Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-13

DOI: *10.15244/pjoes/209835* ONLINE PUBLICATION DATE: 2025-09-25

Review

Wetlands in Saudi Arabia: Review and Assessment of the Environmental Hazards in Al-Asfar Lake

Khalid G. Biro Turk*

Water and Environmental Study Centre, King Faisal University, Al-Ahsa 31982, Saudi Arabia

Received: 27 June 2025
Accepted: 23 August 2025

Abstract

Wetlands are among the most significant ecosystems on the planet. Therefore, this review paper aims to provide a comprehensive overview of wetlands in Saudi Arabia's arid climate, highlighting the environmental risks that affect the ecosystem of Al-Asfar Lake. The majority of Saudi Arabia is characterised by dry terrain. However, there are several tiny and large natural wetlands and constructed wetlands located along the Red Sea and Arabian Gulf coastlines. Al-Asfar Lake is situated prominently in the eastern region of Saudi Arabia. This article summarises the analytical aspects of the available publications on wetlands in Saudi Arabia, particularly taking Al-Asfar Lake as a case study. The review consequently revealed that water quality and environmental hazards were the main concerns of Al-Asfar Lake's ecosystem and biodiversity. This review also highlights the necessity of conducting thorough investigations of wetlands in Saudi Arabia to describe and identify their locations, coverage area, land-use system, and important flora and fauna. Such investigations can include evaluating the lake's hydrology, water quality, and the conditions of the flora and fauna. Modelling approaches using wetland eco-hydrological models can be employed considering potential future climate scenarios. The outcomes of such investigations may guarantee the wetland's sustainability for a long time.

Keywords: sustainability, water quality, wetlands, biodiversity, environmental hazards, Saudi Arabia

Introduction

Wetlands are among the most significant and fruitful ecosystems on the planet. Despite occupying only 6% of the planet's geographical area, wetlands account for more than 40% of the world's total ecosystem services [1]. Wetland ecosystems have a significant impact on human well-being through various ecosystem services [2-6]. Wetlands provide human populations with food, agricultural production, fisheries, water quality maintenance, and grazing. Wetlands shelter a diverse array of animal species, including fish, amphibians, crustaceans, birds, and mammals. This is especially true during the migration and breeding season of migratory birds [7]. Wetland usage encompasses tourism, farming, teaching, and wood harvesting [8-11]. Wetlands play a significant role in water supply by retaining and releasing surface and groundwater in the watershed [12]. Wetlands play an essential role in the global cycling of carbon, nitrogen, phosphorus, and sulphur, as well as in atmospheric processes [13-18]. They can help control floods in downstream areas, prevent potential flood damage, and reduce the impacts of drought and climate change risks [19-22].

*e-mail: khalidturk76@yahoo.co.uk, kturk@kfu.edu.sa
ORCID iD: 0000-0002-6244-8869

Moreover, wetlands control erosion by holding the soil in the plant's roots [12].

Wetlands refer to the combination of hydrology, soil, and vegetation that form a wide range of landscape units [23]. Therefore, these combinations are sufficient to support the natural life of diverse habitats within the wetland ecosystem over different climate change conditions [24]. The Ramsar definition of wetlands indicated that they encompass a broad range of water bodies, such as riparian zones, floodplains, bottomland hardwood forests, mangroves, coastal marshes (salt, brackish, and freshwater tidal), and inland freshwater and saline wetlands (emergent wetlands, sedge meadows, wet prairies, fens, vascular plants in bogs, and transient or seasonal wetlands, such as vernal pools and mudflat, and constructed wetlands including waste-water treatment ponds and reservoirs [25]. Nevertheless, the variation in climatic zones defines the global expansion of wetland surface areas [26, 27]. Therefore, the nomenclature and descriptions of wetlands vary according to their place, region, language, and heritage [28]. Thus, the term "wetlands" can be described in various ways, including swamps, marshes, deltas, mangroves, mires, fens, and bogs [23]. The diversity in wetland terminology can confuse the international scientific community, but it may help local communities better understand wetland ecosystems [12].

The global loss of wetlands was estimated to be more than 35% between 1970 and 2015 [25]. Consequently, in many parts of the world, including Saudi Arabia, wetlands face severe threats and problems. The environmental threats and impacts on wetlands caused by climate change are frequently exacerbated by anthropogenic activities and extreme weather patterns [29]. Human activities, such as rapid urbanisation, overfishing, over-cultivation, excessive water extraction for domestic use, agriculture, and inappropriate forest management techniques, have led to the unsustainable use of wetland resources. Furthermore, the sustainability of wetlands is impacted by the development of new livestock and human settlements in and around them. Removing and burning aquatic plants, forests, and other vegetation for residential and commercial uses, like firewood and charcoal, negatively impacts wetland resources. However, the necessity of an operational national wetlands plan, bridging sector-wide policies, and the financial constraints placed on research and management institutions may restrict the development and restoration of wetlands. Furthermore, action plans and long-term, comprehensive management plans established for the sustainability of wetlands may be limited by the absence of community awareness and participation in the management of the wetlands.

This review describes the wetlands in Saudi Arabia, highlighting their locations, the primary land-use and land-cover (LULC) types, and the typical flora and fauna. However, the Al-Asfar Lake wetland area received special attention, considering the environmental risks that impact its ecosystem and biodiversity. Therefore, the review paper aims to identify the wetland areas in Saudi Arabia and highlight their challenges. Also, the review aims to assess the water quality and environmental hazards in Al-Asfar Lake.

Wetlands in Saudi Arabia

With coasts spanning the Arabian Gulf to the East and the Red Sea to the West, the Kingdom of Saudi Arabia covers an area of over 2,145,000 km² [30]. The terrain of Saudi Arabia varies from large mountains to enormous sand deserts as well as coastal and inland plains, with an elevation range of 3,000 m above sea level [31]. The climate in Saudi Arabia is arid to hyper-arid, despite the southwestern mountain ranges receiving an average annual rainfall of 300-500 mm [32, 33]. The air temperature and humidity vary greatly. The daily temperatures in summer range from 35ºC to 45ºC, while winters are short, mild, and pleasant [34, 35]. Humidity increased sharply during the summer in coastal areas of the Arabian Gulf and southern Red Sea [36].

Table 1. Types of Wetland Systems Found in Saudi Arabia, Tinely [39] and Al-Obaid et al. [37].

Wetlands Type	Description
Coastal systems	Include coral islands, reefs, mudflats, mangroves, and freshwater marshes.
Dunefield systems	Include relatively small seeps from the aquifer.
Sabkha systems	Include coastal lagoons and inland marshes.
Karst systems	Include the karstic aquifer-fed and crater-lake outlets.
Mountain systems	Include a variety of seeping points and volcanic marshes.
Geothermal systems	Include springs, which are dominant in southern Tihamah.
Wadi systems	Include seasonal streams and perennially running watercourses.
Man-made structural systems	Including dams and reservoirs, irrigation and drainage canals, and outflows from the treated wastewater plants or industrial areas.

Despite Saudi Arabia's extreme aridity, various wetlands provide a habitat for many wildlife species. Studies have classified the wetlands in Saudi Arabia into eight systems (Table 1) [37]. Saudi Arabia's extensive wetland systems provide habitats for a wide range of aquatic and avian species. However, some wetlands, especially those along the coast, are home to various seabirds that migrate and breed there. Additionally, they support the breeding of turtles, dugongs, fish, and coral inhabitants [38].

Fig. 1 shows the locations of the most recognised wetland areas in Saudi Arabia. The recognition criteria include the locations of wetland sites within coastal and inland areas, considering both natural and man-made wetlands based on the Ramsar classification of wetland types [1]. In addition, the other criterion includes the wetland size (area in hectares), main land-use/land-cover (LULC) types, and typical flora and fauna. Table 2 provides detailed descriptions of these wetlands and their ecosystem services. The wetlands data provide details regarding the region, size, primary land use, and most prevalent fauna and flora.

In Saudi Arabia, these vulnerable ecosystems face challenges from human activities and invasive species. Most coastal zones are now suffering from the expansion of commercial and fisheries activities. Nevertheless, coastal reclamation, primarily driven by commercial, residential, and recreational developments, was mainly responsible for the loss of fish nurseries. The Gulf and the Red Sea lost about 40% and 8% of their intertidal area due to urbanisation growth [40]. Also, the growing populations in coastal cities have increased annually by 2.5% [41], resulting in a significant rise in industrial and domestic sewage discharge pollution, estimated at 1.9 BCM/year in 2020, compared to 1.5 BCM/year in 2017 [42]. However, oil pollution events were observed from time to time along the Gulf Coast. Additionally, risks associated with climate change and rising sea levels could threaten Saudi Arabia's wetlands [37].

