from 234.800 to 289.800 mg/L (Fig. 2E) with a mean value of 258.892 ± 29.915 mg/L . During the monsoon, the levels fluctuated between 124.950 and 142.175 mg/L , averaging 132.604 ± 36.403 mg/L . In winter, chloride concentrations spanned from 178.445 to 221.150 mg/L , with a mean of 201.118 ± 45.311 mg/L . (Fig. 3) All values were within the FAO permissible limits (1065 mg/L). The highest Cl^{-} value was during summer, winter, and monsoon. The increased Cl^{-} levels resulted from the introduction of household waste and urban sewage into the canal. Comparable results were also obtained by Singh et al. from the Kali River, which varied from 20 to 150 during summer and from 17.5 to 115.7 mg/L during winter (G. Singh et al., 2020). Increased EC makes sodium chloride ions more common in natural irrigation water (Raychaudhuri et al., 2014). The concentration of TDS fluctuated with the seasons. In summer, values ranged from 942.500 to 1144.500 mg/L , averaging 1047.333 ± 111.101 mg/L . Monsoon levels varied between 438.725 and 491.335 mg/L , averaging 462.150 ± 130.788 mg/L . During winter, TDS concentrations spanned from 596.000 to 799.500 mg/L , with a mean value of 698.640 ± 184.702 mg/L . These values were below the FAO permissible limit of 2000 mg/L . In summer and winter, 100% of samples fell within the slight to moderate category; in monsoon, 50% were none, and 50% were within the slight to moderate category. TDS values were elevated by industrial effluents, natural organic substances, and influxes into the aquatic environment; the lowest range occurred during the monsoon due to water dilution. A similar TDS range in surface water was obtained by other researchers, who found that TDS varied from 277 to 1510 mg/L and 160 to 730 mg/L in the Kali River (G. Singh et al., 2020).

Mg²⁺ concentrations showed seasonal fluctuations. In summer, levels ranged from 48.610 to 61.865 mg/L, averaging 55.971 ± 5.910 mg/L. During the monsoon, values ranged from 20.555 to 27.795 mg/L, with a mean of 24.223 ± 5.094 mg/L (Fig. 3). In winter, the concentration spanned from 31.565 to 46.750 mg/L (Fig. 2C), averaging 41.738 ± 6.638 mg/L. All mean values were within the FAO-permissible limit of 60 mg/L. A similar Mg²⁺ range of 0.4 to 62.0 mg/L was observed in Uttarakhand and 4–84 mg/L by Kothari from the Nainital area (Singh, Tewari, and Kumar, 2020; Kothari et al., 2021). K⁺ concentrations varied across seasons (Fig. 2F). In summer, levels ranged from 7.505 to 26.215 mg/L, averaging 19.379 ± 9.666 mg/L. During the monsoon, concentrations were lower, ranging from 1.080 to 2.675 mg/L, with a mean of 1.984 ± 0.696 mg/L. In winter, potassium levels spanned from 4.890 to 14.920 mg/L, averaging 10.608 ± 4.755 mg/L. The K⁺ in the Agra canal may be due to wastewater discharges from colonial-era infrastructure. K⁺ content in river water samples ranged from 6.5–95.9 mg/L in summer and 5.2–91.9 mg/L in winter. The significant sources of Na⁺ and K⁺ in the Kali River include the confluence of sewage and agricultural runoff (G. Singh et al., 2020), which also serves as a nonpoint source of pollutants in the Agra Canal. K⁺ was within the FAO permissible limits (78 mg/L). During the summer, the SO₄²⁻ concentration ranged from 22.150 to 51.00 mg/L, with a mean value of 38.32 ± 14.198 mg/L. In the monsoon, the SO₄²⁻ varied from 16.175 to 22.710 mg/L, with a mean value of 19.76 ± 6.629 mg/L. In the winter, the SO₄²⁻ ranged from 16.650 to 33.135 mg/L, with a mean value of 25.36 ± 7.9 mg/L; in all seasons, the values were within the FAO permissible limits (960 mg/L). Water containing more than 1000 mg/L SO₄²⁻ is toxic for plant growth and development. The recorded SO₄²⁻ in the Kali River water ranged from 12.8 to 64.8 mg/L during summer and 10.5 to 45.8 mg/L in winter, reflecting increased SO₄²⁻ content due to mixing organic waste and sewage from industrial regions into the river (G. Singh et al., 2020).

