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Water Quality Features and Metal Pollution in Wadi El Rayan Lakes, Egypt

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ABSTRACT

Located in the Western Desert of Egypt, 125 kilometers southwest of Cairo, the Wadi El-Rayan protected area encompasses two man-made aquatic ecosystems, known as Wadi El-Rayan lakes. These lakes play a crucial role in regional irrigation and have an extreme economical importance in fishing, sustained solely by agricultural runoff of El-Wadi drain. This study aimed to comprehensively assess the water quality status and heavy metal pollution (Fe, Cu, Cd, Pb, Cr, Co, Ni, Zn, Al, Mn) in the Wadi El-Rayan lakes by evaluating physicochemical characteristics, heavy metal concentrations, and applying established water quality and metal pollution indices. Water samples were collected seasonally in 2021 from winter to autumn. Our data declared a significant elevation in organic contamination; nutrient salts, and chlorophyll-a in the upper lake compared to the lower lake. Conversely, the lower lake exhibited a fifteen-fold rise in salinity. This salinity upsurge, averaging 31.68%, limits the suitability of the lower lake for irrigation. according to the Canadian Water Quality Index (CWQI) classification, the upper lake was identified as "marginal" across all sites for aquatic organisms and "fair" for irrigation, while the lower lake was "fair" for fish habitat. The Oregon Water Quality Index (OWQI) indicated critically poor water quality in both lakes. Pollution and heavy metal pollution indices (PI and HPI) underscored varying degrees of metal contamination, particularly concerning aquatic life in both lakes. According to the Pollution Index (PI) of individual metals, Co displayed serious pollution effects, while Pb showed slight pollution effects across all sites. While, Cu showed slight local effect on the area affected by El-Wadi Drain. Other metals showed no significant pollution. This study raises a critical alarm regarding the escalating pollution, advocating for immediate intervention to mitigate the degradation of these vital aquatic resources, preventing a scenario reminiscent of Lake Qarun's ecological transformation.

INTRODUCTION

Environmental pollution has become one of the world's serious issues, both acute and chronic pollution events can impose additional stress on aquatic species. Heavy metal contamination of aquatic habitats has gained increasing importance as a major environmental concern in recent years **(Mitra *et al.*, 2022; Zhang *et al.*, 2023; Younis *et al.*, 2024)**. **Fathi and Flower (2005)** and **Taher *et al.* (2021)** reported that the water quality of the aquatic ecosystem is a key factor affecting the health status of aquatic life including fishes. Bioaccumulation of heavy metals as well as pesticides in fish may critically influence its meat quality as it affects the growth rate and the physiological & biochemical indices of fish **(Elewa *et al.*, 2007; Gaber, 2007; Salaah *et al.*, 2022)**. Potential, toxic chemical substances have accumulated in the environment as a result of human activities such as industrial, waste municipal and agricultural actions, leading to degradation of the aquatic environment that seriously threatens the health of fish **(Authman & El-Sehamy 2007; Salaah & El-Gaar, 2020)**. Wadi El-Rayan lakes are exposed continuously to environmental changes **(Abou El-Geit *et al.* 2013; Abd Ellah, 2016)**. Despite their nutritional value, fishes are highly susceptible to environmental contamination from heavy metals, which bioaccumulate over time in their muscles and constitute a risk to consumers' health **(Nędzarek *et al.*, 2019; Abd-Elghany *et al.*, 2024)**.

Wadi El-Rayan Protected Area (WRPA) is a vast, naturally depressed region spanning 703km² in Egypt's Western Desert, southwestern Fayoum **(Sayed & Abdel-Satar, 2009)**. In 1973, WRPA was introduced as a reservoir for effluent from nearby agricultural drainage wastewater of Fayoum Governorate due to the rising water levels in Qarun Lake and the consequent threat to surrounding structures. According to **Galindo *et al.* (2007)**, the ecological deterioration of Wadi El-Rayan lakes (WRL) is associated with water level drop due to evaporation in such closed basins. Moreover, reduced agricultural drainage water supplies could directly result in less water in the lakes, which results in the lakes' area shrinking **(El-Zeiny & Effat, 2017)**. WR lakes are very crucial for both fishing and recreational activities **(El-Sayed, 2011; Taha *et al.*, 2019)**.

Economically, WR lakes are very crucial for both fishing and recreational activities **(El-Sayed, 2011)**. According to the Millennium Ecosystem Assessment, these functions are categorized as provisioning services **(Taha *et al.*, 2019)**. UWRL has brackish water that is used for reclamation and irrigation for around agriculture area. While, the LWRL is a closed saline lake that receives its water from the UWRL through connecting channels **(Sayed & Abdel-Satar, 2009; Goher *et al.*, 2019; Abd El-Mageed *et al.*, 2021)**.

Recently, WR wetlands have faced serious problems which impacted all aspects of their ecosystems **(Eid *et al.*, 2020)**, such as the significant decline in the water level of their two lakes, decreasing the natural vegetation cover and biodiversity **(Orimoloye *et al.*, 2020)**.

Dense metallic elements are a critical class of inorganic contaminants in aquatic systems, their occurrence and resistance in water bodies amplify their environmental impacts **(Goher & Khedr, 2024)**. These heavy metals can induce damage at the molecular level, disrupting the cellular integrity of aquatic life and potentially trigger various disorders in fish **(Khalil *et al.*, 2017)**. Furthermore, some essential trace elements like copper (Cu) and zinc (Zn) can pose a serious risk when discharged at levels exceeding permissible water quality standards, entering the food web and undergo biomagnification in fish organs, including gills and liver, among other tissues **(Zaghloul *et al.*, 2020; Pattipeiluhu & Fendjalang, 2024; Zaghloul *et al.*, 2024)**.

Recently, WR region has undergone considerable environmental alterations, largely attributable to extensive human activities such as aquaculture and agriculturalization **(Abd Ellah, 2016)**. Therefore, this study aimed to comprehensively assess the current water quality status of the Wadi El Rayan lakes by evaluating physicochemical characteristics and quantifying the concentrations of ten heavy metals (Fe, Cu, Cd, Pb, Cr, Co, Ni, Zn, Al, Mn) across different seasons. Furthermore, it seeked to determine the overall water quality through established Water Quality Indices (CWQI, OWQI) and to quantify metal contamination using Pollution and Heavy Metal Pollution Indices (PI, HPI), thereby elucidating the ecological impacts of escalating human activities and providing critical data to advocate for an immediate intervention to mitigate environmental degradation.

MATERIALS AND METHODS

Study area and sampling

Wadi EL-Rayan lakes were estimated with a maximum total area in 2000 (106.330km^2); unfortunately, the area and water volume have been reduced, especially in the LWRL **(Hereher, 2015)**. The total study area is located between latitudes 29°11\30.0\\ and 29° 17\14.0\\ N and longitudes 30° 25\53.0\\ & 30° 31\10.9\\ E **(Goher *et al.*, 2019)**. The study area is formed of two artificial lakes, the first (upper) and the second (lower) lakes. The upper Wadi El-Rayan Lake (UWRL) was completely filled in 1980 and allowed the water to inflow to the lower Wadi El-Rayan Lake (LWRL) **(Khedr *et al.*, 2023)**.

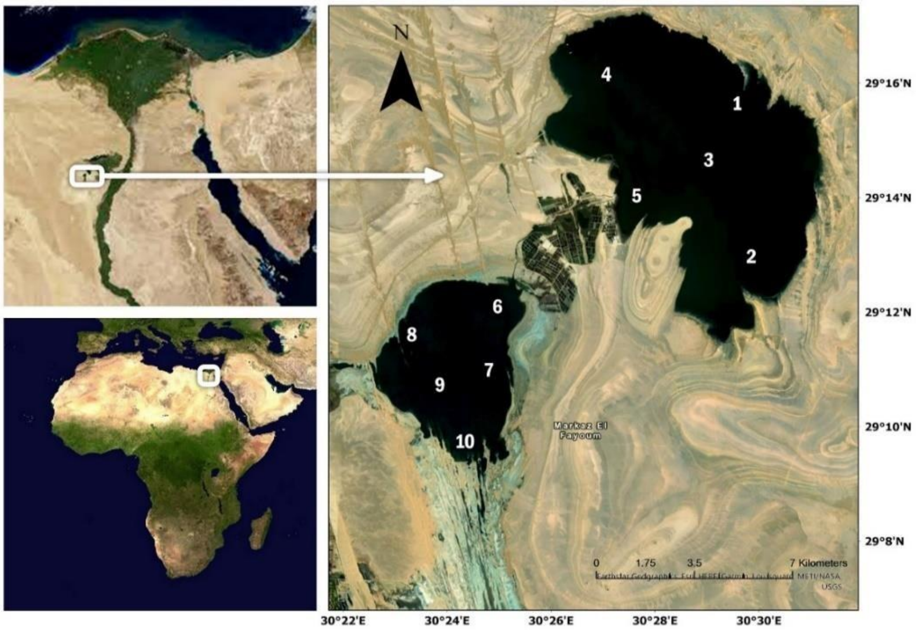

Fig. 1. Map of Wadi El Rayan lakes sample sites **(Khedr *et al.*, 2023)**

Eleven subsurface water samples were seasonally collected during January, April, July and October 2021 using 2L Ruttner Water Sampler, with 5 samples from each lake (UWRL and LWRL) and El-Wadi Drain. Sites 1-5 represent the Upper Wadi El-Rayan Lake (UWRL), while sites 6-10 represent the Wadi El-Rayan Lower Lake (LWRL) (Fig. 1). Water samples were kept in 2L polyethylene bottles in an ice box at about 2^{o}C and were analyzed in the laboratory. To ensure sample integrity during transport and storage, water samples intended for heavy metal analysis were collected in meticulously cleaned 1-liter polyethylene containers. Immediately upon collection, five milliliters of concentrated nitric acid (HNO_3) were added to each sample to reduce the pH below two **(APHA, 2017)**. This acidification served a triple purpose: inhibiting microbial proliferation, arresting oxidative processes, and preventing the precipitation or adsorption of heavy metal ions onto the container walls. Subsequently, the acidified samples were stored under refrigeration.

