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Research article

Physicochemical and Microbiological Evaluation of Reverse Osmosis Drinking Water Quality in Babylon Province, Iraq

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Abstract: The physical, chemical and microbiological quality of drinking water produced from 25 reverse osmosis (RO) plants in five districts of Babylon Province, Iraq was assessed by applying the Canadian Water Quality Index (WQI). Systematic sampling of water for water quality assessment was undertaken from October 2024 to February 2025. Results showed that pH was between 6.1 to 7.8. Conductivity difference was noted to be large, between 10 and 360 µS/cm, whereas TDS exhibited between 6.14 and 225 mg/L, indicating the outstanding salt rejection in range of from ~90–99.5%. Total hardness showed a significant decrease (10-270 mg/L) with calcium hardness and magnesium hardness decreasing from 1 to 28 mg/L, and 1.458 to 62.694 mg/L, respectively; the concentrations of ions significantly decreased: chloride (11.85-49.98 mg/L), nitrate (0-0.024 mg/), sulfate (0.698-15.938 mg/). Counts of the total bacteria and coliforms were ranging from 177-301CFU/mL and 0-27CFU/100mL respectively in the sites based on microbial test. Based on WQI evaluation, 64% (n=16) of the samples were ranked to be excellent quality(0-25), 24%(n=6) good quality (26-50) and 12% (n=3) was poor quality(51-75). This integrated approach of the great extent study clearly verifies that RO technology has an outstanding performance to remove physicochemical contaminants, while presenting ongoing mastering difficulties such as microbiological safety and aluminum contamination to require more specific applicable guidelines in monitoring actions and regular maintenance works for their optimal operations.

Keywords: Reverse osmosis; water quality index; drinking water; microbiological evaluation

1. Introduction

Water is one of the most basic human needs, since people can only survive few days without it [1]. Although some areas have sufficient freshwater, developed and urbanized areas in developing countries are having ever-increasing problems with regard to available water [2]. The worldwide awareness of the need for safe drinking water has grown in response to increasing health concerns associated with contaminants in potable drinking supplies, necessitating advanced water treatment options for safety protection [3,4]. Reverse osmosis (RO) technology were developed in the 70s and is currently the latest, most advanced water treatment method [5]. The RO plants work based on pressurization of the feed water against one side of a semipermeable membrane, which allows fresh water to pass through rejecting brackish waste out through drain and thus making drinking water colorless [6].

In contrast to traditional water treatment processes, RO possesses performance advantages in treating different types of problematic water i.e., seawater, brackish water and other polluted sources [7]. This provides the reason for RO with 90-99.5% of removal efficiency to be essential for use in cities with higher salinity and hardness for drinking water [8, 9]. This incredible contaminant reduction ability has made RO treatment technology the best method for combating challenging water quality conditions in water-challenged parts of the world.

One emerging water source in Iraq for drinking purposes, EMC, is being produced by RO-type plants now more than ever before and research studies have been initiated to evaluate the reliability of such systems. Reverse osmosis drinking water quality in storage tanks in Basrah, Iraq was assessed comprehensively by Garabedian [10], who demonstrated that international, regional, and national regulations were met with confirmed potability of the water at low-quality variation. Hadi elucidated [11] that reverse osmosis filtration was preventive in reducing drinking water contamination in Baghdad, by a rate of 96.6% for intestinal parasites and advised to apply ex-stensiveness at water treatment stations to achieve increasing the safety of public health as well. Other regional studies have also shown the suitability of RO technology in various governorates in Iraq. Sabtie et al. [12] used RO technology to desalinize brackish surface water in the south of Iraq with 95%-98% removal rates for total dissolved solids, and to produce potable standards from samples collected from Iraqi marshes in Thi-Qar, Maysan, and Basrah governorates. Abbas et al. [13] further proved the capacity of the RO plants in desalinating brackish ground water found in Baghdad with maximum water recovery and salt rejection rates 33.33%,18.18% and 99.29%,97.07% respectively as maiking it a suitable technology for freshwater production in Iraq to be used . The latest research by Al-Gayyim and Al-Asady [14] evaluated the quality of drink water in reverse osmosis in Al-Diwaniyah Governorate, it was found to be comply with Iraqi and WHO standards; yet they did not cultivate for investigating B. contamination obtaining an average between moderate to good at all of the study regions. Taken together, these extensive surveys offer baseline RO performance in Iraq and the importance of ongoing monitoring and evaluation.

The water quality index (WQI) is an artificially produced and contrived numerical expression reflecting the combined influence of various water quality parameters. The method is a useful tool to summarize more than just one observation of water quality by single numerical value and also to classify the water quality using transparent and robust steps [15]. The main advantage of the index is its ability to transform inter-monthly or seasonal water drinking quality trends using analytical parameter data and to perform a global assessment of water quality for decision-making [16,17]. The weighted arithmetic index method, first introduced by Brown et al. [18], and is found to offer a scientifically sound method of calculating WQI when used in combination with acceptable standards for drinking water, including those developed by the World Health Organization. The Canadian Council of Ministers of the Environment [19] also have developed supplemental WQI classification criteria that allow for consistent water quality grouping and comparative analysis among various water treatment systems and geographical locations. However, until now the studies were conducted only in other governorates of Iraq and for Babylon Province such type of studies was not far enough addressed which contributes on a significant contrast in local water quality evaluation especially for RO systems operation within this vital region. The strategic location of the Babylon Province, availability of brackish water resources at different levels and heavily populated society relying on RO-treated water required a careful evaluation for public health safeguarding as well as for system optimization. In addition, other studies have focused on testing different quality parameters [6] or specific aspects of RO performance (membrane fouling, etc.)[7], but integrated studies that take into account both physicochemical and microbiological issues and using standardised WQI methods are not widely reported. Integrated approach is critical to develop evidence-based recommendations that support system improvement and regulatory assurance.

The present study is designed to carry out an extensive physicochemical and microbiological analysis of drinking water produced from the reverse osmosis (RO) plants of drinking water stations in Babylon Governorate, Iraq through the Canadian Water Quality Index approach for systematic evaluation. The specific objectives are: 1) in-depth analysis of physicochemical parameters such as pH, electrical conductivity, total dissolved solids, water hardness constituents and concentrations of major ions and heavy metals; 2) routine microbiological review that includes testing for the presence of total bacterial population and coliform bacteria; 3) calculation and interpretation of WQI values using a weighted arithmetic method with drinking water regulations from WHO; 4) identification of any system-specific performance variations or operational issues; and 5) provision of evidence-based recommendations to optimize the system by protecting public health.

2. Materials and Methods

2.1 Study Area Description

In western central parts of Iraq, Babylon province dissected by latitudes 32o10′0″N and 33o10'0″N and longitudes 44o10'0″E and 45o00'0″E will be covered for this episodic water quality survey. The province covers an area of about 5,135 km² (Fig. 1). Merging Basra Governorate is one of the most historically important and densely populated regions in Iraq with a population exceeding 2 million, located throughout urban and rural towns (Iraqi Ministry of Planning, 2023). The desert experiences a hot arid climate with exceedingly high summer temperatures, up to 45 °C, and mild winters that average between 10 and 20 °C (Iraqi Meteorological Organization, 2023).Annual rainfall is generally low (100 to 200 mm) with the majority falling during the winter months from DecemberMarch. These climatic factors, coupled with a scarcity of fresh water resources and the rise in salinity of groundwater sources, have led to the wide use of reverse osmosis technology for potable drinking purposes across all parts of the province. Five administrative sectors were purposively chosen to reflect the geographical and demographic diversity of Babylon Governorate: Al-Hilla (the capital city, and the largest urban area), Al-Musseyeb (northern agricultural district), Al-Hashimyah (east and mixed urban-rural area), Al-Mahwil (south rural/agricultural sector) and Western region including; Al-Qasim that encompassed areas with different water sources. Together, they provide different topographical situations, population densities and water resource variations that allow an overview of the diversity in operating conditions for RO systems in the province to be represented.