In summer, the NO₃⁻ ranged from 2.825 to 4.105 mg/L, with a mean value of 3.418 ± 0.77 mg/L. In monsoons, NO₃⁻ varied from 2.225 to 3.285 mg/L, with a mean value of 2.623 ± 0.799 mg/L. In winter, it ranged from 1.650 to 3.580 mg/L, with a mean value of 2.63 ± 0.799 mg/L. All values were within the FAO permissible limit of 10 mg/L. The most important plant nutrient affecting the purity of fresh water is nitrogen (Singh et al., 2022). During the summer, Boron concentrations ranged from 1.725 to 1.905, with an average of 1.808 ± 0.095, indicating elevated levels likely due to higher evaporation rates and lower dilution. During the monsoon season, the concentration dropped significantly, ranging from 0.250 to 0.30, with an average of 0.267 ± 0.021. This reduction is likely due to increased rainfall and runoffs, which dilute boron levels in the environment. During winter, concentrations increased again, ranging from 1.350 to 1.625, with a mean of 1.453 ± 0.236. These seasonal patterns suggest that boron accumulation is influenced by hydrological conditions, with the lowest concentrations observed during the monsoon and the highest recorded during the summer. All values were within the FAO permissible limit of 2.00 mg/L. As per CGWB & CPCB (2000), in summer and winter, 100% of samples fall within the range of slight to moderate. During the monsoon season, 100% of samples fall into the None category, indicating that boron is suitable for irrigation (Figure 2).

During the summer, the mean COD concentration was 53.195 mg/L with a standard deviation (SD) of 7.304 mg/L. The minimum and maximum values recorded were 50.065 mg/L and 61.485 mg/L, respectively. In the monsoon season, the mean COD concentration decreased to 37.775 mg/L, with a standard deviation of 6.764 mg/L. The value ranged from 33.950 mg/L to 41.250 mg/L. Conversely, the winter season exhibited relatively higher COD levels, with a mean value of 49.899 mg/L and an SD of 9.743 mg/L. During this period, the minimum and maximum COD concentrations were 42.800 mg/L and 64.730 mg/L, respectively. These results indicate a seasonal influence on COD levels, with the highest concentrations generally observed during summer and winter, and a notable reduction during the monsoon. All values were within the FAO permissible limits of 250 mg/L. Organic waste and industrial discharges are mainly responsible for higher COD and other organic pollutants in the Kali River. COD ranged from 4.0 to 535.0 in summer and 3.6 to 470 in winter (G. Singh et al., 2022). In Summer and winter possess similar cation and anion sequences HCO₃⁻ > Cl⁻ > Na⁺ > Ca²⁺ > Mg²⁺ > SO₄²⁻ > K⁺ > NO₃⁻ > B, while monsoon exhibits the ratio HCO₃⁻ > Cl⁻ > Ca²⁺ > Na⁺ > Mg²⁺ > SO₄²⁻ > NO₃⁻ > K⁺ > B and In winter HCO₃⁻ > Cl⁻ > Ca²⁺ > Na⁺ > Mg²⁺ > SO₄²⁻ > K⁺ > NO₃⁻ > B. All the analyses indicate that cations and anions were within the permissible limits (Table 3). However, attention is needed to monitor industrial effluents, hygienic practices among farmers, and the productive use of wastewater for irrigation (Jose & Gupta Gangopadhyay, 2014).

