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Is the Sundarbans of Bangladesh in a State of Pollution?

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Abstract

The Sundarbans is the world's most extensive natural mangrove forest and home to various natural resources. The population in the vicinity has increased, causing more dependency on the resources of the Sundarbans. The increasing industrialization, urbanization, aquaculture, intensive agricultural practices, seaports, tourism facilities, and so on in the peripheral areas of the Sundarbans have made significant changes in the surrounding and upstream land uses of the Sundarbans. This situation may have detrimental influences on the ecosystem components of the Sundarbans. Therefore, it is highly demanded to prepare a piece of baseline information or database of different sources of pollution and their present status in the various components of the Sundarbans. This effort helps to identify issues and concerns, determine the key elements of the ecosystem to monitor the level or overall quality of the Sundarbans ecosystem. The present study systematically collects the potential sources of pollution, types, and current levels in the ecosystem components of the Sundarbans using academic databases, libraries, and online resources. Discharge of industrial waste into water, soil and air, heavy metal pollution, use of agrochemicals, oil (refined and crude) pollution, plastic materials from urban areas, and tourism are the major issues and concerns related to the sustainability of the Sundarbans ecosystem. The air quality of the Sundarbans is in good condition with 0 - 50 AQI of Bangladesh. While BOD, COD, TDS, TSS varied from 2.0 to 3.8 mg/L, 21.6 to 416 mg/L, 146.9 to 24,100 mg/L and 54 to 155 mg/L, respectively. Soil EC, organic carbon, total nitrogen, and total phosphorus ranged from 3.01 - 5.82 mS/cm, 1.41% - 2.69%, 0.51 - 1.05 mg/g, and 0.32 - 0.51 mg/g respectively. The air, water and soil quality parameters varied with the sites and seasons and not much at the state of contamination. Indeed, we must pay much attention to the Sundarbans' air, water and soil quality with the massive and progressive change of the nearby land use pattern.

Keywords

Ecosystem, Mangroves, Monitoring, Pollution, Soil, Sundarbans

1. Introduction

Sundarbans is the world's largest single tract of natural mangrove forest and a transboundary ecosystem. It is in the southern part of the Ganges delta in Southwestern Bangladesh and the Southeastern part of the West Bengal province of India. This forest covers about 10,000 km^2 of land and waterbody, of which 60% is located in the Bangladesh territory and the rest in the Indian part (BFD, 2017). This mangrove forest is rich in aquatic and terrestrial resources (Aziz & Paul, 2015; Mahmood, 2015). Since the early human habitation in the Bengal delta's southern part, people have depended on the Sundarbans for their livelihood and protection from natural calamities like tidal surges and cyclones (Saenger, 2011; Hale et al., 2019). With time, the population in the vicinity of the Sundarbans has increased, causing more dependency on the resources of the Sundarbans (Abdullah et al., 2016). At the same time, people converted a larger area of this forest for agricultural activities and human habitation. Presently, we are also doing the same practices but in different ways. We are not converting the forest area, but we have made significant changes in the surrounding and upstream land uses of the Sundarbans for the local people's and the country's economic improvement (Sharmin et al., 2021). The development of aquaculture, intensive agricultural practices, urban areas, seaports, tourism facilities, industrial states, and so on in the peripheral areas of the Sundarbans and some activities (like resource collection, tourism, and shipping route of international and local communication) may have a significant influence on the pristine ecosystem of the Sundarbans of Bangladesh (Mahmood et al., 2021; Sharmin et al., 2021). These anthropogenic activities in and around the Sundarbans ecosystem are responsible for the sources of pollutants like heavy metals, solid wastage, agrochemicals, and oil pollution, which can influence the physiological and morphological features of the flora and fauna of the Sundarbans (Rahman et al., 2009; Duke, 2016; Costa-Böddeker et al., 2017; Marzieh et al., 2021). It is high time to control the pollution and monitor the Sundarbans' soil, water, and air quality to understand better and manage the ecosystem. Therefore, this study synthesizes the available literature to identify the sources of pollution, pollutants and their present status, and the indicators for monitoring the Sundarbans' soil quality.

2. Sources of Pollution

The land uses of the surrounding areas of the Sundarbans have been changed with time to meet the society's and country's demands. The agriculture-based economy of Bangladesh has started its journey towards industrialization to become a developed country by 2041. Meanwhile, Bangladesh has achieved self-sufficiency in agriculture production. The coastal areas of Bangladesh are the most resourceful and have ample scope for future development. The establishment of notable industrial estates, modernization and expansion of seaports and airports, urbanization, tourism, and intensive agriculture and aquaculture are of prime importance in the coastal areas of Bangladesh in both public and private sectors. Sundarbans mangrove forest of Bangladesh is situated downstream of the three coastal districts (Khulna, Bagerhat, and Satkhira). Inherently, these areas were the third largest industrial zone of Bangladesh. Presently, these areas have gained importance for the further expansion of industrial development with the construction of Padma Bridge (which connects the capital city) and the modernization of 2^{nd} largest seaport at Mongla. These industrial momenta, intensive agriculture/ farming, and urbanization, are potential anthropogenic sources of pollutants to the Sundarbans. These activities and the discharged pollutants may affect the Sundarbans mangrove forest to specific and different extents (Rahman et al., 2009).

2.1. Industries

The industrial establishment has increased significantly in Southwestern Bangladesh. These industry estates include small to medium to heavy industries in Mongla Export Processing Zone, Bagerhat, Khulna, and Jessore (BEZA, 2015). As of April 2018, 190 industrial projects had been approved around the Mongla seaport in the Environmentally Critical Area (ECA) of the Sundarbans (65 km from the World Heritage site). UNESCO (2019) reports that 154 medium to heavy industries, small and cottage industries, agriculture, and natural resource-based industries operate in the ECA bordering the Sundarbans. The distance from the outer boundary of the Sundarbans Reserve Forest to the industries is between 5 and 10 km. All these industries were established in the 1990s and 2000s. Among them, 130 are categorized as "orange" (**Table 1**) (primarily non-polluting) and 24 as "red" (having a significant pollution threat to the surrounding environment) (**Table 2**) (MEFCC, 2019). At the same time, many existing and newly established red-category industries exist in the urban areas, especially in Khulna, Jessore, and Bagerhat. It can be assumed that most of these discharges are treated and untreated effluents into the rivers connected to the Sundarbans' River network.