Experimental

The methodology employed in this review comprises a description of the study area and an evaluation of water quality indicators and environmental hazards (Fig. 2). Based on this assessment, several challenges and opportunities were identified to ensure the sustainability of Al-Asfar Lake.

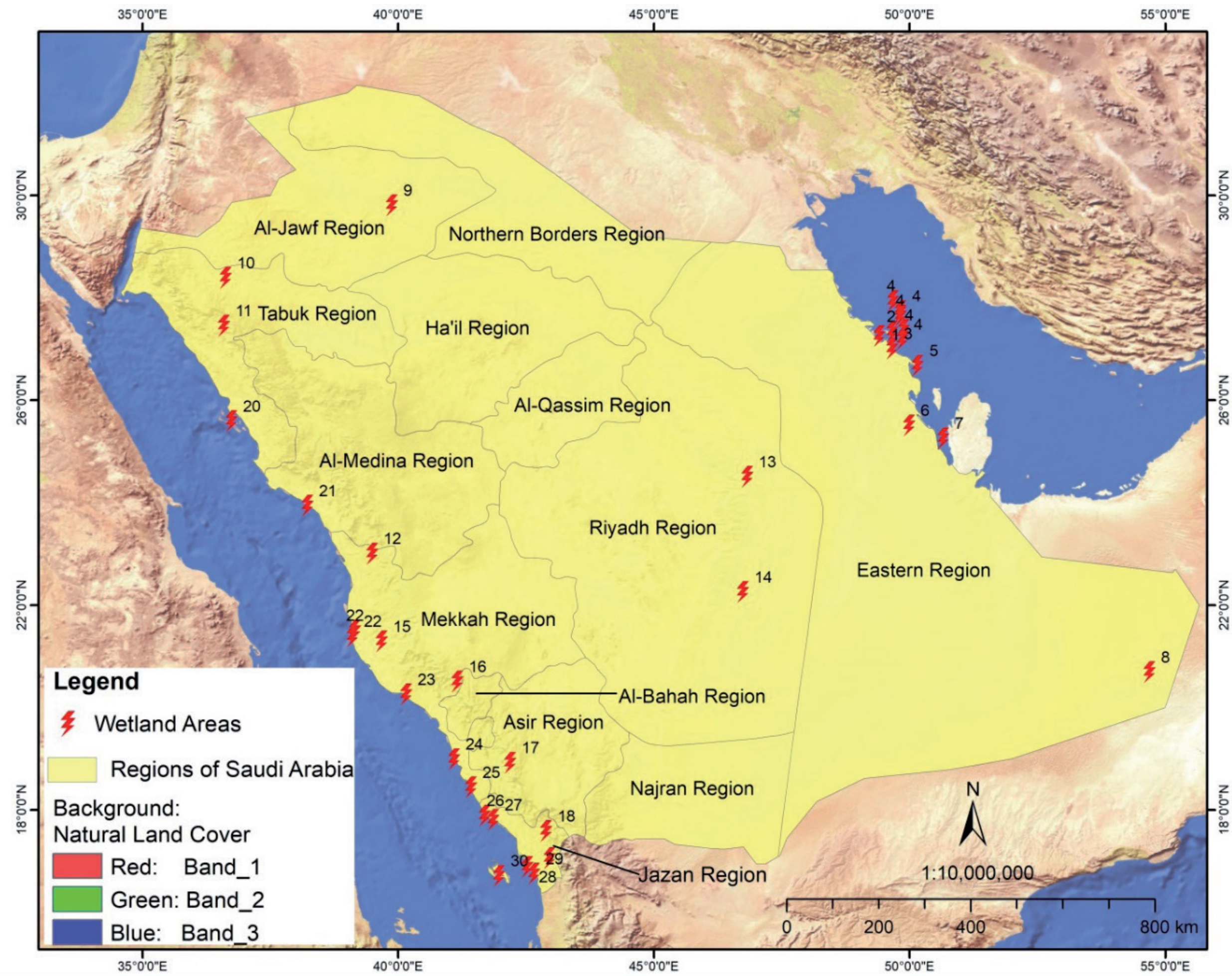

Fig. 1. Locations of the wetland areas in Saudi Arabia. The numbers refer to the names of the wetlands as indicated by "ID" in Table 2.

Table 2. Description of wetland area in Saudi Arabia, Scott [43].

ID	Name	Area (ha)	Land Use	Important Flora and Fauna
1	Dawhat ad-Dafi and Dawhat al-Musallamiya	2000	Livestock, fisheries, and the cement industry.	Mangrove, turtles, and birds.
2	Abu Ali	12500	Oil industry.	Sea grasses and birds.
3	Sabkhat al-Fasl Lagoons	500	Urban lands and a golf course.	Birds.
4	Harqus	2	The four islands form the "Gulf Coral Islands". They dominated with shelter for local fishermen & fringing reefs for recreation.	Turtles and birds.
4	Karan	128		
4	Kurain	8		
4	Jana	33		
4	Juraid	20		
5	Tarut Bay	41000	Industrial and urban areas, palm groves, and farms.	Mangroves, seagrasses, Sea snakes, turtles, and birds.
6	Al-Ahsa Lagoons	7500	Cultivated lands.	Oasis fishes, frogs, turtles, and birds.
7	Gulf of Salwah	62500	Remarkably undeveloped.	Sea grasses and birds.
8	Uruq al-Mutaridah	40	Bedouin settlement.	Birds.
9	Dawmat al-Jandl	2500	Agriculture.	Birds.
10	Tabuk (King Faisal Airbase)	Not defined	Not defined.	*Phragmites*, *Tamarix,* and birds.
11	Jabal Qaraqir	160000	Grazing and irrigated cultivation.	Birds.
12	Wadi Rabigh Springs	35	Grazing and small cultivation.	Acacia trees and birds.
13	Al-Ha'ir	2500	Grazing and irrigated agriculture.	*Tamarix*, *Phragmites,* and birds.
14	Uyun Layla	3000	Intensive cultivation, livestock, and a tourist resort.	Birds.
15	Makkah Wastewater Stream	300	Livestock.	*Salvadora persica* and birds.
16	Wadi Turabah	5000	Cultivation.	High diversity of plants and birds indeed occurs.
17	Shallal ad-Dahna	200	Grazing and cultivation.	Wetland plants, *Primula verticillata,* and birds.
18	Wadi Lajb	250	Not defined.	*Celtis Africana*, *Diospyros mespiliformis* and birds.
19	Malaki Dam	2500	Cultivation and grazing.	*Dobera glabra* trees, Turtle, and birds.
20	Al-Wajh Bank	288000	Seasonal fishing.	Mangrove, *Salicornia* bushes, and birds.
21	Yanbu Royal Commission Zone	700	Oil production.	Mangrove and birds.
22	Jeddah (central), north of Port	900	The two sites are in Jeddah. Urbanisation, livestock grazing, and small-scale fishing are the most common.	A small patch of mangrove and birds.
22	Jeddah South Corniche			
23	Qishran Bay	40000	Fishing, livestock grazing, and falcon trapping.	Large stands of mangrove, turtles, and birds.
24	Umm al-Qamari	14.7	Fishing occasionally occurred.	Different species of plants and birds.
25	Khawr 'Amiq	150	Fishing and camel grazing.	Mangrove is the dominant plant, and there are also birds.
26	Kutambil Island	8	Fishing occasionally occurred.	Birds.
27	Shuqaiq Mangrove	200	Small fishing.	Mangrove is the dominant plant, and there are also birds.

28	Jizan Bay	200	Urban land and fishing.	Birds.
29	Khawr Wahlan	1000	Fishing and heavy grazing of camels and goats.	Freshwater marsh flora and birds.
30	Farasan Islands	70000	Urban and settlement, grazing of camels and goats, palm plantations, sorghum cultivation, and small-scale fishing.	*Rhizophora mucronata* stand, sea grass species, turtles, and birds.