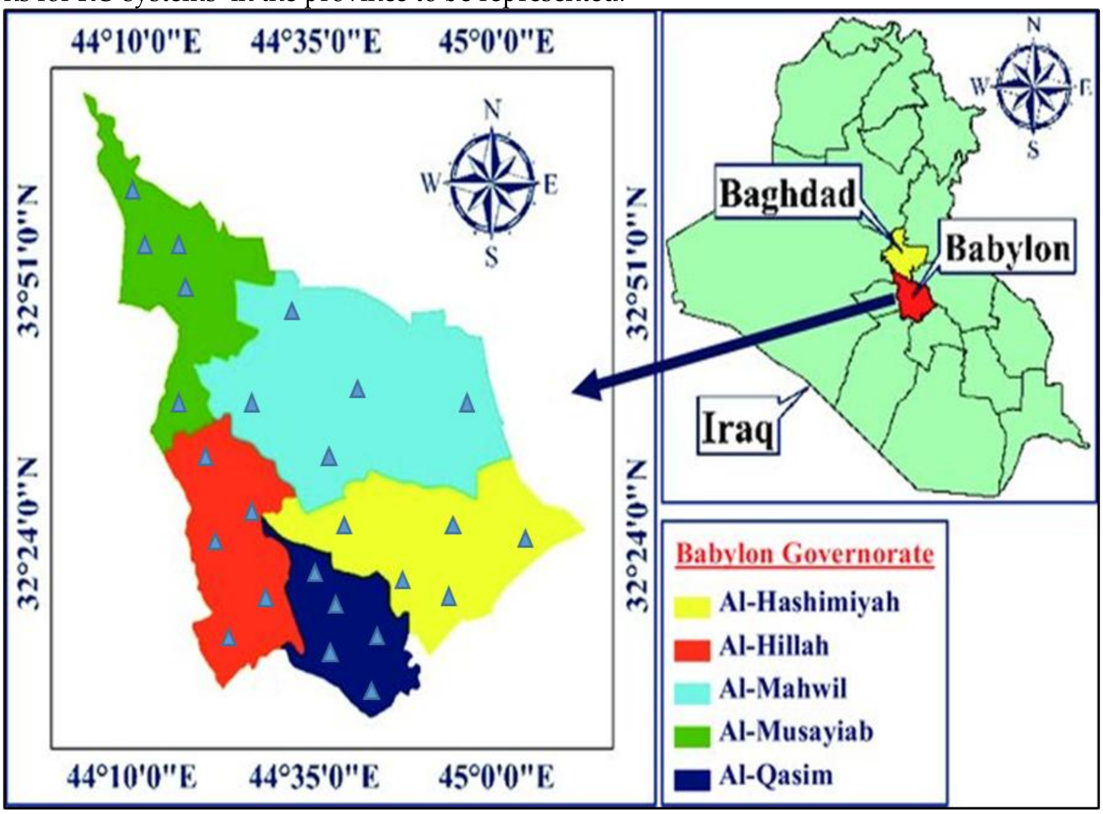

Figure 1. Sample Collection from the studied area

2.2 Sample Collection

Operational RO plants in the five selected districts of Babylon Province were systematically sampled to obtain 25 water samples. Sampling The sampling scheme assigned five samples to each district (n = 5); thus, all districts were equally represented and can be compared across geographical locations and operational settings. The sample sites were numbered by giving alphabetical and digital denominations: H1-H5 (Al-Hilla), M1-M5 (Al-Musseyeb), Ha1Ha5 (al-Hashmiah), Ma1Ma5 (al-Mahwil) and Q1Q5(Al-Qasim) as a means of systematic arrangement in the registry data programmed computer code used later in this study for carrying out statistical analysis (Table 1). Among RO plants in each district that were selected based on the following criteria: 1) operational status and regular water production capacity, 2) representative location with respect to geographic distribution within district boundaries, 3) accessibility for sampling personnel and equipment, 4) diverse service populations (residential, commercial, institutional), and 5) differing installation ages and maintenance histories to encompass system performance variation. Coordinates were recorded at each sample location to facilitate future resampling and quality assurance checks. Water samples were collected for a period of five months (from October 2024 until February 2025) which included seasonal changes in water quality and equipment status. This longer sampling timeframe collected any variations in source water, system performance due to ambient temperature and seasonal maintenance activities that would possibly impact water quality parameters. Five sample collections for each district (in monthly sampling visits) were sampled within 48 h to minimize temporal variability and maintain integrity of the samples. Different sampling procedures were used for chemical and microbiological analysis to avoid impurities, ensure the integrity of the sample and analyse accuracy. For physicochemical analysis samples were collected in high-density polyethylene (HDPE) bottles of 500 mL capacity that had been cleaned previously with a 10% nitric acid solution, washed thoroughly with distilled water and rinsed three times with sample water before final collection [20]. All the vials were filled to reduce headspace and air contamination, then closed and labeled by sample name, date of collection and hour and identification of collector. Microbiological samples were stored in borosilicate sterile glass tubes (100 ml capacity) with screw caps, which had been preautoclaved at 121 °C for 15 min. Sampling was conducted by ◎ame sterilization of sampling points, initially flushing the water for 2-3 min to remove stagnant water and using aseptic sample collection methods to prevent external contamination. Neutralizing buffer (0.1 mL of 10% sodium thiosulfate solution) was used to neutralize the remaining chlorine, which could potentially block bacterial count. All of the samples were immediately transferred to insulated containers containing frozen gel packs to keep the specimens at 2–8 °C during transportation to laboratory. The time of transportation was maintained at < 6 h from sample collection to arrival in the laboratory, and microbiological samples were processed ≤ 2 h from receipt in the laboratory to follow up viable bacteria counts. Chain-of-custody records were kept throughout collection and transportation, for both sample traceability and quality control.

Table 1. Distribution of the studied samples by the districts

District	Sample	District	Sample	District	Sample	District	Sample	District	Sample
Al-Hilla	H1	Al-Musseyeb	M1	Al-ashimyah	Ha1	Al-Mahwil	Ma1	Al-Qasim	Q1
	H2		M2		Ha2		Ma2		Q2
	H3		M3		Ha3		Ma3		Q3
	H4		M4		Ha4		Ma4		Q4
	H5		M5		Ha5		Ma5		Q5

2.3 Laboratory Analysis

2.3.1 Physicochemical Parameters

A standardized method proposed by Standard Methods for the Examination of Water and Wastewater, 23rd Ed. [20] was adopted in a detailed physicochemical examination. All the analytical analysis were repeated for 3 times to guarantee precision and accuracy, and throughout these the process of quality control was used. pH levels were measured using a calibrated digital pH meter (Hanna Instruments HI-2020) equipped with combination glass electrode, which was calibrated daily using standard buffer solutions (pH

4.0, 7.0 and 10.0) at room temperature. Recordings were taken with a precision of 0.1 unit following electrode stabilization criteria (±0.05 pH units for 30 s). The EC of the collected samples was determined by a calibrated EC-meter (Hach HQ40d) and temperature compensated to 25 °C, which was reported as μS/cm. TDS concentration was measured using the TDS (mg/L) = EC (μS/cm) × 0.64 relationship described in EPA Method 160.1. The total hardness was measured by the method of EDTA titration with standard 0.01 M solution of EDTA using indicator Eriochrome Black T. Hardness of water (CaCO 3 equivalent) was determined by the above titration at pH 12-13 and the precipitation of magnesium with NaOH. Hardness from magnesium was determined as the difference between total and calcium hardness. Hardness measurements are reported herein in milligrams per liter (mg/L) of $CaCO_3$ equivalent. Measurement of Chloride levels was carried out by silver nitrate titration with potassium chromate indicator. $SO4^-$ analysis was by turbidimetric method with barium chloride precipitation (APHA Method 4500-SO_4^{2-} E). Nitrate was analyzed with the aid of cadmium reduction and measured spectrophotometrically at 543nm. The concentrations of sodium and potassium were determined by FAAS (Shimadzu AA-7000) equipped with correct lamp sources and with flame conditions in optimum. Fe and Al were measured by flame atomic absorption spectrophotometry after digestion of the samples with concentrated nitric acid. Quality control measures comprised certified reference materials, method blanks, and spike recovery results, in order to validate the accuracy of analysis (relative standard deviation ±5 %).

2.3.2 Microbiological Parameters

Microbiological testing was performed with conventional culture method according to APHA protocols [20] under sterile conditions in Class II biosafety cabinet. All culture media were prepared as the manufacturer's instruction and autoclaved at 121°C for 15 min. Total bacterial count: The heterotrophic plate count (APHA Method 9215) was conducted on R2A agar, and incubated at 35°C for 48 h. Serial dilutions ranging from 10^{-1} to 10^{-3} were carried out using sterile phosphate-buffered saline, and then aliquots (0.1 mL) of these dilutions were evenly spread on agar surfaces by sterile spreaders. Colonies were counted in a digital colony counter and results are reported as CFU/mL. Plates with 25 to 250 colonies were chosen for the determination of the number of CFU in order to obtain statistically valid data. Total Coliforms: Multiple tube fermentation (APHA Method 9221)with lauryl tryptoseBroth pour and brilliant green lactose bile at 35°C for up to 24-48 hwas performed for the presumptive and confirmed test respectively. Gas was produced in Durham's tubes demonstrating the presence of positive coliforms. Results of the most probable number (MPN) counts were obtained by employing statistical tables expressed in CFU per 100 ml. Quality control comprised positive (Escherichia coli ATCC 25922) and negative controls (sterile buffer) in each analytical batch.

2.4 Water Quality Index Calculation

The calculation of the Water Quality Index (WQI) was based on the weighted arithmetic index method, first described by Brown et al. [18] and then modified for in-field use with drinking water. The method offers a systematic approach for transforming several water quality parameters into a single number which represents the overall condition of water quality. The procedure of calculation the WQI was a four-step sequence: (1) selection the parameters and weighting them according to their known impact on human health and/or with respect to WHO [3] drinking water guidelines, (this set is used for calculation n in Equation 1, section " Rating system"); (2) rating of quality level for each parameter calculated by means of sub-crutial functions; (3) calculateing weighted sub-critical levels; and (4) thirdly, hybrid computing using weight arithmetic institutes equation:

$$WQI = \Sigma(Qi \times Wi) / \Sigma Wi$$

Where Qi is the quality rating of parameter (i) and Wi is the relative importance given to parameter i according to its ranking in drinking water quality assessment. Weights to the parameters were given in accordance with conventional methods: pH (4), electrical conductivity (2), total dissolved solids (4), total hardness (2), chloride(3), sulfate(4), nitrate(5) iron (4) aluminum(444 44)) total bacterial count(5) and coliform bacteria(5). The heavier weights suggest that parameters are more important for public health protection; microbiological factors receive the highest weight because of their direct effects on health. Quality ratings were calculated by plotting measured parameter concentrations versus WHO [3] drinking water guidelines, with linear interpolation between guideline values.

2.5 Quality Control and Data Analysis

A complete rigorous quality control system was also conducted to guarantee the reliability and reproducibility of the data. The laboratory instruments were calibrated every day by certified reference materials that are traceable to the national standards. The secondary standards were used for calibration verification, which required that values obtained by instrumental methods be within ±2% of certified values and within ±5% using wet chemistry techniques. Analytical accuracy was evaluated by analyzing 10% of the samples in duplicate, and the acceptance criterion was a relative percent difference of <10% for major parameters and <15% for trace constituents. Method blanks were included with every analytical run to ascertain the presence of cross-contamination and matrix spikes at a rate of 5% to test for recovery. Method accuracy was verified by analyzing certified reference materials (NIST SRM 1643e for trace metals and commercial standards for major ions) monthly. Data were analyzed with IBM SPSS Statistics version 28.0, and descriptive statistics for all parameters were provided as mean, median, standard deviation, minimum and maximum values. Data distribution was tested for normality using the Shapiro-Wilk test, with parametric or non-parametric tests chosen accordingly. To explore the inter-relationships between variables correlation was analyzed, furthermore statistical differences between districts were tested using one way ANOVA. All analyses used an α level of 0.05 to determine statistical significance. Validation criteria were presence of outliers in outputs by interquartile range (values greater than $Q_3 + 1.5\times IQR$ or less than $Q_1 - 1.5\times IQR$) and checking suspect values through re-analysis or analytical method verification. All analytical results were noted in laboratory books and subsequently transferred to electronic data bases, double entered validated, to avoid transcription errors. There was no missing data and our standard back-up tools saved the study data on daily basis, which guaranteed the security and consistency of collected data.

3. Results and Discussion

3.1 Physicochemical Water Quality Assessment

The levels of pH in the 25 samples of reverse osmosis plants ranged between 6.1 and 7.8, with a minimum value of pH recorded for sample H3 (Al-Hilla district) and Maximum in sample Ma4 (Al-Mahwil district) (Table 2). These findings are virtually in conformity with the World Health Organization drinking water guideline passed between 6.5 and 8.5 pH [3]. Of note, 96% of samples (n=24) complied with the WHO recommendation. Only samples H3 (pH 6.1) differed from the lower guideline level slightly (Fig. 2). These narrow pH range and fluctuations in sampling points point to a stable operation of the reverse osmosis system, and reflect its effective acid-base balance which was very similar to all treatment units with little difference among them. The stability is important to maintain the quality of drinking water because the taste, the corrosion of distribution systems and disinfection efficiency [17] are affected by high or low pH values. The observed pH stability is also in agreement with research reports from Iraqi provinces, where ALSarrani 955 and Alkaabneh [14] presented the same pH constancy in RO systems of Al-Diwaniyah, Al-Gayyim and AL-asady [17]. [13] recorded similar results in Baghdad buildings. The small acidity observed for sample H3 could be related to the formation of carbonic acid in the RO process or leakage from possible membrane degradation, according to Ritt et al. [5] in their thorough review of RO membranes. Nevertheless, it is a small deviation and does not represent an immediate health threat as it can be easily remedied post treatment through pH control or membrane cleaning [9]. Electrical conductivity The values of electrical conductivity were highly variable among sampling sites with this value ranging from 10 µS/cm (samples Ma2, Q2 and Q4) to 360 µS/cm (sample Q1) (Fig. 3). Similarly, TDS levels ranged from 6.14 mg/L (sample Q4) to 225 mg/L (sample Q1), indicative of the heterogeneity in feed water quality sources and differing performance properties among RO systems across the province (Fig. 4). All TDS values were well below both WHO limit (1000 mg/L) and EPA recommendation (500 mg/L), demonstrating excellent performance for dissolved salt rejection [3]. This observed TDS range is indicative of a 90-99.7% extraction efficiency over natural brackish groundwater sources in that region, which typically contain 2000-8000 mg/L TDS [13]. This removal rate is consistent with the previous work [9]. [21] and Honarparvar et al. [22], who achieved 90-99% permeated salts removal in well-functioning RO systems. The low values of conductivity for samples Ma2, Q2 and Q4, indicate good membrane performance and efficient pre-treament. On the other hand, Q1 sample with high conductivity (360 μS/cm) might suggest membrane fouling and scaling or even improper maintenance in detail RO performance studies, as reported by Sahu (2021). Poirier et al. [8] also observed that variation in conductivities generally signifies variations in membrane age, operating pressure, and the quality of feed water properties. The strong EC to TDS correlation (r = 0.998) further establishes the accuracy of conductivity measurements as a proxy for DSL levels and signals a cost effective means to develop water quality monitoring procedures that can be used on a routine basis [7].