2.2. Agrochemicals

A range of fertilizers, insecticides, fungicides, herbicides, rodenticides, and other chemicals are used to improve crop production and aquaculture (**Table 3**), but with little concern or knowledge about their negative impact on the surrounding ecosystems (Miah & Uddin, 2005; BFA, 2008; Chowdhury & Hassan, 2013;

Ahamed et al., 2018). Nowadays, agricultural activities have intensified around the Sundarbans using chemical fertilizers and insecticides. The excessive use of these chemicals leads to them draining into the rivers and being carried downstream through the Sundarbans to pose a significant risk to coastal waters. These pollutants get incorporated into the food chain and accumulate in higher tropic levels, disrupting ecosystem biochemical cycles. Some agrochemicals, notably pesticides and herbicides, are highly toxic and found to accumulate and persist in coastal and marine biota. They can also affect seagrass beds and other aquatic vegetation. Overall, agrochemical pollution leads to biodiversity loss, increased mortality of fish and shellfish, and human health risk through food chain contamination (Rahman et al., 2009).

Table 1. Orange category (primarily non-polluting) industries (Source: MEFCC, 2019).

• Rice processing facilities	• Crab farms and hatcheries	• Plastic recycling factory
• Fish farms	• Edible oil mills	• Small ice cream factories
• Ice factories	• Towel production factory	• Brick kilns and
• Welding workshops	• Poultry farm	• Condensed natural gas (CNG) filling station
• Betel-nut grading mills	• Paper packaging factories	• Paper cutting factory
• Plastic factory producing tooth brushes and pens	• Bitumen storage facility	• Cellphone network towers
• Trolley bag factory	• Cement/oven bag making factory	• Small saline water purifiers
• Restaurants	• Saw mills	

Table 2. Range category (having a significant pollution threat to the surrounding environment) industries (Source: MEFCC, 2019).

• Cement factories	• Factory for assembling metal fencing	• Bulk petroleum storage facilities
• LPG bottling plants	• Artificial hair implant factory	• Shipyards
• Cylinder manufacturing factory	• Car seat heater assembling factory	• Jetty
• Cigarette packaging factory	• Factory for assembling metal fencing	• Petroleum refinery

Table 3. List of fertilizers, insecticides, fungicides, herbicides, and rodenticides commonly used in the periphery of the Sundarbans. Sources: Miah & Uddin, 2005; BFA, 2008; Chowdhury & Hassan, 2013; Ahamed et al., 2018.

Fertilizer	Insecticide	Herbicide	Rodenticide
Ammonium molybdate, ASP, Boric Acid, DAP, Gypsum, Manganese sulphate, MOP, Potassium sulphate, Solubor, SSP, TSP, Urea, Zinc sulphateheptahydrate, Zinc sulphate monohydrate, Zincoxide	Carbofuran, Carbosulfan, Chlorpyrifos, Diazinon, Dimethoit, Fenitrothion, Fenthoit, Fentrothion, Fozalon, Malathion,	Hunter, Machete, Miracle, Panida, Sathi (Pyrajosulfuran ethyl), Serius (Pyrajosulfuran ethyl), Topstar (Oxadiazyl)	Brodifacoum, Bromadiolone, Flocoumafen, Yusidion, Zinc phosphide,

The uncontrolled application of chemical fertilizers on agricultural land has been increasing. Most of them are nitrogen- or phosphorus-based compounds, which have led to nutrient enrichment (eutrophication) in the Sundarbans region in recent years. This can cause algal blooms, changes in the structure of aquatic communities, decreased biological diversity, fish death, and oxygen depletion events.

2.3. Oil Pollution

The number of seagoing vessels and others transporting domestic goods using the Passur river has increased significantly. The number of ships sailing from Mongla port has increased from 454 to 1557 during the last 19 years (Mongla Port Authority, 2022). The number is expected to increase further with the modernization of the port, operation of the new Rampal power plant, and development of industrial estates in the Mongla Export Processing Zine (EPZ) and Khulna. This Passur River is rich in aquatic diversity. It is famous for Hilsa fish and other species of fish and shrimp, Gangetic dolphin (*Platanista gangetica*), Irrawaddy dolphin (*Orcaella brevirostris*), and crocodiles. The diversity and abundance of the aquatic resources of this river are likely affected by the increasing movement of seagoing vessels.

Mechanized boats, fishing trawlers, goods-carrying vessels, and passenger/tourist's vessels discharge bilge and ballast water and leak or spill oil in the river. Bangladesh imports an average of 1231 thousand tons of crude oil annually (TILASTO, 2017). This import is transported from the outer anchorage to inland areas using smaller tankers. A certain portion of the oil accidentally leaks into the sea and from capsized vessels. However, spills receive the most attention because of their extent and effects on the ecosystem.

Several notable oil spills have occurred in the waterways of the Sundarbans. In 1990, a giant oil spill of an unknown origin was detected along the coast near Jongra forest camp in the Chandpai Range. In 1992, a vast oil slick appeared on the Khulna coast. A significant oil spill from a Panamanian-registered ship capsized near the Dhangmari Forest Station in 1994. Oil from its fuel tank spread about 15 km downstream, affecting a considerable part of the Sundarbans. In December 2014, about 350,000 liters of crude oil were spilled from an oil tanker in the Shela River of the Sundarbans. It spread over 350 km^2 of the Sundarbans (IUCN, 2012).

Oil spills threaten mangrove trees, seedlings, plankton, soil micro, and macro organisms, birds, fish, and aquatic animals, pollute water and affect soil quality in the mangrove ecosystem (Duke, 2016). The light fraction of the oil is the most toxic, but fortunately evaporates or degrades rapidly. The heavier fraction causes most of the chronic impacts on mangroves. The thin layer of oil on the water's surface affects the multiplication of planktonic organisms and interferes with their growth and reproduction. Fish can also absorb oil directly when feeding, tainting their tissues. Aromatic hydrocarbons in crude oil are persistent and carcinogenic, tending to be biologically accumulated in fish tissue and further accumulated at higher tropic levels of the food chain (Iftekhar, 2004).