The one-way analysis of Variance (Figure 3) was also performed for the data to evaluate the seasonal effects on irrigation water indices (SAR, RCS, Na%, PI, MR, and KI). The results indicate that a seasonal variation exerted a statistically significant influence on sodium-related parameters, particularly SAR, Na%, and KI ($p < 0.05$), with higher mean values observed during summer compared to monsoon and winter. These findings suggest evapo-concentration effects during the dry season. Furthermore, PI exhibited significant seasonal differences ($p < 0.05$), with monsoon values significantly higher than winter, indicating improved permeability conditions during the recharge period. In contrast, RSC values showed seasonal variation but remained within non-hazardous limits; differences were statistically moderate ($p > 0.05$), suggesting limited carbonate hazard fluctuation across seasons. Magnesium Ratio (MR) displayed comparatively smaller seasonal variation, and post hoc comparisons (Tukey HSD) indicated no statistically significant difference between summer and monsoon ($p > 0.05$), although winter values were marginally higher. Overall, the ANOVA results confirm that seasonal hydrochemical dynamics significantly affect sodium hazard indices, whereas carbonate and magnesium-related parameters exhibit comparatively stable behavior.

3.2. Comparison Analysis of Heavy Metals in Agra Canal Water with FAO Standards.

In the summer, Fe levels ranged from 1.596 to 3.411 mg/L, with a mean value of 2.547 ± 0.969 mg/L. During the monsoon, Fe ranged from 1.796 to 3.207 mg/L, with a mean value of 2.320 ± 1.243 mg/L. In the winter, Fe levels varied from 0.550

to 3.210 mg/L, with a mean value of 2.344 ± 1.217 mg/L. Elevated levels in summer were due to higher evaporation rates and reduced water flow, resulting in higher concentrations of dissolved elements. Zn ranged from 1.265 to 1.810 in the summer, with a mean value of 1.587 ± 0.271 . In the monsoon, it ranged from 0.100 to 0.215, with a mean value of 0.151 ± 0.128 , and in the Winter, Zn ranged from 0.528 to 0.561, with a mean value of 0.543 ± 0.518 . Other researchers in the Gomti River, Lucknow, obtained similar Zn (0.01-0.02) mg/L values (V. K. Singh et al., 2005). All the values are within the FAO- permissible limits (2.0 mg/L). Cu levels ranged from 0.060 to 0.117 mg/L in the summer, with a mean value of 0.093 ± 0.067 , and in the monsoon, Cu ranged from 0.006 to 0.045 mg/L, with a mean value of 0.020 ± 0.016 . It ranged from 0.006 to 0.055 in winter, with a mean value of 0.030 ± 0.019 . Singh obtained the Cu (0.001-0.004 mg/L) range from the Gomti River (Singh et al., 2005). All values are within the FAO-permissible limits (0.20 mg/L). Ni varied from 0.017 to 0.050 mg/L, with a mean value of 0.034 ± 0.019 in the summer, from 0.009 to 0.032 mg/L in the monsoon, with a mean of 0.017 ± 0.012 , and from 0.012 to 0.032 with a mean of 0.021 ± 0.011 mg/L in winter. The highest value was observed in summer, followed by winter and monsoons, with all values within the FAO permissible limit (0.20 mg/L). Pb ranged from 0.025 to 0.085, with a mean value of 0.058 ± 0.040 mg/L in the summer, from 0.008 to 0.045 mg/L in the monsoon with a mean value of 0.029 ± 0.026 , and from 0.030 to 0.070 mg/L, with a mean value of 0.051 ± 0.023 in the winter. The FAO permissible limit for Pb is 5.00. The Cr range in summer was 0.030 to 0.070 with a mean value of 0.046 ± 0.018 mg/L; in Monsoon, Cr ranged from 0.016 to 0.028 with a mean value of 0.023 ± 0.021 ; in winter, it ranged from 0.024 to 0.069 with a mean value of 0.046 ± 0.016 . All values are within the FAO-permissible limits (0.10 mg/L). The Cd and As concentrations were 0.001 and 0.005, respectively, throughout the study at all locations, possibly due to the unavailability of sources. All the heavy metals fall within the FAO irrigation-permissible limits (Table 2), indicating the suitability of canal water for irrigation. Trace elements are essential for crop growth, but excessive levels of heavy metals in irrigation water can harm crops. (Jeong et al., 2016). The dominance pattern of trace elements in river water was in the order metals $Fe > Zn > Cu > Pb > Ni > As > Cd$, in monsoon $Fe > Zn > Cr > Pb > Ni > Cu > As > Cd$, and in winter $Fe > Zn > Cr > Pb > Ni > Cu > As > Cd$. Mandal obtained the Fe-dominant pattern from the Ganga River. (Mandal et al., 2019).