Geographical Location and Significance of Al-Asfar Lake

Al-Asfar Lake is an artificial (man-made) shallow lake located in a desert in the Eastern Region of Saudi Arabia (Fig. 3) [44]. It is inhabited by a diverse array of flora and fauna, including frogs, fish, turtles, birds, and various algal and waterweed species. As a vital local ecosystem, Al-Asfar Lake's ecosystem services benefit people in numerous ways, including water purification, shoreline stabilisation, storm protection, sediment and nutrient retention, timber production, cultural values, and recreation and tourism [45]. Al-Asfar Lake is located northeast of the Al-Ahsa district, which encompasses

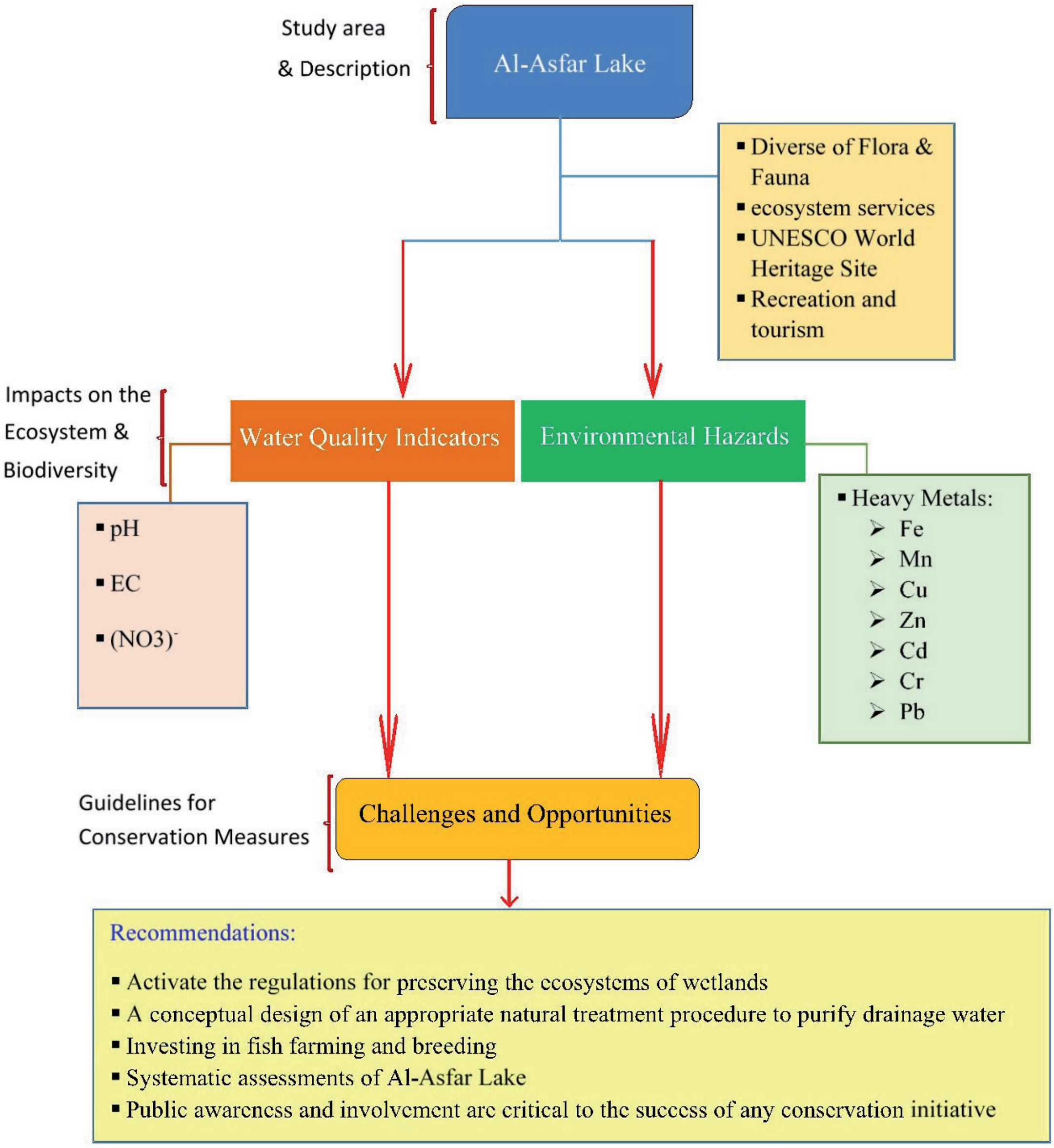

Fig. 2. Flowchart for the methodology applied in this review.

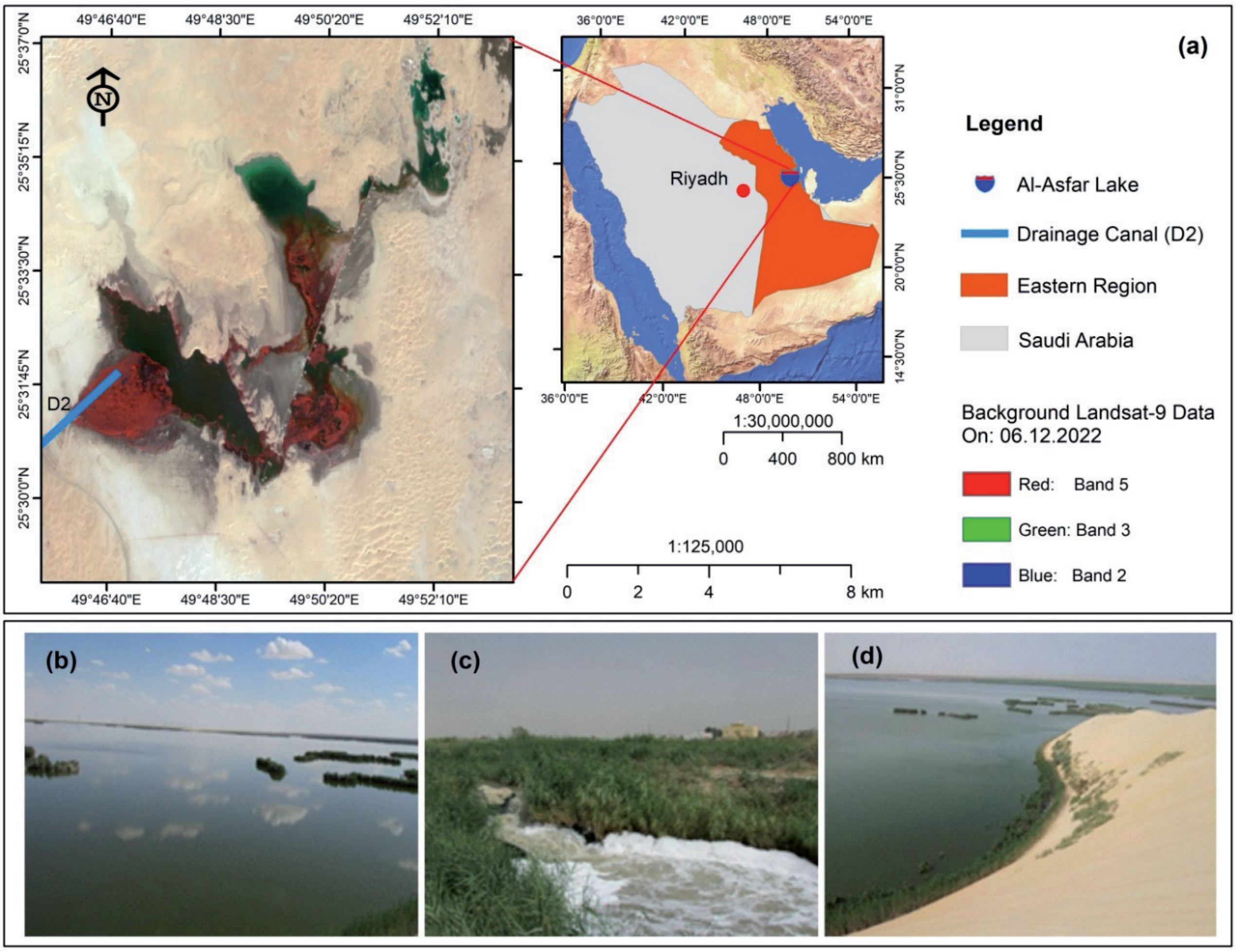

Fig. 3. Location of Al-Asfar Lake. a) The geographical location of Al-Asfar Lake; b) An overview from Al-Asfar Lake; c) The discharge outflow of D2 to Al-Asfar Lake; d) Dunes surrounding Al-Asfar Lake.

extensive agricultural lands known as the Al-Ahsa Oasis, designated by UNESCO as a World Heritage Site. The population in the area is reaching 1.3 million people, while the date palm plantation is the dominant land use system in the oasis. The primary water source for Al-Asfar Lake is the collection of drainage water from the irrigation system installed in the oasis in 1971, which serves around 22,000 farms [46]. The drainage water to Al-Asfar Lake is delivered through the drainage canal D2, discharging about 328 million m^3/year to the lake (Fig. 3c)). Also, the lake received additional treated sewage water, estimated at 12780 m^3/year, supplied from the Al-Hofuf treated wastewater plant [47]. The total area covered by water in Al-Asfar Lake is approximately 20.8 km^2 [48]. Dunes encircle the lake and contain large stretches of vegetation (Fig. 3d)).

