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A concise study on essential parameters for the sustainability of Lagoon waters in terms of scientific literature

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Abstract: Agriculture encompasses both plant growing (agronomy, horticulture, and forestry) and animal husbandry. Aquaculture is the aquatic embodiment of agriculture. Lagoons are the main sources of aquaculture in various countries around the world which especially yield shrimp, finfish, macrophytes, and mollusk. Agricultural effluents are highly affecting the lagoon water quality parameters in Sri Lanka since most of the agricultural farmlands in the country are on coastal landmasses. It leads to the increased risks of lagoon water contamination. Therefore, it is essential to identify the water quality parameters affected by anthropogenic agricultural activities and establish their threshold limits for ensuring the sustainability of lagoons. This study has identified the influential lagoon water quality parameters associated with agricultural effluents using bibliographic references, tested the existing values of the most influential parameters in five Sri Lankan lagoons, and briefly discussed their fate and transport. The lagoon water quality was classified into biological, physical, and chemical parameters and studied for their importance in enhancing the water quality. The overall experimental findings on temperature, turbidity, pH, salinity, DO, BOD, COD, phosphates, nitrates, ammonia content, and faecal coliforms in water specimens suggest that the selected Sri Lankan lagoons are heavily polluted because of the accumulation over the decades from the agricultural lands which worsens even more with this salinity from the seawater when the tide comes in. This paper concludes that there is a growing need for mechanisms that can be used to monitor and apply control measures to effectively manage lagoon water quality not only for the integrity of the lagoon itself but also for the dependent ecosystems both in and out of the lagoon.

Key words: Agricultural effluents, water quality, threshold limits, lagoon water contamination, physiochemical characteristics

Highlights

1. No evidence has been found in the literature to date with a prime focus on the challenges that lagoon waters face in terms of their water quality and the associated aquaculture.
2. Lagoon water for aquaculture is contaminated by the runoff from terrestrial agriculture, where fertilisers are applied.
3. The contaminants from the agricultural effluents are classified into physical, biological, and chemical groups.
4. A holistic methodology is proposed that can be used to produce framework tools for sustainable monitoring of lagoon waters.

1. Introduction

Agriculture is the practice of cultivating natural resources to sustain human life and provide economic gain. It combines the creativity, imagination, and skill involved in planting crops and raising animals with modern production methods and new technologies (Kul, 2022; Nie et al., 2022). One of the main components of agriculture that has been the subject of enormous research in the last couple of decades is aquaculture, the systematic cultivation of aquatic creatures primarily for human food. It is indeed equivalent to agriculture, although instead of plants or cattle, fish are the source of cultivation. Therefore, aquaculture is often recognised as fish farming. Most of the seafood

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produced in Europe, Asia, and South America is harvested from aquaculture operations (Padua et al., 2017; Rocha et al., 2022). Lagoons are important aquaculture sources in many nations, particularly for shrimp, finfish, macrophytes, and mollusc farming. Healthy water quality for the optimum dwelling of aquatic species is highly essential to establishing a sustainable aquaculture industry. However, contamination of chemical effluents and improper aquacultural practices in lagoons will be detrimental to the water quality.

A lagoon is a type of shallow water body that is reinforced from the oceans by coral reefs, sandbars, and islands, which formed about 6000–7000 years ago due to Holocene Sea level rise and marine transgressions, which covered about 13% of the worldwide coastal regions (Kjerfve, 1994). Many economic activities related to transportation and industrial progress in countries like Sri Lanka, Thailand, Italy, and Cyprus, such as tourism, aquaculture, and fishing, are being conducted based on lagoons. It provides a habitat for a number of fauna and flora and serves as a breeding site and nursery for aquatic organisms (Silva et al., 2013). Lagoons are getting contaminated by a variety of pollution sources, including industrial, domestic, and agricultural waste, which contributes to water quality deterioration and has an impact on aquatic organisms and communities that rely on lagoon ecosystems (Afolabi and Raimi, 2021; Okoyen et al., 2020; Raimi et al., 2022a; Raimi et al., 2022b).

The economy of Sri Lanka is highly dependent on conventional agriculture activities based on paddy cultivation. Most of these farmlands are situated in the coastal ends of the country, especially within the Eastern, Northern, and Southern provinces. The total coverage of agricultural farmlands in Sri Lanka is about 45.46%, with the coastal farmlands making up 69% of them. Agriculture is the main economic sector in Sri Lanka, which is ahead of the other commodities based on tourism, textiles, and tea exports. Chemical fertilisers are extensively used in Sri Lankan agricultural systems to seek quick harvests and maximise profit (Kishore et al., 2021). However, these chemical fertilisers produce chemical compounds that are harmful to water-borne organisms. In particular, to Sri Lankan lagoons, agricultural effluents are highly polluting the water quality of lagoons, as observed by the increased levels of eutrophication, the floating of dead aquatic species, and the advent of waterborne diseases that constantly prevail in the surrounding community (Silva et al., 2013). Among the three mentioned sources of contaminants (agricultural, industrial, and domestic), agricultural effluents are the most contaminating sources of lagoon water pollution in Sri Lanka (Adikaram et al., 2017; Mateo-Sagasta et al., 2017). Therefore, it is necessary to obtain a systematic approach regarding the processes, functions, and structure of lagoons to facilitate environmental sustainability during their utilisation for human wellbeing.

Optimum features of lagoon water for accommodating ecological demands would be viable breeding sources for fisheries, shrimp farming, habitat for fauna and flora, useful for the surrounding community, and even for drinking purposes. Therefore, the utilisation of lagoons for human needs and other requirements largely depends on water quality parameters (Afolabi and Raimi, 2021; Olalekan et al., 2023; Raimi et al., 2022a; Raimi et al., 2022b). The consideration of the above-mentioned information based on the enormous agricultural, environmental, and economic benefits of lagoons as well as their impending risks of getting environmentally contaminated due to anthropogenic agricultural activities has made this review study essential for researchers focusing on the mitigation of agriculture-based pollutions on lagoon water quality.

Water quality is a measure of the definite state of water in terms of the requirements of several aquatic biotas for optimal human use (Shah, 2017). Water quality parameters elaborate comprehensive information on the ecological impacts of lagoon water contamination due to domestic, agricultural, and industrial effluents (Odipe et al., 2018). Water is categorised into four groups based on its attributes, such as infected water, contaminated water, palatable water, and potable water (Chatterjee, 2010). Contaminated water comprises undesired physical, chemical, biological, and radioactive elements, making it unsafe for consumption or household purposes. Infected water is classified due to its contamination with pathogens. Potable water has sustainable benefits such as safe consumption and domestic efficacy. Palatable water comprises chemicals that do not pose a risk to humans. Lagoons contain all these types of water due to natural and anthropogenic activities.

This study includes biological, chemical, and physical parameters of lagoon water under its scope. The most influential parameters on the dynamic nature of lagoons are comprehensively elaborated in Table 1. Our research study has analysed every parameter in detail using published research articles from high-impact journals with high citation counts, significant novelty, and relevance. The review elaborates on corresponding parameters with respect to their threshold magnitudes in toxicology. Furthermore, it is noteworthy to mention that some experimental studies were also conducted by the authors using Sri Lankan lagoon water specimens and the available laboratory facilities to compare the lagoon water quality with the prerequisites mentioned for corresponding parameters in the literature sources.

The objectives of this study are (i) to collect the relevant information from the authentic scientific literature regarding the important parameters influencing the attributes of lagoon water; (ii) to investigate the nature of

Table 1. Classification of water quality parameters (Spellman, 2008).

