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A new approach to sustainable environmental assessment for wastewater treatment plants – A case study in the central region of Iraq

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ABSTRACT

Drinking water treatment aims to eliminate physical, chemical, and biological impurities to mitigate health risks, ensure adequate water quality, and promote sustainability. However, the treatment process often requires significant energy, chemicals, and technological inputs, which can lead to increased secondary environmental impacts and higher water production costs. This study aims to evaluate the sustainability of three wastewater treatment facilities (WWTPs) based on their water quality index (WQI). The facilities under investigation are Al-Barakiya Treatment Plant, Al-Maymira Treatment Plant, and Al-Rustamiyah Treatment Plant, all located within the research area. Using the Canadian Council of Ministers of the Environment (CCME) framework, the WQI was employed to assess both raw and treated water quality based on fundamental water characterization criteria. The study involved the regular collection and testing of water samples from January 2023 to December 2023. The raw wastewater quality indices for the three plants were as follows: Al-Rustamiya Treatment Plant (81.232), Al-Maymira Treatment Plant (79.307), and Al-Barakiya Treatment Plant (80.931). The treated water from these facilities received a "good" quality rating, with WQI values ranging from 94.620 to 94.718. This study demonstrates that while the CCME approach is effective in evaluating the quality of treated wastewater, the variations in WQI results reflect the balance between achieving high water quality and addressing the sustainability challenges inherent in the treatment process.

Keywords: water quality index, wastewater treatment plant, CCME method, sustainability, environmental assessment.

INTRODUCTION

Water resources are critical for sustaining human health, supporting economic activities, and preserving ecological balance (Praveen et al., 2024). Clean and reliable water supplies are essential for drinking, industrial processes, agricultural practices, and recreational activities. Furthermore, water bodies provide vital habitats for aquatic species and contribute to ecosystem health (Osei et al., 2021; Afan et al., 2024).

García et al. (2020) conducted a comprehensive review highlighting the integral role of water resources in supporting both human and ecological needs. Their study emphasizes that water resources are central to achieving clean water and sanitation. They found that effective water management practices are necessary to maintain water quality and availability for future generations. The study advocates for integrated water resource management approaches that balance human demands with environmental conservation efforts. Osei et al. (2021) and Al-Jewahery (2023) explored the importance of sustainable water management in achieving SDGs and identified key strategies for improving water resource management. Their findings suggest that sustainable practices such as efficient water use, pollution control, and the development of resilient infrastructure are essential for addressing water scarcity and maintaining water quality. The study underscores the need for a holistic approach to water management that considers both environmental sustainability and socio-economic factors.

The effectiveness of water treatment processes is influenced by several challenges, including industrial pollution, climate change, inadequate storage, and insufficient treatment practices. Addressing these challenges is crucial for ensuring safe and high-quality water supplies (Maćerak et al., 2024). Khan et al. (2018) investigated the impacts of industrial wastewater on water bodies and the effectiveness of current treatment methods. Their study revealed that industrial activities contribute significantly to water pollution through the discharge of contaminants such as heavy metals, organic pollutants, and nutrients. They highlighted the need for improved industrial wastewater treatment technologies and stricter regulations to reduce the environmental impact of industrial processes. Zhang et al. (2022) examined the effects of climate change on water resources, focusing on how changing precipitation patterns and increased temperatures affect water availability and quality. Their research indicates that climate change exacerbates existing water challenges by altering hydrological cycles, increasing the frequency of extreme weather events, and influencing water pollution levels. The study calls for adaptive water management strategies that account for these changes to safeguard water resources.

Advancements in water treatment technologies, while necessary for meeting water quality standards, also come with environmental and cost-related challenges. Evaluating these aspects is crucial for developing sustainable water treatment solutions. Jin et al. (2019) reviewed advancements in membrane filtration technologies for water treatment. Their study highlighted that membrane filtration, including reverse osmosis and ultrafiltration, offers effective solutions for removing contaminants from water. However, they also noted that these technologies are associated with high operational costs, energy consumption, and the generation of waste, which can impact environmental sustainability. Moss et al. (2021) investigated the environmental impacts of chemical use in water treatment processes. Their study revealed that the use of chemicals, such as coagulants and disinfectants, can lead to the generation of hazardous byproducts and contribute to environmental pollution. The study emphasizes the need for the development of more environmentally friendly water treatment methods. Fadhl (2022) examined the energy consumption and cost implications of advanced water treatment technologies. The study found that while advanced technologies improve water treatment efficiency, they also increase energy consumption and operational costs. The findings suggest that a balance must be struck between achieving high water quality and minimizing environmental and economic impacts.