The land use system in the Al-Asfar Lake area consists of open surface water, aquatic vegetation, shrubs, grass, Sabkha land, sand, and bare lands (Fig. 4b), Turk et al. [49]). Sabkha land refers to low-relief flats that are formed by the accumulation of evaporated precipitation, often found in coastal deserts or inland settings. These flats are characterised by wavy and crinkly laminae and are influenced by periodic wetting and desiccation of the surface [50].

Assessment of Water Quality Indicators and the Environmental Hazards

The water quality indicators investigated in this review were the pH, electrical conductivity (EC), and nitrate ($NO3^-$). The data source used for the water quality analysis was collected from five studies conducted at Al-Asfar Lake between 2009 and 2022 (Table 3). Using the data in Table 3, statistical analysis was performed with Microsoft Excel 2010 [51].

The environmental hazards of Al-Asfar Lake were assessed using the concentrations of heavy metals in the lake water. The pollution levels of iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), cadmium (Cd), chromium (Cr), and lead (Pb) were obtained from two studies conducted by Hussein et al. [52] and Altammar et al. [53]. Additionally, this review highlighted the contamination of plants and fish by heavy metals. However, the Geostatistical Analyst in ArcGIS

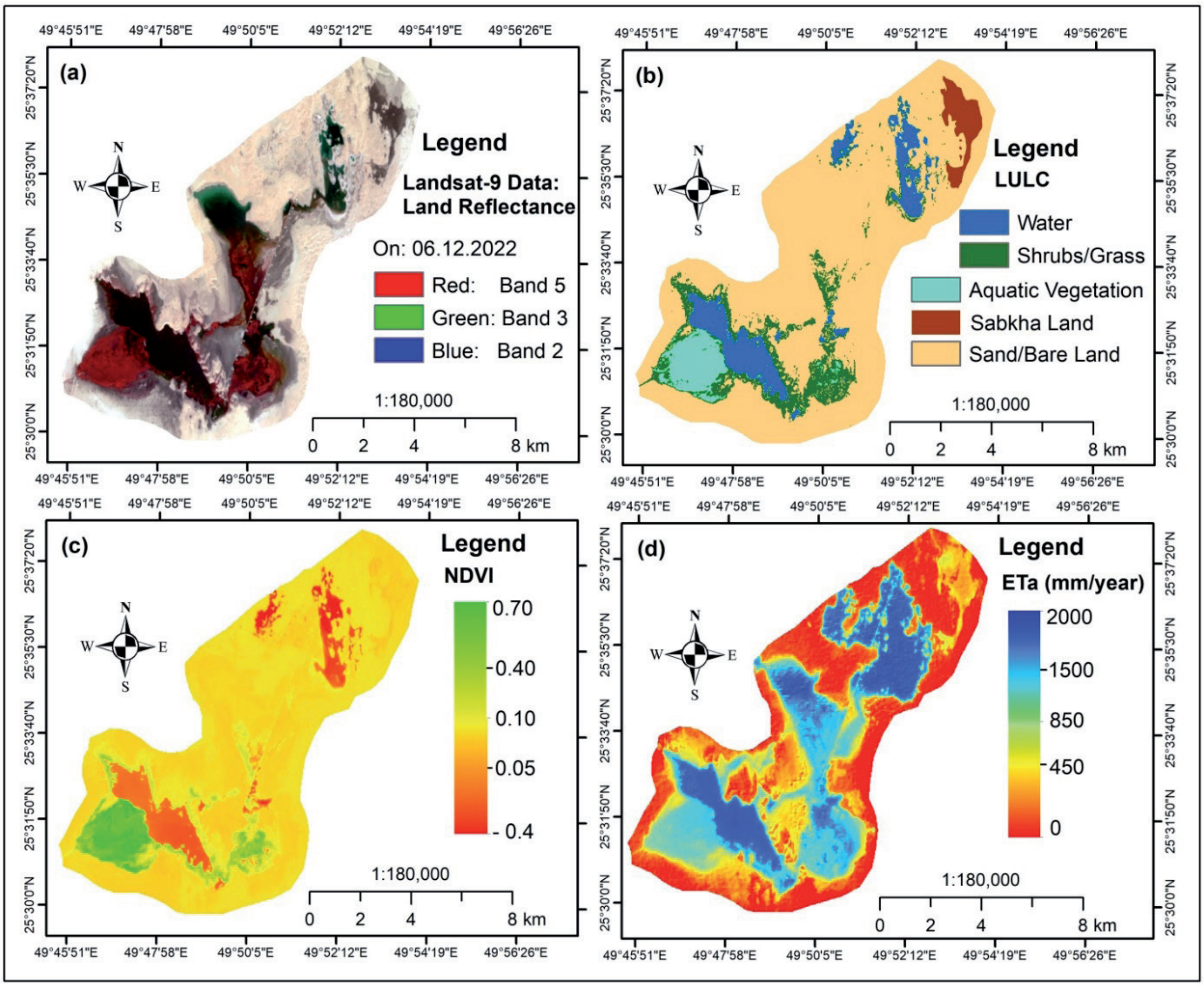

Fig. 4. Biophysical characteristics from the Al-Asfar Lake wetland area. a) The spectral reflectance from Landsat-9 data; b) Land-use and land-cover (LULC); c) The Normalised Difference Vegetation Index (NDVI); d) The actual evapotranspiration (ETa).

Table 3. Water Quality Indicators of Al-Asfar Lake.

Year	pH	EC (dS/m)	$NO3^-$ (ppm)	Reference
2009	7.0 – 8.3	9.5 – 102.3	0.9 – 41.0	Al-Dakheel et al. (2009)
2011	7.0 – 9.0	8.1 – 12.1	1.0 – 2.3	Fahmy and Fathi (2011)
2011	7.0 – 8.3	9.5 – 102.3	0.9 – 41.0	El Mahmoudi et al. (2011)
2016	7.3 – 8.7	8.3 – 11.3	0.8 – 2.3	Hussein et al. (2016)
2022	7.6	11.6	No Data	Al Mousa et al. (2022)

10.2 software was used to perform data interpolation for the heavy metals [54].

The evapotranspiration from the Al-Asfar Lake area affects the lake's water levels; hence, the varieties of vegetation, plants, and animal species can also be impacted. Therefore, the annual evapotranspiration rates of the lake area were assessed for the different land-use/land-cover (LULC) classes using the remote sensing data and biophysical models [49].

Results and Discussion

The Impacts of Al-Asfar Lake on the Ecosystem and Biodiversity

Water Quality of Al-Asfar Lake

The water quality assessment of Al-Asfar Lake is crucial for its aquatic organisms and will be necessary for the potential use of this water for the local ecosystem restoration. Table 3 summarises some water quality indicators for Al-Asfar Lake. The mean water pH values ranged from 7.6 to 8.0, indicating that Al-Asfar Lake water tends to be neutral to alkaline (Fig. 5). The general tendency for the pH to be alkaline may be due to an increase in planktonic algae activity [55]. Nevertheless, the significant volume of irrigation water removed from Al-Ahsa Oasis and the breakdown of organic matter are responsible for the variations in pH levels observed in Al-Asfar Lake [56]. However, field observations revealed that the pH values were high at the discharge point of the D2 Lake, indicating that agricultural fields are the primary source of the lake's water pH [52]. The aquatic environment's biological processes and chemical reactions are greatly influenced by pH [57]. On the other hand, the bacterial activity in the water can be impacted by pH levels. Toxic substances can be reduced to less harmful forms by a tiny quantity of acidic pH [58, 59].

Investigations revealed that Al-Asfar Lake's average electrical conductivity (EC) varied significantly from 9.8 to 40.5 dS/m (Fig. 6). The main body of the lake's water was associated with low EC values. However, the exceptionally high values of the EC were closest to the inland Sabkha (Fig. 4b)), indicating a substantial increase in water salinity in this lake area [42].

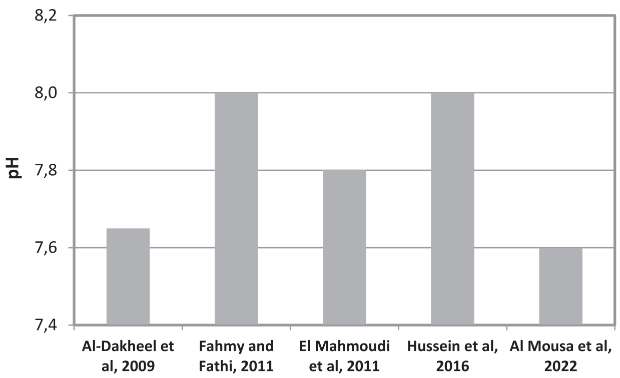

Fig. 5. The mean pH values in Al-Asfar Lake were obtained from various studies.