Water quality parameters		
Physical	**Chemical**	**Biological**
Temperature	pH	Bacteria (faecal contamination)
Turbidity	Salinity	Virus
Total dissolved solids	Dissolved oxygen	Algae
Total suspended solids	Biological oxygen demand and chemical oxygen demand	
	Alkalinity	
	Hardness	
	Oil and grease	
	Sulphate	
	Phosphate	
	Nitrate	
	Ammonia	
	Potentially toxic elements	

Sri Lankan lagoon waters in accordance with identified literature sources and test the existing nature of Sri Lankan lagoons by collecting the data from the big five lagoons in the nation; and (iii) to provide the researchers with a comprehensive methodology to setup a framework that could be applied beyond the geographical boundaries for a long-term monitoring plan to withstand the risks of physiochemical and biological contamination of lagoon waters as identified in this research article. The goals were met by testing the selected parameters on water samples from five Sri Lankan lagoons: Jaffna, Negombo, Batticaloa, and Koggala, and comparing the results to the allowable ranges found in scientific literature. The trends of pollution were briefly discussed in this paper under relevant subtopics along with their corresponding discussions, and a comprehensive monitoring plan for lagoons was proposed for the long-term establishment of sustainability. The novelty and significance of our review study are that (i) this would be the first review article in the world that extracts the required information regarding the essential water quality parameters of lagoons. (ii) The proposed methodology in our manuscript to derive this sustainable monitoring plan for lagoon waters can be adapted in any part of the world beyond geographical boundaries.

2. Literature review

2.1 Physical parameters influencing the quality of lagoon water

2.1.1. Temperature

The biological activities in lagoon water are immensely influenced by temperature. It is an influential factor in terms of palatability, solubility, viscosity, odour, and the biosorption of potentially toxic elements and metalloids (Abbas, Ismail, Mostafa, & Sulaymon, 2014). It regulates metabolic activities, growth, reproduction, distribution, and migration of aquatic organisms in lagoon ecosystems (Suski, Killen, Kieffer, & Tufts, 2006). Risks due to climate change impact such as the urban heat island (UHI) effect and wastewater discharge into lagoons due to anthropogenic activities all contribute to an increase in lagoon water temperature (Briciu et al., 2020). Since the majority of lagoon species are cold-blooded, sudden changes in temperature due to environmental imbalances would stress the equilibrium and cause fatal results for fish species (Hall & Wazniak, 2005). According to the reference to previous studies, the flow of agricultural runoff into the lagoon raised the temperature of the Sri Lankan lagoon waters and contributed passively to coral bleaching and the loss of breeding habitats for marine fishes (El-Naggar, 2020) by inducing the assimilation of nitrate and phosphate, which results in eutrophication. The average temperature measurements of the five selected Sri Lankan lagoons are provided in Table 2.

2.1.2. Turbidity

Agricultural effluents, such as wastewater from farmlands, are a leading source of contamination in surface water in terms of the variation in turbidity (Rey-Romero et al., 2022). The turbidity of lagoon water is determined by the amount of suspended solids it contains. Both the light reflectivity of lagoon water and the extent of light penetration through water could be deduced by quantifying its turbidity. A turbidity test is conducted to estimate the ability of lagoon water to discharge waste corresponding to colloids (Meride and Ayenew, 2016). The content of suspensions such as clay, organic materials, plankton, silt, and other related particulates affects the amount of turbidity (Alley, 2007; Davis, 2010). These particulates are emitted into lagoons due to various agricultural and industrial activities. They serve as hotbeds for microorganisms; therefore, prompt disinfection is required for the continuous supply of lagoon water for the existence of aquatic species.

Higher turbidity causes suspended matter to accumulate potentially toxic elements, agricultural pesticides, and organic compounds such as polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) via adsorption (Cole et al., 2000). Determining the turbidity of water after rainfall might indicate the emergence of a new contaminant in a lagoon. Turbidity measurements must be conducted on lagoon water specimens every three to four h under extreme care if the lagoon is proposed to be used for drinking water purposes (Davis and Cornwell, 2008). Table 2 of this manuscript illustrates the turbidity test results conducted using turbidity tubes with water samples from five Sri Lankan lagoons that have surrounding farmland effluents.

2.1.3. Total dissolved (TDS)

The measure of total mineral content in a lagoon water sample is described by the measure of TDS. If the lagoon water was optimum in pH and higher in TDS, the root systems of aquatic plants would be further nourished (Abinaya et al., 2018; Chen et al., 2018). However, due to agrochemical, industrial, and fuel contamination, the Sri Lankan lagoons generally contain a higher pH and higher TDS. Moreover, higher chemical contamination is recorded in Sri Lankan lagoons because of the chemical fertilisers and the discharge of cattle slurry into lagoons, which have caused drastic ecological losses in recent times (Adikaram et al., 2021). It shows that the higher TDS of lagoon water could not only help on its own for enhanced aquatic biodiversity. Water can be effectively classified based on TDS, as mentioned in Table 3.

Minerals such as chlorides, bicarbonates, sulphates, potassium, magnesium, sodium, and calcium are soluble after undergoing certain chemical transformations and produce detrimental changes in the taste and colour of water (Zejak et al., 2022). An extremely mineralized water sample contains excessive TDS and produces more deformations in water quality (Kader et al., 2022). Hard water is formed as a result of higher TDS. The most important factors in TDS are the constituents of chlorides, potassium, and sodium. These ions do not exist in higher amounts, but their presence would cause long-term effects. Most urban lagoons are contaminated due to urban runoff, pesticides, fertilisers, and construction debris, which lead to rising TDS in lagoons (Madarasinghe et al., 2020). Therefore, a comprehensive understanding of TDS using authentic past study results is mandatory to evaluate the undergoing sequences and formulate effective solutions.

2.1.4. Total suspended solids

The total amount of waterborne solids with larger than 2mm particle sizes found as suspensions are categorised as TSS (Saranga et al., 2021). On the contrary, total dissolved solids (TDS) are larger than 2 microns. The major constituents of TSS are inorganic compounds. Algae and bacteria are common examples of TSS. These TSS form in lagoons, often surrounded by the surrounding ecosystem. Due to the water contamination by decaying organics in lagoons, silty suspended solids accumulate at the bottom of the water, while other TSS species float on both the middle and surface. The concentration of suspended solids is inversely proportional to the clarity of water.

TSS is the standard parameter to measure lagoon operators. It is a conventional pollutant that mostly induces the grooming of algae cells, sulphur bacteria, and protozoa

Table 2. Physical characteristics of the selected Sri Lankan lagoons.

Physical Parameters	**Jaffna lagoon**	**Negombo lagoon**	**Batticaloa lagoon**	**Koggala lagoon**	**Puttalam lagoon**
Temperature (°C)	34.27	27.51	32.28	25.17	29.88
Turbidity **(NTU)**	3.35–20.14	4.86–13.11	7.92–24.71	8.10–28.52	5.44–17.87

Table 3. Classification of water according to TDS (Al-Shujairi, 2013).

Type of water	**TDS range (mg/L)**
Fresh water	Less than 1500
Brackish water	1500–5000
Saline water	More than 5000

(Wiley et al., 2009). TSS levels beyond a certain threshold would raise water temperatures and also reduce the concentration of dissolved oxygen in lagoons. The main cause is the absorption of intense heat from solar radiation by the suspended particles in lagoon water (Kader et al., 2022; Paaijmans et al., 2008). Algae use carbonates and bicarbonates from the suspended solids as carbon sources, which leads to a high rate of algal blooms in lagoons. Furthermore, these suspended solids are clogged into fish gills and lead to their immune systems fusing while declining their larval maturation, which is a serious biological effect (Kiprono, 2017; Tarras-Wahlberg et al., 2003). Table 4 shows the TSS types and the products in lagoon water effluents due to those corresponding TSS over time.