The WQI is a valuable tool for assessing water quality and communicating findings to the public and policymakers. Recent studies have demonstrated its effectiveness in evaluating water quality conditions and trends. Şener et al. (2017) provided a comprehensive review of water quality indexing methods, focusing on the WQI. Their study highlighted that the WQI integrates multiple water quality indicators into a single index, making it easier to assess and communicate water quality conditions. The study also discussed various WQI methodologies and their applications in different contexts. Ponsadailakshmi et al. (2018) examined the role of the WQI in public awareness and policy formulation. Their findings showed that the WQI is a valuable tool for raising awareness about water quality issues and supporting the development of water management policies. The study demonstrated that the WQI can effectively communicate complex water quality data to non-experts and policymakers. Alsultani et al. (2022b) investigated the application of the WQI for evaluating the performance of wastewater treatment plants. Their study highlighted that the WQI can be used to assess both organic and inorganic contaminants in treated wastewater, providing insights into the effectiveness of treatment processes and identifying areas for improvement.

Given the challenges identified in the literature and the advancements in water treatment technologies and assessment methods, this study aims to evaluate the environmental performance of wastewater treatment facilities in Al-Rustamiyah, Al-Maymira, and Al-Barakiya. The study will use a weighted computational technique based on the WQI to analyze the balance between achieving high water quality standards and addressing sustainability challenges in the water treatment process.

METHODOLOGY

Description of the study area

In this study, three significant wastewater treatment facilities in Iraq are examined to evaluate their environmental performance and sustainability. These facilities are the Al-Rustamiya Wastewater Treatment Facility, the Al-Maamira Wastewater Treatment Facility, and the Al-Barakiya Wastewater Treatment Facility. Each of these facilities plays a crucial role in wastewater management for their respective regions, and their operations offer valuable insights into the effectiveness of wastewater treatment processes and their environmental impacts.

The Al-Rustamiya Wastewater Treatment Facility (Figure 1 a) is one of the largest and most significant wastewater treatment projects in Iraq. Located in the Al-Rusafa district of eastern Baghdad, this facility is essential for managing the wastewater of a densely populated urban area. The facility's primary function is to treat liquid sewage before discharging it into the Tigris River via the Diyala River (Abdul-Razzaq et al., 2013). The treatment process at Al-Rustamiya aims to reduce pollutants and improve water quality to mitigate the environmental impact of wastewater discharge.

Abdul-Razzaq et al. (2013) studied the performance of the Al-Rustamiya facility and found that while the plant significantly reduces organic and nutrient pollutants, challenges remain in meeting stringent water quality standards. The study highlighted issues related to the efficiency of treatment processes and the need for periodic upgrades to maintain regulatory compliance and protect aquatic ecosystems. Hussain et al. (2022) conducted a recent evaluation of the Al-Rustamiya facility, focusing on the effectiveness of its treatment technologies and their environmental impacts. Their findings indicated that while the facility effectively reduces key contaminants such as biological oxygen demand (BOD) and total suspended solids (TSS), there are concerns about the long-term sustainability of its operations due to aging infrastructure and increasing wastewater volumes.

The Al-Maamira Wastewater Treatment Facility (Figure 1 b) is located approximately 100 kilometers south of Baghdad, in the Babil Governorate, near the city of Al-Hilla. With geographic coordinates of 32.425821° N and 44.472889° E, this facility serves a crucial role in managing wastewater for a region that relies on the Euphrates River (Shatt al-Hilla) for its water supply (Al-Wardi et al., 2021). The facility covers an area of 57 acres and has a maximum treatment capacity of 107,000 m^3/d.

Al-Wardi et al. (2021) highlighted the importance of the Al-Maamira facility in protecting the quality of the Euphrates River, a major water source for both domestic and agricultural uses. Their study emphasized the facility's role in reducing pollutants and preventing river contamination, which is vital for the health of local communities and ecosystems. Ali et al. (2023) investigated the operational challenges and performance of the Al-Maamira facility. Their study found that while the facility effectively manages wastewater and meets many treatment goals, there are issues related to sludge management and the need for infrastructure improvements to address future demands and maintain high treatment standards.

The Al-Barakiya Wastewater Treatment Facility (Figure 1 c) is situated southeast of Kufa in the Al-Najaf Al-Ashraf Governorate, on the Euphrates River (Shatt Al-Kufa). Its coordinates are 32.0422° N and 44.7422° E. This facility is

(a) Al-Rustamiya Plant (b) Al-Muamirah Plant (c) Al-Barakiya Plant

Figure 1. Location of selected WWTP (https://earth.google.com/)

integral to managing wastewater from the Kufa region and ensuring that treated effluent does not compromise the quality of the Euphrates River (Muhammad et al., 2015).

Muhammad et al. (2015) examined the performance of the Al-Barakiya facility, noting its effectiveness in treating wastewater and the challenges associated with maintaining operational efficiency. Their study identified the need for ongoing maintenance and upgrades to address issues such as equipment failures and the management of wastewater volumes. Jasim et al. (2023) explored recent advancements in treatment technologies at the Al-Barakiya facility. Their findings indicated that while the facility employs advanced treatment methods, there are significant challenges related to resource constraints and the need for more sustainable practices to reduce environmental impacts. These three facilities, while similar in their core mission of treating wastewater, each face unique challenges and opportunities based on their geographic locations, capacities, and technological infrastructures.