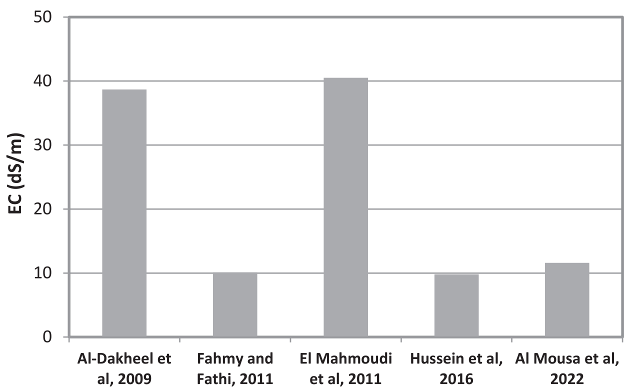

Fig. 6. The mean values of the EC in Al-Asfar Lake from different studies.

Therefore, understanding the EC of the lake water is crucial as it provides a deeper insight into the water quality of Al Asfar Lake.

On average, the nitrate NO_3^- levels in Al Asfar Lake were between 1.55 and 9.10 ppm (Fig. 7). Fahmy and Fathi [55] noted that high values of NO_3^- were observed in the winter, while low values were observed in the summer. These elevated NO_3^- values highlight the impact of drainage water from the fields on the lake water [60]. Additionally, ammonia oxidation in lake water may contribute to increased NO_3^- levels [56, 61].

Al Asfar Lake receives large volumes of dissolved materials and chemical components from the D2 outflow, including phosphorus and nitrogen. Nevertheless, most of these dissolved characteristics and chemical constituents likely originate from wastewater and leachate in the irrigation water, which can leach into the lake [62].

Environmental Hazards of Al-Asfar Lake

The pollution in Al-Asfar Lake has reached a critical level, posing a severe threat to its aquatic life and the entire ecosystem. The presence of heavy metals, known for their ability to accumulate in living organisms, further exacerbates the situation [63]. Harmful effects occur when these organisms' metabolic, storage, detoxification, clearance, and excretion rates fail to keep up with the heavy metal intake [64].

Hussein et al. [52] discovered that the heavy metal contents in the surface water of Al Asfar Lake for iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), cadmium (Cd), chromium (Cr), and lead (Pb), varied from 0.027 to 0.159 ppm, 0.007 to 0.142 ppm, 0.005 to 0.017 ppm, 0.005 to 0.066 ppm, 0.001 to 0.033 ppm, and zero ppm, respectively. They also noted that the contents of Fe, Mn, and Zn were below the internationally permitted limits [65]. Fig. 8 illustrates the spatial distribution of these heavy metals and their associated environmental hazards in the main area of Al-Asfar Lake. Nevertheless, in a recent study, the concentrations of the heavy metals increased significantly, reaching values of 0.887, 1.678,

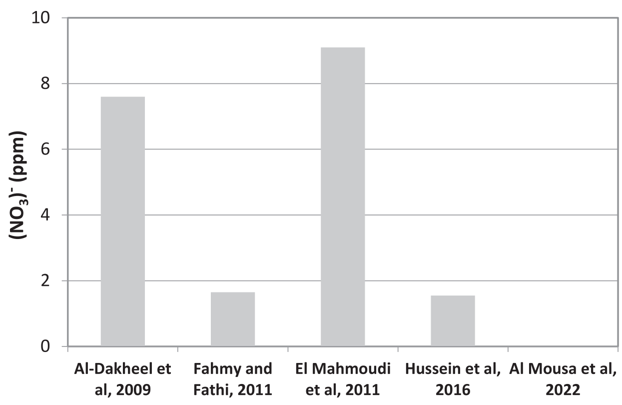

Fig. 7. The mean values of the NO_3^- Al-Asfar Lake from different studies.

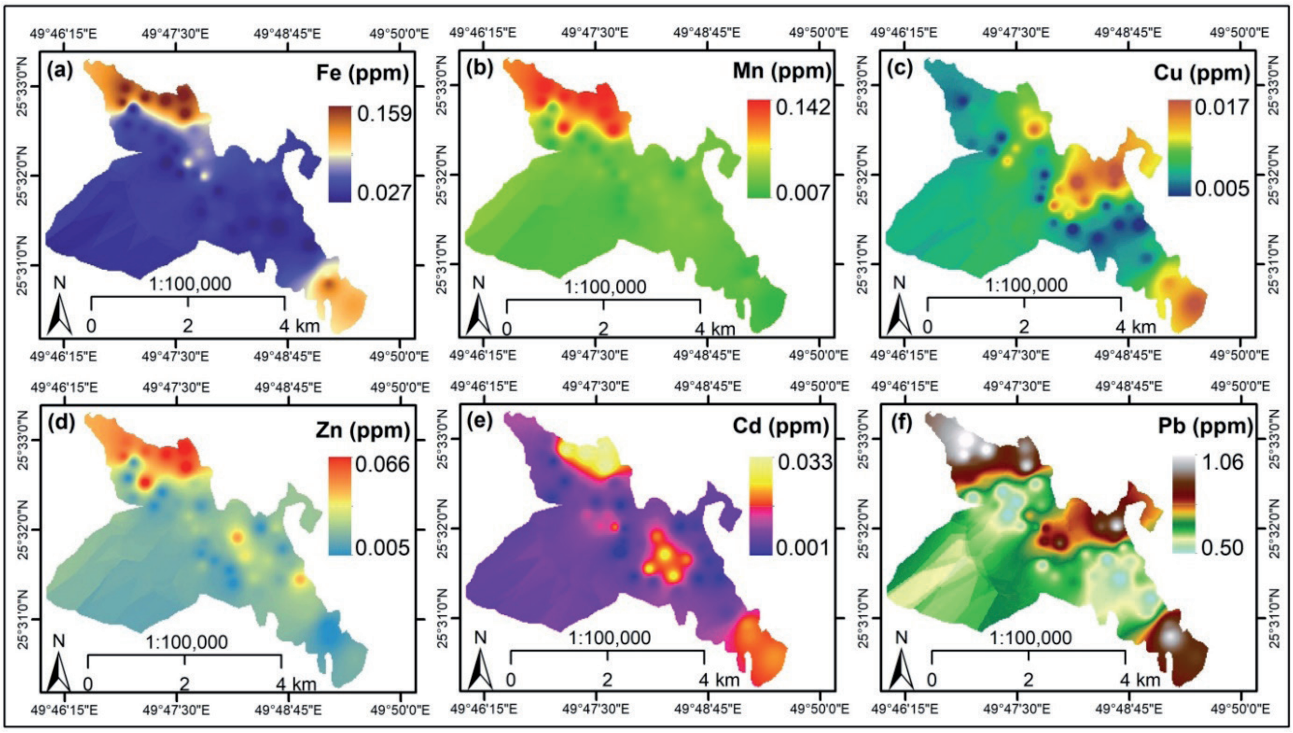

Fig. 8. The spatial distribution of heavy metals in Al-Asfar Lake. a) Iron "Fe" levels; b) Manganese "Mn" levels; c) Copper "Cu" levels; d) Zinc "Zn" levels; e) Cadmium "Cd" levels; f) Lead "Pb" levels.

0.769, 1.059, 1.037, 0.588, and 1.060 ppm for Fe, Mn, Cu, Zn, Cd, Cr, and Pb, respectively [48]. Similarly, Abdel-Moneim [66] noted that heavy metals, including Ni, Fe, Zn, Co, Ba, Pb, and Cd, were predominant in the lake water and exceeded the international permissible limits. Nevertheless, Isinkaralar et al. [67] showed that high pollution levels were detected in the city centre, where commercial land use predominates. At the same time, low values were observed in the region, which is rich in water surfaces, bicycle paths, landscape design, and features that slow traffic.

The drainage water flowing to Al Asfar Lake carried significant amounts of chemical fertilisers in addition to the urban wastewater, resulting in high Pb, Cu, Cr, and Cd contents. Furthermore, two fish species, the *Tilapia Zilli* and *Aphanius dispar*, found in Al-Asfar Lake, were assessed for heavy metal concentrations. *Tilapia Zilli* exhibited the highest concentrations of heavy metals in the kidney, except for Cu and Cd, which were found highest in the liver. In the case of heavy metal accumulation in *Aphanius dispar*, the highest accumulation was observed in the kidney, while the muscles accumulated the lowest amount [55]. As integral parts of the marine food chains, fish can amass significant quantities of heavy metals in water [68]. Therefore, due to their high nutritional requirements, fish can serve as a marker of heavy metal pollution in the aquatic environment [69]. Also, Ibrahim et al. [70] indicated that the accumulated heavy metals for the *S. litoralis* plant leaves in Al-Asfar Lake were 205.5 ppm for Cr, 107.9 ppm for Cu, 74.99 for Zn and 0.9 ppm for Cd, which all are above the permissible levels of the Food and Agriculture Organization (FAO) and the World Health Organization (WHO) [71].