2.2. Chemical parameters influencing the quality of lagoon water

2.2.1. pH

pH is one of the important indicators for lagoon water quality. It is one of the key factors that ensures the longevity of aquatic species. pH represents the intensity of active hydrogens in water. The optimum pH magnitude for lagoon water is 7.0, while the increase beyond the optimum amount is defined as acidic and the decrementing values from 7.0 are termed alkaline (Alley, 2007; Kader et al., 2022). There are several natural and man-made elements that might influence the pH of lagoon water. The majority of natural changes are caused by interactions with carbonate and bicarbonate compounds, as well as other elements. Acid rain, wastewater, residential garbage, and mining discharges can all alter the lagoon's pH. The anthropogenic activities induce variations in lagoon water CO_2 concentrations and organic material decomposition intensities, which passively influence the pH levels (Alam & Zohura, 2020). The recommended levels of pH for lagoon water are 6.5–8.5 according to the bibliographic references (Abowei, 2010; Davis and Cornwell, 2008) for the existence of a healthy ecosphere.

Since the majority of aquatic animals have adapted to a definite pH in aquatic ecosystems, the slight change in water pH could dearly cost its biodiversity (Cole et al., 2000). Because the fertility of fish eggs is drastically affected by the low pH of the water body due to the cell membrane being damaged by water acidity (Kiprono, 2017), past studies have suggested that pH below 4.0 or greater than 10.0 (i.e. pH 4.0 or pH > 10.0) would disseminate the survival of most aquatic species, including amphibians, since they cannot endure the metabolic activities in such pH ranges (Abowei, 2010; Cole et al., 2000). Algal growths are heavily induced in bodies of water beyond the pH of 8.5, which discrepancies the respiration of fishes (Ali et al., 2020). If the lagoon waters become more acidic, it induces the dissolution of potentially toxic elements and leads to a complicated level of toxicity for aquatic species. The water quality test results for pH conducted according to ASTM E70 guidelines in five different lagoons in Sri Lanka are provided in Table 5.

2.2.2. Salinity

Salinity is the measure of mineral salt concentration in water. It is calculated using the freshwater discharge, evaporation, surface runoff, and precipitation classifications. Low salinity in lagoon water could result in ammonia toxicity in lagoon water, which could lead to eutrophication (Valencia-Castaeda et al., 2019). Along with temperature, salinity is a key determinant of the productivity of organisms in lagoons, and variations in salinity have affected the breeding rates of aquatic fishes (Lawson, 2011; Perera and Priyadarshana, 2015). The salinity of lagoon water mainly depends on two factors, namely rainfall and proximity to the sea. It increases the salinity of lagoon water because of the influx of saline water from the sea. Due to the higher rate of evaporation, the salinity of lagoon water will be comparatively higher in the dry season. The global salinity of lagoon water exists between 33 and 37 ppt at 30 °C (Huber et al., 2000). In the context of the overall sustainability of aquatic ecosystems, a proper level of salinity maintenance is highly preferable. However, high salinity is a preferred habitat for prawns (Sugirtharan, Pathmarajah, & Mowjood, 2015), and the ample salinity for the dwelling for prawn species

Table 4. Reflection of excess TSS types (Richard & Bowman, 1991).

Excess TSS	**Form of existence**
Algae	Overgrowth of algae
Bacterial flocs	Accumulation of sludge
Filamentous bacteria	Low oxygen conditions in lagoon water (i.e. water septicity)
Old sludge particles	Necessity for sludge removal in lagoon water
Raw wastewater solids	Improper stabilization of wastes due to lack of aeration prevails in lagoon water
Sulphur bacteria	Over-exhibition of anaerobic microorganisms

Table 5. Chemical and biological characteristics of the selected Sri Lankan lagoons.

Chemical parameters	Jaffna lagoon	Negombo lagoon	Batticaloa lagoon	Koggala lagoon	Puttalam lagoon
pH	7.1–8.9	7.1–8.3	6.4–9.1	7.3–8.3	7.2–9.4
Salinity (ppt)	34.7–36.1	30.8–33.1	37.0–38.2	43–45.7	32–34.5
DO (ppt)	3.8–6.6	3.9–5.6	2.3–6.8	4.1–6.9	5.5–7.3
BOD, at 30 °C (mg/L)	25–170	30–120	10–210	15–130	10–140
COD (mg/L)	120–330	60–340	170–440	30–380	80–420
	170–390	150–370	200–490	110–380	130–460
Phosphate (mg/L)	0.01–0.28	0.03–0.24	0.06–0.56	0.02–0.44	0.02–0.27
Nitrate (mg/L)	0.36	0.92	0.71	1.28	0.96
Ammonia (ppb)	226	333	262	195	352
Faecal coliform (MPN per 100 mL)	2500	2510	1500	2100	2310

was 4–25 ppt (Banerjee, 2008). Salinity test results for the Sri Lankan lagoon water samples are provided in Table 5.

2.2.3. Dissolved oxygen (DO) levels in lagoon water

Due to the necessity of oxygen for survival, DO has a distinguished value among the other water quality parameters since it has a direct influence on the longevity of aquatic biodiversity. Dynamic models are designed in field experiments for estimating the waste assimilating capacity (WAC) for organic wastes that need to be deposited into a body of water in order to maintain ideal DO conditions in lagoons, respective to natural and anthropogenic activities in the ecosystem (Hendriarianti et al., 2019). In lagoons, the atmosphere and aquatic plants are the main suppliers of oxygen. Plant decays, faecal excretions, domestic wastes, oil leakage from boats, industrial aspects, and agricultural aspects are all inhibitors of DO levels in lagoons. The increase in DO in the water would raise the pH. Furthermore, the atmospheric pressure of oxygen gas, temperature, and salinity are the main influencers in determining the DO levels in lagoon waterbodies (Lawson, 2011). In Table 5, the mean magnitude ranges of dissolved oxygen in the selected Sri Lankan lagoon water specimens are provided.

2.2.4. Biochemical oxygen demand (BOD)

Biochemical oxygen demand (BOD) is the quantity of oxygen consumption by bacteria and fellow microorganisms when decomposing organic material in an aerobic environment at a certain temperature. It is a statistic for determining water quality. BOD measurements are being used to remediate polluted lagoons. BOD has an effect on the quantity of dissolved oxygen in streams and rivers. The pH, microbe intensity, temperature, organic materials, and trace materials in lagoon water all influence the levels of oxygen in aquatic species (Tawalbeh et al., 2020). It is also critical to understand that high BOD levels have similar impacts as low dissolved oxygen (DO) levels.

Bacteria and other microorganisms consume organic substances during fermentation. The broken organics were converted into simple compounds consisting of CO_2 and H_2O. The released energy is used up by microbes for their reproduction and growth. Water is considered to be contaminated at BOD levels exceeding 4 mg/L. The tolerance range of BOD is between 5 and 6 mg/L in relation to Sri Lankan Central Environment Standards, which is the governing body of water quality and maintenance in the inland water bodies of the country. Table 5 illustrates the BOD measured in five Sri Lankan lagoons using the manometric method.

2.2.5. Chemical oxygen demand (COD)

In terms of the lagoon water ecosystem, chemical oxygen demand (COD) is the amount of oxygen consumed in the lagoon water for chemical oxidation in organic substances. Elevated COD levels result from the depletion of oxygen content due to high microbial decomposition. It leads to detrimental aquatic life. COD serves in the lagoon as an indicating parameter for biodegradable and nonbiodegradable organic content from its channels. The study related to municipal wastewater hydrodynamics using lagoon systems shows that redox potential (ORP) and COD show proportionality between the two parameters (García-Martínez et al., 2017). High ORP due to higher oxygen requirements for organic oxidations caused high concentrations of COD in the field study. Furthermore, COD parameters seem to always be higher than the BOD of a particular sample (Metcalf et al., 1991).