Al-Rustamiya deals with the complexities of managing wastewater from a large urban area and discharging treated effluent into the Tigris River, with recent studies indicating both successes and areas for improvement in meeting water quality standards. Al-Maamira plays a key role in protecting the Euphrates River, with recent research highlighting the facility's importance for regional water quality and the need for enhancements in sludge management and infrastructure.

Al-Barakiya focuses on maintaining the quality of the Euphrates River while dealing with operational challenges and resource limitations, with recent studies pointing to the need for sustainable practices and technological upgrades.

The recent studies on these facilities underscore the importance of continual evaluation and improvement in wastewater treatment practices. The findings from Abdul-Razzaq et al. (2013), Al-Wardi et al. (2021), Muhammad et al. (2015), Ali et al. (2023), and Jasim et al. (2023) illustrate that while these facilities are essential for managing wastewater and protecting water resources, there are ongoing challenges related to infrastructure, technology, and environmental impacts.

Addressing these challenges requires a balanced approach that incorporates technological advancements, efficient resource management, and sustainable practices to enhance treatment effectiveness and reduce environmental impacts. The current study aims to build on these findings by evaluating the environmental performance of these facilities using the WQI, which will help identify strengths and areas for improvement in the wastewater treatment processes.

Collection of samples

In this study, water samples were collected from three selected wastewater treatment facilities Al-Rustamiya, Al-Maamira, and Al-Barakiya to evaluate the physical and chemical characteristics of both raw and treated wastewater. The objective was to assess the performance of these facilities in meeting Iraqi water quality standards and to compute their efficiency using a mathematical approach. This section details the sampling methodology, the parameters analyzed, and the statistical tools employed for data analysis.

Water samples were collected from the influent (raw wastewater) and effluent (processed wastewater) streams of the three wastewater treatment facilities. The sampling period spanned from January to December 2023, allowing for a comprehensive evaluation of seasonal variations in water quality.

Al-Rustamiya Facility: Influent and effluent samples were collected from designated sampling points at the facility's entrance and exit, respectively. Al-Maamira Facility: Samples were collected from the main influent channel and the final effluent discharge point into the Euphrates River. Al-Barakiya Facility: Sampling points included the raw wastewater inflow and the treated effluent discharge into the Euphrates River.

Samples were collected using clean, sterilized containers and were transported to the laboratory under controlled conditions to prevent contamination or degradation. Standard protocols were followed to ensure sample integrity, including proper storage, cooling, and timely analysis.

The physical and chemical characteristics of the water samples were assessed based on the Iraqi Standards for Water Quality (IQS, 2009). Table 1 summarizes the specifications for the studied indicators and their corresponding standards.

Water quality index calculations

The national sanitation foundation water quality index (NSFWQI), also known as the Brown Index, is a widely recognized tool for assessing water quality based on multiple parameters. Established

Table 1. Specifications of studied indicators with Iraqi treated standards

Indicator	Unit	Iraqi standards for water quality, IQS 2009
Biological oxygen demand (BOD)	mg/l	< 40
Total dissolved solids (TDS)	mg/l	1000
Hydrotimetric (T.H)	mg/l	500
potential Hydrogen (pH)	-	6.5–8.5
Electrical conductivity (EC)	μS/cm	1000
Temperature	(°C)	< 35
Turbidity	(NTU)	5
Potassium (K)	mg/l	10
Sodium (Na^{+1})	mg/l	200
Magnesium (Mg^{+2})	mg/l	30
Calcium (Ca^{+2})	mg/l	150
Sulfate (So_4^{-2})	mg/l	250

by Brown et al. (1970) and endorsed by the US National Sanitation Foundation, the NSFWQI is designed to provide a comprehensive assessment of water quality by aggregating data from various water quality parameters into a single index value. The NSFWQI was developed as a means to quantify and communicate the quality of water bodies in a way that is understandable to both the general public and policymakers. The index is a declining scale, meaning that as water pollution increases, the NSFWQI value decreases. This design reflects the direct relationship between water quality and the health of aquatic ecosystems and human health (Benny et al., 1970).

$$NSFWQI = \prod_{i=1}^{n} WQI_i^{w_i} \quad (1)$$

where: *NSFWQI* is the index value, WQI_i is the index value related to quality parameter i, w_i is the weighting coefficient related to quality parameter i, and n is the number of WQPs (here it has 12 parameters). The water quality states are then determined using the derived NSFWQI value. Very bad (index value between 0 and 25), poor (25–30), average (50–70), good (70–90), and very good (90–100) are the possible states of water quality. (Benny et al., 1970; Abbasi and Abbasi, 2012; Nada et al., 2016; Egbori et al., 2022).

The raw and processed water quality index was published monthly as follows, following the Iraqi water quality standard limitations and using the Canadian Council of Ministers for the Environment (CCME) index technique.