2.4. Tourism

The Sundarbans is gaining popularity as an important destination for domestic and international tourists. Tourism is now an important source of revenue for the Sundarbans Forest Divisions. It also contributes to the local and national economy. The Sundarbans has seven important tourist destinations: Koromjol, Koromjol, Kalagachia, Kotka, Kochikhali, Nilkomol (Hironpoint), and Dublar Char. Every year, thousands of visitors attend the famous three-day-long "Rash Mela" Hindu festival on Dubla Char of the Sundarbans. The number of tourists is highly variable and depends on several factors, such as local facilities and the national and international economic and political situation (Uddin, 2011; Kumar, 2015). However, the tourist influx in the Sundarbans has increased considerably, from about 50,000 in 2003 to about 200,000 in 2019 (BFD, 2019).

Visits are mainly concentrated for the period from November to March. There needs to be an official assessment/ record of tourist carrying capacity for the above destinations. But the huge number of tourists cause impacts: littering the forest floor and waterways (plastic bottles and other garbage); disturbing the wildlife by the use of loudspeakers, shouting, scaring and unusual body language; and often starting in the forest floor for fun (Hussain, 2014). The Forest Department issues tourist permits at random. However, it has released the negative influences of uncontrolled tourism in the Sundarbans and adopted a tourism policy for the Sundarbans in 2014. However, not all of the policy guidelines are being followed properly due to a shortage of staff and insufficient managerial capacity of the Forest Department.

2.5. Heavy Metals

Cadmium, chromium, copper, nickel, lead, mercury, and arsenic are the most common heavy metals identified in the mangrove ecosystem. They occur naturally but are also released into the environment through anthropogenic processes. Mangroves act as pollutant sinks. Heavy metals can combine with soil organic matter to form a complex and become unavailable to the mangrove biota (Adrino, 1986; Mahmood et al., 2001; Lacerda et al., 1991). There are toxic limits to heavy metal concentration (Jones Jr., 1998; Jones Jr. et al., 1991). Further study is required on heavy metal pollution status and its impact on biodiversity in the Sundarbans (Nriagu, 1996; Macfarlane et al., 2007). However, river water of the Sundarbans contained 0.04 - 0.10 μg/ml, 0.03 - 0.16 μg/ml 0.01 - 9.66 μg/ml, of cadmium, lead and zinc respectively. While sediment contained 6.25 - 7.38 μg/g, 33.7 - 50.33 μg/g, and 24.91 - 62.0 μg/g of cadmium, lead, and zinc respectively.

Ranjan et al. (2018) reported that the sediment of the Sundarbans along the Passur River contained a comparatively higher concentration of heavy metal (Co, Cr, Cu, Fe, Ni, Pb, Fe, and Zn) than the Indian part of the Sundarbans. Co, Cr, Cu, Pb, and Zn enrichment factors were higher than 1 (highest for lead, Pb), indicating contamination due to anthropogenic sources. The moderate accumulation of Cr, Ni, and Pb in sediment may be part of natural geo-accumulation. Heavy metal contamination in mangroves affects both plants and aquatic resources. Heavy metals disrupt various physiological functions in mangrove plant species when present at toxic concentrations. They damage cellular structures causing wider phytotoxic responses (Lacerda et al., 1991; Vangronsveld & Clijsters, 1994). Mangrove seedlings are known to be very vulnerable to heavy metals toxicity through disrupting the physiological processes (Mahmood et al., 2001; Huang et al., 2020), but there has been no specific study on metal toxicity in the mangrove species of the Sundarbans.

2.6. Microplastic

More than 7.5 million people live close to the Sundarbans' boundaries in Bangladesh, and they rely on the vast ecosystem services the Sundarbans provide (Kumar et al., 2022). But this forest has serious plastic management issues (van Bijsterveldt et al., 2021). The plastics materials come from industrial or wastewater discharge, settlement areas, local fishing activities, recreational and tourism activities, etc. Environmental forces, such as wind, wave action, and abrasion, cause plastic pieces to break down into smaller sizes, including macro- (25 mm), meso (25 mm - 5 mm), micro- (5 mm - 1 m), and nano-plastics (1 m), respectively. Plastic is trapped and buried in mangrove sediment in various degrees of degradation at least 20 cm depth in a mudflat (van Bijsterveldt et al., 2021). Microplastics can get into mangrove soils by irrigation, mulching with plastic, diffuse urban runoff, flooding, and fallout from the atmosphere. Sometimes synthetic clothing released into the urban environment via municipal runoff can be the source of microplastic (Tiwari et al., 2019; Kumar et al., 2022). The environment contains microplastics in a variety of forms, including spherical beads (pellets), films, pieces, foam, and fibers (Tiwari et al., 2019; Garua & Sharma, 2021). Among different types of microplastics, microfibers can reduce soil bulk density, aggregation, and water infiltration and affect soil's water-holding capacity by blocking soil pores (Lozano & Rillig, 2020). The presence of plastics in the soil can reduce seed germination (Garua & Sharma, 2021).

3. Present Status of Air, Water and Soil Quality in Sundarbans

There have been some initiatives to generate seasonal and spatial baseline data on water, soil, and air quality along the river channel from Sutarkhali on the Shibsa River to Hiron point under the Environmental Monitoring Study of Khulna 1320 MW Coal-based Thermal Power Plant. Data on river bottom sediment quality has also been collected (BIFPCL, 2021).

3.1. Air Quality

Air pollution in the Sundarbans arises mainly from burning fossil fuels (particularly coal and petroleum), exhaust from factories and industries, and agricultural activities. Such pollution affects not only human health but also the forests. Air pollutants can influence tree conditions, physiology, and biogeochemical cycling. It can also reduce tree resistance to insects and disease and ultimately affect ecosystem functions (Percy & Ferretti, 2004). At a regional or local scale, emission of pollutant gases (e.g., nitrous oxide, Sulphur dioxide, carbon monoxide, ozone, and ammonia), particulates (PM2.5, PM10), and heavy metals may significantly affect the forests that are located downwind of source points (e.g., industrial estates, urban areas, farms, etc.).