The COD test determines the quantity of oxygen required for the chemical oxidation of organic compounds and mineral salts in water, such as ammonia and nitrates (Kader et al., 2022). Unlike BOD, COD determines the extent of oxygen that needs to be removed from an organic substance after absorbing water due to bacterial activities. The COD test is built upon the concept that a strong oxidising agent has the heavy potential, under an acidic medium, to completely oxidise any organic substance into carbon dioxide (Meng et al., 2020). After this oxidation, the intensity of organic substances in the specimen is estimated by determining the oxidants. Titration with an indicator solution is typically used. COD is measured in milligrammes per litre of solution and represents the mass of oxygen used per litre of solution. Unlike the BOD test, which takes 5 days, the COD test takes only 2–3 h. Table 5 shows the COD results obtained from the selected Sri Lankan lagoon waters.

2.2.6. Alkalinity

Alkalinity is the ability of aqueous solutions to neutralise strong acids. The presence of calcium, sodium, and potassium carbonates, bicarbonates, and hydroxides causes lagoons to be alkaline (Patil and Patil, 2010). The sources of these compounds are salt sediments, industrial wastes, and dissolved rocks. An experimental study based on the Malala lagoon in Hambantota, Sri Lanka, has identified its alkalinity as 2.14 mmol/L with a tolerance of 0.59 mmol/L (Titus et al., 2017). The ambient alkaline levels for shrimp, fish, and planktons breeding in lagoon water were extracted from a literature source (Boyd, 2019) and illustrated in Table 6. Excessive alkalinity may disrupt the dynamic nature of the lagoon ecosystem and lead to the destruction of its biodiversity.

Alkalinity contributes to aquatic species through buffering pH alterations that indirectly reduce the vulnerability of aquatic species to acid rain (Apau et al., 2012). This buffering against acidity protects the aquatic species from undergoing a sudden pH change in their surroundings (Omer, 2020). Alkalinity does not change at the top, middle, or bottom of water columns in lagoons (Titus et al., 2017), but the decrease in alkalinity leads to eutrophication effects in water bodies (Verspagen et al., 2014). Therefore, the increase in the alkaline or acidic nature of lagoon water is also an indicator of chemical pollution.

2.2.7. Hardness

The extent of mineralization in lagoon water is often described by its hardness. Lagoon water gets hardened mainly due to the increased concentration of calcium ions (Ca^{2+}), magnesium ions (Mg^{2+}), or both ions (Patil & Patil, 2010; Spellman, 2008). The existence of these metal ions during rock formation is a substantial cause of water hardness in lagoon water. The most common example is the deposition of limestone near the water bodies (Nadiri et al., 2022). Common forms of these ions are bicarbonates, chlorides, nitrates, and sulphates (Davis and Cornwell, 2008). Ions like barium (Ba^{2+}), strontium (Sr^{2+}), and iron (Fe^{2+}) have negligible contributions to water hardness.

Water hardness is classified into temporary and permanent hardness. Temporary hardness is the result of carbonates and bicarbonates, while permanent hardness is due to chlorides and sulphates (Metcalf et al., 1991). Generally, water hardness is given as the total calcium and magnesium contents in water, given in milligrammes per litre of $CaCO_3$ (Omer, 2020). The occupation of toxic elements like As, Cd, Pb, and nitrate compounds causes hardness in lagoon water. However, most countries, including Sri Lanka, do not have predetermined policies or regulations regarding the thresholds for hardness. Therefore, they are not comparable since some literary sources offer a suggested range while others mandate minimum or maximum limit levels. Our conclusion regarding the hardness of the water is well supported by a data-analytical study focused on water hardness in European Union member countries (Kozisek, 2020).

2.2.8. Oil and grease

The lagoon environment endures significant pollution due to oil and grease from effluents from petroleum-related disciplines such as transportation, industrial and municipal solid wastes, urban runoff, offshore effluents, and sediment erosion (Nadiri et al., 2022). The probable reasons for oil and grease contamination are unplanned infrastructure development, thus causing hindrance to human benefits. Oil sediments in lagoon water surround the gills of fish under low and high oil concentrations, causing suffocation for respiration.

Table 6. Recommended level of alkalinity for breeding of aquatic species

Species	Allowable alkaline level (mg/L)
Shrimp	30–500
Fish	30–500
Plankton	20–50

Oil pollution is responsible for the destruction of coral reefs and leads to increased erosion of the lagoon coast. It also provides a passive contribution to the destruction of mangroves (Tong et al., 1999).

In the Sri Lankan context, the main mode of oil contamination in lagoon waters is the transportation of engine boats in the lagoons. Tolerance limits for oil and grease within the discharged effluents according to Sri Lankan standards are up to 20 mg/L (Najim and Kithsiri, 2021). However, a recent study has indicated that the oil and grease levels in Sri Lankan lagoons are getting exceeded beyond the allowable limits due to the existence of seaports in the territories (Kanchana et al., 2021).

2.2.9. Sulphate content

Sulphates are common pollutants in lagoons. The concentration of sulphates and their complex accumulation are directly influenced by the leaching of natural deposits, atmospheric deposition, and human discharges. In general, industrial activities like tanneries, textile mills, paper mills, mines, agricultural runoffs, and smeltings release sulphates into lagoons. However, high sulphate concentrations are of particular concern to the mining industry. The most common forms of sulphates are gypsum ($CaSO_4.2H_2O$), barites ($BaSO_4$), and epsomites ($MgSO_4.7H_2O$), and water contact with these kinds of sulphates will pollute lagoons with sulphates (Greenwood & Earnshaw, 2012). Compounds such as Na_2SO_4, K_2SO_4, and $MgSO_4$ have high solubility in water during the sulphate compound contaminations, while $CaSO_4$, $BaSO_4$, and the other cationic sulphates exhibit low solubility (Delisle and Schmidt, 1977).

Elevated sulphate concentrations in lagoon water cause long-term consequences for aquatic life. The maximum sulphate content in lagoon water should not exceed 2700 mg/L (Kader et al., 2021; Meays et al., 2013). Turbidimetric experiments quantify the sulphate content in lagoon water. This test considers the reaction of sulphate ions with aqueous barium chloride induced in an acidic medium to study the resulting turbidity (Hatiboruah et al., 2021). The passive outcome of a turbidimetric test is that the turbidity would be proportional to the sulphate concentration in the water specimen.

2.2.10. Phosphate content

Agricultural runoff, detergents, home, and industrial untreated sewage are all causes of phosphate pollution in the lagoon. For healthy aquatic life, the maximum permitted phosphate content is 0.4 mg/L (Bama et al., 2013). Higher phosphate content would cause eutrophication, which gives both short-term and long-term BOD in lagoons. The maximum phosphate limit that a lagoon could buffer without eutrophication is 0.1 mg/L (Muthucumaran et al., 2015). Phosphates are one of the most important constituents required in lagoon water since they significantly contribute to the formation and propagation of aquatic plant root systems. But they should not exceed their threshold limits.

2.2.11. Nitrate content

Nitrates are soluble compounds that are washed into groundwater and then gradually into lagoons. It is the primary source of algal blooms. The maximum contaminant level for nitrates is 10 mg/L (Boyer, 2014). Nitrogen-polluted water appears grey and results in health impacts including dizziness, fatigue, and cardiac problems for aquatic organisms (Davis, 2002; Raimi et al., 2022b). Nitrates reach lagoons through faeces, solid waste deposits, septic tanks, agro fertilisers, and wastewater sewage (Odipe et al., 2018). The main sources of nitrates are municipal waste, domestic waste, and agricultural effluents.