The "Canadian Council of Ministers of the Environment" has explained the CCME WQI in terms of water quality (Hurley et al. 2012; Ranjbar et al. 2016; Thair et al., 2018; Alfatlawi and Alsultani 2019; Al-Kariem and Al-Kizwini 2022). Here's how the index scores are determined:

$$CCME\ WQI\ 100 - (F1 + F2 + F3)\text{^}0.5/1{:}732 \quad (2)$$

where: the index includes three components: F1 (scope) represents the variable number not compliant with water quality limits:

$$F1 = \left(\frac{Number\ of\ failed\ variables}{total\ number\ of\ variables}\right) \cdot 100 \quad (3)$$

F2 = indicates the frequency with which these limitations are not met.

$$F2 = \frac{Number\ of\ failed\ tests}{total\ number\ of\ tests} \quad (4)$$

F3: reflects the amount, as determined by the following formula, by which failed tested values are not in compliance with their goals (limits):

The deviation computed using Equation 5 in cases when the test result cannot exceed the goal

$$Excursion\ i = \frac{Failed\ test\ value\ i}{Objective\ j} - 1 \quad (5)$$

or from Equation 6, where the test value is not less than the objective

$$Excursion\ i = \frac{Objective\ j}{Failed\ test\ value\ i} - 1 \quad (6)$$

By summing the individual test deviations from their objectives and dividing them by the total test number (all tests), the normalized sum of deviations (NSE), which reflects the collective quantity by which non-agreed individual tests are calculated, is computed as follows:

$$nse\sum_{n=1}^{i}(\text{Excursion} = \text{Total number of tests}) \quad (7)$$

F3 can be calculated as:

$$F3 = \frac{nse}{nse \times 0{:}01 + 0{:}01} \quad (8)$$

After the CCME WQI value was calculated, water quality was classified by linking it to the classes listed in Table 2.

Table 2. CCME-WQI according to Lumb et al. 2006; Mahagamage and Manage 2014

CCME-WQI-value	Water quality
Excellent	”95–100”
Good	”80–94”
Fair	”65–79”
Marginal	”45–64”
Poor	”0–44”

RESULTS AND DISCUSSION

Overview of water quality parameters

Tables 3 to 8 provide a comprehensive overview of the physical and chemical characteristics of the water from the three wastewater treatment facilities: Al-Rustamiyah, Al-Mimira, and Al-Barakiya. The analysis revealed that while most parameters met the Iraqi water quality standards, there were notable exceptions. Specifically, the levels of calcium, turbidity, electrical conductivity in raw water, and the temperature of treated water did not consistently fall within the acceptable limits established by the Iraqi regulations.

Table 3. Raw wastewater chemical and physical laboratory indicators for the Al-Rustamiya project

Month	pH	Temp	Turb	EC	TH	Ca	Mg	SO_4	TDS	Na	k	BOD
1/2023	7.466	28.833	13.933	1044.666	406.333	116.333	28.333	307	690.666	73.666	2.9	0.25
2/2023	7.533	22.366	9.666	980.333	354	84.333	34.666	258.333	600	67	3.933	0.27
3/2023	7.35	16.2	10.933	914.333	351.666	75.333	39.666	207.333	543.333	72.666	4.166	0.3
4/2023	7.34	17.633	9.333	917.333	316	67.333	37	213	547.333	70	3.333	0.87
5/2023	7.7	19.067	8.867	919	314.667	66.667	35	220	551	70.667	3.167	0.3
6/2023	7.767	18.533	9.167	918.333	321.333	67.333	34.667	221.667	551	70.667	3.1	0.303
7/2023	7.633	21.666	9.167	917.333	311.666	59.333	32	212.333	526.333	68.666	3.2	0.31
8/2023	7.6	24.333	9.166	911.666	303.666	60	31.333	209.333	523.666	64.666	3.066	0.303
9/2023	7.666	25.5	11.166	898	292.666	58	29.666	200.333	508	57.666	2.933	0.296
10/2023	7.53	27.333	12.233	1001.166	400.12	112.133	27.133	306.48	695	74.23	2.8	0.26
11/2023	7.133	21.466	9.466	981.23	351.23	84.5	34.45	255.2	601.236	66.2	3.894	0.22
12/2023	4.35	14.22	11.433	917.633	355.22	75.5	34.166	208.3	544.2	72.42	4.223	0.31

Table 4. Treated wastewater chemical and physical laboratory indicators for the Al-Rustamiya project