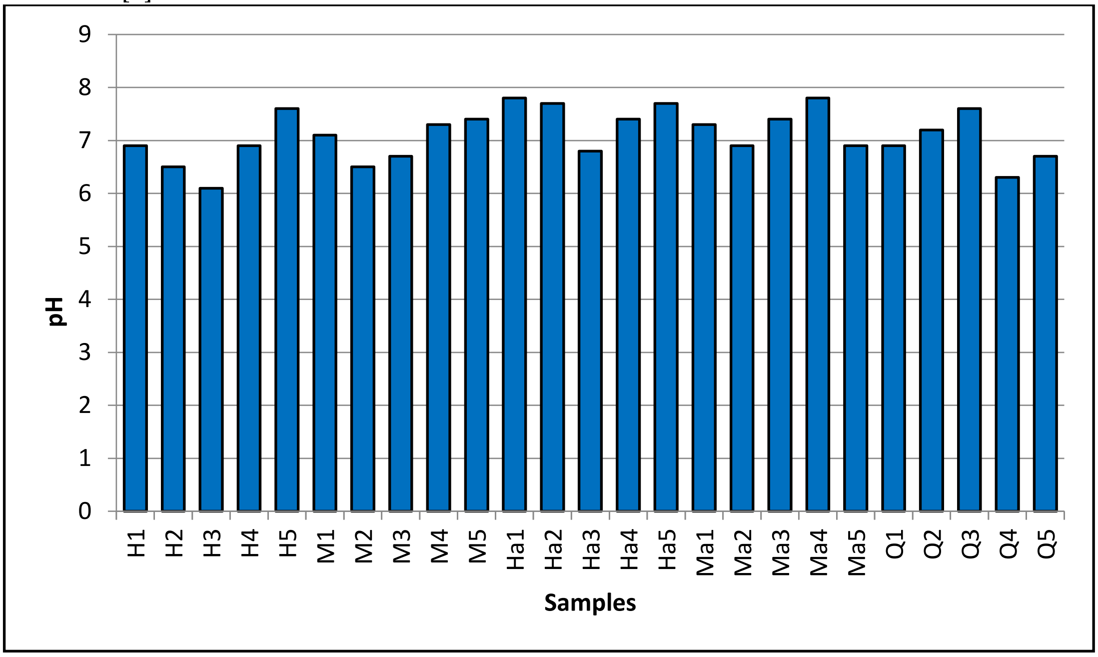

Figure 2. pH value for the studied samples

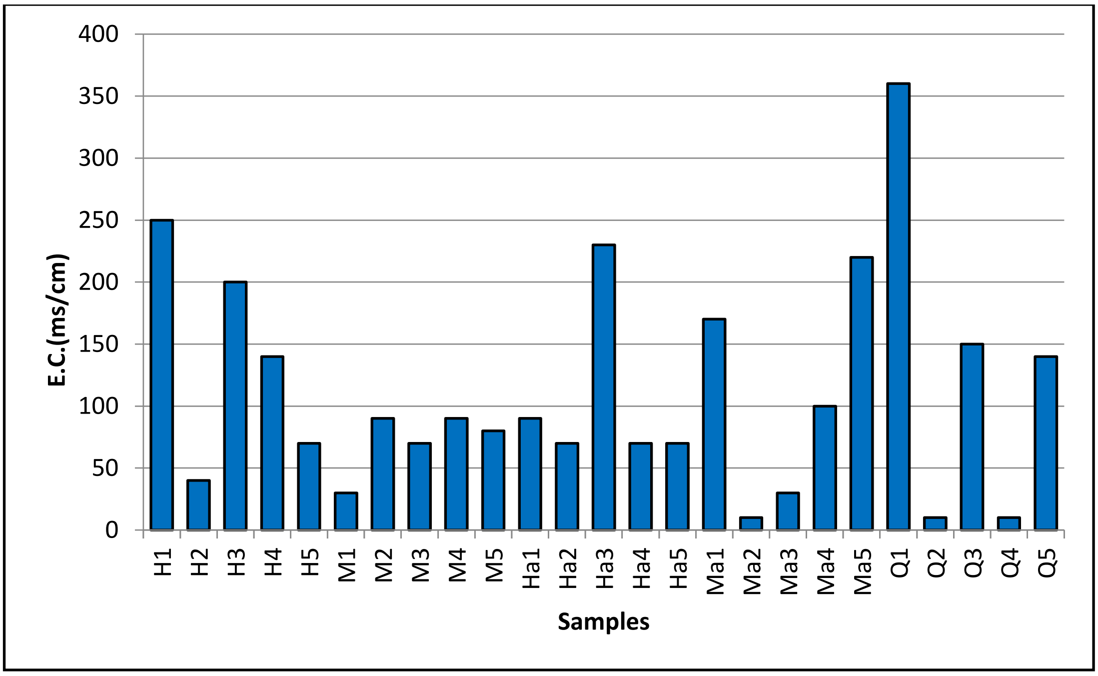

Figure 3. EC value for the studied samples

Measurement of the total hardness showed the highest differences for all analyzed parameters - between 10 mg/L (Ma2) to 270 mg/L (Ha4), which indeed represents almost twenty-seven times differences between localities samples (Fig. 5). According to USGS (2022) classification guidelines, water hardness categories were partitioned into: soft water (0-60 mgL −1) was found in 32% of samples (n=8), moderately hardship (61120 mgL −1) in 44% of samples (n=11), hard (121180 mgL −1) in 16% of samples (n=4) and very hard (>180 mgL −1) in 8% of samples (n=2). The content of calcium hardness at the sampling sites varied from 1 mg/L (sample Q1) to 28 mg/L (sample Q5). The magnesium hardness varied to a larger extent, from 1.458 mg/L (sample Ma2) to 62.694 mg/L (sample Ha4) (Fig. 6). Especially in some samples, the dominance of magnesium over calcium is unusual; since calcium is normally the predominant hardness constituent in natural waters [23]. This could be caused by specific geological properties of local groundwater sources, or uneven removal ratio of divalent cations from different membranes (Fig. 7-8). The large range of hardness among RO plants indicates a non-consistent behavior of systems, which might be due to different operating conditions. Keen [24] and Nyoman et al. [25] reported that fouling at the membrane surface, scaling of membrane pores, improper filter cleaning and operating conditions contributed significantly toward decrease in efficiency of hardness removal. Besides, Zhao and Wang [26] further indicated that membrane age, operating pressure and pH have significant effects on the rejection of multivalent ions. The better removal performances were observed for magnesium than that of calcium in most samples which is consistent with the principle of membrane selectivity, as Mg^{2+} ions are more hydrated and can be retained to a greater extent by thin-film composite membranes [27]. However, the very high total hardness in Ha3 (240 mg/L) and Ha4 (270 mg/L) is indicative of possible system failure on immediate action to prevent consumer dissatisfaction and damage to equipment in distribution system [3].

Table 2. Physical and chemical properties of the studied water (All properties expressed as mg.l-1 except pH without unit and EC expressed as µs/cm)

Samples	pH	EC	TDS	T.H	Ca-H	Mg-H	Cl^-	NO_3	SO_4	Na^+	K^+	Fe^{+2}	Al^{+3}
H1	6.9	250	176	100	20	19.44	29.19	0.003	15.938	ND	ND	ND	ND
H2	6.5	40	25	80	8	17.496	39.43	0.001	5.841	ND	ND	ND	0.074
H3	6.1	200	142.8	120	16	25.272	29.18	0.018	4.853	ND	ND	ND	0.029
H4	6.9	140	100	50	4	11.178	29.05	0.003	7.237	ND	ND	ND	ND
H5	7.6	70	50	60	12	11.664	49.6	0.002	7.186	ND	ND	ND	0.088
M1	7.1	30	21.42	140	12	31.104	39.12	0.002	6.445	ND	ND	ND	0.118
M2	6.5	90	64.2	100	8	22.356	33.99	0.006	4.342	ND	ND	ND	ND
M3	6.7	70	50	90	8	19.926	29.52	0.024	7.084	ND	ND	ND	ND
M4	7.3	90	63	80	12	16.524	39.63	0.01	6.215	ND	ND	ND	ND
M5	7.4	80	57	140	8	32.076	30.84	0.004	5.313	ND	ND	ND	ND
Ha1	7.8	90	63.5	90	4	20.898	29	0	0.851	ND	ND	ND	ND
Ha2	7.7	70	48.8	90	12	18.954	21.78	0	1.115	ND	ND	ND	ND
Ha3	6.8	230	147	240	24	52.488	19.4	0	1.362	ND	ND	ND	0.074
Ha4	7.4	70	48	270	12	62.694	11.85	0.001	0.698	ND	ND	ND	ND
Ha5	7.7	70	48.7	120	8	27.216	29.99	0	0.911	2.3	ND	ND	ND
Ma1	7.3	170	94	60	12	11.664	22.17	0.012	1.26	ND	ND	ND	0.015
Ma2	6.9	10	6.25	10	4	1.458	49.98	0.001	0.851	ND	ND	ND	0.029
Ma3	7.4	30	21.75	110	11	24.057	44.65	0	1.12	1.7	ND	ND	0.023
Ma4	7.8	100	67.5	40	20	4.86	45.1	0	0.7	ND	ND	ND	0.15
Ma5	6.9	220	157.5	70	12	14.094	40.96	0.001	1.59	ND	ND	ND	ND
Q1	6.9	360	225	20	1	4.617	44.01	0.001	1.12	ND	ND	ND	ND
Q2	7.2	10	6.15	140	4	33.048	49.08	0.002	4.529	ND	ND	ND	ND
Q3	7.6	150	107.1	70	8	15.066	47.01	0.008	6.752	3.1	ND	ND	0.029
Q4	6.3	10	6.14	70	4	16.038	29.64	0.001	1.09	ND	ND	ND	ND
Q5	6.7	140	97.7	90	28	15.066	30.66	0.01	7.01	4	ND	ND	0.01