According to the phytoplankton analysis, the lake's water is eutrophic and dominated by Chlorophyceae. However, the microplastic content in lake water varied from 0.7 to 7.8 items L^{-1} [4].

Al-Asfar Lake water was contaminated by pesticides, personal care products, and pharmaceuticals. The detected pesticides in Al-Asfar Lake include Acetamiprid, Bifenthrin, Carbendazim, Carbofuran-3-hydroxy, Chlorfenvinphos, Chlorpyrifos, Cyhalothrin, Diazinon, Fluvalinate, Imazalil, Imidacloprid, Isoproturon, Tebuconazole, Terbuthylazine-2-hydroxy, Thiabendazole, and Thiametoxan. However, the greatest concentration of diazinon ever measured was 1016 ng L^{-1}, which exceeded the maximum permitted threshold of 100 ng L^{-1} for the individual pesticide in water [72]. The most frequently occurring pesticides were carbendazim, diazinon, and Imidacloprid [47]. Due to their high water solubility, these three pesticides were relevant in water and were movable by drainage and runoff. Also, 24 different types of PPCPs were detected in Al-Asfar Lake, indicating a significant impact of anthropogenic pollution [47].

The annual Actual Evapotranspiration (ETa) from the Al-Asfar Lake open water was about 2000 mm $year^{1}$, while it was 1600 mm $year^{1}$ from the aquatic vegetation. However, shrubs and grasses showed an annual ETa of around 800 mm $year^{1}$, while bare land showed only 200 mm $year^{1}$, which is considered less than the long-term average rainfall (Fig. 4d), Turk et al. [49]). ET is crucial for determining the water balance in arid regions and for affecting their future climate and land-use change [73, 74]. Accordingly, the annual fluctuation of ET over Al-Asfar Lake can directly impact the lake's ecosystem and hinder restoration efforts and water management. However, the Normalised Difference Vegetation Index (NDVI, Fig. 4c)) was inconsistent with the ETa values from the different LULC types and their spectral reflectance from the Landsat-9 image (Fig. 4a)).

Moreover, the vegetation of Al-Asfar Lake showed a significant increase from 4.2 km² in 1990 to 14.9 km² in 2020, with most of the vegetation area dominated by reed beds of *Phragmites australis*, *Typha*, and *Juncus acutus* species [75]. However, Youssef et al. [76] identified approximately 39 plant species belonging to 20 families in the Al-Asfar Lake wetland area, with more than 61% of these species being perennial shrubs. The eutrophication of the lake water due to the inflow of wastewater, fertilisers, and agricultural nutrients resulted in an increasing number of reed beds. Accordingly, a range of geomorphological hazards, including annual changes in shorelines, sand creep, salinity increases, changes in the lake's physical and chemical characteristics, and the lake's susceptibility to salt weathering, can have a substantial impact on Al-Asfar Lake's environmental system, and the vulnerability of the lake to salt weathering [53].

Conclusions

This review emphasises the need for thorough investigations of Al-Asfar Lake to evaluate various factors quantitatively. Such investigations can include assessing the lake's hydrology, water balance, sediment load, water quality, and the conditions of the flora and fauna surrounding the lake. Modelling approaches using wetland eco-hydrological numerical models should be employed, particularly in consideration of potential future climate scenarios. The outcomes of such investigations may ensure the lake's sustainability for a long time and the ability of its natural ecology to self-regulate and maintain its balance. Also, the pollution load entering the lake can be significantly reduced. Therefore, to assess the possibility of restoring the environmental conditions in Al-Asfar Lake, a comprehensive concept of wetland ecosystem health can be implemented as an action plan. However, to manage the Al-Asfar Lake ecosystem sustainably, stakeholders must adopt measures that conserve biodiversity, protect water resources, mitigate the effects of climate change, and facilitate community engagement to adopt best practices that enhance their economic benefits.

Recommendations

Restoring the Al-Asfar Lake wetland area can help develop ecosystem services and improve the sustainable management of the lake resources. Therefore, specific guidelines and standards can be established to conserve and sustain the lake's ecosystem for future use, as Al-Asfar Lake's water quality is degrading, and there are signs of pollution. Accordingly, several challenges and opportunities for Al-Asfar Lake can be summarised in the following recommendations:

– The related authorities and stakeholders should work to activate the regulations and policies related to preserving the ecosystems of wetlands to limit their excessive exploitation and the deterioration of their environment.
– To enhance Al-Asfar Lake's water quality, a conceptual design of an appropriate natural treatment procedure to purify drainage water before its entry can be established. Such a process can protect aquatic organisms and the lake's ecosystem.
– From an economic perspective, Al-Asfar Lake holds significant potential. By investing in fish farming and breeding, the lake can generate revenue and contribute to improving water quality for agricultural purposes. This dual benefit proposes a win-win situation for the environment and the local economy.
– Systematic assessments of Al-Asfar Lake that aim to discover the status of the wetland ecosystem, identify health considerations, and identify the blocks where the health condition is declining over a specific period are essential for wetland conservation.
– Research projects aiming to employ wetland eco-hydrological numerical models should be initiated. These models will provide numerous tools to assess the complex relationship and processes between wetland ecology and hydrology, thereby explaining the intricate wetland environment. Integrating hydrology, water quality, and sediment transport models can enhance the aquatic environment [77].
– Plants are the foundation of any wetland ecosystem. Three types of plants are frequently used in wetlands: submerged, floating, and emergent. Direct seeding or planting of macrophytes and hydrophytes is a proactive strategy for restoring degrading wetland ecosystems [78, 79].
– Public awareness and involvement are critical to the success of any conservation initiative. Increasing public awareness about the wetland's significance for human welfare is not just a suggestion but a crucial step in Al-Asfar Lake protection and conservation initiatives. By involving the public in the solution, we can ensure the long-term sustainability of the lake's ecosystem.
– As a cultural and tourism site, Al-Asfar Lake might be a unique place to establish recreational tourism, sports resorts, research facilities, and educational units.
– Sustainability is a crucial measure for Al-Asfar Lake; therefore, future research should focus on the lake's microbiological, algal, floral, and animal biodiversity, as well as its interactions with climate change.

Conflict of Interest

The authors declare no conflict of interest.