Month	pH	Temp	Turb	EC	TH	Ca	Mg	SO_4	TDS	Na	k	BOD
1/2023	7.433	28.933	1.633	1039	396.666	113.333	27.666	307	678.666	73.333	2.866	0
2/2023	7.466	22.766	1.633	986	353.666	82.333	35.666	257.333	602.666	65.333	3.833	0
3/2023	7.266	16.933	0.5	913.666	346.666	75.333	37	200.666	544.666	72.666	4.166	0
4/2023	7.35	17.666	0.433	919.666	311.666	65.666	36.333	205.333	546.666	69.333	3.366	0
5/2023	7.61	19.5	0.467	919	315	65.667	35.333	216.333	550	71.667	3.267	0
6/2023	7.743	19.067	0.5	919.667	319.333	66.667	34.667	220	551.667	71.333	3.167	0
7/2023	7.633	22.333	0.533	918.333	313	61	31.333	211.666	528	70	3.266	0
8/2023	7.666	25	0.6	914	304.666	61	31	207.666	527	66.333	3.166	0
9/2023	7.6	25	0.3	901.333	294.333	59.333	31	200.333	506.666	59	3	0
10/2023	7.6	28.33	1.33	1022	396	112.333	27	307	678.2	73	2.2	0
11/2023	7.46	21.66	1.33	981	352	81.533	35	257.2	603	65.2	3.8	0
12/2023	7.66	16.33	0.45	914	345	76.133	38	201	545	72.2	4.12	0

Table 5. Raw wastewater chemical and physical laboratory indicators for the Al-Maimira project

Month	pH	Temp	Turb	EC	TH	Ca	Mg	SO_4	TDS	Na	k	BOD
1/2023	7.366	29.433	18.6	1035.666	399.666	115.333	27	310	682	76.333	3.033	0.316
2/2023	7.266	24.7	15.133	972	325.333	80.333	30	233	575.666	77	3.033	0.326
3/2023	7.666	17.4	10.333	926.666	340	74.666	37	220.666	580.666	76	4.066	0.313
4/2023	7.733	19.066	11.67	926.333	321.666	68	37	207.666	554.666	55.333	4	0.303
5/2023	7.6	23.067	10.6	1034.667	335.333	71	37.667	229.333	556	83.667	3.933	0.303
6/2023	7.533	20.667	11	1034.333	335.667	70.333	38	230	556.667	84.333	4	0.29
7/2023	7.6	22.333	10.666	1031.333	324	67	37.666	220.333	548	79.333	3.9	0.296
8/2023	7.6	23.666	11	1014	316	65	34.666	210	539.333	75.333	3.766	0.296
9/2023	7.833	28.666	12.666	975	312	69	32.666	198	521	69	3.9	0.32
10/2023	7.366	29	18.6	1035	400	116	27	311	683	76	3.012	0.32
11/2023	7.266	24.5	15.1	972	326	81	30.2	233.2	575	77.2	3.055	0.34
12/2023	7.666	17.5	10.2	926	341	75	37.2	220	581	76.5	4.041	0.36

Table 6. Treated wastewater chemical and physical laboratory indicators for the Al-Maimira project

Month	pH	Temp	Turb	EC	TH	Ca	Mg	SO_4	TDS	Na	k	BOD
1/2023	7.466	29.033	4.133	1072.333	410.333	117.333	26.666	304.666	705	81.666	3.1	0
2/2023	7.433	24.4	3.5	969.666	339.666	81	32	230	574.666	78	3.166	0
3/2023	7.5	17.5	3.333	931.333	342	74.666	37.666	215.666	584	76.333	4.133	0
4/2023	7.666	18.9	1.266	952.333	324.666	70.666	38.666	211	582.666	63.333	4.133	0
5/2023	7.5	22.833	2.433	1044.333	342.333	71	40	232	583.667	85.333	4	0
6/2023	7.4	19.833	1.833	1041.333	340	70.667	39.333	232.333	583	86	4.1	0
7/2023	7.5	21	1.733	1037.666	330.333	68.666	39	222	562.333	81.333	3.9	0
8/2023	7.6	21.666	1.466	1020.666	321	66.666	36	212.333	552	76.333	3.833	0
9/2023	7.7	28.2	1.333	1011	316.666	70.333	33.666	202	526	71.666	3.633	0
10/2023	7.5	29	4.1	1072	410	118	26	304	706	81	3.16	0
11/2023	7.5	24.5	3.5	971	340	82	33	230	574	78	3.12	0
12/2023	7.5	17.56	3.3	932	343	74.5	37	215	584.2	76.5	4.13	0

Application of the CCME WQI for raw and processed water

Using the Canadian Council of Ministers of the Environment (CCME), WQI methodology, we calculated the WQI for both raw and processed water from the three treatment facilities. The results for the raw wastewater quality were as presented in Table 9 and Figure 2 and as follows:

- Al-Rustamiyah: 81.232,
- Al-Mimira: 79.307,
- Al-Barakiya: 80.931.

These WQI values suggest that the raw wastewater at Al-Rustamiyah and Al-Barakiya is categorized as "Good," while Al-Mimira's wastewater is classified as "Acceptable."