The Sundarbans mangrove forest is situated downwind of urban and industrial areas in and around Khulna city and the industrial estate and seaport areas of Mongla. Such sites have been increasing in recent years to meet the demands of the increasing population and expansion of economic activities. In these circumstances, there is an urgent need to monitor air quality in the Sundarbans regularly. The CEGIS (Center for Environmental and Geographic Information Service) conducted an air quality survey with seasonal (pre-monsoon, monsoon, post-monsoon, and winter) variations from 2014 to 2016 (CEGIS, 2014, 2015, 2016). The coordinates of the study sites were 89˚35'50.4"E and 22˚28'24.8"N, 89˚35'34.2"E and 22˚17'43.1"N, 89˚30'42.06"E and 22˚1'12.10"N), and 89˚27'53.2"E and 21˚46'27.60"N for Koromjol, Harbaria, Akram Point and Hiron Point respectively (**Figure 1**).

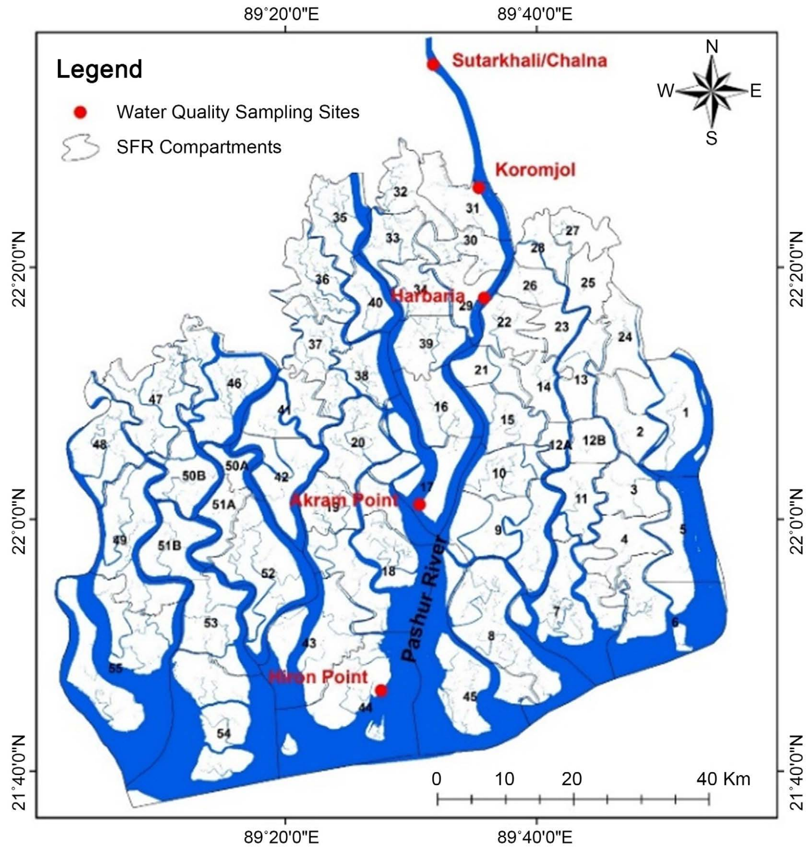

Figure 1. Sample collection sites (Sutarkhali, Koromjol, Harbaria, AkramPoint and Hiron Point) (Source: CEGIS).

The mean concentration of particulate matter ($PM_{2.5}$ and PM_{10}) differed significantly at the sampling sites and seasons. Comparatively higher concentrations of particulate matter were detected at the northern sampling sites (Karamjal and Harbaria) during winter and pre-monsoon season. The concentration of $PM_{2.5}$ for all the sampling sites ranged from 8 to 25 μg/m^3, which indicates good quality (Green) with 0 to 50 AQI of Bangladesh (**Figure 2**). In the case of PM_{10}, the concentration range was 19 to 81 μg/m^3 for all the sampling sites. The sites in the southern part of the Sundarbans (Akram Point and Hiron Point) showed good quality (green) with 0 - 50 AQI of Bangladesh. The northern sampling site (Koromjol and Harbaria) showed moderate quality (yellow green; 51 - 100 AQI) during the winter season (**Figure 2**). However, the concentrations of the particulate matter ($PM_{2.5}$ and PM_{10}) for the Sundarbans are within the limit value ($PM_{2.5} \leq 65$ and $PM_{10} \leq 150$ μg/m^3) (DoE, 2018).