Table 4: The recommended irrigation water class norms and the percentage of samples within each class, as reported by FAO, CGWB, and CPCB (2000).

Parameter	Water Class FAO Norms ^a	Range ^e	Percentage of Sample			CGWB & CPCB 2000 norm ^{b, c}		Percentage of Sample		
			Summer	Monsoon	winter	Water Class	Range	Summer	Monsoon	winter
pH	—	6.5-8.4	100	100	100	—	—	—	—	—
EC (dS m ⁻¹)	None Slight to moderate Severe	<0.7 0.7-3.0 >3.0	0% 100% 0%	0% 100% 0%	0% 100% 0%	Excellent Good Medium Bad Very bad	<0.25 0.25-0.75 0.75-2.25 2.25-4.00 >4.00	0% 0% 50% 50% 0%	0% 50% 50% 0% 0%	0% 0% 100% 0% 0%
HCO ₃ ⁻ (meq l ⁻¹)	None Slight to moderate Severe	<1.5 1.5-8.5 >8.5	0% 100% 0%	0% 100% 0%	0% 100% 0%	NA	NA	NA	NA	NA
TH	NA	NA	NA	NA	NA	Soft Moderately hard Hard Very hard	<75 75-150 150-300 >300	0% 0% 0% 100%	0% 50% 50% 0%	0% 0% 66.7% 33.3%
Cl ⁻ (meq l ⁻¹)	None Slight to moderate Severe	<4 4-10 >10	0% 100% 0%	50% 50% 0%	0% 100% 0%	NA	NA	NA	NA	NA
TDS (mg l ⁻¹)	None Slight to moderate Severe	<450 450-2000 >2000	0% 100% 0%	50% 50% 0%	0% 100% 0%	NA	NA	NA	NA	NA
NO ₃ ⁻ (mg l ⁻¹)	None Slight to moderate Severe	<5 5-30 >30	100% 0% 0%	100% 0% 0%	100% 0% 0%	NA	NA	NA	NA	NA

Boron (mg l⁻¹)	None	<0.7	0%	100%	0%	Sensitive crops	<1.0	0%	100%	0%
	Slight to moderate	0.7 – 3.0	100%	0%	100%	Semi-tolerant	1.0-2.0	100%	0%	100%
	Severe	>3.0	0%	0%	0%	Tolerant	2.0-4.0	0%	0%	0%
						Unsatisfactory	>4.0	0%	0%	0%
SAR	None	<3	100%	100%	100%	Excellent	0-10	100%	100%	100%
	Slight to Moderate	3 – 9	0%	0%	0%	Good	10-18	0%	0%	0%
	Severe	>9	0%	0%	0%	Medium	18-26	0%	0%	0%
						Bad	>26	0%	0%	0%
						Very bad	>26	0%	0%	0%
RSC	NA	NA	NA	NA	NA	Excellent	<1.25	100%	100%	100%
						Good	1.25-2.0	0%	0%	0%
						Medium	2.0-2.5	0%	0%	0%
						Bad	2.5-3.0	0%	0%	0%
						Very bad	>3.0	0%	0%	0%
Na%	NA	NA	NA	NA	NA	Excellent	<20	0%	0%	0%
						Good	20-40	41.7%	100%	100%
						Medium	40-60	58.3%	0%	0%
						Bad	60-80	0%	0%	0%
						Very bad	>80	0%	0%	0%
PI	NA	NA	NA	NA	NA	Class I	<25	0%	0%	0%
						Class II	25-75	100%	100%	100%
						Class III	>75	0%	0%	0%
MR	NA	NA	NA	NA	NA	Suitable	<50	100%	100%	100%
						Unsuitable	>50	0%	0%	0%
KI	NA	NA	NA	NA	NA	Suitable	<1	100%	100%	100%
						Unsuitable	>1	0%	0%	0%