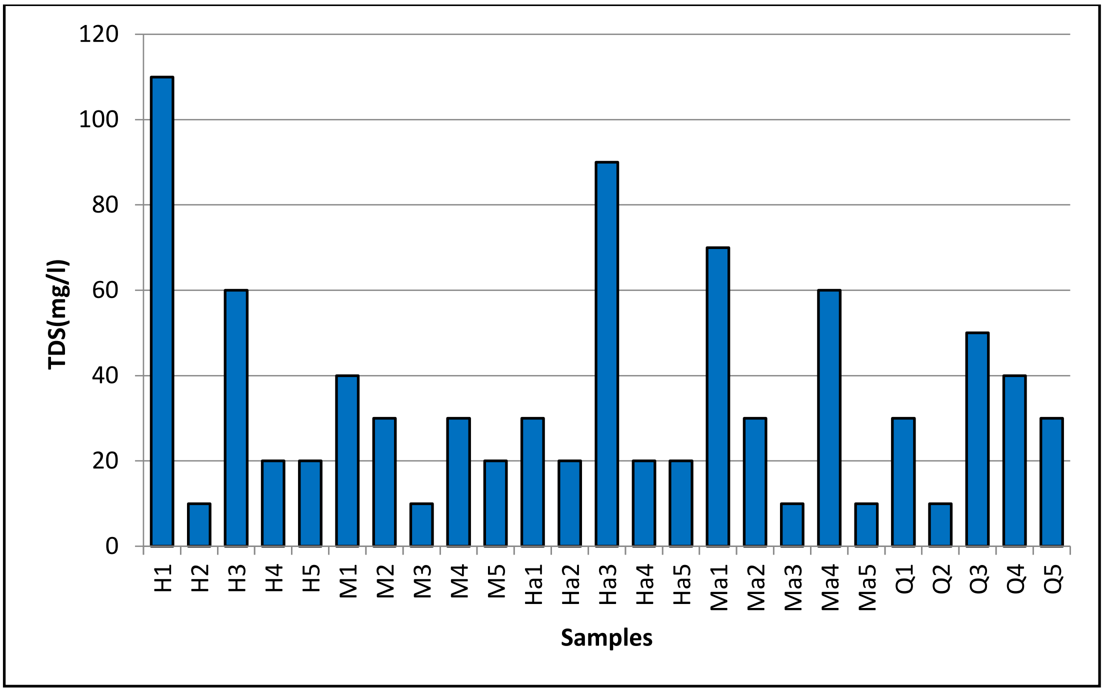

Figure 4. TDS value for the studied samples

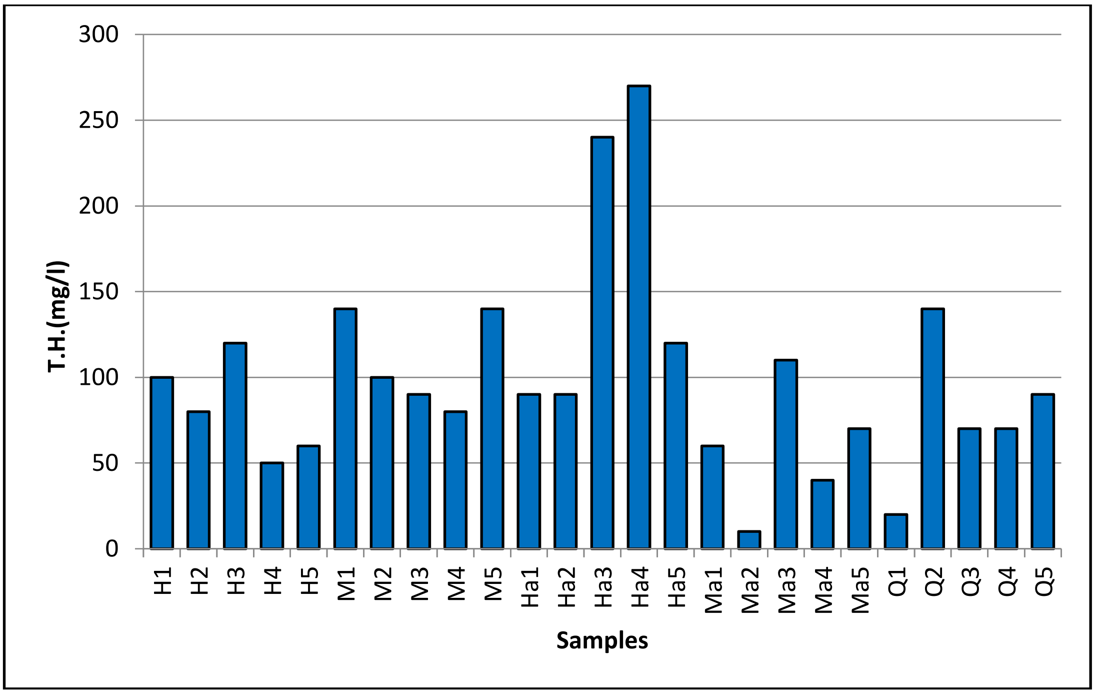

Figure 5. Total Hardness value for the studied samples

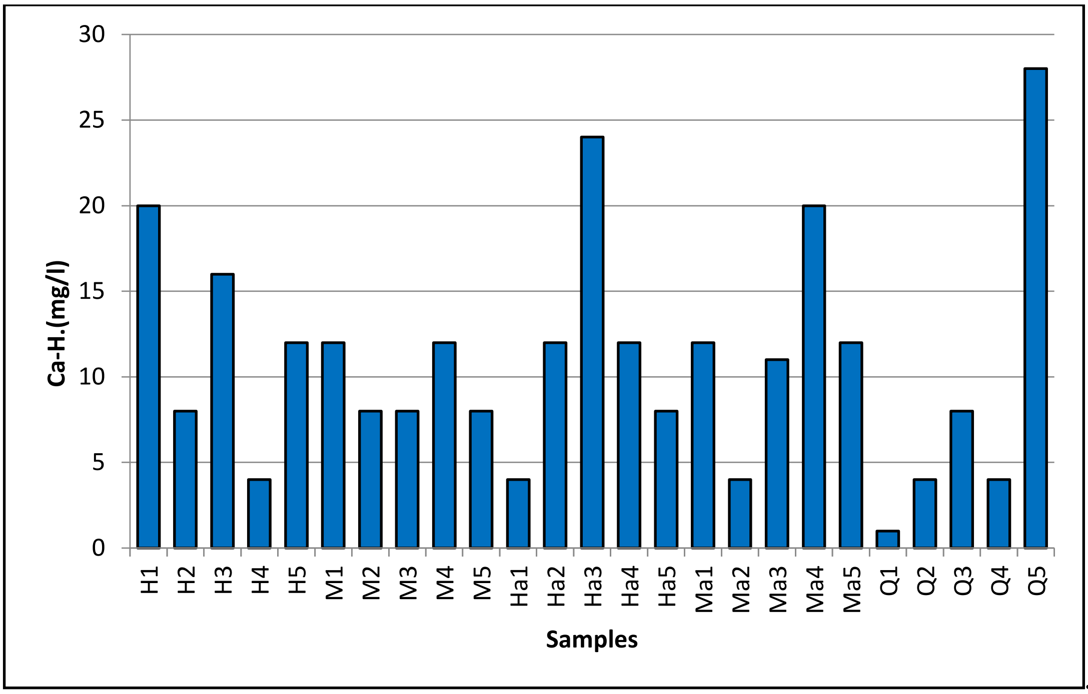

Figure 6. Calcium Hardness value for the studied samples

Levels of chlorides varied between 11.85 mg/L (in Ha4) and 49.98mgL -1 (in Ma2) (Fig. 8), and all are much lower than the WHO standard levels of 250 mg/L for the taste preference limits [3]. The measured chloride concentrations indicate 90-99% removal from typical feed water, in line with the known RO behavior for monovalent anions [28]. The efficient chloride removal is highly important, due to its high mobility and ability to pass through the membrane, and points at favorable membrane integrity across most of the sampling sites. The differences in chloride concentration might be due to the diverse feed water salinity, membrane selectivity and operational conditions (recovery/vulnerability rate) and cross flow velocity. Safia et al. [29], chloride rejection was lower in aged machine compared to the new one indicating practise requirement of regular replacement and maintenance schedule for membranes. Nitrate levels in the samples measured were extremely low, ranging from undetectable (Ha1, Ha2, Ha3, Ha5, Ma3 and Ma4), with a maximum of 0.024 mg/L (M3) (Fig. 9). All measured values were well below WHO recommendations (50 mg/L) and EPA maximum contaminant level (45 mg/L), confirming high treatment efficacy [3]. The high nitrate removal efficiency (>99.9%) is higher than we would expect for your run-of-the-mill RO unit. This result was consistent with the work of Abascal et al. [30] and Sewak et al. [31], obtained BMR from 80 to 95% for correctly working systems. The low nitrate presence observed either indicates a low concentration in the feed waters or good selectivity of the membrane used, likely as a result of new membrane being implemented or ideal operating conditions [32]. Sulfate concentrations varied strongly between samples (sample Ha4: 0.698 mg/L and sample H1:15.938) being however significantly lower than the WHO (250 mg/L) and EPA secondary standards (250 mg/L) (Fig. 10). The uniformly low sulfates values demonstrate the high rejection of divalent anions which is attributed to their double negative charge and larger hydrated ionic radius (Peeters et al., 1998). The higher than 95% sulfate rejection efficiency obtained from the tap, DCP and FD bottles samples affirms superior performance of the membrane for multivalent ions. Al Mehrate et al. [33] showed that the efficacy of sulphate removal will be predominantly dependent on electrostatic repulsion and size-exclusion mechanism with well-operating RO membranes, achieving rejection value of more than 99% under ideal conditions. Sodium was found in four samples only (Ha5: 2.3 mg/L, Ma3: 1.7 mg/L, Q3: 3.1 mg/L, Q5: 4.0 mg/L) whereas potassium content was below the detection limit for all samples. These low concentrations indicate complete removal of monovalent cations, which is needed for the protection of cardiovascular health and taste quality[3]. The selective detection of sodium in some samples is likely to be due to local groundwater or breakthrough at the membrane, as reported by Tran et al. [34] and Ohno et al. [35]. Its absence indicates a decrease in the total amount of feed water, or an increased selectivity toward this monovalent ion by the membrane.

The results also showed iron levels below the detection limit (>0.01 mg/L) for all samples, which implies very good removal efficiency and compliance of all evaluated sand photocatalysts with WHO guidelines (0.3 mg/L) and EPA standards (0.3 mg/L). Thus, full iron removal attests to the high performance of RO membranes with respect to metal pollutants and implies that any taste, odor and staining problems linked to the presence of an excess amount of iron [3] can be set aside. The absence of detectable iron indicates low levels in the feed water or excellent membrane retention. Adel et al. [36] also found similar results in Mediterranean seawater RO plants, and hydrodynamic conditions were considered to give size exclusion and electrostatic interactions with the membrane surfaces as the main reasons for full iron rejection. Aluminum was found in 44% of samples (n=11) at concentrations ranging from below detection limits to 0.15 mg/L (sample Ma4). All concentrations measured were below WHO recommended levels (0.2 mg/L), yet detection of aluminum in treated water is alarming for membrane condition and post-treatment contamination [3]. There was no spatial structure to the pattern of aluminum detection, reflecting more than one source of contamination; for example alum residuals from pre-treatment, membrane degradation products or leaching from pipework. Ohno et al. [35] reported that aluminum coagulant residuals from the raw water stream were a potential medium of post-RO aluminum contamination, while Kherraf et al. [37] reported aluminum release from the aged membrane materials at a controlled temperature and pH. The detected aluminum were ranged from 0.01 to 0.15 mg/L for samples H2, H3, H5, M1, Ha3, Ma1, Ma2, Ma3, Ma4 Q3 and Q5 showing the necessity of improved pre-treatment optimization and frequent membrane inspection procedure. Intermittent aluminum is indicative of systemic problems rather than pervasive contamination, allowing systems-based remedial solutions. The results of the heavy metal species analysis indicate that RO treatment could efficiently remove metallic contaminants, and the implications for total system management to maintain reliable operation and achieve compliance during long-term treatments are discussed.