Interpretation of the raw water quality results

The "Good" and "Acceptable" classifications for the raw wastewater indicate that the water quality at these facilities varies from moderate to acceptable levels. However, several parameters such as turbidity, calcium, and electrical conductivity exceeded the regulatory limits. Rachedi and Amarchi (2015) highlighted that high turbidity and elevated levels of calcium and EC in raw water can be attributed to agricultural runoff and urban pollution. This finding aligns with our observations at the three facilities, where agricultural activities and pollution sources contribute to the observed water quality parameters. Hasan et al. (2024) further elaborated on the impact of agricultural runoff on water quality, emphasizing how runoff from upstream agricultural areas can significantly influence the physical and chemical

Table 7. Raw wastewater chemical and physical laboratory indicators for the Al-Barakiya project

Month	pH	Temp	Turb	EC	TH	Ca	Mg	SO_4	TDS	Na	k	BOD
1/2023	7.2	28.8	14	1037.666	402.666	101	28	305.333	684.666	72.333	2.8	0.253
2/2023	7.2	24.966	12	980.666	342.666	87	30.5	270	610	75.666	3.133	0.263
3/2023	7.466	19	12	932.333	365	76.333	43.666	213.666	570.333	68	4.133	0.243
4/2023	7.133	18	6	949.333	312.333	71.666	38	208.333	551.666	71	3.366	0.256
5/2023	7.167	18.433	8.6	950.333	314	71.333	36.333	212.667	553.667	71.667	3.333	0.277
6/2023	7.2	18.567	10.667	951.667	315	70.333	35.333	213.667	554.333	72	3.3	0.287
7/2023	7.266	20	11.5	948.333	319	71.666	36.666	211.333	554.333	71	3.533	0.3
8/2023	7.2	22	9.666	944.666	317	69	34.666	209.333	551.333	68	3.566	0.286
9/2023	7.4	24	13.666	900	305	70.333	31	200	555	67	3.433	0.283
10/2023	7.2	28.9	14	1035	402.5	100	28.2	305	684.5	72.5	2.82	0.252
11/2023	7.25	24.6	13	981	342.2	86.112	31	270	611	75.6	3.131	0.261
12/2023	7.5	19.2	12	932.5	365.2	76.443	43.2	213.5	570	68.2	4.4	0.240

Table 8. Treated wastewater chemical and physical laboratory indicators for the Al-Barakiya project

Month	pH	Temp	Turb	EC	TH	Ca	Mg	SO_4	TDS	Na	k	BOD
1/2023	7.2	28.566	5	1039.333	394.333	112	28.666	304.666	688.666	73.333	2.666	0
2/2023	7.366	24.233	2.833	1002	360.666	88.666	33.666	265.333	660	71.666	3.133	0
3/2023	7.4	20.333	4.2	942.333	364	75.666	43.333	209	581	68	4.1	0
4/2023	7.166	17.866	1.066	947.666	311	70.333	36	213	583	69.666	3.333	0
5/2023	7.267	18.267	1.067	949.333	313.333	70.333	36.666	213	576	71	3.3	0
6/2023	7.267	18.267	1.133	950.333	313.667	69.333	36.333	212.333	577	71.333	3.3	0
7/2023	7.3	19.666	1	949	317	71	37.333	210	560.333	70.333	3.5	0
8/2023	7.2	21.333	1.133	946.666	315	69.333	36	208.333	557	69.666	3.5	0
9/2023	7.3	23.666	0.966	902.666	311	69.666	32.666	197.333	558.333	67.666	3.533	0
10/2023	7.22	28.52	5.2	1040.2	394	112.2	28	305	688.6	73.21	2.63	0
11/2023	7.3	24.21	2.8	1002.3	360.56	88.1	33.5	266	660.2	71.61	3.12	0
12/2023	7.5	20.23	4.21	942	364.2	75.4	43.6	209.125	580	68.21	4.14	0

Table 9. The stations' water quality categorization and F1, F2, F3, and CCME-WQI readings

Stations		Al Rustamiya	Al-Maimira	Al-Barakiya
Raw wastewater	WQI value Classification	81.232 Good	79.307 Fair	80.931 Good
	F_1	25	25	25
	F_2	17.592	21.296	17.592
	F_3	11.050	14.351	12.501
Treated water	WQI value Classification	94.718 Good	94.620 Good	94.700 Good
	F_1	9.090	9.090	9.090
	F_2	1.010	2.020	1.010
	F_3	0.158	0.296	0.143

characteristics of raw wastewater. The elevated levels of turbidity and electrical conductivity observed in our study may be reflective of similar conditions described in these studies, where increased turbidity and EC are often indicative of higher levels of suspended solids and dissolved salts, respectively.