^a (G. Singh et al., 2022), ^b(Nagaraju et al., 2016), ^c (Mandal et al., 2019), ^d(Ayers et al.,1985), ^e (Murthy et al., 2010).

3.3. IWQ indices

3.3.1. SAR

SAR is an ideal index for evaluating the possibility of Na-alkali hazard because it measures the soil's capacity to adsorb Na⁺ from irrigation water. Irrigation water with a higher SAR value can damage soil structure through a cation-exchange reaction between Na⁺ in water and Ca⁺² and Mg⁺² in soil (Islam & Mostafa, 2022). Good quality water is necessary for irrigation (Riaz et al., 2018). In Summer, the SAR values ranged from 3.177 to 3.615, with a mean value of 3.326 ± 0.38. During the rainy season, the SAR values ranged from 1.395 to 1.531, with a mean of 1.458 ± 0.119. In winter, the SAR values ranged from 1.560 to 1.980, with a mean value of 1.788 ± 0.239. SAR falls in the excellent category for irrigation (Fig. 4A). Similar results were obtained from West Bengal, India, where the SAR values were relatively low (0.07–2.84) compared to the prescribed standard limits (Mandal et al., 2019). All the SAR samples fell within the excellence category as per the FAO (Table 4).

3.3.2. RSC

In Summer, the RSC values ranged from -6.144 to -2.913 me/l, with a mean value of -5.163 ± 2.320 me/l. In the monsoon season, the RSC values varied from -0.907 to -0.177 me/l, with a mean value of -0.42 ± 0.908 me/l. In winter, the RSC values ranged from -2.959 to -2.300 me/l, with a mean value of -2.709 ± 0.473 me/l. The FAO permissible limit for RSC in irrigation water is 1.25 me/l (Fig.4 B). All recorded 100% samples across the seasons are below this limit, indicating that water quality is suitable for irrigation and that there is no risk of sodium carbonate affecting soil structure or permeability. RSC assessment of IWQ is helpful as carbonates, Ca⁺², and Mg⁺² precipitate. In the research, RSC evaluates the potential for soil degradation due to excess sodium in the water. In the Kali River (UP), the RSC values were measured in both the pre- and post-monsoon seasons, ranging from 0.28 to 3.62 meq/l and 0.21 to 2.43 Meq/l, respectively. (G. Singh et al., 2022).

3.3.3. Na %

In Summer, the range of Na% % was 41.290 to 47.173, with a mean of 42.903 ± 4.976. In the monsoon, it varied from 32.500 to 34.695, with a mean of 32.743 ± 3.014. In winter, the PI ranged from 32.172 to 55.659, with a mean value of 33.407 ± 2.333. In summer (41.7 %), monsoon, and winter, 100% of values fall in the good category. Meanwhile, 58.3 % (summer) values fell within the medium category (Table 4), indicating irrigation suitability (Fig. 4C). Nagaraju reported a range of Na% from 10.29 to 68.95 in GW (Nagaraju et al., 2016). In irrigation water, if the sodium concentration is high, Na⁺ ions can replace Mg⁺² and Ca⁺² ions on clay particles. (Vincy et al., 2015). In the Sonipat District of Haryana, the Na% in the study area ranged from 53.55% to 93.00% (Bhat et al., 2016).