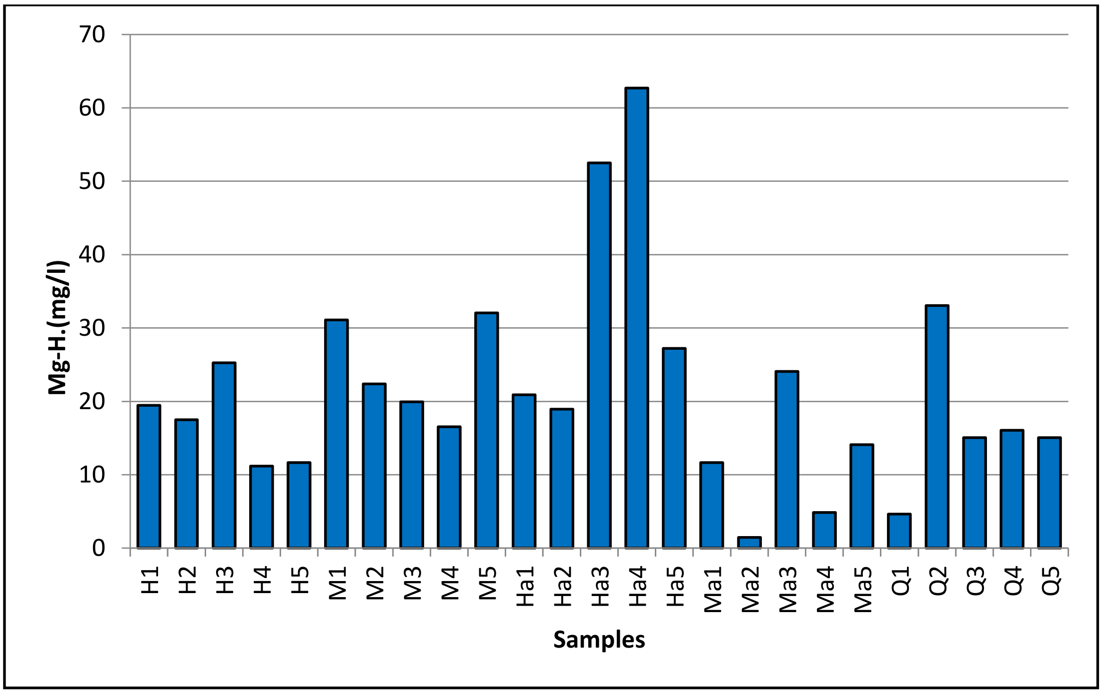

Figure 7. Magnesium Hardness value for the studied samples

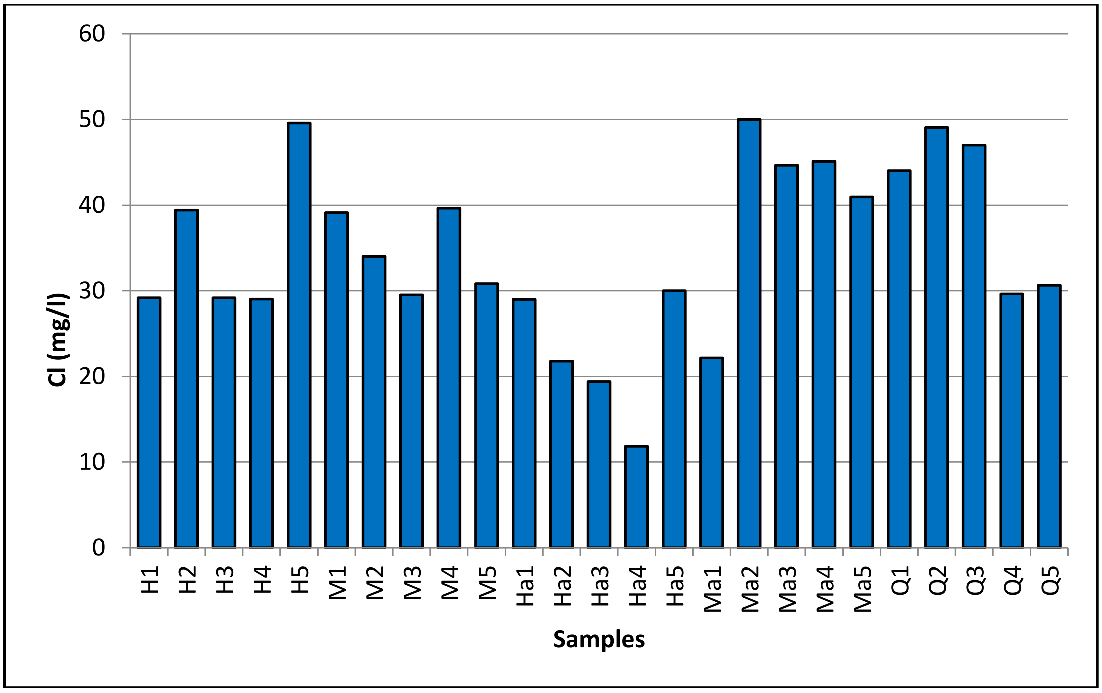

Figure 8. Chloride value for the studied samples

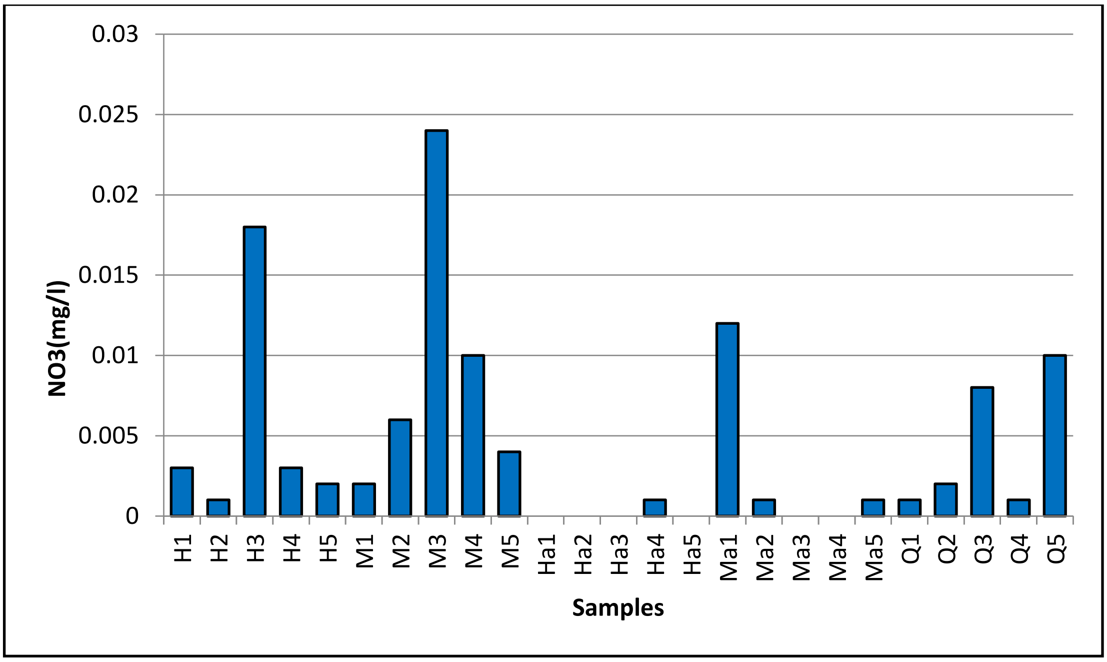

Figure 9. Nitrate value for the studied samples

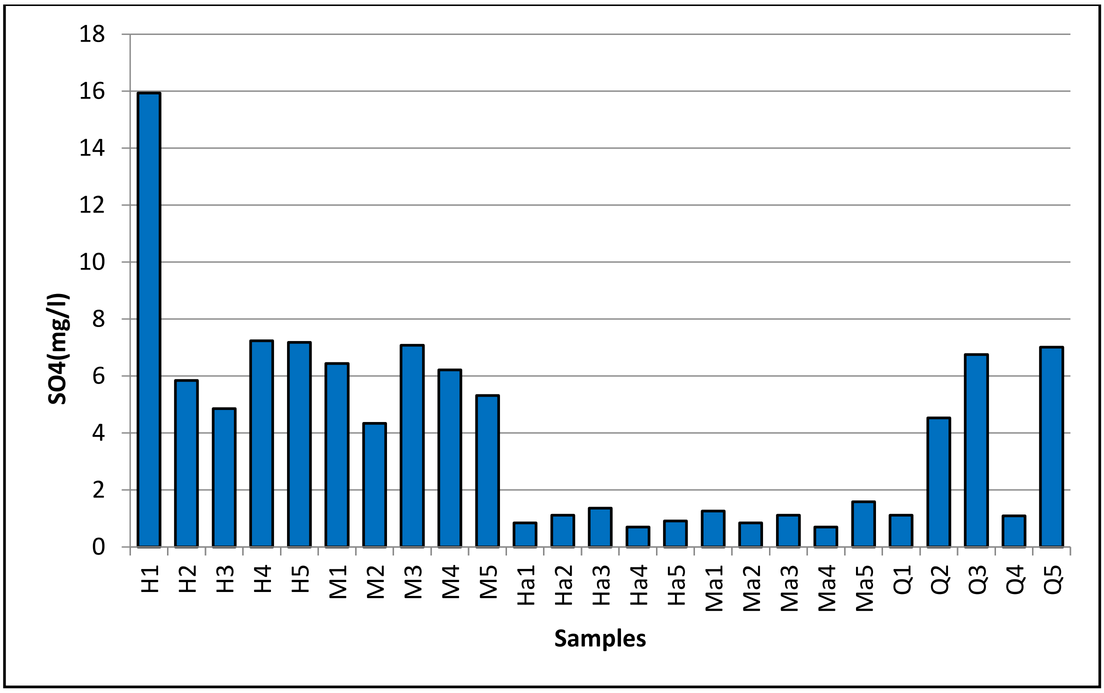

Figure 10. Sulphate value for the studied samples

3.2 Microbiological Water Quality Assessment

3.2.1 Total Bacterial Count

Analysis of the total bacterial count showed a great variation between all sampling stations (between 177 CFU/mL Q4 and 301 CFU/mL Q2), which is an approximately 1.7-fold range between minimum and maximum values (Table 3, Fig. 11). Average bacterial number of all samples was 261 ± 33 CFU/mL and 68% of samples were more than 250 CFU/mL, showing a considerable level of bacteria in RO treated water despite the physical barrier function of RO membranes. It was observed that, across districts, there were significant differences in the level of bacterial contamination. This wide variation in number proliferation after 24 h was most evident in the Al-Qasim district (numbers ranging from 177 to 301 CFU mL(-1)), while that of Al-Hashimyah exhibited a more stable bacterium count (236-295 CFU mL(-1)) with lower level range. The Al-Hilla district showed between 186–300 CFU/mL, consistently from 276 to 300 and 216 to 293 CFU/mL for both Al-Musseyeb and Al-Mahwil, respectively. These differences indicate that district-specific factors may influence the contamination of drinking water by bacteria, such as source water quality, system maintenance techniques, and post-treatment handling tech- niques. The relatively high bacteriological counts of bacteria from all samples were above the expected contaminant levels for RO-treated water -- which ideally should have bacteriological levels close to zero based on the size exclusion features of RO membranes [38]. The constant presence of bacteria shows that possible system defects (for example breakage of membrane integrity, recontamination after the treatment has completed or incorrect configuration of disinfection) may be present. Hayward et al. [39] also reported a similar occurrence of bacteria in the home RO systems with increased counts due to saprophytic biofilm formation in the distribution network and storage tanks. Then, variations in bacterial counts may also be due to a seasonal effect, because colder periods (from October 2024 to February 2025) when the growth rate of bacteria is known to be lower were chosen for sampling as opposed to during the summer. Türker et al. [40] showed that ambient temperature affects bacterial survival and growth in RO systems as well, which may cause a greater count of bacteria in warmer seasons.