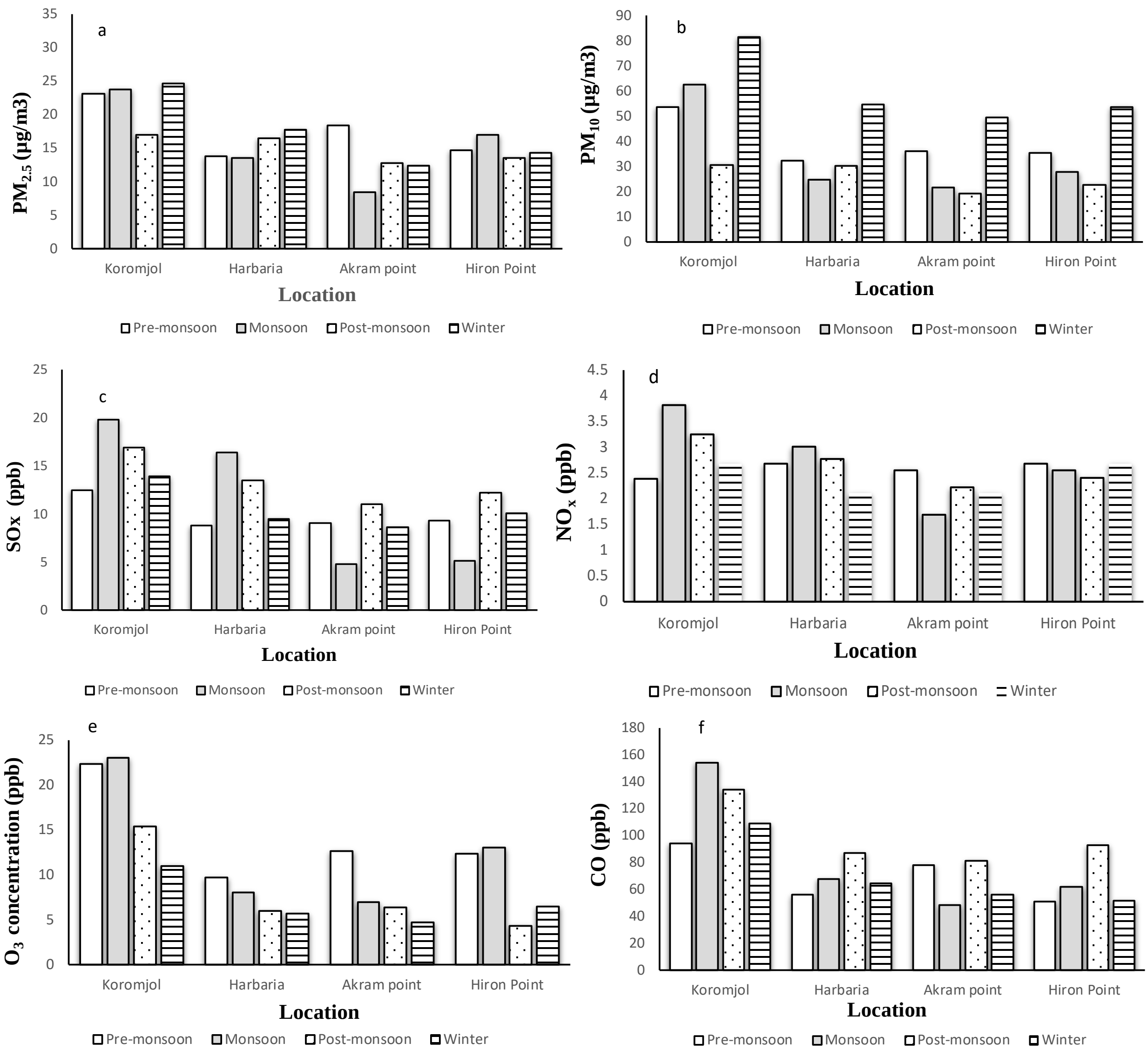

Figure 2. Air quality parameters ($PM_{2.5}$, PM_{10}, SOx, NOx, O_3 and CO) of Koromjol, Harbaria, Akram Point and Hiron Point of the Sundarbans.

The concentration of sulfur oxides (SOx), nitrogen oxide (NOx), ozone (O_3), and carbon monoxide (CO) in the air of the sampling sites showed vitiation among the sites and seasons without any distinct pattern. The concentration ranges of SOx, NOx, O_3 and CO was 4 - 20 ppb, 1 - 4 ppb, 6 - 23 ppb, and 48 - 154 ppb, respectively (**Figure 2**). In conclusion, the air quality of the Sundarbans is good condition with 0 - 50 AQI as recommended by Bangladesh (DoE, 2018).

3.2. Water Quality

Urbanization, industrialization, crop cultivation, and aquaculture have increased considerably around the Sundarbans during the last decade. These activities, together with sand mining in the southwest region and forestry activities, significantly affect the water quality of rivers, lakes, and groundwater (IUCN, 2012). Water quality describes the chemical, physical, and biological characteristics of water. Physico-chemical parameters /indicators are usually used to assess water quality: pH, salinity, total dissolved solids (TDS), total suspended solids (TSS), biological oxygen demand (BOD), chemical oxygen demand (COD), nutrients (nitrogen and phosphorus), and toxicants (insecticides, herbicides, and heavy metals). Water quality (pH, temperature, salinity, BOD, COD, TDS, TSS, NO_3, PO_4, SO_4, As, Pb, and Hg) assessment was conducted for five locations (Sutarkhali in the north to the Hiron Point) along the Passur River (most significant river channel of the Sundarbans) as a baseline survey for the period of 2014 to 2016 (CEGIS, 2014, 2015, 2016).

The water pH at all five sites was neutral to slightly alkaline throughout the year. Water temperature an important factor for aquatic flora and fauna, which ranged between 21.2˚C in the winter and 31.1˚C for the monsoon, although similar high water temperature was observed for other seasons (**Figure 3**). There was no significant ($P > 0.05$) variation in water temperature among the sampling sites. Water salinity of the Passur River varied with the seasons. It is an important factor for mangroves, influencing the soil salinity and the diversity and composition of flora and fauna (Tomlinson, 1986). The highest mean water salinity was 20.7 ppt during the pre-monsoon season at Hiron Point and the lowest 0 ppt during the post-monsoon season at Sutarkhali, Koromjol, and Harbaria. However, significantly ($P < 0.05$) higher mean water salinity was observed throughout the year at Akram Point and Hiron Point. The mean Biological Oxygen Demand (BOD) varied from 2.0 to 3.8 mg/L. However, there was no significant ($P > 0.05$) variation in BOD among the sampling sites and seasons. Conversely, Chemical Oxygen Demand (COD) varied significantly ($P < 0.05$) among the sampling sites and seasons. Comparatively higher mean COD (416 mg/L) was observed for Hiron Point during the monsoon season and a lower value (21.6 mg/L) for Sutarkhali during the post-monsoon season. The concentration of total dissolved solids (TDS) was highest during the pre-monsoon period, followed by winter, for all the sampling sites. The highest mean TDS (24,100 mg/L) was detected at Hiron Point during the pre-monsoon, while lowest