Analysis procedures

The used analysis methods were recommended by the American Public Health Association **(APHA, 2017)**. Water temperature, electrical conductivity, and pH value were measured *in situ* using Thermo scientific Orion Star (A 329 multi-parameter instrument). The transparency was measured using the Secchi disk (diameter 30cm). Salinity (total dissolved solids –TDS) and total suspended solids (TSS) were determined by filtering a known volume of sample by GF/C and evaporating at 180 and 105^{O}C, respectively. Dissolved oxygen (DO) was measured using the modified Winkler method **(APHA, 2017)**. Biochemical oxygen demand (BOD) was determined using the 5-day method **(APHA, 2017)**. Chemical oxygen demand (COD) was analyzed using the Dichromate method. Carbonate and bicarbonate were measured titrimetrically with standard H_2SO_4 (0.02 N) using phenolphthalein and methyl orange as indicators and values were determined according to **APHA (2017)**. Ammonium (NH_4) was determined by the phenate method. Nitrite (NO_2) was determined using the colorimetric method with the formation of a reddish-purple azo dye. Nitrogen–nitrate (NO3) was measured as nitrite after cadmium reduction. Orthophosphates (P–PO_4) were estimated using the ascorbic acid molybdate method. Silicates (SiO_4) were determined using the molybdosilicate method. Total nitogen (TN) and total phosphorus were determined as NO_3 and PO_4, respectively, after digestion **(APHA, 2017)**.

Water samples underwent a nitric acid digestion procedure, modified from established protocols to quantify the total burden of heavy metals, encompassing organically and inorganically bound species in both dissolved and particulate phases **(APHA, 2017)**. Subsequent elemental analysis for aluminum (Al), cadmium (Cd), cobalt (Co), chromium (Cr), copper (Cu), iron (Fe), manganese (Mn), nickel (Ni), lead (Pb), and zinc (Zn) was performed using a Perkin Elmer Optima 7000 Inductively Coupled Plasma Emission Spectrometer (ICP-ES) equipped with an ultrasonic nebulizer (USN). The specific wavelengths employed for each element in this analysis are detailed in Table (1). Further details regarding the preparation and analysis of HM samples are provided in the supplementary file (ST1).

Table 1. Wavelengths and detection limits of ICP-ES for the studied heavy metals

Wavelength	Al	Cd	Co	Cr	Cu	Fe	Mn	Ni	Pb	Zn
nm	396.152	226.499	238.892	267.716	324.747	259.933	257.604	231.602	220.35	213.855
DL (µg/L)	0.9	0.1	0.25	0.25	0.3	0.3	0.04.	0.5	1.5	0.2

Water quality indices

The suitability of El-Rayan lakes' water for aquatic life and irrigation was evaluated using two established integrated water quality indices: the Oregon Water Quality Index (OWQI) and the Canadian Water Quality Index (CWQI), following the methodologies outlined by **Sarkar and Abbasi (2006)** and the Canadian Council of Ministers of the Environment **(CCME, 2021)**, respectively. Detailed information regarding the calculation and interpretation of these indices can be found in the supplementary data (ST2 and Tables S1 and S2).

Metal pollution indices

To evaluate the extent of heavy metal (HM) pollution in the El-Rayan Lake's water, two HM indices were calculated. The first, the Pollution Index (PI), assesses the impact of individual metals and categorizes pollution levels into five distinct grades (Table S3 in the supplementary data) **(Caerio *et al.*, 2005)**. The second, the Heavy Metal Pollution Index (HPI), evaluates the combined effect of multiple HMs on water quality, indicating the overall degree of pollution and its implications for aquatic organisms **(Hassouna *et al.*, 2019)**. Comprehensive details regarding the calculation and interpretation of these metal indices are available in the supplementary data (ST3).

Statistics

Using Excel-Stat software (2019), a one-way ANOVA test was conducted to assess the significance of variance in the collected data across different seasons and sites. Additionally, pair correlation coefficients (r) and standard deviations were calculated.

RESULTS AND DISCUSSION

Physical characteristics

The recorded water temperatures in the UWRL, and LWRL, ranging from 14.20 to 30.47°C and 14.6 to 31.02°C during winter and summer, respectively (as depicted in Fig. 2), generally fell within a range considered suitable for fish survival. As illustrated in Fig. (2), the highest water temperature (31.02°C) was observed in summer at station 10 in the LWRL, while the lowest temperature (14.2°C) was recorded in winter at station 5 from the UWRL. Statistical analysis declared a significant positive correlation (*P*< 0.01) between temperature and COD in both the UWRL and LWRL, and a significant negative correlation (*P*< 0.05) between temperature and DO in the LWRL. However, localized variations within the same season suggest potential influences from specific environmental factors such as water turbidity and the extent of plant coverage **(Shi *et al.*, 2022)**. It is well-established that temperature plays a crucial effect in regulating nutrient cycling dynamics, DO, and the abundance of macrophytes **(Fletcher *et al.*, 2000; Lønborg *et al.*, 2021)**, ultimately impacting the overall health of aquatic organisms. Water transparency, a parameter influenced by both water color and turbidity, exhibited a range of 20-130cm in the UWRL and 70-240cm in the LWRL, as demonstrated in Fig. (2). Notably, transparency was generally higher in the LWRL, particularly during spring, with a peak value of 240cm recorded at station 10. This increased transparency in the LWRL may be attributed to the presence of vegetation within the connecting channel, which likely facilitated the settling of suspended particulate matter, thereby enhancing water clarity **(El-Shabrawy & Dumont, 2009)**. According to **Różańska-Boczula and Sender (2025)**, macrophytes play a crucial role in lakes by stabilizing clear-water conditions and influencing water quality. They help reduce turbidity, enhance water transparency, and stabilize the clear-water state in lakes. In the UWRL, transparency showed a strong negative correlation with TSS (r = -0.81, n = 20, *P* < 0.01) and a moderate negative correlation with COD (r = -0.45, n = 20, *P* < 0.05). Conversely, transparency displayed a significant positive correlation with DO in both the UWRL (r = 0.70, n = 20, *P* < 0.01) and the LWRL (r = 0.64, n = 20, *P* < 0.01).

Electrical conductivity (EC), a measure directly influenced by the concentration of ions in water **(Reith *et al.*, 2025)**, exhibited a significantly higher range in the LWRL compared to the UWRL, as shown in Fig. (2). This disparity likely stems from the increased load of TDS in the LWRL, a phenomenon that has progressively intensified due to a reduction in water inflow from the Upper Lake **(Abdel-Moniem, 1991; Sayed & Abdel-Satar 2009)**; this decrease in inflow has led to a reduction in the water volume of the LWRL. EC fluctuated between 1.86 and 3.28 mS/cm in the UWRL and between 35.65 and 48.99 mS/cm in the LWRL, displaying a seasonal trend in descending order: autumn > summer > winter > spring. The peak electrical conductivity of 48.99mS/ cm was observed at station 9 during autumn, while the lowest value of 1.86mS/ cm was recorded at station 1 during the same season. Statistical analysis indicated a highly significant spatial difference (*P*< 0.001) in EC within the UWRL and between the two lakes. The observed elevation in EC values is consistent with an increase in total dissolved solids **(Kumar & Bahadur, 2009)**, a finding corroborated by a strong positive correlation with TDS (*P*< 0.01, r = 0.99), aligning with the observations of **Abdel-Satar (1998)** and **Shah *et al.* (2006)**.