3.3.4 PI

In Summer, the PI ranged from 51.870 to 61.340 with a mean value of 54.602 ± 6.866; in monsoon, it varied from 58.242 to 63.374 with a mean value of 61.511 ± 2.256; and in winter, it ranged from 50.803 to 52.690 with mean value 51.796 ± 2.388, all the values fall into class II (25-75) (Fig.4 D) which is suitable for irrigation. Long-term irrigation water use affects soil permeability. The soil's salt content, Ca²⁺, Mg²⁺, and HCO₃⁻ all affect PI value. Other researchers also obtained

similar findings, ranging from 27.68 to 92.33 (Nagaraju et al., 2016). Long-term irrigation can impact soil permeability. In the pre- and post-monsoon seasons, the PI of the Kali River ranged from 67 to 93 (G. Singh et al., 2022).

3.3.5. MR

In the summer, the MR range was 40.031-46.433, with a mean of 42.165 ± 6.729 . The monsoon range was from 39.215 to 43.968, with a mean value of 41.788 ± 3.100 . In winter, the temperature ranged from 43.809 to 47.868, with a mean value of 46.607 ± 2.999 . All MR values were less than 50 (Fig. 2E), and 100% of the samples were suitable for irrigation (Fig. 4E). Similar MR values of Kali River water were recorded at 34.79 ± 5.66 pre-monsoon and 32.23 ± 8.07 post-monsoon (G. Singh et al., 2022). In 1972, Paliwal developed a ratio known as the magnesium hazard index. (Murthy et al., 2010). A high MR value (>50 %) reduces crop yield by increasing soil alkalinity. (Bhat et al., 2016; Vincy et al., 2015).

3.3.6. KI

In summer, KI ranged from 0.663 to 0.872 with a mean value of 0.721 ± 0.158 . During the monsoon, KI values ranged from 0.471 to 0.486, with a mean value of 0.479 ± 0.067 . It ranged from 0.455 to 0.492 in winter, with a mean value of 0.467 ± 0.048 . 100% of KI values across all seasons were < 1, indicating irrigation suitability for Agra Canal water (Fig. 4F). If KI is > 1, then it will not be suitable for irrigation (Aly et al., 2015; Bhat et al., 2016). KI values ranged from 1.03 \pm 0.17 to 1.15 \pm 0.21 in the pre- and post-monsoon seasons, respectively (G. Singh et al., 2022). Similar results were also obtained in Saudi Arabia, where the study had Kelly's ratios ranging from 0.45 to 1.95, with an average value of 1.02 (Aly, Al-Omran, and Alharby, 2015)