References

1. GARDNER R.C. Ramsar Convention: Transboundary Ramsar Sites. In The Wetland Book. Springer Netherlands, pp. 1, **2016**.
2. MOOR H., HYLANDER K., NORBERG J. Predicting climate change effects on wetland ecosystem services using species distribution modeling and plant functional traits. Ambio. **44** (Suppl 1), S113, **2015**.
3. McINNES R.J., EVERARD M. Rapid Assessment of Wetland Ecosystem Services (RAWES): An example from Colombo, Sri Lanka. Ecosystem Services. **25**, 89, **2017**.
4. de VICENTE I. Biogeochemistry of Mediterranean Wetlands: A Review about the Effects of Water-Level Fluctuations on Phosphorus Cycling and Greenhouse Gas Emissions. Water. **13** (11), 1510, **2021**.
5. KHATUN R., TALUKDAR S., PAL S., KUNDU S. Measuring dam induced alteration in water richness and eco-hydrological deficit in flood plain wetland. Journal of Environmental Management. **285**, 112157, **2021**.
6. DHAWI F. Harnessing the Power of Plants in Hydroponics for Wastewater Treatment and Bioremediation. In Springer Water: Vol. Part F2309, **2024**.
7. ATIIM J.A., ALHASSAN E.H., ABOBI S.M. Evaluating the contribution of wetlands to food security and livelihoods improvement in the Savelugu Municipality, Ghana. Wetlands Ecology and Management. **30** (3), 561, **2022**.
8. TURNER M.G., GARDNER R.H. Quantitative methods in landscape ecology the analysis and interpretation of landscape heterogeneity. Springer New York, pp. 536, **1991**.
9. MITSCH W.J. GOSSELINK J.G. The value of wetlands: importance of scale and landscape setting. Ecological Economics. **35** (1), 25, **2000**.
10. BENDOR T., BROZOVIĆ N., PALLATHUCHERIL V.G. The Social Impacts of Wetland Mitigation Policies in the United States. Journal of Planning Literature. **22** (4), 341, **2008**.
11. KUMSA A., NEMOMISSA P.S., LEGAS A., GURMESSA D. Remote Sensing and GIS Application for Land use/ Land cover Change Analysis: Case Study of Jarmet Wet-Land and its Surrounding Environments in Western Ethiopia. Preprints. 2019070275, **2019**.
12. MITSCH W.J., BERNAL B., HERNANDEZ M.E. Ecosystem services of wetlands. International Journal of Biodiversity Science, Ecosystem Services & Management. **11** (1), 1, **2015**.
13. HOWELL C.J., CROHN D.M., OMARY M. Simulating nutrient cycling and removal through treatment wetlands in arid/semiarid environments. Ecological Engineering. **25** (1), **2005**.
14. KOKFELT U., REUSS N., STRUYF E., SONESSON M., RUNDGREN M., SKOG G., ROSÉN P., HAMMARLUND D. Wetland development, permafrost history and nutrient cycling inferred from late Holocene peat and lake sediment records in subarctic Sweden. Journal of Paleolimnology. **44** (1), **2010**.
15. REDDY K.R., NEWMAN S., OSBORNE T.Z., WHITE J.R., FITZ H.C. Phosphorous cycling in the greater everglades ecosystem: Legacy phosphorous implications for management and restoration. Critical Reviews in Environmental Science and Technology. **41** (SUPPL. 1), 149, **2011**.
16. DEKLE J., STROSNIDER W.H.J., WHITE S.A. Phosphorus uptake and release patterns in overwintering constructed floating wetlands. Water Science and Technology. **89** (3), **2024**.
17. FANG J., LÜ T., LIU J., HE S., YANG X., DOU H., ZHANG H. Responses of nitrogen cycling and related microorganisms to brackish wetlands formed by evapotranspiration. Pedosphere. **34** (1), **2024**.
18. SUN C., QIU M., LU X., WANG Y. Core microbiota play important roles in maintaining soil multi-nutrient cycling in lakeshore wetland of plateau lake Caohai. Land Degradation and Development. **35** (4), **2024**.
19. MCCARTNEY M.P., DE LA HERA A. Hydrological assessment for wetland conservation at Wicken Fen. Wetlands Ecology and Management. **12** (3), 189, **2004**.
20. AYDIN H., YENIGUN K., ISINKARALAR O., ISINKARALAR K. Hydrological low flow and overlapped trend analysis for drought assessment in Western Black Sea Basin. Natural Hazards. **121**, 1833, **2025**.
21. ISINKARALAR O., ISINKARALAR K., YILMAZ D. Climate-related spatial reduction risk of agricultural lands on the Mediterranean coast in Türkiye and scenario-based modelling of urban growth. Environment, Development and Sustainability. **25**, 13199, **2023a**.
22. GUVEN D.S., YENIGUN K., ISINKARALAR O., ISINKARALAR K. Modeling flood hazard impacts using GIS-based HEC-RAS technique towards climate risk in Şanlıurfa, Türkiye. Natural Hazards. **121**, 3657, **2025**.
23. AMLER E., SCHMIDT M., MENZ G. Definitions and Mapping of East African Wetlands: A Review. Remote Sensing. **7** (5), 5256, **2015**.
24. ISINKARALAR O., ISINKARALAR K. Projection of bioclimatic patterns via CMIP6 in the Southeast Region of Türkiye: A guidance for adaptation strategies for climate policy. Environmental Monitoring and Assessment. **195**, 1448, **2023b**.
25. GARDNER R.C., FINLAYSON C.M. Ramsar Convention on Wetlands. In Global Wetland Outlook: State of the World's Wetlands and their Services to People. **2018**.
26. DUGAN P. Wetlands in Danger: World Conservation Atlas. Applied Geography. **14** (3), **1993**.
27. LEHNER B., DÖLL P. Development and validation of a global database of lakes, reservoirs and wetlands. Journal of Hydrology. **296** (1-4), 1, **2004**.
28. MITSCH W.J., MITSCH R.H., TURNER R.E. Wetlands of the Old and New Worlds: ecology and management. Global Wetlands, Old World and New, Elsevier Science B.V., Amsterdam, **1994**.
29. GOPAL B. Future of wetlands in tropical and subtropical Asia, especially in the face of climate change. Aquatic Sciences. **75** (1), 39, **2012**.
30. ALNASER Z.H.A., CHOWDHURY S.R., RAZZAK S.A. Constructed Wetlands for Wastewater Treatment in Saudi Arabia: Opportunities and Sustainability. Arabian Journal for Science and Engineering. **48** (7), 8801, **2022**.
31. AL-AHMADI K., AL-AHMADI S. Spatiotemporal variations in rainfall-topographic relationships in southwestern Saudi Arabia. Arabian Journal of Geosciences. **7** (8), 3309, **2013**.
32. ALMAZROUI M., NAZRUL ISLAM M., ATHAR H., JONES P.D., RAHMAN M.A. Recent climate change in the Arabian Peninsula: annual rainfall and temperature

analysis of Saudi Arabia for 1978-2009. International Journal of Climatology. **32** (6), 953, **2012**.

33. DASARI H.P., LANGODAN S., VISWANADHAPALLI Y., VADLAMUDI B.R., PAPADOPOULOS V.P., HOTEIT I. ENSO influence on the interannual variability of the Red Sea convergence zone and associated rainfall. International Journal of Climatology. **38** (2), 761, **2017**.
34. ALSARMI S., WASHINGTON R. Recent observed climate change over the Arabian Peninsula. Journal of Geophysical Research. **116** (D11), **2011**.
35. ATTADA R., DASARI H.P., CHOWDARY J.S., YADAV R.K., KNIO O., HOTEIT I. Surface air temperature variability over the Arabian Peninsula and its links to circulation patterns. International Journal of Climatology. **39** (1), 445, **2018**.
36. HOTEIT I., ABUALNAJA Y., AFZAL S., AIT-EL-FQUIH B., AKYLAS T., ANTONY C., DAWSON C., ASFAHANI K., BREWIN R.J., CAVALERI L., CEROVECKI I., CORNUELLE B., DESAMSETTI S., ATTADA R., DASARI H., SANCHEZ-GARRIDO J., GENEVIER L., EL GHARAMTI M., GITTINGS J.A., ZODIATIS G. Towards an end-to-end analysis and prediction system for weather, climate, and Marine applications in the Red Sea. Bulletin of the American Meteorological Society. **102** (1), **2021**.
37. AL-OBAID S., SAMRAOUI B., THOMAS J., EL-SEREHY H.A., ALFARHAN A.H., SCHNEIDER W., O'CONNELL M. An overview of wetlands of Saudi Arabia: Values, threats, and perspectives. Ambio. **46** (1), 98, **2017**.
38. GLADSTONE W. The ecological and social basis for management of a Red Sea marine-protected area. Ocean and Coastal Management. **43** (12), **2000**.
39. TINLEY K.L. Survey of Saudi Arabian wetlands. Riyadh: IUCN/ NCWCD Report, **1994**.
40. SAMBAS A., SYMENS, P. Developing a conservation plan for wetlands in Saudi Arabia: the NCWCD system plan for protected areas. In MOSER M., VAN VESSEM J. (Eds.). Wetland and Waterfowl Conservation in South and West Asia. Proceedings International Symposium. Proceedings International Symposium, 14-20 December 1991. IWRB Special Publication No. 25, **1991**.
41. GaStat (General Authority for Statistics, Saudi Arabia). Population annual growth rate in Saudi Arabia. https://www.stats.gov.sa/en/news/242. (Accessed on 01.12.2024). **2018**.
42. MEWA (Ministry of Environment Water and Agriculture). Statistical book 2020, in Arabic, Saudi Arabia. https://www.mewa.gov.sa/ar/InformationCenter/Researchs/Reports/GeneralReports/%d8%a7%d9%84%d9%83%d8%aa%d8%a7%d8%a8%20%d8%a7%d9%84%d8%a7%d9%95%d8%ad%d8%b5%d8%a7%d9%8a%d9%94%d9%8a%202020.pdf. (Accessed on 24.11.2024). **2020**.
43. SCOTT D.A. A Directory of Wetlands in the Middle East. IUC: Gland, Switzerland and IWRB, Slimbridge, United Kingdom, **1995**.
44. ELSOHABY I., SAMY A., ELMOSLEMANY A., ALORABI M., ALKAFAFY M., ALDOWERIEJ A., AL-MARRI T., ELBEHIRY A., FAYEZ M. Migratory Wild Birds as a Potential Disseminator of Antimicrobial-Resistant Bacteria around Al-Asfar Lake, Eastern Saudi Arabia. Antibiotics. **10**, 260, **2021**.
45. ASSIRI M.E., ALI MD.A., SIDDIQUI M.H., ALZAHRANI A., ALAMRI L., ALQAHTANI A.M., GHULAM A.S. Remote Sensing Assessment of Water Resources, Vegetation, and Land Surface Temperature in Eastern Saudi Arabia: Identification, Variability, and Trends, Remote Sensing Applications. Society and Environment. **36**, 101296, **2024**.
46. AL-DAKHEEL Y.Y., HUSSEIN A.H.A., EL MAHMOUDI A.S., MASSOUD M.A. (2008). Soil, Water Chemistry and Sedimentological Studies of Al Asfar Evaporation Lake and its Inland Sabkha, Al Hassa Area, Saudi Arabia. Asian Journal of Earth Sciences. **2** (1), 1, **2008**.
47. PICÓ Y., ALVAREZ-RUIZ R., ALFARHAN A.H., EL-SHEIKH M.A., ALSHAHRANI H.O., BARCELÓ D. Pharmaceuticals, pesticides, personal care products and microplastics contamination assessment of Al-Hassa irrigation network (Saudi Arabia) and its shallow lakes. Science of The Total Environment. **701**, 135021, **2020**.
48. ABDELKARIM A. Monitoring and forecasting of land use/land cover (LULC) in Al-Hassa Oasis, Saudi Arabia based on the integration of the Cellular Automata (CA) and the Cellular Automata-Markov Model (CA-Markov). Geology, Ecology, and Landscapes. 1, **2023**.
49. TURK K., ZEINELDIN F., ALJUGHAIMAN A.S. Mapping and assessment of evapotranspiration over an oasis in arid ecosystem using remote sensing and biophysical modelling. Arabian Journal of Geosciences. **14** (19), **2021**.
50. BASKAUF S.J. Introduction to Biological Sciences Lab (BSCI 1510L) Excel Reference and Statistics Manual. Nashville, TN: Vanderbilt University, http://researchguides.library.vanderbilt.edu/bsci1510L, **2016**.
51. MOUNTNEY N.P. Sedimentary Environments | Deserts. Editor(s): Richard C., Selley L., Robin M., Cocks I. & Plimer R. Encyclopedia of Geology, Elsevier, pp. 539, **2005**.
52. HUSSEIN A.H.A., EL MAHMOUDI A.S., AL NAEEM A.A. Assessment of the Heavy Metals in Al Asfar Lake, Al-Hassa, Saudi Arabia. Water Environment Research. **88** (2), 142, **2016**.
53. ArcGIS Help Library, http://desktop.arcgis.com/en/arcmap/latest/get-started/main/get-started-witharcmap.htm., **2013**.
54. ALTAMMAR F., EL SEMARY N., ALDAYEL M. The Use of Some Species of Bacteria and Algae in the Bioremediation of Pollution Caused by Hydrocarbons and Some Heavy Metals in Al Asfar Lake Water. Sustainability. **16**, 7896, **2024**.
55. FAHMY G.H., FATHI A.A. Limnological Studies on the Wetland Lake, Al-Asfar, with Special References to Heavy Metal Accumulation by Fish. American Journal of Environmental Sciences. **7** (6), 515, **2011**.
56. AL-SHEIKH H., FATHI A.A. Ecological Studies on Lake Al-Asfar (Al-Hassa, Saudi Arabia) with Special References to the Sediment. Research Journal of Environmental Sciences. **4** (1), 13, **2010**.
57. OSMAN A.G.M., ALAL-AWADHI R.M., HARABAWY A.S.A., MAHMOUD U. Evaluation of the Use of Protein Electrophoresis of the African Catfish Clarias gariepinus (Burchell, 1822) for Biomonitoring Aquatic Pollution. Environmental Research Journal. **4** (3), 235, **2010**.
58. ADEOGUN A.O. Impact of industrial effluent on water quality and gill pathology of clarias gariepinus from Alaro Stream, Ibadan, Southwest, Nigeria. European Journal of Scientific Research. **76** (1), 83, **2012**.
59. AL MOUSA A.T., KHALIFA A.Y., ALDAYEL M.F. Isolation and Characterization of Arylamidase-Producing Pseudomonas Alcaligenes from the Water of Al-Asfar Lake, Al Ahsa Oasis, Saudi Arabia. Journal of Agriculture and Crops. **91**, 122, **2022**.