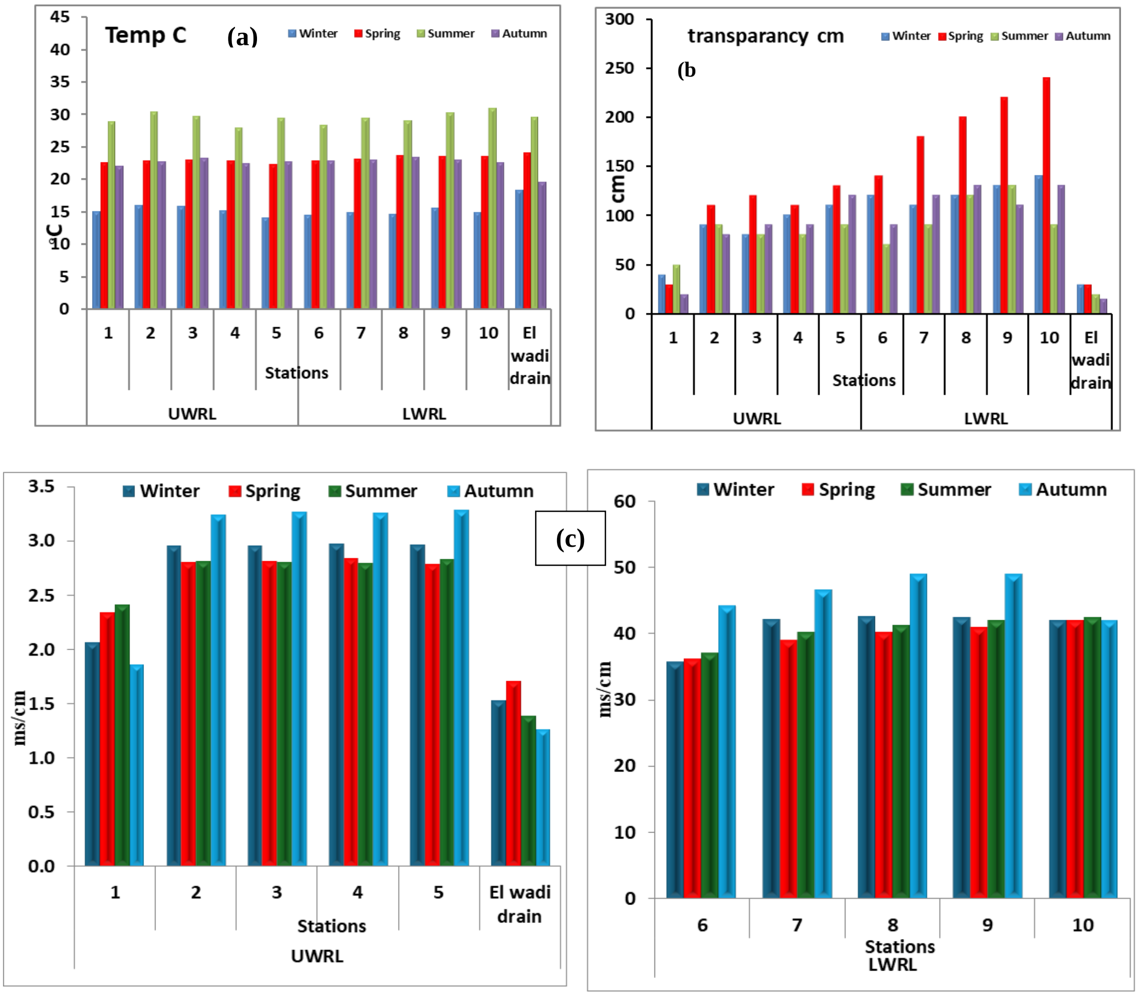

Fig. 2. Seasonal variation of **(a)** temperature (ºC), **(b)** transparency (cm), and **(c)** EC (mS/Cm^2) in the UWRL, and LWRL during 2021

TSS is a measurement of the particulate matter that is suspended within the water column and is the portion of solids remnant after the filtration includes organic residues **(APHA, 2017)**. TSS in the UWRL were much higher than the LWRL (Fig. 3), which was in opposite distributed pattern of transparency. The highest value of TSS of 32.19mg/ L was recorded during autumn in the UWRL at station (1) that received effluents from El -Wadi drain. While the minimum TSS of 6.18mg/ L was recorded at station (10) in the LWRL. These results are in harmony with those previously obtained by **Goher *et al.* (2019)**. The TSS value in El-Wadi drain (47.61-52.68) is higher than that of Wadi El Rayan lakes that showed 12.08-32.19 and 6.18-22.76 for UWRL, LWRL, respectively. This suppression primary associate with algae by interfering with photosynthesis **(Fanela *et al.*, 2019)**. TSS along with TDS may increase as a result of surface-level decaying plant materials sinking **(Riza *et al.*, 2023; Khedr *et al.*, 2025)**. TSS in the UWRL is positively correlated ($P< 0.01$) with BOD, COD, and metals as Al, Fe, Cd, Mn ($P< 0.01$), and Pb ($P<0.05$), while it is negatively correlated ($P< 0.05$) with DO. On the other hand, TSS is positively correlated ($P< 0.01$) with BOD, COD, Chl-a, Fe, Co, and Zn in the LWRL.

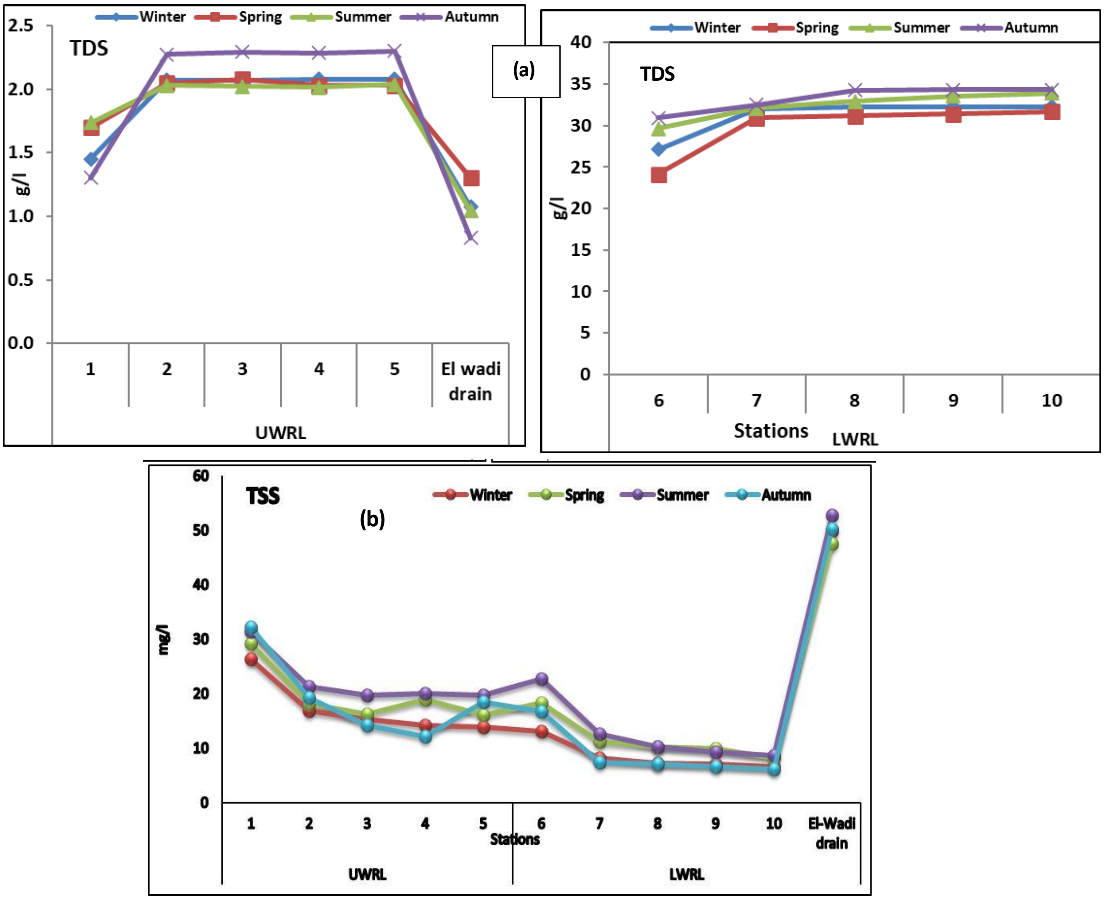

Fig. 3. Seasonal variation of **(a)** salinity (TDS, g/L), and **(b)** TSS (mg/L) in the UWRL, and LWRL during 2021

Salinity is often expressed as total dissolved solids (TDS), representing the concentration of dissolved salts in water. Based on TDS data in Fig. (3), UWRL and LWRL are classified as brackish and saline water bodies, respectively, indicating salinization, particularly in the LWRL. This result aligns with previous findings of **Sayed and Abdel-Satar (2009)** and **Nassif and Amer (2023)**. The TDS concentrations in the LWRL are primarily regulated by the rate of water evaporation and the volume of water discharged from the UWRL **(Abd El-Karim, 2004; Abd Ellah *et al.*, 2016)**, as it is a closed basin without a natural outlet. While the Upper Lake, considered an open basin, maintains a relatively stable brackish salinity of approximately 2%, minor temporal fluctuations have been observed **(Shama *et al.*, 2011)**. Coupled with the prevailing arid climate characterized by extremely high annual evaporation rates exceeding inflow **(Abd Ellah *et al.*, 2016)**, the water in the LWRL exhibits saline characteristics. Our investigation revealed a peak TDS value of 34.33g/ L in the LWRL during autumn at station 10 (Fig. 3). Conversely, the minimum TDS value (1.30g/ L) was recorded at station 1, finding potentially linked to dilution effect from El Wadi drain, as suggested by **Abd El-Mageed *et al.* (2021)**.