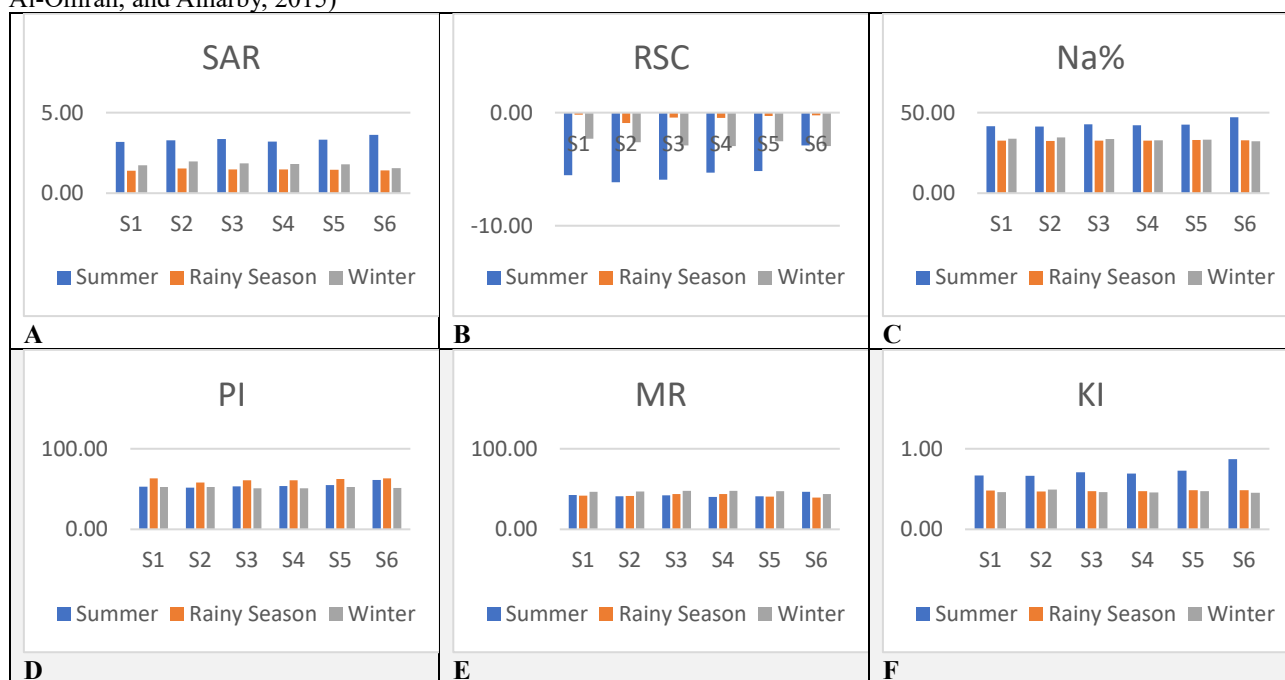


Figure 4: (A, B, C, D, E, F) Comparison of mean values of WQIs among seasons and sampling sites

4. Conclusion and Recommendations

This research reveals crucial insights into the irrigation water quality of the Agra Canal. Various irrigation parameters (EC, pH, NO_3^- , TDS, Mg^{2+} , Ca^{2+} , Na^+ , Cl^- , TH, SO_4^{2-} , Boron, and heavy metals) and potential implications of WQI, including SAR, RSC, MR, Na%, PI, KI, were analysed, the mean values of the parameters compared with FAO and CGWB & CPCB (2000) irrigation standards, all the parameters was within the permissible limits. All water quality indices are within allowable limits, and Agra Canal water may be suitable for irrigation. However, according to the questionnaire survey, crops and vegetables are degrading, so further experimentation and investigation are needed to determine the cause of their degradation. Understanding why canal-irrigated plant crops produce low-quality vegetables will be a new challenge. The outcomes of this study contribute to a deeper understanding of the existing water quality conditions and provide essential information for decision-makers, water resource managers, and agricultural stakeholders to adopt informed strategies for sustainable irrigation practices. Cleaning the Agra canal is also required at defined intervals, and sewage must be prevented from entering the canal. Still, the direct discharge of industrial effluents and municipal wastewater, which contribute to elevated EC and other pollutants in the Agra canal, should be restricted.

5. Abbreviations

Sodium adsorption ratio (SAR), Sodium percentage (Na%), Residual sodium carbonate (RSC), Permeability index (PI), Magnesium ratio (MR), Kelley index (KI), Zinc (Zn), lead (Pb), Chromium (Cr), Cadmium (Cd), Water Quality Indices (WQI), Central Pollution Control Board (CPCB), Central Ground Water Board (CGWB), Food and Agriculture Organization (FAO) Electrical conductivity (EC), Chemical oxygen demand (COD), Bicarbonate (HCO_3^-), Carbonate (CO_3^{2-}), Chloride (Cl^-), Nitrate, (NO_3^-), Sulfate (SO_4^{2-}), and cations; Calcium, (Ca^{+2}), Magnesium, (Mg^{+2}), Sodium (Na^+), Total dissolved solids (TDS), Hardness (TH), Potassium, (K^+).

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