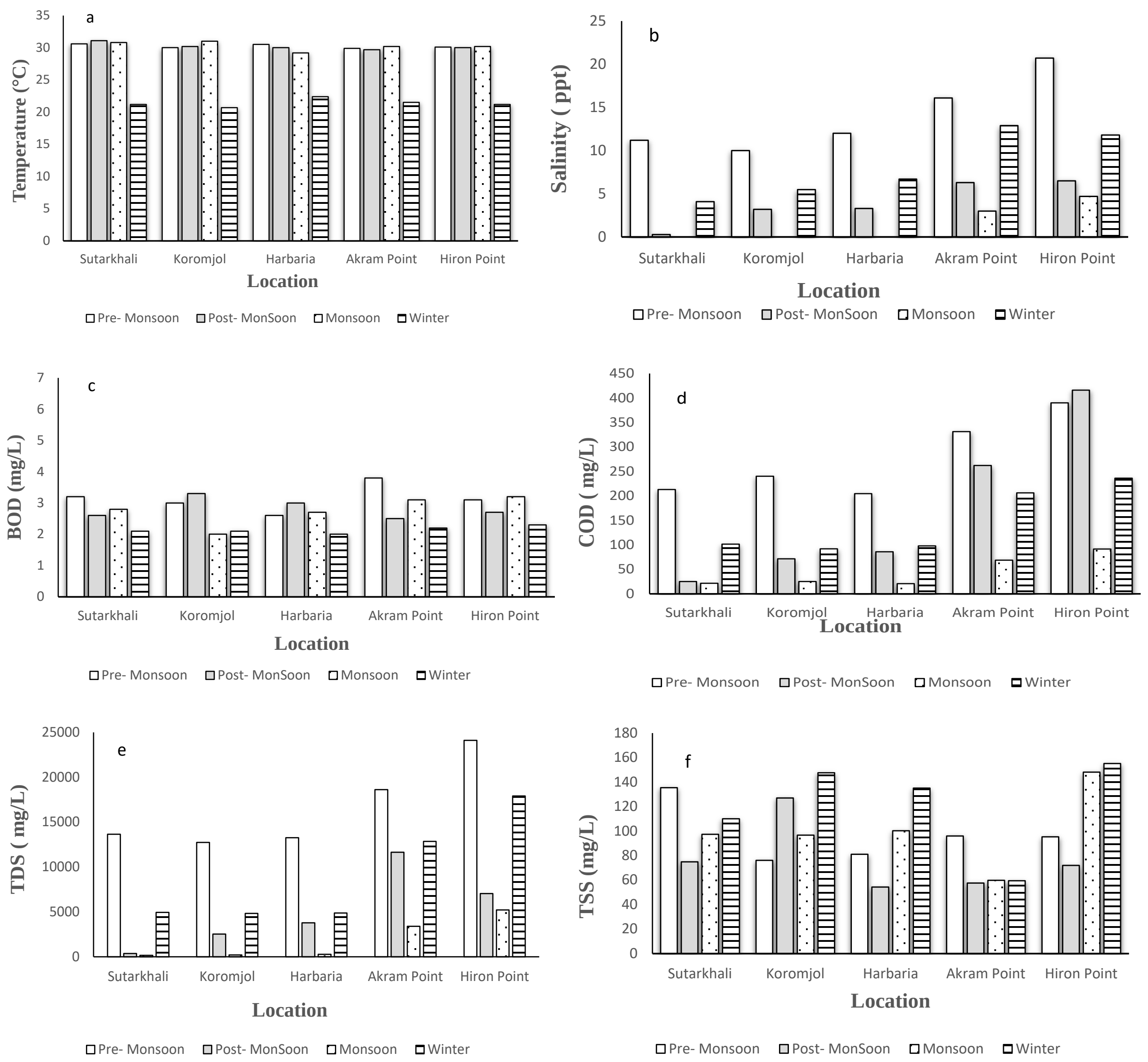

Figure 3. Water physic-chemical parameters of the Sundarbans.

(146.9 mg/L) was at Sutarkhali during the post-monsoon season. Total suspended solids (TSS) ranged from 54 to 155 mg/L. but, there was no significant ($P > 0.05$) variation among the sites and seasons (Figure 3). However, the values of BOD, COD, TDS, and TSS of the Passure River water showed within the range in comparison to the river water quality report of Bangladesh (DoE, 2015) and other mangrove rivers of the world (Toriman et al., 2013; Rahaman et al., 2003; Gandaseca et al., 2016).

Nitrate (NO_3) and Phosphate (PO_4) concentrations varied significantly between seasons, but almost similar concentrations were observed at the different sampling sites. A higher concentration of nitrate (7.6 to 10.87 mg/L) was found during the pre-monsoon season, and a higher concentration of phosphate (0.91

to 3.44 mg/L) post-monsoon. Sulphate (SO_4) varied in all seasons and between sampling sites. There was a higher concentration (2033.33 mg/L) during the pre-monsoon at Hiron Point and a lower concentration (14 mg/L) during the post-monsoon at Sutarkhali (**Figure 4**). The seaward sites had a higher concentration of sulphate than the northernmost site. The sampling site "Hiron Point" is located at the extreme south of the Sundarbans; at the same time, it is very close to the sea. However, seawater is the primary source of sulphate in the mangroves (Mahmood et al., 2004). It could be the reason for observing higher sulphate concentrations in sampling sites close to the sea.

Arsenic (As) is one of the critical heavy metals. A comparatively higher mean concentration (0.004 mg/L) of arsenic was observed during the monsoon season and low (0.0022 mg/L) during the post-monsoon season. The highest mean arsenic concentration was found at Hiron Point, and the lowest was at Sutarkhali. The concentration of lead (Pb) in water samples was higher during the pre-monsoon season (0.147 to 0.374 mg/L) and low during the monsoon season (0.007 to 0.101 mg/L). At the same time, mercury (Hg) concentration was less than 0.00015 mg/L for all sites and seasons (**Figure 5**). However, the concentration of As, and Hg in river water is an acceptable limit for the river water. While, water sample of the seaward sampling sites contained higher concentration of Pb than the acceptance level (Bhakta & Munekage, 2010).