The escalating salinity within this ecosystem poses significant environmental challenges, particularly for the LWRL **(Abd Ellah *et al.*, 2016)**. Salinity increased from 2.41‰ in 1984-1985 **(Saleh *et al.*, 1988)** to 14.3‰ in 2010 **(Abd Ellah, 2016)**, to 16.5‰ in 2015 **(EASRT, 2015)**, and further to 31.68‰ at 2021. The volume of water entering the Lower Lake has decreased considerably over time, dropping from approximately 127 million m³/year in 1996 **(Abd Ellah, 1999)** to 35.2 million m³/year in 2014 **(EASRT, 2015)**. This decline has coincided with an expansion of fish farms and agricultural land in recent years, as the primarily water source for these activities come from the Upper Lake through pipelines **(Afefe *et al.*, 2016)**. As a result of these processes, the LWRL exhibits significantly higher concentrations of various ions compared to the UWRL **(Abd El-Mageed *et al.*, 2021)**.

pH, an indicator of the overall alkaline or acidic nature of a water body, can fluctuate considerably over time due to atmospheric exposure, biological processes, and temperature shifts **(Saalidong *et al.*, 2022)**. The analyzed water samples predominantly leaned toward alkalinity, potentially influenced by planktonic algae that lead to elevation of photosynthetic activity or the inherent chemical composition of the water **(El-Sherif *et al.*, 2025)**. Statistical analysis of pH values in the UWRL revealed significant temporal and spatial variations ($P < 0.001$), while the LWRL exhibited significant temporal differences ($P < 0.01$). The recorded pH ranges were 7.78-8.97 in the UWRL and 8.04-8.83 in the LWRL (Fig. 4), in contrast with the El-Wadi Drain, which showed a pH range of 7.40-7.91. The highest pH value (8.92) was observed at station 2 in the UWRL during summer, possibly linked to increased photosynthetic rates. During photosynthesis, the consumption of carbon dioxide (CO_2) reduces bicarbonate concentration, consequently leading to higher pH values **(Yousry *et al.*, 2009; Ezzat *et al.*, 2012)**, a phenomenon often associated with dense vegetation and phytoplankton populations **(Sabae, 2004)**. Conversely, the lowest pH values of 7.78 and 7.93 were recorded at station 1 in the UWRL during autumn and winter, respectively. The relative pH decrease during colder seasons may be related to the increased solubility of CO_2 at lower water temperatures, which subsequently decrease the pH value **(Abdo *et al.*, 2012)**.

The observed decrease in pH during certain periods might also be a consequence of reduced phytoplankton activity, alongside the decomposition processes carried out by bacteria and fungi in the sediment. These microbial activities can release hydrogen sulfide and methane, as well as generate organic acids and other byproducts of organic matter breakdown **(Ahmed, 2012)**. The pH levels recorded in the lake's water appear to be within a suitable range for normal fish productivity. Specifically, the optimal pH for the Nile tilapia (*Oreochromis niloticus*) culture is reported to be between 7 and 8 **(Rebouças *et al.*, 2016)**.

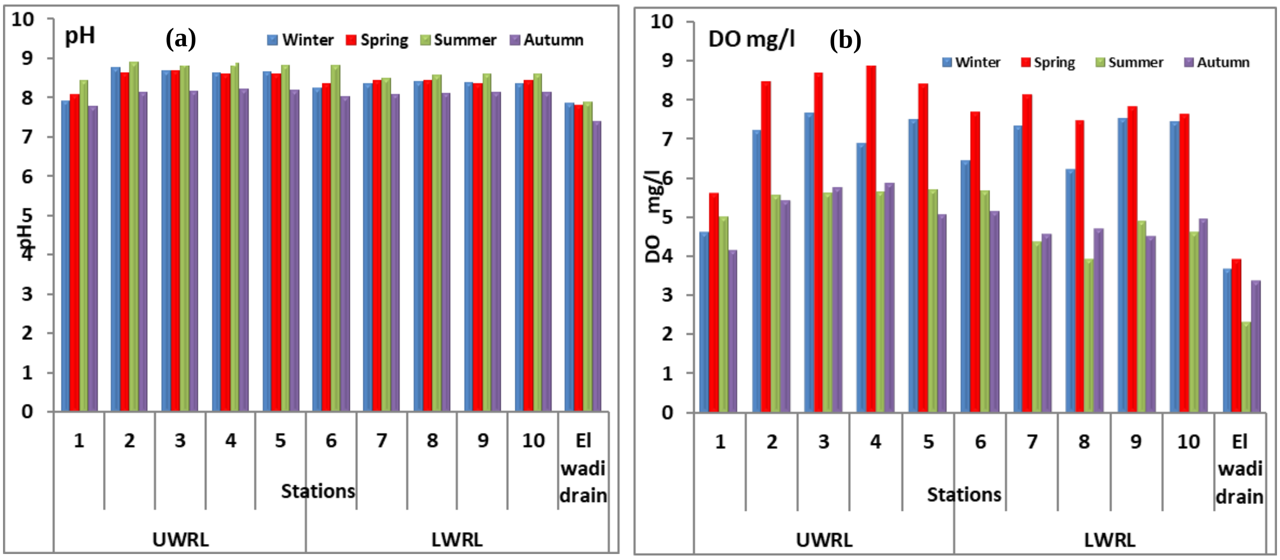

Fig. 4. Seasonal variation of **(a)** pH and **(b)** DO (mg/L) in the UWRL and LWRL during 2021

Dissolved oxygen (DO) is a paramount parameter for the survival and well-being of aquatic organisms **(Mahmoud, 2002)**, and a key indicator of an aquatic system's water quality. Typically, unpolluted waters exhibit DO concentrations of ≤10mg/ L. However, the discharge of effluents rich in organic matter and nutrients can lead to a significant depletion of DO levels (**Zhang et al., 2024**). A DO concentration below 5mg/ L can negatively impact the function and survival of biological communities, while levels below 2mg/ L can be lethal for most fish species **(Ali et al., 2022).** In our results, DO concentrations in the UWRL ranged from 4.13 to 8.39mg/ L, and in the LWRL from 3.91 to 8.11mg/ L (Fig. 4). Notably, the El-Wadi Drain displayed considerably lower DO values, ranging from 2.32 to 3.92mg/ L. The DO levels observed in the Wadi El-Rayan lakes are subject to both daily and seasonal variations, influenced by fluctuations in water temperature, photosynthetic activity, and the impact of effluents from the El-Wadi drain. A consistent observation was that DO concentrations were generally higher in the UWRL compared to the LWRL, a phenomenon potentially linked to the difference in water salinity, as increased salinity typically reduces the solubility of oxygen in water **(EFFLER *et al.*, 1997; Leidonald *et al.*, 2019)**. The highest DO value recorded was 8.93mg/ L during spring at station 4 from the UWRL, which could be attributed to elevated photosynthetic activity resulting from an abundance of phytoplankton during this season, leading to a significant release of oxygen into the surrounding water **(Ezzat *et al.*, 2012)**.