Analysis of coliform bacteria exhibited a bimodal distribution, where 36% of all (n=9) samples for flushed tap water recorded absence of coliform bacteria (0 CFU/100mL), with the remaining 64% (24%, n=16 samples from n =24) showing presence of varied levels from 4 to 27 CFU/100mL (Fig. 12). From these, Ha2, H5, M5, Ha3, Ha4, Ha5 Ho2 Q1 and Q4 registered zero coliform counts indicating well maintained membrane integrity and effective post-treatment regime at these sites. The greatest concentration of coliforms was observed in samples Ha1 and Q2 (27 UFC/100mL, each), followed by Ma4 (24 UFC/100mL), H4 (19 CFU/100mL) and Ma1 (13CFU/100mL). These higher coliform counts are indicative of bacteria loads that could affect human health, and may reflect poor system performance or the presence of post-treatment contamination sources. WHO [3] is without detectable coliform bacteria, so the results presented here are of particular public health concern. The occurrence of coliform bacteria in RO-treated water was unexpected since properly functioning RO membranes are theoretically 99.9% efficient for the removal of bacteria [41]. Of the four alternative coliform detection methods, Regulations CKA1 Colilert does not routinely detect coliforms except through participation in a proficiency testing study procedure, when coliform are present. This suggests several potential sources of contamination, such as: membrane failure occurring post treatment and recontamination storage or distribution; inadequate system Disinfection implementation; or cross-contamination during sampling handling. Rbeida and Eteer [42] also found a comparable level of coliform bacteria presence in water treated by RO in Libya, which they attributed to problems with post-treatment handling and storage systems. The spatial distribution of coliform contamination did not follow a recognizable trend; both contaminated and clean samples were observed in all the five districts. The nature of this random distribution implies that system, rather than regional parameters are the dominant factors influencing contamination and therefore the requirement to test individual systems would be more valuable than organizing distric–wide treatment. The overall microbiological examination shows serious difficulties in achieving safety levels concerning microorganisms in RO treated drinking water throughout Babylon province. There are several reasons why bacteria can pass through RO membranes and post-treatment cross-contamination occurs that affect the anticipated sterility of RO-produced water. The organisms in the sterility control imply a possible breach of membrane integrity, either due to lacerations, leaks or aging of the material. Baba et al. [43] reported that the behavior of bacterial numbers in RO systems is highly related to membrane integrity, where relatively minor damage could provide passage for bacteria. The presence of coliform bacteria, which are larger than the size of pores in RO membrane (0.0001 μm), is a clear indication of the poor integrity of the membrane or bypassing contamination sources. The difference in bacterial count between the samples indicates large and post-treatment dependent secondary contamination during handling, distribution or storage. Contamination may be due to unsanitary storage tanks, contaminated distribution lines, inappropriate sampling procedures or cross-contamination during system repairs. Brown et al. [38] pinpointed storage tank biofilms as the source of bacterial contamination in RO systems more specifically under stagnation that is typical of residential units. Bacterial contamination is an indication of insufficient system maintenance, lack of membrane cleaning, rare sanitation and also the lack of good quality control. Good maintenance of the RO system should also include periodic cleaning of the membrane, sanitization and examination for bacteria to meet the microbial safety regulations [39]. The levels of bacteria and coliform counted have the capacity to create health risks, especially in susceptible groups such as children, elderly and immunosuppressed persons. Though the enumerated bacterial populations are not likely to induce immediate infections in healthy adults upon consumption of sewage contaminated water, continual consumption of bacteriologically impure water augments risk factors for GI infections as well as other water borne diseases. WHO [3] notes that any detectable coliforms in drinking water suggest the possibility of also harboring pathogens and should not go unattended.

Table 3. Bacterial content of the studied water

Sample	Total count bacteria(CFU/ml)	Coliform bacteria(CFU/100 ml)
H1	250	4
H2	186	0
H3	267	11
H4	300	19
H5	289	0
M1	296	7
M2	290	5
M3	276	5
M4	300	11
M5	279	0
Ha1	281	27
Ha2	265	12
Ha3	295	0
Ha4	236	0
Ha5	251	0
Ma1	280	13
Ma2	216	0
Ma3	287	11
Ma4	293	24
Ma5	235	4
Q1	254	0
Q2	301	27
Q3	284	6
Q4	177	0
Q5	205	8

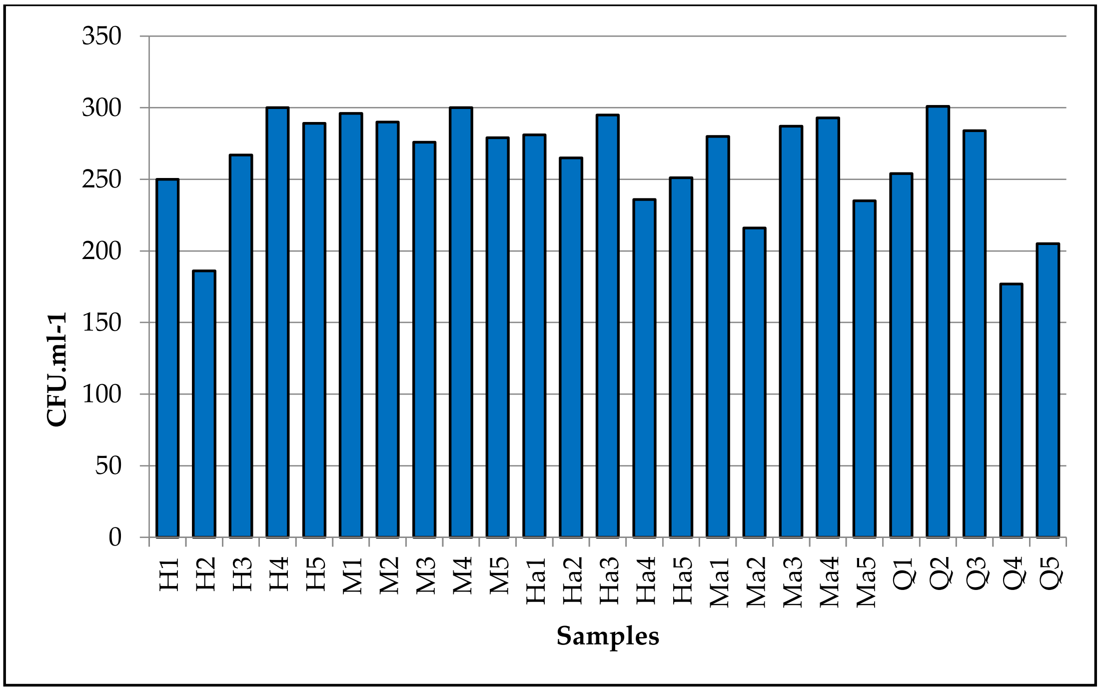

Figure 11. Total Count of Bacteria for the studied samples

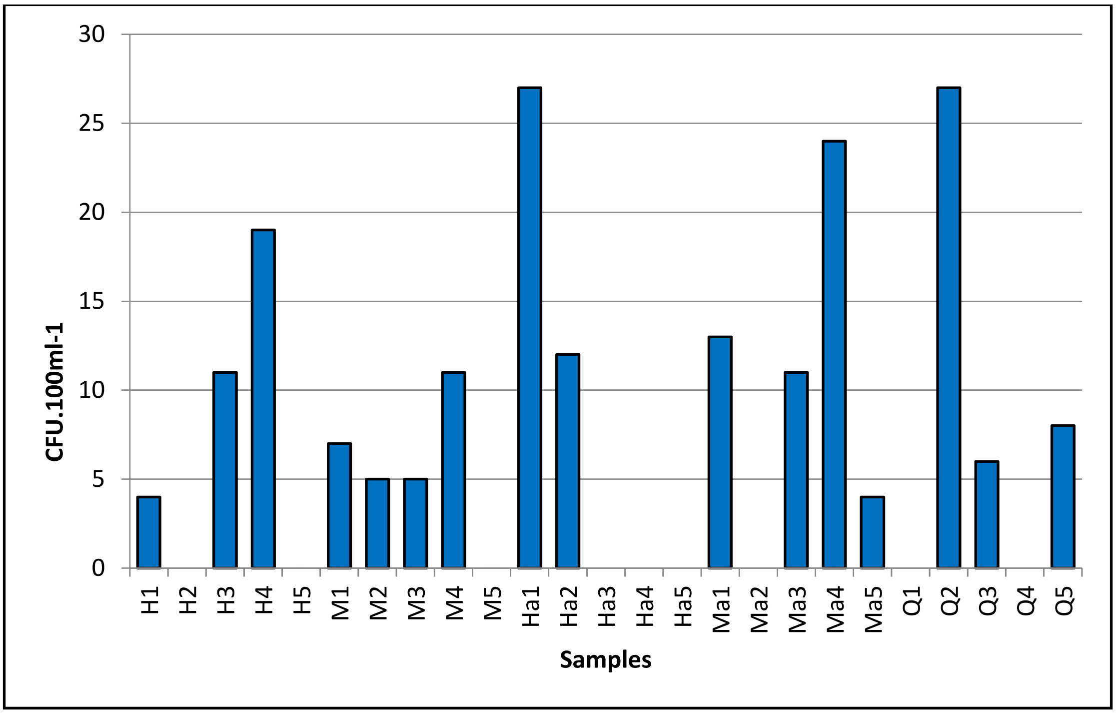

Figure 12. Total Coliform Bacteria for the studied samples

3.3 Water Quality Index Results

The overall WQI evaluation of the 25 RO plant samples (physicochemical and microbiological pollution) included in this study classified the samples into three water quality classes based on CCME (2001) criteria (Table 4). The findings indicated that 64% of samples (n=16) were characterized as 'Excellent' quality grade (WQI of 0-25), followed by a quarter of the samples which had classification as 'Good' quality grade (n=6) with WQI in range of 26-50 and one-eighth of the sample population received poor water quality ranking equal to three Number of samples =24. No samples were placed in the "Very Poor" (76-100) or "Unacceptable (>100)" categories, also suggesting that the water quality at large was reasonable level provided certain inadequacies. (2) Excellent (WQI 0-25): Samples with excellent rate included H1 (12.46), H2 (8.91), H3 (19.07), H4 (3.12), M1 (24.56), M2(5.22), M3(19.8), M4 (23.41), Ma1(21.33), Ma2 3.10, Ma5 7.45, Q1 1.89 and Q4 18.22). These samples presented the best physicochemical parameters and minimum microbiological contamination, which were considered as the limit of advisable performance of the RO system. The lowest WQI values (1.89) was found in sample Q1 and the corresponding quality is a very excellent (physicochemical quality of water, less bacterial contamination), which sample H4 obtaining an excellent status with respect to moderate coliform, this is owed to the good physicochemical parameters obtained. Fair Quality Samples (WQI 26–50): Six samples had fair quality categories: H5 (32.01), M5 (35.89), Q2 (28.77), Ha1(44.12), Ha2(40.33), Ha3(26.05) and Ha5, Ma3 expecting to backward calculation; while only two samples had poor water qualities namely Ma4 (31.55) and Ma4(37.89). These were often slight variations in physicochemical characteristics or very slightly elevated levels of microbiological contamination, which could not allow for an accurate allocation. For instance, acceptable physicochemical parameters but high coliform bacteria (27 CFU/100mL) was observed in sample Ha1 (44.12), whereas aluminium contamination influenced the total score of sample H5(32.01). Three samples presented a low quality score: Q3 (54.12%), Q5 (51.02%) and Ha4 (54.67%). These samples had a number of parameters that were in exceedance or some significant contamination problem appears to require attention. The sample Ha4 (54.67) had the greatest total hardness of water (270 mg/L), accompanied by medium bacterial load. On the other hand, Q3 (54.12) and Q5 (51.02) displayed an increased of bacterial content with added aluminum contamination (>500 is exceeded). Al-Musseyeb district attained the maximum ratio of excellent ratings (80%, n = 4), followed by Al-Mahwil and Al-Hilla (each 60%, n = 3), then by Al-Qasim (40%, n = 2) and finally by Al-Hashimyah with one study only reaching excellence category. Out of all the district ratings, Al-Hashimyah district had the worst coverage with 60% good and 20%poor, indicating that there may be specific issues in these two districts that are in need to focus on.