Thermal treatment for nitrates is irrelevant since nitrates cannot evaporate like water. Nitrate pollution would cause higher carbon emissions due to greenhouse gas production (S. Kader, S. Chadalavada, et al., 2022). The total dissolved inorganic nitrogen is the sum of nitrates (NO_3), nitrites (NO2), and ammonium (NH_4). Nitrification of lagoon waters can be explained as follows:

$$NH_3 + O_2 + \textit{Nitrosomonas sp}\text{ bacteria} \rightarrow NO_2$$

$$NO_2 + O_2 + \textit{Nitrobactor sp}\text{ bacteria} \rightarrow NO_3$$

2.2.12. Ammonia level

Ammonia exists in lagoon water due to the microbial activities involving nitrogen-containing compounds and sewage effluents, especially the discharge from farmlands in Sri Lankan scenarios. Ammonia pollution in lagoons occurs primarily due to wastewater effluents from anthropogenic activities like industries and public services like hospitals, as well as improper solid waste disposal by dumping outside lagoons (Vesilind & Morgan, 2004). The reduction of these nitrogen compounds results in ammonia in small amounts in bodies of water. The existence of ammonia levels beyond 0.1 mg/L nitrogen indicates water contamination. The maximum allowable ammonia limit in lagoon water surfaces is 0.8 mg/L (800 ppb) (Buijs and Toader, 2007). Excessive sewage pollution causes pathogenic offspring in lagoons. In terms of health issues, the presence of ammonia should be seriously considered to prevent the possibility of sewage pollution due to microorganisms in lagoons (Vesilind & Morgan, 2004). Water temperature, DO, and algal concentrations in lagoons have an undisputed influence on the effluent rates of ammonia and nitrogen. Therefore, it can be inferred that the maintenance of DO and algal blooms under the tolerance limit is essential to prevent any contamination due to ammonia breeding in the lagoon.

2.2.13. Potentially toxic elements (PTEs)

Human activities are the main contributors to PTE contamination in lagoons. Both agricultural and industrial effluents, due to the toxic chemicals used in all those scenarios, could accelerate PTE contamination in lagoon water (Renu, Agarwal, & Singh, 2017). Lagoons accumulate highly concentrated PTEs due to their biochemical nature. Environmental toxicity PTEs due to anthropogenic pressure on ecosystems have dwindled lagoon water quality, declined the existence of lagoon species, and led to the destruction of resources. The presence of potentially toxic elements beyond the allowable range could challenge the health of humans since they are carcinogenic and nonbiodegradable (Qasem, Mohammed, & Lawal, 2021), thus causing the aquatic fish to be inconsumable due to their intake of potentially toxic element-contaminated water.

The most commonly found potentially toxic elements in lagoons are lead (Pb), arsenic (As), zinc (Zn), cadmium (Cd), mercury (Hg), nickel (Ni), chromium (Cr), and copper (Cu). PTEs induce hatching delays, deformities, and mortality in fish (Sfakianakis, Renieri, Kentouri, & Tsatsakis, 2015). The toxicity of PTEs could vary according to their type, compound formation, and quantity of deposition (Lawson, 2011). The maximum contaminant level standards for those potentially toxic elements established by the United States Environmental Protection Agency (USEPA) are summarised in Table 7.

2.3. Biological parameters influencing the quality of lagoon water

2.3.1. Bacteria

The intestinal guts of warm-blooded species produce faecal coliforms (Seo, Lee, & Kim, 2019). The existence of faecal coliforms is an indicator of the quality of water to be used for drinking purposes. These coliforms survive longer in water than most pathogenic bacteria. Total coliforms contain both faecal and nonfaecal bacteria. When effluents from laundry sinks and domestic and industrial wastewater enter the lagoon, coliform bacteria enter via pastures, a faulty septic system, and animal waste. The existence of faecal coliforms in lagoon water could change its odour and cause some health-related effects on the organisms. Since most tropical countries like Sri Lanka, Thailand, and southern India, as well as Eastern European countries, traditionally use reared cattle, buffaloes, and pigs for ploughing farmlands (Lesschen, van den Berg, Westhoek, Witzke, & Oenema, 2011), the nearby lagoons closer to coastal agricultural fields are susceptible to faecal contamination.

Despite their pathogenic properties, their main advantage is that they can be used as a reliable and easy indicator of faecal pollution. The main source of faecal bacteria is sewage. Surface water class II standard values for faecal coliform and total coliform are 14 and 70 MPN/100 mL, while class III standards for surface water are 200 and 1000 MPN per 100 mL. The total coliforms and faecal coliforms were measured via membrane filtration (Munasinghe-Arachchige, Delanka-Pedige, Abeysiriwardana-Arachchige, Zhang, & Nirmalakhandan, 2019).

2.3.2. Virus

Lagoons are becoming the predominant breeding places for viruses in recent times. The adverse effect of viral contamination of lagoons is the spread of diseases that affect the environmental balance. Impacts of viruses on the lagoon's water quality lead to harmful drawbacks in biological and economic aspects. Lagoons have been identified as a primitive source of mosquito-borne diseases in several case studies. Viruses of the genus *Culex annulirostris* and *Orbivirus* have been found in stretch lagoons in Australia, causing blue tongue disease in sheep, cattle, donkeys, and horses (Cowled et al., 2009). These viruses, which include adenovirus, enterovirus, rotavirus, astrovirus, and hepatitis A and E viruses, are mostly transmitted during faecal contaminations, especially from agricultural sources (Lesschen et al., 2011; Wu, Zeng, & Wu, 2022). Studies conducted in the urban lagoons of Rio de Janeiro determined the breeding of rotavirus, norovirus, and human adenovirus within the surface water of the lagoon (Vieira et al., 2012). Shrimp farming in Sri Lanka in 1990 was heavily destroyed by the spread of the *Monodan baculovirus* and the white spot syndrome virus, which were detected in the agricultural wastewater discharge in Puttalam lagoon (Arthur, 1998).

Table 7. The maximum contaminated level standards for the most hazardous potentially toxic elements (Gunatilake, 2015).

Potentially toxic elements	Maximum contaminated level (ppm)
Arsenic	0.05
Cadmium	0.01
Chromium	0.05
Copper	0.25
Nickel	0.20
Zinc	0.80
Lead	0.006
Mercury	0.00003

In the statistical sources of the Sri Lankan context, it is evident that the country had suffered an enormous loss of 1 billion Sri Lankan rupees due to white spot disease in fishery exports (Senarath & Visvanathan, 2001). Moreover, the brood stocks in Sri Lanka's Puttalam lagoon region were affected by yellow head disease back in 1998, which coincided with white spot disease and resulted in a whopping 70% drop in shrimp exports (Munasinghe, Stephen, Abeynayake, & Abeygunawardena, 2010). The reasons for the viral contamination of lagoons are the destruction of mangrove habitats and paddy cultivation at surrounding locations.

2.3.3. Algal bloom

Algal blooms in lagoon water bodies are a common occurrence due to nutrient enrichment from wastewater, agricultural waste, and stormwater drainage (Kader, Jaufer, Bashir, & Raimi, 2023). Overgrowth of algae causes high TSS and BOD in lagoon ecosystems, which causes problems for aquatic organisms (Lapointe, Herren, Debortoli, & Vogel, 2015). Furthermore, the overgrowth of algae species releases toxic substances into lagoon waters, depletes deep water oxygen, decreases water column transparency, reduces the health and size of corals, mitigates the overall aesthetic value of lagoons, conceals economic repercussions, and declines the existence, biomass, and diversity of aquatic plants (Smith, 2003). When the effluent discharges to the lagoon are high intensity, algal blooms happen more in the offshores compared to the lagoon water (Hsieh, Chuang, Shih, Weerakkody, et al., 2021) due to the high turbidity of the interior lagoon water and the short residence time of algae.