The biochemical oxygen demand (BOD) levels varied between 4.78-8.59mg/ L and 3.65-6.64mg/ L, while COD recorded values varied between 21.84-30.21mg/ L and 19.15-27.10mg/ L in the UWRL and LWRL, respectively (Fig. 5). Generally, the highest BOD and COD values were recorded at station 1, situated near the discharge point of the El-Wadi Drain, indicating the influence of agricultural effluents rich in organic matter. This observation aligns with findings from several previous studies **(Goher *et al.*, 2019; Abd El-Mageed *et al.*, 2021)**. Furthermore, elevated temperatures during the warmer periods (summer and spring) corresponded with higher BOD and COD levels, likely due to the acceleration of organic matter oxidation and increased bacterial activity **(Morgan-Sagastume & Allen, 2003; Scofield *et al.*, 2015; Chapra *et al.*, 2021).**

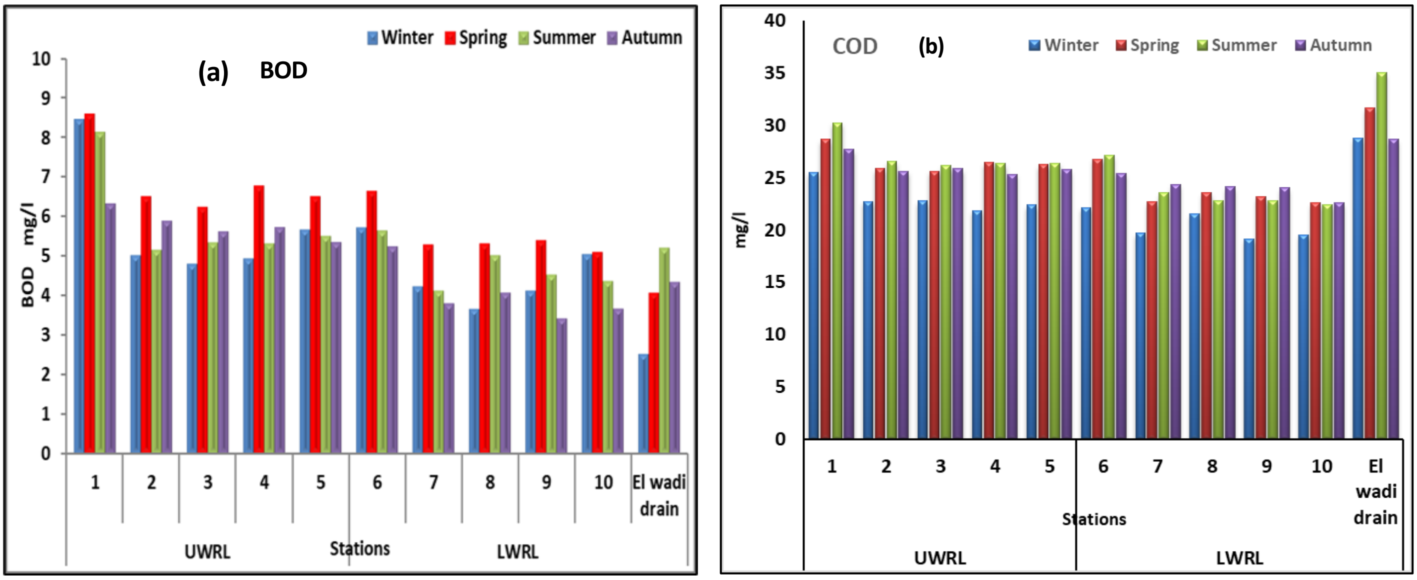

Fig. 5. Seasonal variation of **(a)** BOD (mg/L), and **(b)** COD (mg/L) in Wadi El Rayan lakes during 2021

Conversely, lower BOD and COD concentrations were observed during the colder seasons (autumn and winter). A statistically significant difference ($P< 0.01$) in both BOD and COD was noted between the two lakes, with relatively higher values in the UWRL, potentially attributable to the impact of agricultural discharge from the El-Wadi Drain and differences in salinity, a finding consistent with reports by **Abdel-Satar *et al.* (2010)** and **Goher *et al.* (2019)**. The corresponding BOD and COD values in the El-Wadi drainage water ranged from 6.77 to 9.88mg/ L and 28.66 to 35.0mg/ L, respectively. In general, the BOD of the wastewater was lower than the COD, a phenomenon explained by the fact that more compounds can be chemically oxidized than biologically oxidized **(Clark & Micheal, 1972; Shama *et al.*, 2011)**. Additionally, an inverse relationship exists between DO and oxygen utilization as measured by BOD and COD.

Carbonate ions (CO_3^{2-}) were detected in concentrations ranging from 0.00-24.80mg/ L in the Upper Wadi El-Rayan Lake (UWRL) and 10.2-20.8mg/ L in the LWRL, as depicted in Figs. (6, 7). The peak CO_3^{2-} concentration (24.8mg/ L) observed at station 2 in the UWRL during summer, that could be related to the increased activity of photosynthesis alongside with the elevated water temperatures, which reduce the solubility of carbon dioxide (CO_2) **(El-Sharkawy, 2010)**. This finding contrasts with the results reported by **Goher (2002)** in Qarun Lake. Conversely, the carbonate was completely depleted at station 1 during both winter and autumn in the UWRL.

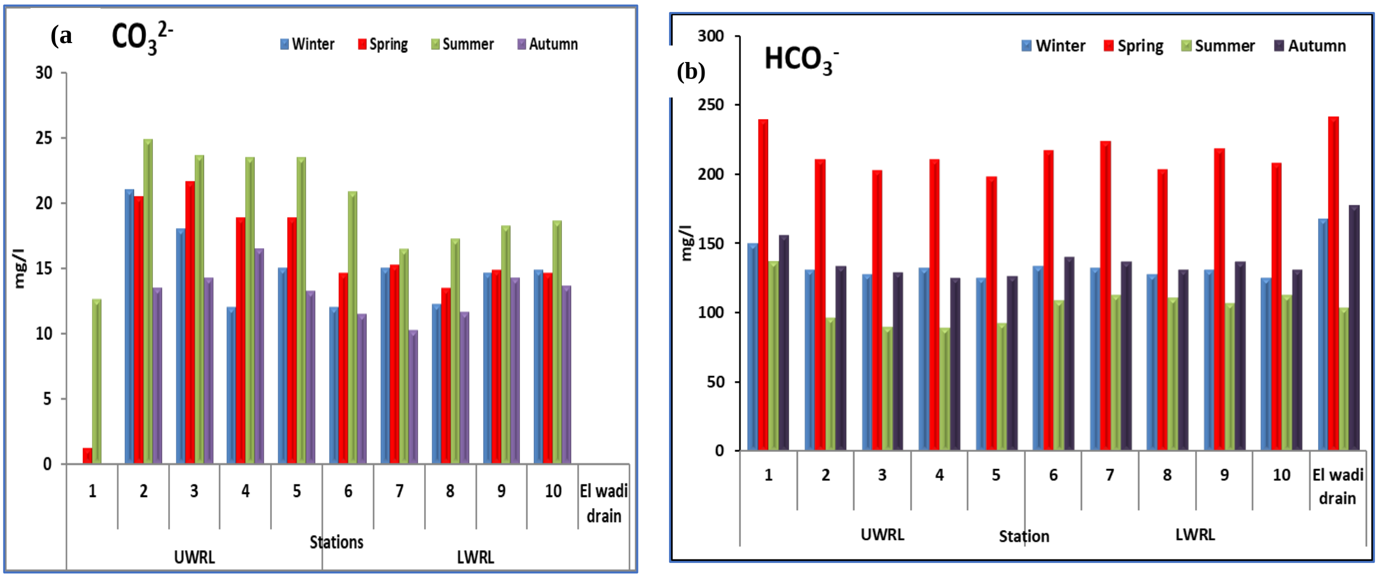

Fig. 6. Seasonal variation of **(a)** carbonate (mg/L), **(b)** bicarbonate (mg/L) ions in Wadi El Rayan lakes

Bicarbonate (HCO_3^-) plays a crucial dual role in aquatic ecosystems: it acts as the primary buffering system, stabilizing water pH, and serves as a source of carbon dioxide (CO_2) for photosynthesis. Photosynthetic activity, driven by light, leads to an increase in pH and the formation of bicarbonate, a process that reverses in darkness **(Ghoniemy, 2005)**. Seasonal fluctuations in bicarbonate concentrations were observed in the Wadi El-Rayan lakes, ranging from 88.99 to 238.86mg/ L in the UWRL and from 106.69 to 223.58mg/ L in the LWRL. The highest bicarbonate concentration (281.4mg/ L) was recorded at station 1 during spring, an area influenced by the El-Wadi drain effluent. Conversely, the lowest bicarbonate concentration (122mg/ L) in the lake water was seen at station 8 during the autumn season (Fig. 6). These variations highlight the dynamic interplay between biological activity, water chemistry, and seasonal changes in influencing the bicarbonate levels within the Wadi El-Rayan lakes **(El-Sayed, 2011)**.

Nutrients and Chl-a

Nitrogen and phosphorus are recognized as key nutrient elements that serve as indicators of a water body's potential fertility **(Emara, 2010)**. The nutrient status of a lake reflects both natural processes and the influence of human activities **(Abdel-Satar & Goher, 2009)**. In this study, the distribution of different nitrogen forms (ammonia - NH_4, nitrite - NO_2, nitrate - NO_3, and total nitrogen - TN) exhibited an irregular pattern in both lakes, particularly in the UWRL. The seasonal variations in the concentrations of NH_4, NO_2, NO_3, TN, orthophosphate (PO_4), total phosphorus (TP), and silicate (SiO_4) in the UWRL were within the ranges of 0.020-3.218mg/ L, 0.88-205.10µg/ L, 0.067-1.299mg/ L, 0.63-5.13mg/ L, 8.8-83.6µg/ L, 38.5-171.05µg/ L, and 5.79-9.54mg/ L, respectively (Fig. 7). In the LWRL, the corresponding concentration ranges for NH_4, NO_2, NO_3, TN, PO_4, TP, and SiO_4 were 0.071-0.551mg/ L, 2.93-12.89µg/ L, 0.036-0.125mg/ L, 0.520-0.913mg/ l, 7.7-27.50µg/ l, 9.9-72.6µg/ l, and 6.17-14.49mg/ L, respectively (Fig. 7). In contrast, the nutrient concentrations in El-Wadi drainage water were as follows: NH_4 ranged from 1.578 to 3.805mg/ L, NO_2 from 191.04 to 315.56µg/ L, NO_3 from 0.733 to 2.225mg/ L, TN from 4.19 to 7.56mg/ L, PO_4 from 100.1 to 205.7µg/ L, TP from 204.6 to 328.9µg/ L, and SiO_4 from 7.74 to 13.12mg/ L.