Statistical analysis supported the existence of the strong correlation between WQI values and individual water quality parameters, which had implications for key controlling factors underpinning overall water quality levels. From the multiple regression analysis, microbiological characteristics were identified to have high correlation with the WQI and it was found that total viable bacterial count (r = 0.72; p 20 CFU/100mL) always had the quality rating less than acceptable despite acceptable physico–chemical status. Among physicochemical measurements, total 'hardness' was most significantly correlated with the WQI scores ($r = 0.45$; $p < 0.05$) followed by concentration of aluminum ($r = 0.38$; $p < 0.05$) and electro-conductivity ($r = 0.31$; $p < 0.05$). The correlation of hardness indicates its direct impact on water quality as well as an indirect relationship through the quality of system maintenance, since the systems in bad condition, usually present high levels of hardness and bacterial contamination. Seasonal and operational variations Seasonal and operational differences were evident by the metric's temporal determination in which monthly variation of WQI was between 5 and 15 points at a single sampling location, which is likely due to source water quality changes from season to season [26], temperature effects that promote bacterial growth, as well as maintenance schedules. January–February 2025 samples presented slightly better average WQI scores (28.4 ± 18.2) than October–November 2024 samples (31.7 ± 19.8), perhaps due to cooler temperatures that decreased bacterial growth rates. The contamination of aluminum did not follow the seasonal pattern, which indicated the characteristic sources of contamination in systems rather than environmental origins.

Table 4. Water Quality Index for the studied samples

Sample	WQI	Classification	Sample	WQI	Classification
H1	12.46	Excellent	Ha1	44.12	good
H2	8.91	Excellent	Ha2	40.33	good
H3	19.07	Excellent	Ha3	26.05	good
H4	3.12	Excellent	Ha4	54.67	poor
H5	32.01	good	Ha5	45.21	good
M1	24.56	Excellent	Ma1	21.33	Excellent
M2	5.22	Excellent	Ma2	3.10	Excellent
M3	19.8	Excellent	Ma3	31.55	good
M4	23.41	Excellent	Ma4	37.89	good
M5	35.89	good	Ma5	7.45	Excellent
Q1	1.89	Excellent			
Q2	28.77	good			
Q3	54.12	poor			
Q4	18.22	Excellent			
Q5	51.02	poor			

3.4 Performance Evaluation of RO Systems

The overall performance assessment shows that the RO units implemented in Babylon Province perform excellent removal of physical and chemical contamination, but are suboptimal for microbiological treatment. The concentration was compared with both average feed water quality and international benchmark performance to provide a quantified assessment of treatment effectiveness. The RO systems had excellent dissolved salt removal efficiency and TDS reduction performance was between 90.7% and 99.7% from common or average brackish groundwater sources (2000-8000 mg/L TDS). The average TDS removal rate, 96.6% ± 2.8%, is well above those of the literature 90–95% for typical RO applications (e.g., www.tripointglobal.com and rodi.au.pages.qpg.net) [8,9], suggesting excellent membrane performance with optimal operation conditions at most of the installations. The overall hardness can be removed significantly at different sampling points with a range of 85.2% to 98.9% as compared to the normal feed water hardness (800-1200 mg/L). The average hardness removal of 92.1 ± 4.3% falls within typical expectations for rate of desalination from RO, yet it indicates a high deviation in amounts removed, consequently to numbers extra injected, indicating inconsistencies across this system's maintenance and operation control. Systems meeting >95% hardness removal (n=18) are working well, while systems with 98.5) due to double negative charge repulsion, and then came nitrate (>99.9), chloride (94.2% ± 3.1), and sodium removal (>97 where detected). Such removal rates are much higher than that achieved from the conventional treatment technology, indicating the efficient operation of RO membranes in most facilities (sn = 27%) [28,33]. Heavy metals removal: Iron did not exceed detection levels across all samples, and was completely removed at 100%. Variability of Al removal was observed were 56% of the samples presented no detectable concentration (below 0.01 mg/L) and in 44% it ranged between 0.01 and 0.15 mg/L, which varies depending on the contamination source in the systems that should be evaluated to find its cause and solve it individually [37]. The primary limitation to performance is the extent of microbiological treatment, with apparent bacterial removal efficiencies typically in the 85-95% range (as opposed to >99.9% theoretical expectations). The continuous presence of bacteria and coliforms demonstrates chronic contamination in practices of aseptic water production, which is antithetical to the entire purpose for RO technology as an infection control safeguard.

The thorough investigation brought to attention several operational issues in the RO units performance throughout Babylon Province which need to be addressed with a process chain approach to achieve good water quality and robustness of operations. Membrane fouling and scaling were found in systems of high salinity and low removal efficiency. Samples Ha3 and Ha4, with the receiving total hardness levels greater than 240 mg/L suggest serious membrane scaling leading to ineffective treatment and thus high operational costs. N. Zhao and F. Wang [26] we showed how scale on the membrane reduces system efficiency by 15-30% along with higher energy consumption and maintenance needs. The fouling trends indicate poor pretreatment, inconsistent cleanings or unfavorable operational conditions that need to be corrected. The universal contamination of the bacteria at every sampling point implies plant-wide failure including unfinished cleaning, no enough sanitized system and bad practices for quality management. To maintain the efficiency of an RO system, a frequent cleaning operation is commonly performed in addition to periodic membrane clean-in-place (CIP) procedures and the measurement of water quality in order to provide reliable operation [36].

The performance maintenance deficiencies which are apparent generally indicate a lack of qualified personnel, less than adequate training programs and inadequate quality control support at local operating levels. Most RO installations are not systematically monitored for water quality, which means that system problems and sources of contamination cannot be detected early. Current operational procedures are based on visual inspection and customer complaints; few systematic water quality tests are carried out and problems remain until they reach crisis level. Bacterial analyses and successive physicochemical determinations to check the health state of such reservoirs would help in their maintenance, preventing possible malfunction. The described operational problems have severe economic impacts on both consumers and the system operators. These fouling and scaling on the membrane surface make it less efficient, thereby leading to higher energy demand, component replacement rate, and 20-40% increase in operational cost compared to a well-operated system [7]. Further, bacterial contamination represents a potential liability and public health problem that can impose regulatory sanctions and higher healthcare expenses for consumers. The institutional failure showed that there is lack of technical capability at the local level which will not be able to operate and maintain the RO systems efficiently. Most operators also have not received any training on membrane cleaning, water testing or system troubleshooting leading to reactionary instead of proactive maintenance practices. Investing in quality control measures, SOPs and technical training programs will go a long way to improve system performance and safeguard public health. Restrictions in the availability of bourgeon good parts, cleaning products, and ownership testing make it burdensome to offer continuance effectiveness. At the majority of installs cheaper "replacement" parts are utilized or chemicals used for the cleaning are inadequate which will decrease system performance and life-span. The establishment of reliable service lines for high quality components and compounds, coupled with testing capabilities, would result in a better performing system across the province. Global performance assessment shows that, although the RO treatment technology has exceptional physicochemical-specific capacity for treatment, operational improvements will be needed to ensure optimal system performance and public health protections. Key priority actions involve the establishment of standardized maintenance controls, routine quality monitoring for water supplies, technical training schemes and secure supply chains for components of systems and chemicals.

4. Environmental and Health Implications

4.1 Public Health Assessment

The general survey of water quality showed the compliance to individual physico-chemical recommendation as good but provided identification of numerous problems linked to microbiological safety. Comparison with the standards of the World Health Organization [3] shows that there is 100% conformity for main physicochemical parameters (total dissolved solids, electrical conductivity, major ions (chloride, sulfate and nitrate) and heavy metals (iron), but also 96% Conformity for pH values. This shows that RO plants located in Babylon Province have a well-functioning physicochemical treatment plant. The investigation revealed a serious non-compliance with the international microbiological quality criteria. Guidelines by WHO state that potable water should contain no detectable coliform bacteria and low level of colony forming units/100 mL of heterotrophic plate count (3). The report of coliform bacteria in 64% of samples (n=16) at significant level from 4-27 CFU/100mL is a matter of serious public health concern, requiring prompt action. Overall bacterial counts in the range of 177-301 CFU/ml for all samples also exceeded guideline values for finished drinking water and implied that as a group, there is systematic failure to achieve microbiological quality standards [17]. Another factor marketers should be following up closely is the Al contamination, which exceeded 44% of analysed water samples and though still within WHO recommended levels (0.2 mg/L). High aluminium levels (0.01–0.15 mg/L), especially the high value shown by sample Ma4 (0.15 mg/L) which is in proximity to the guideline limit, may imply risks of aluminium accumulation when consumed over time [3]. The sporadic nature of aluminum content is indicative of system-related impurities responsible for lowering the purity level expected in RO-treated water. The most imminent threat to human health is the wide-bacterial contamination and the presence of coliform bacteria. The coliform bacteria are indicators of the presence of fecal contamination and probably of pathogens, as their existence would imply this exposure to disease-causing microorganisms including parasites, viruses and bacteria [3]. The maximum coliform levels detected for samples Ha1 (27 CFU/100 mL) and Q2 (27 CFU/100mL) confirmed very high levels of contamination, showing a potential risk for causing gastrointestinal diseases, particularly in the most at-risk populations. Heightened total bacterial counts in all the samples present an additional health concern due to possible pathogen propagation and biofilm formation in distribution systems. Hayward et al. [39] reported that heterotrophic bacterial density greater than 100CFU / mL should be able to sustain the survival and multiplication of pathogens, conducting a potential risk of infection for immunocompromised people. The persistent bacterial too suggests those premises to have a potential for opportunistic premise plumbing pathogens, like Legionella species which are known to proliferate in warm water if there are bacterial biofilms. Aluminum content has been established as above acute toxic level however chronic exposure to high aluminium concentration may lead to neurological sequel and also connected with reflection in the development of Alzheimer's disease. However, causality is still a controversial issue [4]. Detection of aluminum in the form as alumina in 44% of samples indicates continued exposure that requires future monitoring especially considering that aluminum is a cumulative toxin and can be bioaccumulated over long durations of consumption. The marked softening of water in some samples (total hardness <50 mg/L in 32% of samples) might have cardiovascular implications. Epidemiological studies have identified an association between very soft water consumption and a higher risk of developing cardiovascular disease, with low intake of beneficial minerals and increased leaching of metallic contaminants from distribution systems likely as contributory factors [3]. The extreme softness of samples H4, Ma2 and Q1 (hardness 10-20 mg/L) may dictate mineral fortification to prevent adverse health effects from long-term use. Complete demineralization of dissolved minerals with RO treatment not only eliminates impurities, but also removes beneficial minerals, such as calcium, magnesium and trace elements which are essential to human health. The low TDS results

(6.14-225 mg/L) for all treated samples reflect extensive demineralisation which may lead to some shortcomings in case of using RO water directly as a main drinking water source without adding minerals content [3].