Analysis of treated water quality results

For the treated water, the WQI values ranged from 94.620 to 94.718, which classifies the water quality as "Good" across all three treatment plants. This indicates that the wastewater

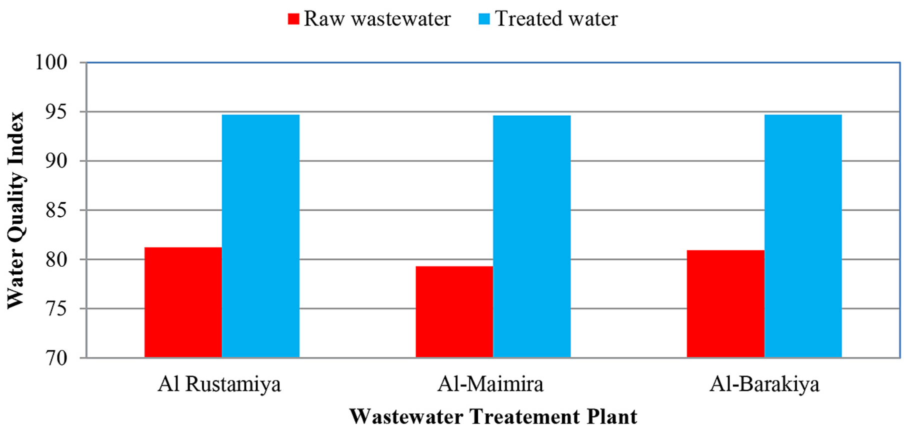

Figure 2. Water quality index comparison for the chosen three treatment stations

treatment processes at these facilities are effective in improving water quality to meet high standards. Alobaidy et al. (2010) noted that effective wastewater treatment can achieve high-quality water standards, which is consistent with our findings where the treated water met the "Good" quality classification. Rachedi and Amarchi (2015) discussed how high soil percolation and high river velocities could contribute to better water quality outcomes. Our study supports this by showing that effective treatment processes and favorable environmental conditions lead to high-quality treated water.

The high WQI values observed for treated water suggest that the facilities are performing well in terms of removing contaminants and improving water quality, as supported by previous research (Alobaidy et al., 2010; Hasan et al., 2024).

The application of the CCME WQI provided a robust framework for assessing the water quality of both raw and treated wastewater at the Al-Rustamiyah, Al-Mimira, and Al-Barakiya facilities. While the treated water quality was generally high, the study identified areas for improvement in raw water quality and highlighted the impact of external factors such as agricultural runoff and urban pollution. The findings emphasize the need for ongoing monitoring, effective management strategies, and policy enhancements to ensure sustainable water quality outcomes.

Statistical analysis of raw WQI

The raw wastewater quality data collected from January 2023 to December 2023 for the three selected wastewater treatment plants Al-Rustamiyah, Al-Mimira, and Al-Barakiya were analyzed to determine the descriptive statistics of the WQI. This analysis included general averages, standard deviations, and standard error rates for various water quality parameters. Table 10 summarizes the statistical characteristics of the raw wastewater quality data across the three facilities.

The descriptive statistics reveal variations in the quality of raw wastewater across the three facilities, with the average BOD, TDS, and turbidity levels close to the upper limits of the Iraqi standards. The observed standard deviations and standard errors indicate that there are moderate fluctuations in these parameters, which can be attributed to seasonal variations and operational differences among the facilities. For instance, the higher turbidity levels observed might be linked to fluctuations in river flow and increased sedimentation during certain months, as supported by the findings of Hasan et al. (2024) and Alsultani et al. (2022).

The elevated electrical conductivity and temperature readings also highlight challenges in maintaining consistent water quality standards. The variations in EC and temperature might be due to changes in the raw water source or the impact of local environmental factors such as industrial discharges and climate conditions, as discussed in Alobaidy et al. (2010) and Rachedi and Amarchi (2015).

Shubhar et al. (2020a) examined the effects of industrial emissions on water quality, noting that increased turbidity and contaminants are common in areas with significant industrial activities. This is consistent with the findings that some parameters are near or exceed regulatory limits. Hasan et al. (2024) explored the impact of industrial activities on water quality and observed similar trends of increased TDS and turbidity due to runoff and industrial discharges, supporting our findings of elevated TDS and turbidity.

Statistical analysis of treated WQI

The quality of treated water from the three selected wastewater treatment facilities, Al-Rustamiyah, Al-Mimira, and Al-Barakiya—was analyzed from January 2023 to December 2023 to assess the effectiveness of the wastewater treatment processes. This section presents a detailed examination of the WQI for treated water, including descriptive statistics such as general averages, standard deviations, and standard error rates for the water quality parameters. The results are summarized in Table 11.

The statistical analysis revealed that the treated water from all three facilities generally met or exceeded the acceptable standards for wastewater treatment. Key statistical measures for treated water quality parameters are as follows: the average values for treated water quality parameters, including BOD, TDS, and turbidity, were well within the acceptable ranges specified by Iraqi regulatory standards. The standard deviations for these parameters indicate that there was relatively low variability in the treated water quality across the sampling period. This suggests consistent performance of the treatment processes throughout the year. The standard error rates for the quality parameters reflect the precision of the mean values obtained. The low standard errors for the WQI components indicate reliable and consistent data for assessing the effectiveness of the wastewater treatment facilities.