60. FATHI A.A., AL-FREDAN M.A., YOUSSEF A.M. Water Quality and Phytoplankton Communities in Lake Al-Asfar, Al-Hassa, Saudi Arabia. Research Journal of Environmental Sciences. **3** (5), 504, **2009**.
61. MA S.N., XU Y.F., WANG H.J., WANG H.Z., LI Y., DONG X.M., XU J.L., YU Q., SØNDERGAARD M., JEPPESEN E. Mechanisms of high ammonium loading promoted phosphorus release from shallow lake sediments: A five-year large-scale experiment. Water Research. 245, **2023**.
62. RADAIDEH J. Improvement of Water Quality of Al Asfar Lake Using Constructed Wetland System. CWWTP 2017: International Conference on Water and Wastewater Treatment Plants. **2017**.
63. ISINKARALAR K., ISINKARALAR O., BAYRAKTAR E.P. Ecological and Health Risk Assessment in Road Dust Samples from Various Land Use of Düzce City Center: Towards the Sustainable Urban Development. Water Air Soil Pollution. **235**, 84, **2024a**.
64. ROESIJADI G. Metallothioneins in metal regulation and toxicity in aquatic animals. Aquatic Toxicology. **22** (2), 81, **1992**.
65. WHO. Guidelines for drinking-water quality: fourth edition incorporating the first addendum. Geneva. World Health Organization, 4 (Licence: CC BY-NC-SA 3.0 IGO.), **2017**.
66. ABDEL-MONEIM A.M. Histopathological and ultrastructural perturbations in tilapia liver as potential indicators of pollution in Lake Al-Asfar, Saudi Arabia. Environmental Science and Pollution Research. **21**, 4387, **2014**.
67. ISINKARALAR O., ISINKARALAR K., AMBADE B. Assessment of Societal Health Risks: Spatial Distribution and Potential Hazards of Toxic Metals in Street Dust Across Diverse Communities. Water Air Soil Pollution. **235**, 302, **2024**.
68. YILMAZ F. The Comparison of Heavy Metal Concentrations (Cd, Cu, Mn, Pb and Zn) in Tissues of Three Economically Important Fish (*Anguilla anguilla*, *Mugil cephalus* and *Oreochromis niloticus*) Inhabiting Köycegiz Lake-Mugla (Turkey). Turkish Journal Science Technology. **4**, 7, **2009**.
69. AGAH H., LEERMAKERS M., ELSKENS M., FATEMI S.M.R., BAEYENS W. Accumulation of trace metals in the muscle and liver tissues of five fish species from the Persian Gulf. Environmental Monitoring and Assessment,. **157**(1-4), 499, **2008**.
70. IBRAHIM S.M.A., ELSHEIKH M.A., AL-SOLAIMANI S.G. Phytoremediation of Heavy Metals Contaminated Wastewater by the Plant *Schoenoplectus Litoratus* (L.) at Alasfar Lake in Alahsa, Saudi Arabia. International Journal of Engineering Research & Technology. **5**, 49, **2016**.
71. FAO and WHO. Joint FAO/WHO Food Standards Programme Codex Alimentarius Commission 13th session, Rome, Italy, 2-7 july 2007. Food and Agriculture Organization (FAO) and the World Health Organization (WHO), 110, **2007**, file:///C:/Users/Ebda3/Downloads/al30_13e.pdf. (Accessed on 30.11.2024).
72. EC. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. Official Journal of the European Parliament, L327, **2000**.
73. RAHIMI S., SEFIDKOUHI M.A.G., RAEINI-SARJAZ M., VALIPOUR M. Estimation of actual evapotranspiration by using MODIS images (a case study: Tajan catchment). Archives of Agronomy and Soil Science. **61** (5), 695, **2015**.
74. QIN M., HAO L., SUN L., LIU Y., SUN G. Climatic controls on watershed reference evapotranspiration varied during 1961–2012 in Southern China American Journal of Water Resources. **55**, 189, **2018**.
75. CHOUARI W. Wetland land cover change detection using multitemporal Landsat data: a case study of the Al-Asfar wetland, Kingdom of Saudi Arabia. Arabian Journal of Geosciences. **14** (6), **2021**.
76. YOUSSEF A., MAL-FREDAN M.A., FATHI A.A. Floristic Composition of Lake Al-Asfar, Alahsa, Saudi Arabia. International Journal of Botany. **5**, 116, **2009**.
77. CAI Y, LIANG J., ZHANG P., WANG Q., WU Y., DING Y., WANG H., FU C., SUN J. Review on strategies of close-to-natural wetland restoration and a brief case plan for a typical wetland in northern China. Chemosphere. 285, **2021**.
78. TROIA A. Macrophytes in Inland Waters: From Knowledge to Management. Plants. **12** (3), **2023**.
79. RODRIGO, M.A. Wetland restoration with hydrophytes: A review. Plants. **10** (6), **2021**.