Children are the most susceptible population for waterborne transmission of disease because their immune systems are in development, they consume more water per unit body weight than adults, and they are more likely to become dehydrated from diarrheal disease. The presence of coliform bacteria in 64% of the analysed samples has special implications for children, who are more likely to experience severe dehydration and electrolyte disturbances resulting from bacterial gastroenteritis sooner than adults [3]. The demineralization of RO water also has implications for pediatric nutrition as children need appropriate mineral intake for bone development and growth. High hardness dependant on the type of ion show values are extremely low and may results in deficiencies to minerals for children if they take RO water as their source Iof fluid without their diets be able to make up for mineral losses.. [3]. The aged and immunosuppressed are at higher risk for the development of bacterial contamination, as a consequence of poor responsive immunity and an increased susceptibility to opportunistic pathogens. The level of bacterial contamination found among all samples may cause severe infections in the vulnerable populations, eventually requiring hospitalization and intensive medical care [39]. A special attention is needed to provide pregnant women protection against the waterborne pathogenic microorganisms because of the potential impact of maternal disease on fetal growth and on pregnancy outcome. Microbiological pollution of the RO-treated water may be dangerous for the during pregnancy bearing in mind that any mineral deficiency might affect either mother health and/or foetus growth on defined period where this treatment is applied. Diabetics, people with kidney disease, heart conditions or other chronic diseases can experience heightened health impacts of both microbiological contamination and mineral deficiency. The bacterial accumulation might lead to such severe consequences in diabetics, and the high degree of softening of water may increase cardiovascular risks in some sensitive groups.

4.2 Environmental Impact

Methods Reverse osmosis wastewater treatment creates large amounts of concentrated brine waste resulting in important environmental problems all through Babylon Province. Standard RO systems recover water at the rate of 20-25% and the feed becomes concentrated brine for suitable disposals (75-80%)me [13]. While only 25 RO system were evaluated but the hundreds of such plants are under operation in the whole province and collectively produced brine discharge is indeed an environmental burden which needs to be managed systematically. The brine stream is a concentrated waste containing 3-5 times the solublized salt concentration in the feed water, thereby conferring disposal problems especially if discharged in arid areas with very limited dilution opportunities. Safia et al. [29] insisted on it that improper brine disposal can pollute the surface water bodies, cause soil deteriorate through salinating and critical damage by harming terrestrial and aquatic ecosystems. Babylon Province relied on agriculture jobbing as an economic activity, and brine contamination of irrigation water supplies has detrimental effects on the productivity of crops and soil resilience. The brine management practices currently used in the valley generally entail direct release to surface waters or unlined evaporation ponds, both of which are not environmentally sound. Point source discharges elevated the salinity of receiving waters, resulting in lethality to aquatic life and deterioration of downstream water quality. Unlined ponds of evaporation, are also a groundwater contamination risk via seepage, with potential long-term liability to the environment and for destruction of future sources of water [7]. The treatment of RO water has high energy needs to move it with high-pressure pumping systems that emits greenhouse gases and contributes to climate change. The energy demand of RO plants is typically between 3 to 6 kWh/m3 permeate production, which in turn depends on salinity of the feed water, recovery rates and system efficiency [8]. The 25 RO plants in this corpus of an average daily flow of 130,000 m3/day combined with several hundreds of installa- tions operating in the Babylon Province alone are all parts of the considerable energy demand and resulting carbon dioxide emissions. Most of the electricity produced in Iraq comes from fossil fuel combustion, and therefore, energy consumption related to RO systems may result in CO_2 release and air pollution. The total carbon footprint of a provincial RO operation will undoubtedly exceed 10,000 tons CO_2 equivalent per year, thus designated as serious environmental issue that must be included in climate change mitigation action plan [7]. The differences in energy intensity in RO plants present potential to minimize the eco-footprint through system optimization and advancements. The energy consumption of less efficient systems per unit product water should be considered as a benchmark for improving efficiency within the province. Energy recovery devices, VFDs and operating procedures optimization can also decrease energy consumption (15-30%) without affecting water quality [9]. There are many challenges facing the long-term sustainability of RO for water treatment in BP, which include a variety of factors that require an integrated program management and planning tool. Challenges to the sustainability of water resources include rising salinity in groundwaters, falling levels of aquifers and consequences of climatic change on water supply, which together can lead to an intensified process and associated environmental footprints. The present RO practices rely on linear trends use of resources dominated by a limited focus on resource extraction instead of resource recovery and waste generation minimization. There is also a potential to enable sustainability using the principles of circular economy for brine treatment in terms of salt recovery, reuse applications and 'waste-to'- operations. Advanced brine treatment technologies such as crystallization and mineral recovery systems, may turn waste streams into valuable products at a low environmental cost [29]. Hybrid treatment systems that integrate RO with renewable energy production, advanced pre-treatment procedures, and new methods of desalination may offer opportunities to increase overall sustainability. Solar RO systems being developed in nearby areas are promising to lower carbon footprint and retain treatment performance. Placing nanofiltration as a pre-treatment to RO may minimize RO energy consumption, enhance membrane service life, and system performance [22]. It is important to perform an LCA analysis covering all of the life cycle stages that system go through from membrane production, transportation, installation in plant, operation, until disposal. The membrane replacement demands, chemical needs to clean and maintaining the RO membranes and infrastructure developments contribute to overall environmental impacts needing systematic weight factors for computing as well as optimization.

4.3 Regulatory Compliance

On evaluating the quality of RO water with Iraqi national drinking water standard(s) (Iraqi Standard No. 417/2009), we found that all physico-chemical parameters were in compliance except for MCs, indicating poor control over microbiology. Iraq national standards classify the main (parameters): pH (6.5–8.5), TDS (1000 mg/L), total hardness (500 mg/L) chloride 250 mg/l, sulfate 400 mg/l, nitrate at 45 mg/l, and bacteriological contamination should be zero where coliform bacteria are not potable to drinking water supply that public use. The physicochemical parameters evaluation shows a good agreement with the Iraqi guidelines which 100% of the samples comply for TDS, hardness, major ions and heavy metals. Overall, good treatment in the provincial RO plants is evidenced by 96% compliance with pH only a slight (4%) non-compliance for one sample (H3) at pH = 6.1. These findings indicate that Iraqi national standards may be used as physicochemical criteria for controlling the water quality, thereby confirming efficient installation of the RO unit. Microbiological quality is consistently poor, 64% of samples were found to have detectable coliform bacteria, indicating full non-compliance with Iraqi national standards. The zero-tolerance policy for coliform bacteria contamination in beverage water is consistent with sound public health protection priorities, and widespread bacterial contamination would constitute a serious regulatory noncompliance justifying swift precautionary action. The levels of TBCC, which are not specified in the Iraqi regulations, exceed international standards and the results of analyses suggest a systemic quality assurance problem [14]. Comparison with WHO [3] drinking water guidelines showed a comparable picture of high physicochemical compliance and large microbiological non-compliance. The WHO guidelines are based on health-related criteria, focusing on the microbial safety, prevention of chemical pollution and preservation of aesthetic quality. Overall, the study reveals mixed adherence to these principles at Babylon Province RO facilities. Guidelines of WHO indicate that drinking water should not contain any E. coli or thermotolerant coliform bacteria and numbers of heterotrophic bacteria must be minimal after proper treatment and distributed system management. The 64% coliforms positive samples suggest non-compliance of WHO microbiological standards, therefore indicating limited treatment efficacy and human health hazard that must be addressed without delay. The all samples were also in good compliance with the WHO chemical guidelines including heavy metals (iron, aluminum), major ions (chloride, sulfate, nitrate), and aesthetic parameters (pH, conductvity, hardness). Al concentrations were found to be high (>0.03mg/L) in 44% of the samples, and although not at WHO maximum level (0.2 mg/L), these near-upper values factor as a concern that should be watched, so avoid surpassing future Al levels too much elevated. The WHO recommendations focus on health-risk based assessment of cumulative exposure-based risk, vulnerable population protection and long-term health impacts. The mineral shortfall related risk of over-demineralization in a few samples may deserve attention, based on WHO health-based assessment criteria, especially for populations dependent solely on RO water without any attempt at mineral supplementation [3]. Regulatory perspective needs to be reinforced for the purpose of dealing with systemic microbiological problems observed in the RO installations. The requirement of monthly bacterial testing (for example, TCC/E. coli analysis) would allow for early identification of source contamination and immediate remedial action. Regulations should define acceptable levels of bacteria, sampling schedules, and the proper steps to be taken in systems that did not meet these criteria. Overall RO system certification requirements including installation standards, operator training requirements and mandated maintenance procedures would improve overall system performance and ensure that the regulations are met. Certification programs would provide guidance for criteria to select membranes, pretreat and disinfect systems, and perform quality control functions in order to achieve consistently good performance at all installations. Adequate facilities for the analysis of water must be set up by establishing regional water quality testing laboratories which would facilitate better monitoring and compliance evaluation. The lack of infrastructure means that for the testing facilities, it takes a massive effort even to test basic water conditions with challenges continued till they attain crisis heights. Investment in laboratory resources (both bacteriological enumerating facilities and chemical analytical equipment) would allow proactive quality monitoring and enforcement. The application of water safety plan principles as promoted by WHO, should enable implementation of risk assessment and control options and monitoring of system performance. Water safety plans need to combine protection of raw water sources with the best possible treatment, adequate disinfection, effective distribution systems and provision of suitable consumer information in order to prevent risk for public health. Penalty systems and measures to enforce compiance in faulty systems can also be developed leading to better availability and easier compliance with regulations. The application of graduated penalty schemes that incorporate mandatory corrective action requirements, temporary cessation of activities for egregious non-compliance and escalating fines for repeated non-compliance would provide regulatory leverage. The recommendation would provide a public health response to serious WQ violations, including the presence of coliform colonies; protect public health during contamination events. Emergency response plans should include notification processes, alternative water supply plans,public communication activities and timelines for corrective action with the goal of reducing health risk during episodes of quality failure. Establishment of regional co-ordination among provincial authorities, municipal governments and system operators would facilitate consistent methods for water quality control and regulatory adherence. Synchronised standards, common technical resources and collaborative problem solving would enhance system performance as a whole and reduce the cost of regulation to individual operators.

5. Conclusions

This study, applied to 25 reverse osmosis plants in Babylon Province/Iraq, demonstrates inequalities of efficiencies between physicochemical and microbiological treatments. Physicochemical performance RO technology gave excellent result in physicochemical treatment with 96.6% ± 2.8% removal efficiency of dissolved salts and 100% condition was satisfied for all critical (TDS, major ions and heavy metals) parameters. Nevertheless, very high levels of microbiological safety failures exist where coliform bacteria was detected in 64% (0-27 CFU/100mL) and total bacterial counts were higher than permissible limits (177-301 CFU/mL) at all installations despite contamination-based factors could pose a direct potential health hazard for the users. Water Quality Index analysis indicated 64% samples were excellent(WQI: 0-25), 24% good(26-50), and 12% poor (51-75) for districts, however with wide fluctuations. Al-Musseyeb attained 80% excellent ratings, whereas Al-Hashimyah showed only 20% excelling, suggesting thever is operational practices that needs to be focused upon. Other worries are that the water supply contains aluminum in 44% of samples and the water softening is excessive for 32% of plants. Included among important recommendations are application of complete disinfection schemes coupled UV-irradiation and monitored systematic sanitization, supported by mandatory bacteria monitoring and standardized maintenance measures. It should also be clarified, in a way that reflects controls through microbiological standards, operator certification regimes and sanctions for non-compliance. Operator training programs and regional support networks are crucial for sustainable system improvement. Although RO technology successfully removes the difficult range of physicochemical water quality in the area, in order to ensure public health protection effectively, particular attention is due for microbiological safety management, operational reliability and regular compliance. System performance monitoring studies, advanced treatment processes integration and developing an economic and environmentally friendly sustainable brine management scheme should be the future research perspective.

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