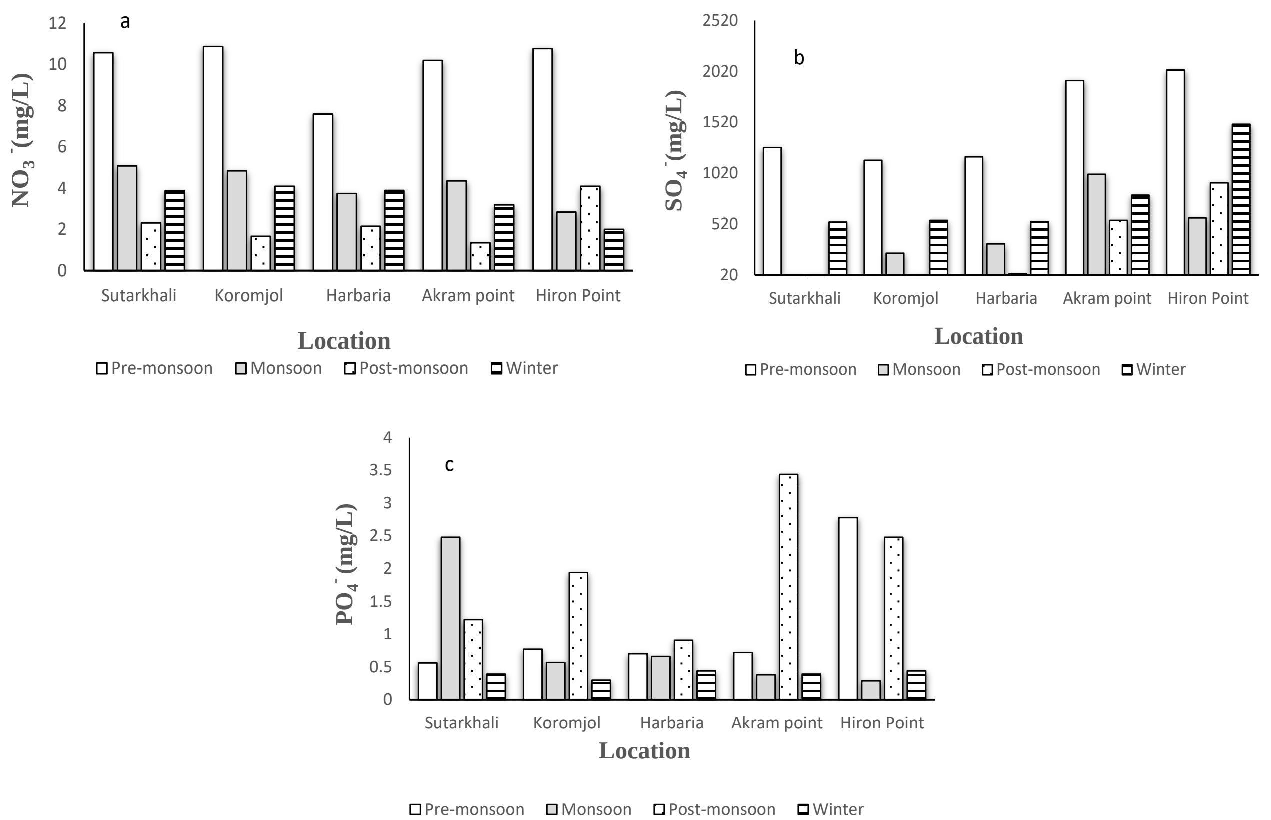

Figure 4. Nutrient concentration in water samples of the Sundarbans.

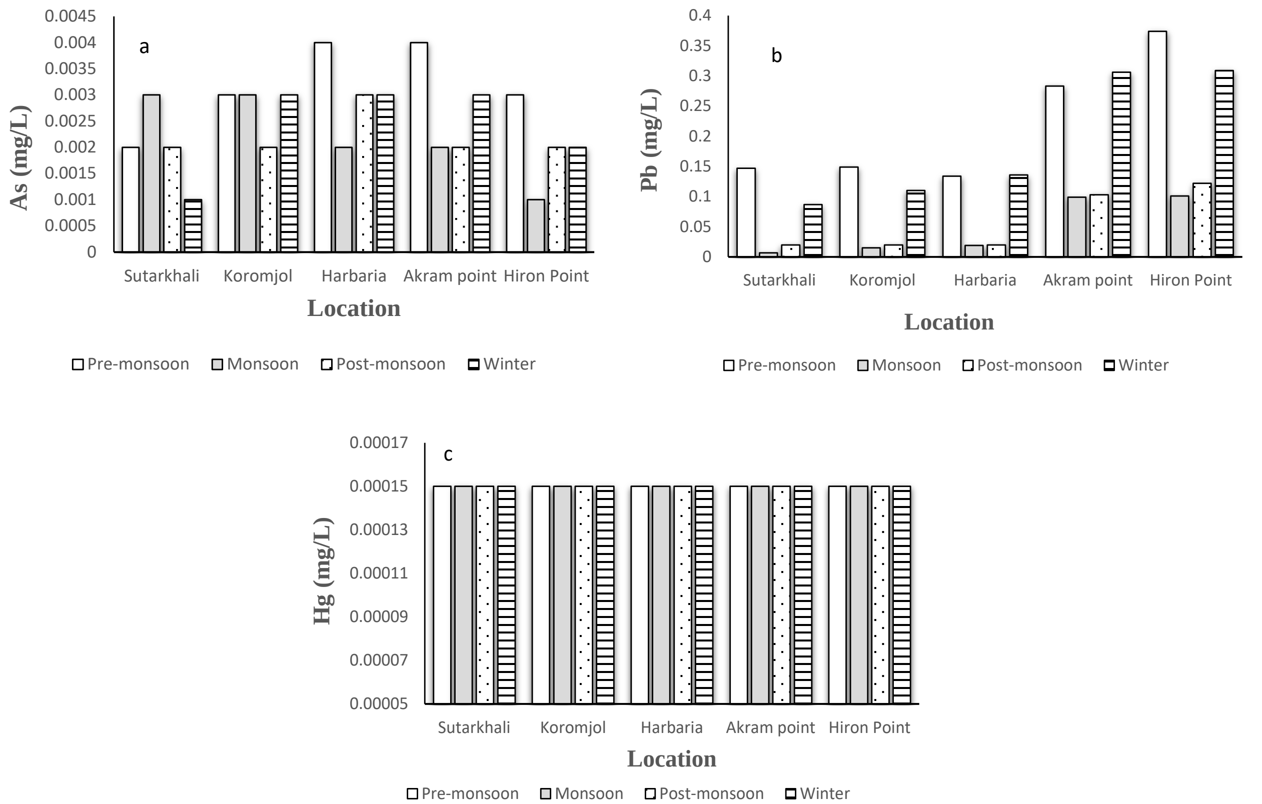

Figure 5. Heavy metal concentration in water samples of the Sundarbans.