Generally, the majority of nutrient salts exhibited a highly significant spatial difference ($P < 0.01$) between the UWRL and LWRL. This disparity is strongly linked to the substantial nutrient load carried by the discharged wastewater from the El-Wadi Drain. Consequently, the highest nutrient concentrations were typically recorded at station 1 in the UWRL, located in proximity to the El-Wadi Drain's inflow, a finding consistent with previous research **(Abdel-Satar & Goher, 2009; Shama *et al.*, 2011; Goher *et al.*, 2019)**. Furthermore, nutrient salts also displayed a significant temporal variation ($P < 0.01$), with a noticeable increase in concentration during the warmer seasons. This seasonal elevation may be attributed to enhanced microbial decomposition rates and increased agricultural runoff carrying fertilizers **(Paerl, 2006)**.

Based on the classification by **Mueller and Helsel (1996)**, the Wadi El-Rayan lakes are categorized as a eutrophic system. Their criteria define oligotrophic lakes as having chlorophyll-a (Chl-a) concentrations below 0.010mg/ L, mesotrophic lakes with concentrations between 0.010 and 0.020mg/ L, and eutrophic lakes with concentrations exceeding 0.020mg/ L.

The seasonal variations of Chl-a concentrations in the lakes are illustrated in Fig. (7). The Chl-a values ranged from 39.16 to 53.16µg/ L in the UWRL and from 9.02 to 27.53µg/ L in the LWRL. Statistical analysis revealed a highly significant spatial and temporal difference ($P < 0.001$) in Chl-a values between the two lakes. In comparison, Chl-a concentrations in the El-Wadi drainage water varied between 13.74 and 31.08µg/ L. The highest Chl-a concentration (53.16µg/ L) was observed at station 2 in the UWRL during winter, while the lowest value (9.02µg/ L) was observed at station 10.

Consistent with **Konsowa**'s **(2007)** findings, total phytoplankton densities were considerably higher in the UWRL compared to the LWRL. This difference is likely attributed to the elevated nutrient concentrations introduced via the El-Wadi Drain. The decline in phytoplankton biomass in the LWRL may be due to the uptake of essential nutrients (nitrogen and phosphorus) by both phytoplankton and the dense macrophyte vegetation present in the connecting canal. **Konsowa (2007)** also reported significantly higher total Chl-a concentrations in the UWRL (2.1-39.9µg/ L) compared to the LWRL (1.2-14.5µg/ L).

Water quality indices (WQIs)

The water quality of the Wadi El-Rayan lakes was evaluated using the Canadian Water Quality Index (CWQI) module, a methodology standardized by the Canadian Council of Ministers of the Environment. This index categorizes water quality into five ranks, ranging from excellent to poor, as shown in Fig. (8). The calculated Water Quality Index (WQI) values for the Wadi El-Rayan lakes indicated varying conditions depending on the intended use and location. In the Upper Wadi El-Rayan Lake (UWRL), the WQI ranged from 63 to 70 for irrigation purposes and from 53 to 64 for aquatic life support across different sampling stations. For irrigation utilization, the water at most stations in the UWRL was classified as "marginal," with the exception of station 1, which fell into the "fair" category. Conversely, for aquatic life support, the

UWRL was consistently classified as "marginal" across all stations. In the Lower Wadi El-Rayan Lake (LWRL), the WQI for aquatic life ranged from 64 to 74 (Fig. 8), classifying the water as "fair" at all stations except station 6, which was categorized as "marginal" for aquatic life. Considering the entire study area, the UWRL exhibited a CWQI of 60.4, classifying it as "marginal" for aquatic life, and a CWQI of 64.96, categorizing it as "fair" for irrigation. The LWRL, due to its progressively increasing salinity (with an average of 31.68‰), is primarily utilized for aquatic life and it is not appropriate for irrigation. Overall, the water in the LWRL was classified as "fair" for aquatic life support, with a CWQI value of 71.

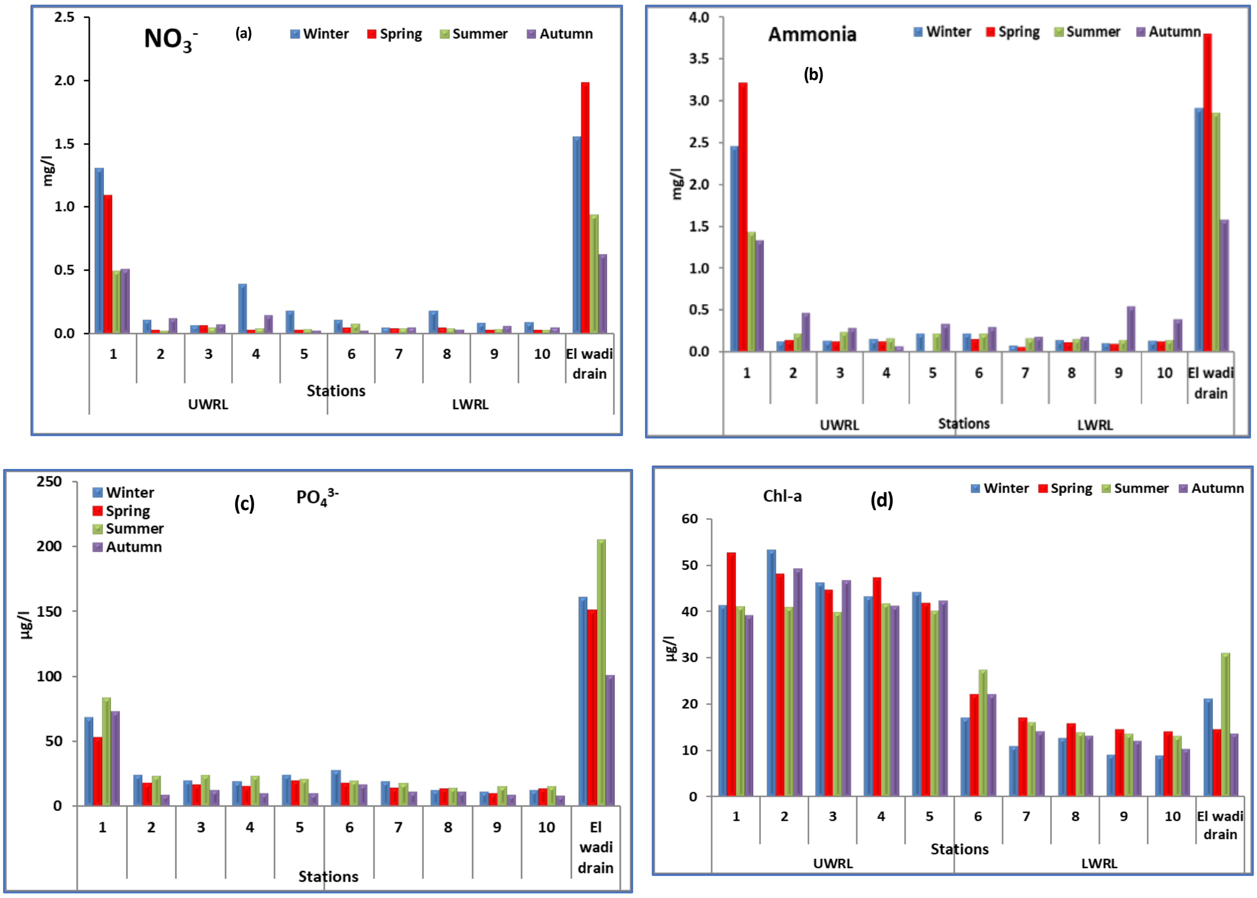

Fig. 7. Seasonal variation of **(a)** NH_4^+ mg/L, **(b)** NO_3^- mg/L, **(c)** PO_4^{3-} µg/l, and **(d)** Chl-a µg/l in Wadi El Rayan lakes during 2021

The Oregon Water Quality Index (OWQI) was employed to assess the trends in water quality within the Wadi El-Rayan lakes. The OWQI provides a single numerical value representing overall water quality by integrating measurements from several key variables. In this study, the parameters used for OWQI calculation included temperature, pH, DO, BOD, TP, NH_4, and NO_3. The calculated OWQI values for the Wadi El-Rayan lakes, as presented in Table (2), fluctuated throughout the year, ranging from 28.16 to 49.10 in the UWRL and from 39.26 to 52.93 in the LWRL. The mean OWQI values across all studied stations were 42.60 for the UWRL and 43.57 for the entire LWRL. These OWQI values indicate that the water quality in both lakes is classified as "Very poor" across all stations, suggesting its unsuitability for fishing activities. The highest annual average OWQI value (52.93) was observed at station 6 in the LWRL during summer, while the lowest value (28.16) was recorded at station 1 in the UWRL during winter.