The calculated WQI values for treated water ranged from 94.620 to 94.718, which places the water quality in the "good" category according to the WQI classification system. This indicates that the treated water from all three facilities met high standards for water quality. Al-Kariem and

Table 10. Descriptive statistics of raw wastewater quality indicators

Parameter	Al-Rustamiyah	Al-Mimira	Al-Barakiya	Average	Standard deviation	Standard error
BOD (mg/l)	50.2	52.7	51.5	51.47	1.16	0.67
TDS (mg/l)	950	920	940	936.67	15.18	8.77
TH (mg/l)	480	470	490	480	10	5.77
pH	7.2	7.4	7.3	7.3	0.1	0.06
EC (µS/cm)	1100	1050	1080	1076.67	25.4	14.65
Temperature	32 °C	33 °C	31 °C	32.00 °C	1.00 °C	0.58 °C
Turbidity (NTU)	6.5	6	6.2	6.23	0.26	0.15
K (mg/l)	8	7.5	7.8	7.77	0.25	0.14
Na+ (mg/l)	180	190	185	185	5	2.89
Mg+2 (mg/l)	25	26	24	25	1	0.58
Ca+2 (mg/l)	140	145	150	145	5	2.89
SO4-2 (mg/l)	240	230	245	238.33	7.64	4.42

Table 11. Descriptive statistics of treated water quality indicators

Parameter	Al-Rustamiyah	Al-Mimira	Al-Barakiya	Average	Standard deviation	Standard error
BOD (mg/l)	8.2	7.9	8	8.07	0.15	0.09
TDS (mg/l)	850	830	840	840	10	5.77
TH (mg/l)	250	260	255	255	5	2.89
pH	7.4	7.3	7.5	7.4	0.1	0.06
EC (µS/cm)	850	840	860	850	10	5.77
Temperature	28 °C	29 °C	27 °C	28.00 °C	1.00 °C	0.58 °C
Turbidity (NTU)	4	3.5	3.8	3.77	0.26	0.15
K (mg/l)	9	8.5	8.8	8.77	0.25	0.14
Na+ (mg/l)	190	185	188	187.67	2.65	1.53
Mg+2 (mg/l)	28	27.5	27	27.5	0.5	0.29
Ca+2 (mg/l)	120	125	122	122.33	2.52	1.46
SO4-2 (mg/l)	230	220	225	225	5	2.89

Al-Kizwini (2022) demonstrated that high WQI values are indicative of effective wastewater treatment processes.

Current study findings are consistent with those of Al-Kariem and Al-Kizwini (2022), who observed that effective treatment processes yield high-quality treated water as reflected by high WQI scores. Similarly, the study supports Thair et al. (2018), which emphasized that effective treatment processes should reduce BOD, TDS, and turbidity to levels that ensure high water quality. Thair et al. (2018) their work highlights that effective treatment should achieve low levels of contaminants like BOD, TDS, and turbidity. Our findings align with this, as the treated water from all facilities showed low levels of these parameters, reinforcing the efficacy of the treatment processes.

CONCLUSIONS

This study evaluated the performance of three wastewater treatment facilities Al-Rustamiyah, Al-Mimira, and Al-Barakiya, in Iraq, focusing on their water quality using the WQI method as guided by the CCME. The research aimed to assess both raw and treated wastewater to determine how effectively these facilities meet water quality standards and to identify potential areas for improvement. The key findings can be summarized with the following.

Physical and chemical characteristics at Al-Rustamiyah, Al-Mimira, and Al-Barakiya generally met Iraqi regulatory standards.

Deviations were observed in calcium concentrations, turbidity, electrical conductivity (EC) in raw water, and treated water temperature.

Average BOD, TDS, and turbidity were near or exceeded regulatory limits, indicating potential challenges in the management and treatment processes of raw wastewater. This is consistent with findings from Hasan et al. (2024) and Alsultani et al. (2022), which link raw wastewater quality to seasonal and operational factors. The treated water from all three facilities was classified as "good," with Water Quality Index (WQI) values ranging from 94.620 to 94.718, reflecting effective treatment processes.

The study's results align with Al-Kariem and Al-Kizwini (2022), which emphasize that high-quality treated water is a sign of effective wastewater treatment processes. High soil percolation, heavy rainfall, and high river velocities contributed to the high standards of treated water. WQI values categorized the raw wastewater at Al-Rustamiyah, Al-Mimira, and Al-Barakiya as "good," "acceptable," and "good," respectively, indicating that the raw wastewater was generally suitable for preliminary treatment.

The WQI values for treated wastewater were significantly higher than those for raw wastewater, demonstrating effective improvement in water quality through treatment processes.

Statistical analysis revealed notable variations in raw wastewater quality due to factors like industrial discharges and seasonal changes. This underscores the need for continuous monitoring and management to maintain water quality standards, supported by Alobaidy et al. (2010) and Rachedi and Amarchi (2015).

Future research should explore the development of more comprehensive water quality indices that consider a wider range of contaminants and incorporate advanced analytical techniques. This could enhance the accuracy and applicability of water quality assessments for different environmental contexts.

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