3. Results and discussion

3.1. Physical parameters

3.1.2. Temperature

Experimental observations show that the temperature of the selected Sri Lankan lagoons exists between 25 °C and 35 °C. Temperatures over 30 °C would result in a decay in the growth rate of aquatic plants (Kara et al., 2004). Furthermore, the phenol toxicity among all species was greater at higher temperatures since phenol became more noxious with increased temperature (Patra et al., 2015). The rise in temperature induces an algal bloom, thus reducing the oxygen concentration of the water and causing the demise of aquatic animals. Since warm water consists of lower dissolved oxygen levels compared to cool water, there would be a toxic nature created in lagoons with excessive surface temperatures, which would challenge the comfort of aquatic species when subjected to temperature increases (Patra et al., 2015).

The above findings of previous research studies were verified through visual observations on Sri Lankan lagoons. The intensity of eutrophication in both the Jaffna lagoon and the Batticaloa lagoon was comparatively much higher than the rest of the lagoons. According to the research study based on eutrophication and hypoxia, the primary contributing elements for the increased eutrophication in the dry season were high seawater temperature due to the excessive fertiliser loading associated with higher POC (i.e. particulate organic carbon) and DOC (i.e. dissolved organic carbon) inputs (Hsieh et al., 2021). This shows that the contamination of the agricultural effluents into lagoon water has significant impacts on its quality, which shows the necessity to regulate the wastewater management networks in the agricultural farmlands.

3.1.3. Turbidity

The maximum turbidity was 28.52 NTU recorded in Koggala Lagoon at the upstream location. The turbidity magnitude was found to be the lowest downstream of Jaffna lagoon. The standard turbidity limit recommended by WRC for sustainable aquatic life and domestic use is 5 NTU (Miyittah et al., 2020). The variation in turbidity values in the lagoons is due to the different patterns of seasonal flows in the corresponding locations, which result in dissimilar sediment deposits. Suspended sediments settle on the bottom when the lagoon water reduces its velocity while travelling from upstream to downstream. In general, the tolerant limit for turbidity in class II and class III water is less than 29 NTU (Jain et al., 2006). Water turbidities of less than 5 NTU are easily detectable in a glass of lagoon water, and they are not tolerable due to aesthetic objections (Davis, 2010). High turbidity nature diminishes the available disinfectants and induces pathogen activities and protects the existence of microorganisms in lagoon water. Therefore, turbidity needs to be controlled within the allowable limits by treating the lagoon water with chemical flocculants to prevent it from exceeding the allowable tolerance.

3.2. Chemical parameters

3.2.1. pH

It was observed that the surface pH was high at the lagoon inlet compared with the inner lagoon. Excessive pH ranges (i.e. pH > 8.5) were observed in coastal plumes of Jaffna, Batticaloa, and Puttalam lagoons since heavy rainfall was experienced due to the southwest monsoon in the first two weeks of July 2022. However, the pH magnitudes during the wet season in Sri Lanka from August to December would be even higher than the measured pH magnitudes in the dry season (Hsieh et al., 2021). There are two possible explanations for such an unusual pH change after a heavy rainfall in the dry season as observed at experimental recordings. One could be the industrial effluent discharge and septic wastewater excretions through runoffs and the photosynthesis of marine phytoplanktons, which increases the pH due to the carbon dioxide fixing (Chrachri et al., 2018; Hsieh et al., 2021).

pH of lagoon water is highly influenced by photosynthetic activities. It is also reported that the seagrass is abundant in lagoons such as Negombo lagoon (Udagedara et al., 2017), Jaffna lagoon (Digamadulla et al., 2017), and Puttalam lagoon (Ranahewa et al., 2018), and this abundance is a significant cause for the large pH variations due to the intense photosynthetic activities of seagrass angiosperms.

3.2.2. Salinity

The salinity values recorded in the dry season are generally higher than the salinity of lagoon water in the wet season. Because the seasonal precipitation of the wet season makes the surface water temperature lower and more uniform compared to the dry season (Hsieh et al., 2021). Salinity increases due to high evaporation in a dry climate, which leads to hypersalinity. Variations in salinity could also occur due to freshwater influx and tidal variations (Kankara and Panda, 2020; Mahanty et al., 2016). They alter the lagoon's nutrient levels, the inflow from inland streams, and the constituents of nutrients. Migratory birds are often attracted to lagoons with a low salinity for food resources since more freshwater fish breed in shallow depths in lagoons (Null and Wurtsbaugh, 2020).

3.2.3. Dissolved oxygen (DO) levels in lagoon water

The required threshold level for lagoon water DO in terms of aquatic life existence is 5.0 mg/L (Tran et al., 2016). In all five lagoons, the value fell outside the recommended limit in many scenarios for raw lagoon water samples. Furthermore, the experimental results recorded in Sri Lankan lagoon waters are significantly lower than a similar type of DO experiment conducted at Aby lagoons, Ivory Coast (Netto, 2018). Because of the large amount of domestic and industrial effluents, the organic content and waste disintegration of Sri Lankan lagoons are comparatively higher than in Ivory Coast. A study conducted in Sri Lankan lagoons regarding the DO levels and the survival of aquatic species found that the lives of fish and other aquatic species become perilous when DO drops below 3.9 mg/L (Sugirtharan et al., 2015), since most of the spots were recorded to be below 5.0 mg/L. It is even reported that the fish species eventually die if the aquatic DO level further dwindles below 2.0 mg/L (Sugirtharan et al., 2015) and causes an imbalance within the aquatic ecosystems.

This study output was even verified during the questionnaire survey conducted among the communities surrounding the Batticaloa lagoon by understanding the lagoon spots where the majority of community members reported the floating of dead fish over the past 6 months, and the pH recorded in those corresponding locations was in the 2.1–4.6 mg/L range. A comprehensive unidimensional model was setup for a case study in Chilka Lagoon (Basavaiah et al., 2014), incorporating biological (mineralization, photosynthesis, and respiration), chemical (i.e. nitrification), and physical (aeration) activities to study the influence of DO in lagoon water. It was found that the photosynthetic activities of aquatic plants were largely controlled by supersaturation. Furthermore, undersaturation of oxygen (Basavaiah et al., 2014) is largely required for nitrification.

3.2.4. Biochemical oxygen demand (BOD)

The measured BOD range of Sri Lankan lagoon water ranges from 15–210 mg/L. It shows that all the selected lagoons are under critical conditions in terms of BOD since they exceed the allowable range. The highest BOD concentration was observed in the Batticaloa lagoon, and the least existed in the Negombo lagoon. The main reason for BOD reductions across lagoons is the variation of rainfall. Negombo lagoon experiences more rainfall than the other four lagoons due to the South West monsoon from May to September (Bandurathna et al., 2021), and the high-intensity rainfall increases the dilution in the lagoon water and leads to a drop in BOD (Longe and Ogundipe, 2010).

The higher levels of BOD indicate that the lagoon is polluted by various organic substances, which could be as a result of oil spills from fishing boats, dumping of solid waste outside the lagoon, excretion of sewage waste, and overuse of shrimp feeds (Bozorg-Haddad et al., 2021). The excess BOD poses a serious threat to a wide array of aquatic species by reducing the dissolved oxygen levels. If the oxygen amount consumed in water bodies was not promptly replaced, it would cause a shortage of oxygen in the aquatic system. Excess BOD in lagoon water can be effectively treated using aeration and by the addition of hydrogen peroxide (H_2O_2) (Aslam et al., 2004; Ksibi, 2006).

3.2.5. Chemical oxygen demand (COD)

COD loading levels of the selected Sri Lankan lagoons with the experiments conducted using unfiltered lagoon water samples in the acidic medium using a DR-5000 spectrophotometer because the spectroscopic method became successful in previous studies, such as those conducted on wastewater effluents (Daud et al., 2015; Rice, Baird et al., 2012). We have used potassium dichromate ($K_2Cr_2O_7$) as the oxidant in the COD test. The experimental results have outlined that the mean COD during the wet season was higher compared with the dry season at all five lagoons, and they have verified the conclusion of Jayasiri et al.'s (2022) study stating that the highest COD in Sri Lankan water bodies is observed during the rainy season. The rainfall significantly alters the lagoon water quality by accelerating the BOD_5, COD, TDS, and phosphates (Momou et al., 2017).