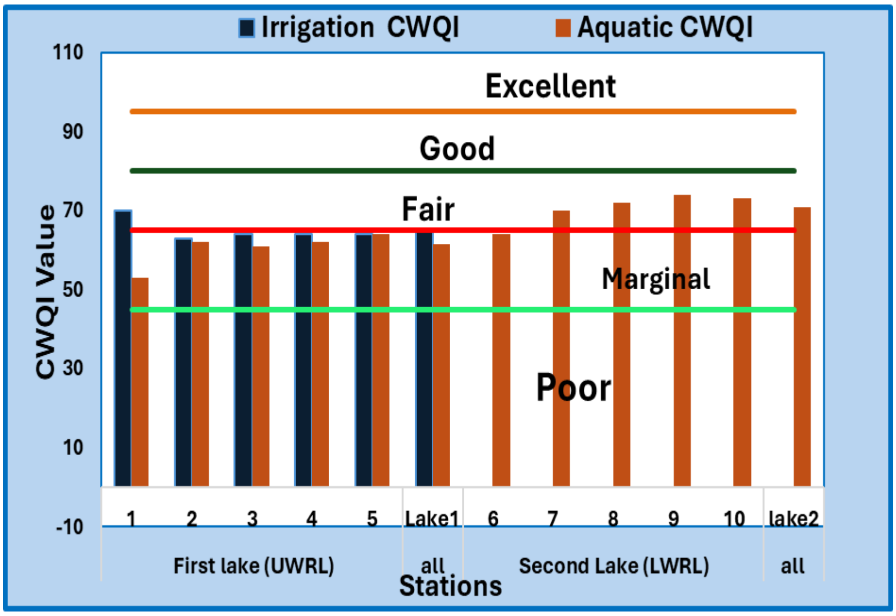

Fig. 8. CWQI of Wadi El-Rayan lakes water for irrigation and aquatic life utilizations

Table 2. Values and categorizations Oregon Water Quality Index (OWQI) in Wadi El Rayan lakes

Station	Winter		Spring		Summer		Autumn	
	Value	Rank	Value	Rank	Value	Rank	Value	Rank
1	28.16	Very poor	29.61	Very poor	37.23	Very poor	35.94	Very poor
2	41.22	Very poor	39.68	Very poor	49.098	Very poor	46.18	Very poor
3	43.16	Very poor	45.61	Very poor	47.075	Very poor	47.22	Very poor
4	39.56	Very poor	46.22	Very poor	48.693	Very poor	45.21	Very poor
5	43.22	Very poor	43.29	Very poor	48.393	Very poor	47.16	Very poor
Average	39.06	Very poor	40.88	Very poor	46.098	Very poor	44.342	Very poor
6	41.62	Very poor	39.26	Very poor	52.926	Very poor	50.28	Very poor
7	43.16	Very poor	43.18	Very poor	45.555	Very poor	46.33	Very poor
8	42.66	Very poor	41.67	Very poor	42.367	Very poor	46.57	Very poor
9	42.28	Very poor	42.11	Very poor	43.402	Very poor	41.26	Very poor
10	41.67	Very poor	41.19	Very poor	40.001	Very poor	43.92	Very poor
Average	42.28	Very poor	41.48	Very poor	44.850	Very poor	45.672	Very poor

Heavy metals

The global proliferation of environmental contamination by trace elements has become a significant concern **(Cui *et al.*, 2011; Hao *et al.*, 2013)**. The term "heavy metals" encompasses essential and non-essential metals and metalloids. While trace amounts of certain heavy metals, such as cobalt (Co), iron (Fe), copper (Cu), nickel (Ni), and zinc (Zn), are vital micronutrients for aquatic organisms, playing crucial roles in various biochemical processes, they become toxic at elevated concentrations. Conversely, other heavy metals, including cadmium (Cd), mercury (Hg), and lead (Pb), are considered non-essential and are toxic even at relatively low levels **(Talab *et al.*,**

2016). Heavy metals (HMs) represent a critical class of persistent inorganic pollutants in aquatic environments, introduced through diverse anthropogenic activities such as wastewater discharge, industrial and agricultural runoff, the use of fertilizers and pesticides, combustion processes, and mining effluents **(Ahamad *et al.*, 2020; Goher & Khedr, 2024)**. Their non-biodegradable nature and slow rate of removal from water contribute to their long-term ecological impact, posing a serious threat to associated organisms particularly fish **(Taslima *et al.*, 2022; Jamil Emon *et al.*, 2023)**. While some trace metals are essential micronutrients at low concentrations, they can become toxic to aquatic life at elevated levels **(Orosun *et al.*, 2016; Ilyas *et al.*, 2023)**. HMs toxicity in fish can disrupt various physiological processes, impede individual growth and development, impair reproduction, and increase mortality rates **(Amundsen *et al.*, 1997; Yi, Yang & Zhang, 2011; Nazir *et al.*, 2015)**. Fish can accumulate heavy metals through three primary pathways: ingestion via the digestive system, absorption across the body surface, and uptake through the gills **(Amundsen *et al.*, 1997; Ilyas *et al.*, 2023)**. Once introduced into aquatic systems, HMs dissolve in the water column and readily bioaccumulate in various tissues and organs of aquatic organisms including fish, subsequently entering the food web through the consumption of contaminated fish **(Authman *et al.*, 2015; Ahmed *et al.*, 2022)**.

Given the continuous environmental shifts affecting the Wadi El-Rayan lakes **(Abou El-Geit *et al.*, 2013)**, a notable increase in HMs concentrations has been observed in the UWRL, especially at station 1 in comparation with the LWRL. This rise is primarily because of the input of sewage and agricultural chemicals, originating from pesticides and fertilizers, carried by the El-Wadi Drain. More broadly, the seasonal variations in HMs levels are often associated with changes in the volume of agricultural drainage discharge, the illicit release of untreated domestic wastewater, and the introduction of industrial waste into these aquatic ecosystems **(Authman *et al.*, 2008)**. Conversely, the present study revealed a notable increase in HMs within the LWRL compared to the UWRL. This is attributed to the reduced water inflow coupled with ongoing evaporation processes, leading to the accumulation of significant quantities of salts, including HMs.

Table 3. Annual average of heavy metals (µg/L) in Wadi El-Rayan lakes

Metal / Station	Cu	Cd	Pb	Zn	Ni	Al	Fe	Mn	Cr	Co
1	**5.48**	**0.84**	**21.29**	**35.04**	**5.32**	**122.36**	**298.48**	**37.06**	**9.31**	**15.01**
2	**4.30**	**0.67**	**15.73**	**21.91**	**4.38**	**95.92**	**235.53**	**26.39**	**7.83**	**13.36**
3	**4.28**	**0.59**	**15.73**	**23.90**	**4.34**	**96.21**	**252.15**	**25.31**	**7.48**	**12.86**
4	**4.06**	**0.54**	**14.05**	**32.98**	**4.86**	**91.56**	**211.63**	**22.60**	**8.91**	**13.28**
5	**4.55**	**0.57**	**13.20**	**18.12**	**4.08**	**105.54**	**225.14**	**21.24**	**7.95**	**12.95**
Average	**4.54**	**0.64**	**16.00**	**26.39**	**4.60**	**102.32**	**244.59**	**26.52**	**8.30**	**13.49**
6	**5.74**	**0.83**	**20.56**	**27.47**	**5.01**	**127.63**	**311.03**	**25.91**	**9.74**	**18.51**
7	**4.14**	**0.77**	**15.78**	**20.69**	**3.87**	**111.27**	**272.08**	**17.92**	**8.16**	**15.20**
8	**4.48**	**0.68**	**17.58**	**23.23**	**4.14**	**118.26**	**288.70**	**22.31**	**9.82**	**14.78**
9	**4.44**	**0.71**	**17.79**	**20.41**	**4.29**	**111.07**	**271.59**	**19.74**	**7.64**	**14.78**

10	**4.19**	**0.69**	**18.15**	**21.27**	**4.10**	**115.27**	**281.59**	**19.71**	**8.47**	**14.78**
Average	**4.60**	**0.74**	**17.97**	**22.61**	**4.28**	**116.70**	**285.00**	**21.12**	**8.77**	**15.61**
Wadi Drain	**8.66**	**1.28**	**28.51**	**59.79**	**13.20**	**170.39**	**403.51**	**58.68**	**22.23**	**29.74**

The average concentrations (in µg/L) of the ten investigated HMs in the UWRL and LWRL are presented in Table (3). Specifically, the UWRL exhibited mean levels (µg/L) of 4.54 for Cu, 0.64 for Cd, 16.00 for Pb, 26.39 for Zn, 4.60 for Ni, 102.32 for Al, 244.59 for Fe, 26.52 for Mn, 8.30 for Cr, and 13.49 for Co. In contrast, the LWRL showed higher average concentrations (µg/L): 8.66 for Cu, 1.28 for Cd, 28.51 for Pb, 59.79 for Zn, 13.20 for Ni, 170.39 for Al, 403.51 for Fe, 58.68 for Mn, 22.23 for Cr, and 29.74 for Co. Notably, the El-Wadi drainage water displayed similar average HMs concentrations to the LWRL: 8.66 (Cu), 1.28 (Cd), 28.51 (Pb), 59.79 (Zn), 13.20 (Ni), 170.39 (Al), 403.51 (Fe), 58.68 (Mn), 22.23 (Cr), and 29.74 (Co) µg/L. the results indicate, in general that the levels of most of the investigated HMs are higher in the LWRL compared to the Upper UWRL.

On the other side, our findings indicated elevated HMs concentrations at station 1 of the UWRL, likely attributable to sewage discharge and agricultural runoff (containing pesticides and fertilizers) via the El-Wadi drain. This observation is consistent with **Authman *et al.* (2008)**, who linked seasonal variations in HMs to fluctuations in agricultural drainage, untreated domestic wastewater, and industrial effluents. Furthermore, **Goher *et al.* (2019)** reported increased concentrations of Mn, Cu, Cr, and Pb in lake water during warmer seasons (summer and spring), potentially due to the release of these metals from sediments during the decomposition of organic matter, a process accelerated by high temperatures and fermentation. The HMs concentration affected by higher water evaporation during warmer periods, leading to higher HMs levels **(Tafa & Assefa, 2014)**. Conversely, a general decrease in the concentrations of most studied metals was observed during colder periods (winter and autumn). This reduction could be due to the adsorption of HMs by organic matter, followed by sedimentation and the precipitation of metals from the water column to the sediments under slightly alkaline pH conditions **(Goher, 2002)**. In the Wadi El- Rayan lakes, Fe was the most abundant metal in the water of both lakes, which is potentially linked to agricultural drainage **(Shama *et al.*, 2011)**. Consequently, the two Wadi El-Rayan lakes exhibit varying degrees of metal contamination, with the LWRL generally being more polluted than the UWRL.

Metal pollution indices (MPIs)

Two different metal pollution indices were used to determine the grades of metal pollution in the water of Wadi El-Rayan lakes and its appropriateness for aquatic life.

Pollution index (PI)

Typically, a pollution index (PI) is calculated for each individual metal based on its concentration. Regarding the calculated PI values, the lake's water exhibited varying degrees of contamination by the measured metals concerning its suitability for aquatic life. Mn, Fe, Zn, Cu, Cd, Al, Cr, and Ni levels indicated no significant pollution effects for aquatic life across all sampling stations in both lakes. However, Co consistently showed serious pollution effects, and Pb exhibited slight pollution effects at all studied locations. Additionally, Cu showed a slight pollution effect at station 1, specifically based on aquatic life criteria, as detailed in Tables (9, 10). Regarding irrigation utilization, the PI values for all metals indicated no pollution effects at all stations in the UWRL, as presented in Table (4).

Table 4. Pollution index of the measured metals in Wadi El-Rayan lakes water according to guideline levels of irrigation and aquatic life utilizations

Metal	Al				Cd			
Lake	irrigation	effect	aquatic life	effect	irrigation	effect	aquatic life	effect
UWRL	0.13-0.18	No Effect	0.07-18	No Effect	0.039-0.061	No Effect	0.05-0.08	No Effect
LWRL			0.08-0.09	No Effect		No Effect	0.07-0.09	No Effect
UWRL	Co				Cr			
UWRL	0.192-0.220	No Effect	9.59-11.00	Seriously	Cr	0.056-0.081	0.12-0.16	No Effect
LWRL			10.63-12.9	Seriously		No Effect	0.13-0.18	No Effect
UWRL	Cu				Fe			
UWRL	0.14-0.19	No Effect	0.87-1.22	No - Slightly	Fe	0.029-0.081	0.049-0.075	No Effect
LWRL			0.88-1.30	No Effect		No Effect	0.046-0.075	No Effect
UWRL	Mn				Ni			
UWRL	0.087-0.130	No Effect	0.17-0.26	No Effect	0.015-0.019	No Effect	0.37-0.47	No Effect
LWRL			0.13-0.19	No Effect		No Effect	0.35-0.48	No Effect
UWRL	Pb				Zn			
LWRL	0.57- 0.077	No Effect	1.33-1.91	Slightly	0.008-0.012	No Effect	0.16-0.29	No Effect
			1.51-1.90	Slightly			0.17-0.27	No Effect

Heavy metal pollution index (HPI)

The heavy metal pollution index (HPI) serves as a holistic assessment tool or rating model, providing an overall evaluation of water quality based on the combined impact of individual heavy metals **(Hassouna *et al.*, 2019)**. As shown in Table (5), the HPI values for the UWRL ranged from 135.51 to 199.85, while the LWRL exhibited a significantly higher range of 893.67 to 1119.89 for aquatic life. For irrigation purposes in the UWRL, the HPI values ranged from 5.05 to 6.30. The HPI values obtained indicate that the combined effect of the studied metals poses a serious pollution threat to aquatic life within the lakes. Considering the critical HPI threshold of 100, our data suggests that aquatic organisms inhabiting the Wadi El-Rayan lakes are likely exposed to significant contamination risks. This aligns with the findings of **Nadmitov *et al.* (2015)**, who stated that an HPI value exceeding 100 signifies undesirable pollution levels for an aquatic ecosystem.

Both the pollution index (PI) and the heavy metal pollution index (HPI) were utilized to assess metal contamination. The PI pinpointed specific metals (e.g., Cobalt, Lead) causing pollution, while the HPI provided a holistic evaluation of overall risk to aquatic life. These indices are not contradictory; the PI identifies individual culprits, and the HPI assesses cumulative impact. Their combined use offers a more complete understanding for targeted and comprehensive environmental management. This involves detecting pollution caused by the accumulation of heavy metals and determining which specific metals exert the most adverse effects.

Table 5. Heavy metal pollution index of the measured metals in Wadi El-Rayan lakes water for aquatic life and irrigation utilizations

		HPI	Category	HPI	Category
Lake	Stations	Irrigation		Aquatic life	
UWRL	1	6.30	Unpolluted	918.3	Polluted
	2	5.35	Unpolluted	810.6	Polluted
	3	5.12	Unpolluted	781.8	Polluted
	4	5.22	Unpolluted	803.5	Polluted
	5	5.05	Unpolluted	785.9	Polluted
	Average	5.41	Unpolluted	820.0	Polluted
LWRL	6			1119.6	Polluted
	7			915.1	Polluted
	8			894.7	Polluted
	9			894.8	Polluted
	10			893.5	Polluted
	Average L			943.5	Polluted

CONCLUSION

This study aimed to comprehensively assess the water quality status and heavy metal pollution in the Wadi El-Rayan lakes, critical man-made aquatic ecosystems in Egypt sustained by agricultural runoff. Our findings reveal a significant dichotomy between the two lakes: the Upper Wadi El-Rayan Lake (UWRL) exhibited elevated organic contamination, nutrient salts, and chlorophyll-a, while the Lower Wadi El-Rayan Lake (LWRL) showed a drastic fifteen-fold increase in salinity, rendering its water largely unsuitable for irrigation. Water Quality Index assessments highlighted concerning conditions, with the UWRL classified as "marginal" for aquatic life by CWQI, and both lakes indicating critically poor water quality according to OWQI. Furthermore, analysis of metal pollution indices underscored varying degrees of contamination, particularly for aquatic life, with Cobalt (Co) exhibiting serious pollution effects across all sites and the LWRL presenting a higher overall risk due to greater Heavy Metal Pollution Index (HPI) values. The observed degradation, driven by continuous agricultural runoff and high evaporation, signifies a critical environmental threat to these vital resources, especially the increasing salinity in the LWRL, poses a serious risk to the ecological integrity and economic utility of the lakes. Therefore, this study calls for prudent and wise environmental management to preserve these important lakes and prevent their degradation. Future efforts should focus on developing sustainable agricultural drainage management practices, exploring potential sources of specific heavy metal contamination (e.g., cobalt, lead), and monitoring the long-term ecological shifts to prevent the LWRL from succumbing to a fate similar to that of the historically impacted Lake Qarun, ensuring the continued viability of this invaluable aquatic ecosystem.

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