The allowable COD range for less polluted water is 20–200 mg/L (Jain and Singh, 2003), and the experimental results on Sri Lankan lagoon waters do not comply with this range at all times. The increase in COD in lagoon waters can be controlled using sedimentation tanks while using coagulants and flocculants to bind the sludge together (Arceivala and Aslekar, 2006; Davis, 2010) in large masses and filtering them out of the tank. It is also possible to use hydrogen peroxide (H_2O_2) to reduce the COD and BOD levels in polluted lagoon water through oxidation. However, the selection of the best possible method entirely depends on a comprehensive feasibility study on the environmental, economic, and technical aspects of the considered lagoons.

3.2.6. Phosphate content

The spectroscopic analysis of phosphate levels in the Jaffna, Negombo, Batticaloa, Koggala, and Puttalam lagoons have shown that the phosphate levels observed at Sri Lankan lagoons are relatively lower, between 0.01 mg per L in the upstream and 0.56 mg per L in the downstream. The allowable phosphate limit for the suitability of aquatic life is 0.4 mg/L as per the Sri Lankan standard guidelines (Jayasiri et al., 2022), and it was derived that the phosphate levels in Jaffna, Negombo, and Puttalam lagoon waters are sufficient for aquatic survival. Appropriate phosphate treatment methods, such as the chemical precipitation method using metal salts in tertiary filtration (Ilyas and Masih, 2018), are required for Batticaloa and Koggala lagoon waters to enhance their viability for aquatic species.

3.2.7. Nitrate content

Nitrification consumes a substantial level of dissolved oxygen in lagoons. A DO level of 2.0 mg/L is adequate for uninhibited nitrification (Luo et al., 2017). According to the spectroscopic outcomes in terms of nitrates from five different Sri Lankan lagoon waters during the dry season in July 2022, the minimum level of NO3-concentration was observed in the Jaffna lagoon at 0.36 mg/L. Jaffna lagoon possessed the highest water temperature with 34.27 °C. It is noteworthy to account here for the fact that the temperature rise could hinder the nitrate runoff levels from effluents (Tjandraatmadja and Diaper, 2006). This phenomenon has resulted in Jaffna Lagoon possessing the lowest NO_3^- concentration and Koggala Lagoon accumulating high NO_3^- levels due to its lowest temperature of 25.17 °C.

In Sri Lanka, most of the domestic and industrial discharges are not treated before being delivered to the environment (Quyen et al., 2021). Excess nitrates accelerate eutrophication in lagoon water. However, the reduction of nitrates into nitrites causes blue baby syndrome (i.e. *methaemoglobinaemia*) for newborn babies and several health effects for humans, such as thyroid disease, cancer, and acute ailments (Ward et al., 2018). The recent newspaper articles, community statements, and research findings on Sri Lankan lagoon waters show ambient evidence for considering the recent nitrate water pollution issues in lagoons as a severe threat. Several ways can be implemented in Sri Lankan lagoon waters to mitigate the nitrate pollution, such as utilising bioreactors, drainage water recycling, and controlled drainage (Liu et al., 2020), and it is a crucial measure to undertake to select and proceed with the most suitable technique to mitigate current nitrate pollution trends in Sri Lankan lagoons.

3.2.8. Ammonia level

The tested specimens from the lagoon waters show that the ammonia levels are within the threshold limit in all five locations. Unlike the nitrate concentration trends, the concentration of ammonia in the dry season is often greater than in the rainy season (Jayasiri et al., 2022). The main modes of ammonia accumulation in lagoon waters are runoff water containing fertilisers (Mateo-Sagasta et al., 2018) and industrial effluents. The concentration of ammonia is diluted during the wet season due to frequent and intense rainfall. The study on ammonia-based research in lagoons should always incorporate readings from both the dry season and the wet season to arrive at a rational conclusion regarding the ammoniacal concentrations and their ecological impacts.

4. Long term monitoring plan to assess the quality of lagoon water

4.1. The necessity of conducting a monitoring plan for lagoon waters

Based on the physiochemical and the biological parametric experimental studies on the water quality of Sri Lankan lagoons, it was decided to propose a sustainable monitoring plan to ensure the long-term serviceability of water quality assessments. The objective of this monitoring plan should incorporate the identification of natural and cultural values of lagoons, and the plan should propose measures to mitigate threats to these values. The Central Environmental Authority (CEA) is the primary responsible authority for Sri Lankan lagoons for verifying the water quality for the viability of sustainable ecosystems. The Road Development Authority (RDA) of Sri Lanka is responsible for providing unhindered transportation via sophisticated roads and drainage systems. The solid waste contamination of lagoons should be prevented by appropriate actions from the municipal councils. Table 8 provides the authorities and policies associated with the conservation of Sri Lankan lagoons, and similar agencies are available in fellow countries where the preliminary approvals are mandatory for the pilot testing of the drafted monitoring plan.

4.2. Methodology for deriving a conceptual framework for implementing the lagoon water monitoring plan

Figure describes our proposed set of methods for designing and developing a conceptual framework that would enable as a tool to deliver a sustainable monitoring plan for lagoon water and the associated agriculture and ecosystems. The uniqueness of our methodology is that it can be implemented beyond the geographical boundaries of countries,

Table 8. The maximum contaminated level standards for the most hazardous potentially toxic elements (Gunatilake, 2015).

Authorities	**Policy**
Central Environmental Authority (CEA)	National Environment Act No. 47 of 1980
National Aquatic Resources Research and Development Agency (NARA)	National Aquatic Resources Research and Development Agency Act (No. 54 of 1981)
Department of Wildlife Conservation (DWC)	Fauna and Flora Protection Ordinance No 2 of 1937 (as amended)
Marine Environment Protection Authority (MEPA)	Marine Pollution Prevention Act 35 of 2008 and Regulations under this Act
Marine Pollution Prevention Act 35 of 2008 and Regulations under this Act	Fisheries and Aquatic Resources Act No. 2 of 1996 and the Regulations under this Act
The Sri Lanka Land Reclamation & Development Corporation (SLLRDC)	Land Reclamation and Development Corporation Act No. 15 of 1968
Coast Conservation and Coastal Resource Management Department	Coast Conservation Act No. 57 of 1981
The National Aquaculture Development Authority (NAQDA)	National Aquaculture Development Authority of Sri Lanka Act No. 53 of 1998

creating an effective framework to monitor the lagoons. The initial step of the framework will incorporate a critical literature review using bibliographical references, such as journal articles, book chapters, conference proceedings, technical reports, experimental findings, and annual reports based on the interaction of agricultural effluents with the lagoons and the associated water quality parameters. This literature study should be supported with a questionnaire survey and a nonstructured interview with targeted groups of experts, such as agricultural researchers, farmers, environmentalists, oceanographers, and research students. The takeaways of the literature review and the interview could be used to acquire key pieces of information regarding the state-of-the-art and the existing knowledge gaps.

A comprehensive data analysis and case study need to be incorporated in the context of Sri Lankan lagoons for identifying the agriculture-based driven causes of lagoon contamination, classifying the agriculture-based driven causes of lagoon contamination, and formulating remedial strategies. Simultaneously, an open-ended questionnaire survey is effective and should be implemented to acquire broad ideas regarding the variety of case studies that could be feasible for lagoon water quality analysis. To cope with the recent demands of water quality research outcomes, the remedial measures need to be derived using multiple statistical methods, risk index evaluations, and fate and transport studies in relation to the agricultural effluents and their contamination of the selected five Sri Lankan lagoons.

The investigations should be carried out with the cooperation of the municipal council to get the support of the local community. Historical data should be acquired with water quality monitoring using suitable technologies such as TECMA (Gandhi, Marcelo, & Leite, 2019). The sample collection should take place by taking lagoon water samples twice a week for the entire year. The selected parameters in this study, like DO, turbidity, temperature, pH, and the salinity of lagoon waters, need to be studied in terms of their fate and transport, and the findings should be statistically analysed, and the correlated risk assessment indices need to be found (Gandhi et al., 2019; Guan, Ren, Tao, Chang, & Li, 2022). Experimental results should be analysed for every season with appropriate statistical representations and risk assessment index studies. The graphs should explicitly show the minimum, average, and maximum magnitudes for each stage. The spatial variations need to be compared with the temporal variations and assessed by comparisons with allowable thresholds, meteorological rainfall data, and the air temperature to determine their influence on altering the biological and physiochemical lagoon water parameters.

The set of outcomes from fate and transport, statistical studies, and the risk index evaluations and statistical studies need to be evaluated with further discussions before proceeding with the framework. The framework needs to be updated and cross-checked based on the data collection survey retrieved from the semistructured interview with targeted groups of experts and the questionnaire within the defined scope of the contents in the framework. The proposed framework should first be trialled through monitoring the selected big five Sri Lankan lagoons according to the framework, and the hotspots and structural deficiencies in the framework need to be revised using the results. This revised framework should be tested on the lagoons in foreign nations where agricultural farmlands are in closer proximity.

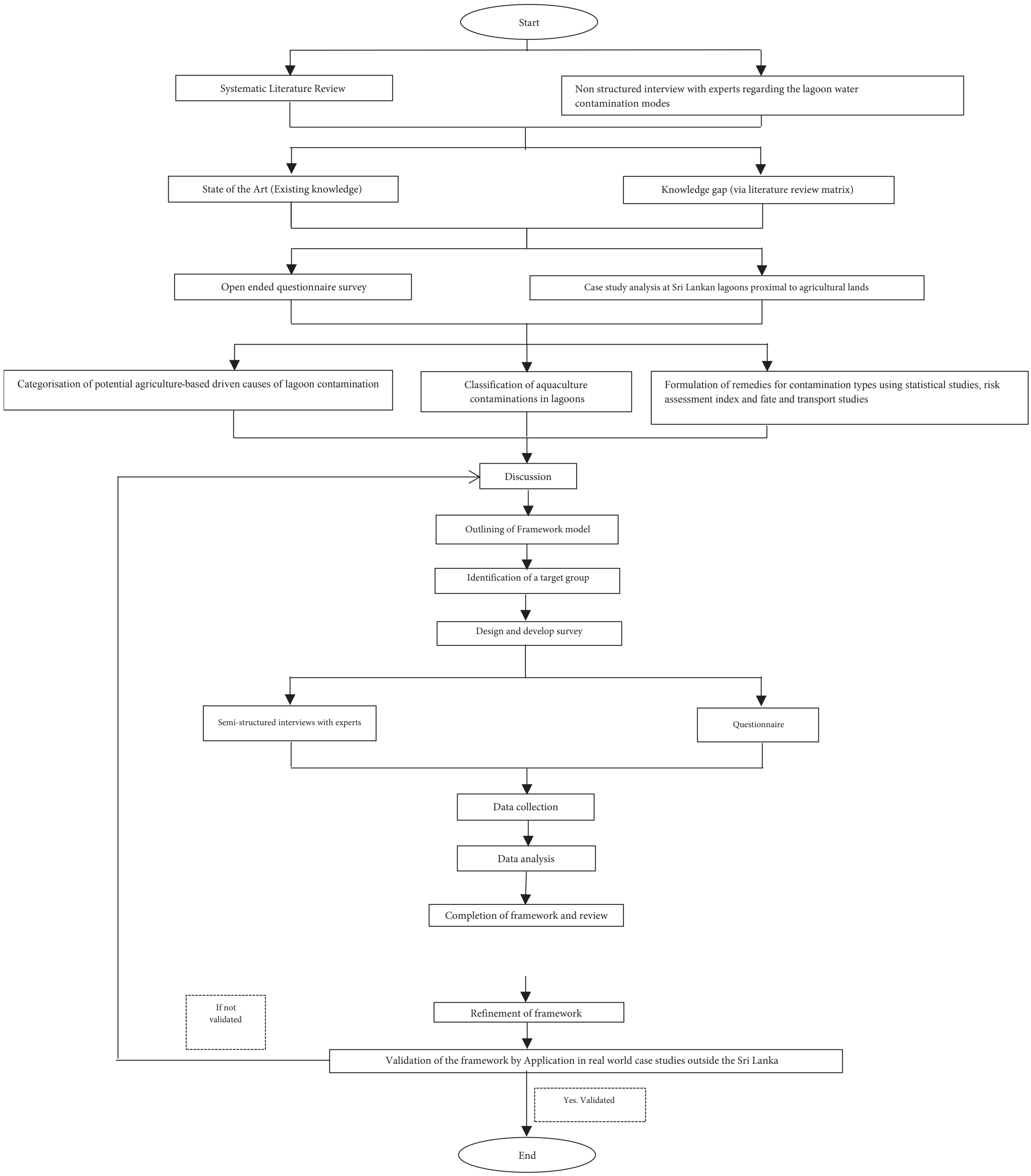

Figure. Proposed set of methodologies for deriving a conceptual framework for establishing a sustainable monitoring plan for the lagoon water ecosystems.

5. Conclusion

This study has effectively described the corresponding effects caused by the change in lagoon water parameters due to the contamination of agricultural effluents. The objective was achieved through the identification of the influential parameters, their classifications, their significance, and their allowable limits, and by proposing the set of methodologies required to produce a framework for a sustainable long-term monitoring plan for lagoons as described in Figure. Appropriate experiments were conducted in accordance with standard procedures to analyse some of the viable parameters in five selected lagoons in Sri Lanka based on the availability of technical facilities in the country, and their values were compared with threshold limits for the corresponding tested parameters. Furthermore, the corresponding agricultural activities responsible for exceeding threshold limits were briefly discussed in this review study with appropriate citations. The experimental results have shown that the values of selected parameters exhibit significant deviations within different Sri Lankan lagoons. The sources of the bibliographic references show that there are substantial variations in those values that could have been experienced between the dry and wet seasons. Hence, the respective changes were described from a rational point of view based on the takeaways of relevant research studies.

For the long-term success of preserving and maintaining high water quality within lagoons, regular and systematic monitoring of the illegal accumulation of waste materials in lagoon waterbodies is critical. This research article shows a way on how the literary sources regarding the lagoon waters can be gathered, classified, and studied regarding their influence on lagoon water quality, and how their takeaways can be inferred to propose a suitable methodology to develop a long-term monitoring plan to ensure the long-term conservation of lagoon water systems in Sri Lanka and other parts of the world to establish sustainable disposal of agricultural effluents to preserve the lagoon water quality for maintaining an unhindered aquaculture system.

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Consent to participate

Not applicable

Consent to publish

Not applicable

Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Authors contributions

Conceptualization, SK and MOR.; methodology, SK, MOR, and VS.; software, SK.; validation, SK, AAI and RW.; formal analysis, SK, MOR and AAI.; investigation, SK, VS and RW.; resources, SK, MOR, and AAI.; data curation, SK and AAI.; writing-original draft preparation, SK, VS, MOR, AAI, and RW.; writing-review and editing, SK, MOR, VS, LJ, and TEB.; visualization, SK and VS.; supervision, MOR, and AAI; project administration, SK. All authors have read and agreed to the published version of the manuscript.

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