3.3. Soil Quality

A baseline survey of parameters (EC, pH, organic carbon, total nitrogen, and phosphorus) of topsoil was conducted during 2015-2019 for the same sample sites as mentioned for air and water quality (BIFPCL, 2021) (**Figure 1**). The pH, EC, organic carbon, total nitrogen, and total phosphorus range for the sampling sites was 6.74 - 7.34, 3.01 - 5.82 mS/cm, 1.41% - 2.69%, 0.51 - 1.05 mg/g, and 0.32 - 0.51 mg/g respectively. Not much variation was detected among the sites, but no pattern in seasonal variation was observed for organic carbon, total nitrogen, and phosphorus (**Figure 6**). The range of pH, EC, organic carbon, total N, and P of the other mangroves of the world was 6.40 - 8.22, 10.63 - 34.75 me/100 g, 0.38% - 13.31%, 0.37 - 0.97 mg/g and 0.001 - 0.026 mg/g respectively (Hossain & Nuruddin, 2016). This indicates that the soil parameters (except total phosphorus) of the sampling sites of the Sundarbans are within the range of the other mangroves of the world.

4. Monitoring of the Soil Quality of the Sundarbans

Monitoring pollution levels is vital for the sustainability of the Sundarbans mangrove ecosystem. Several issues (over-exploitation of resources, habitat degradation, habitat isolation, increased salinity, tourism, increased navigation of sea-going vessels, Industrial pollution, agrochemical, and heavy metal pollution,

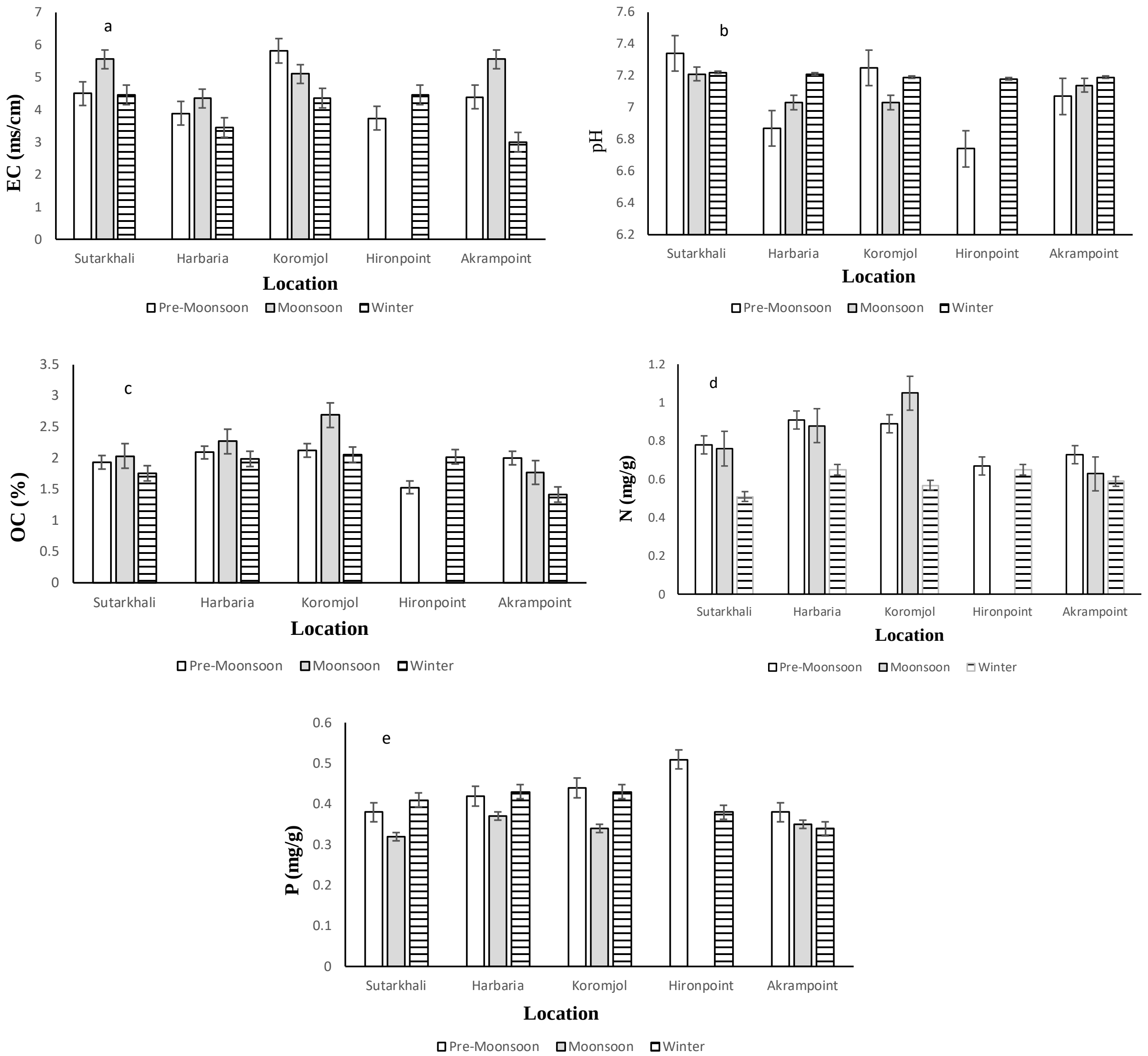

Figure 6. Soil parameters (EC, pH, organic carbon, total nitrogen and phosphorus) of the sampling sites of the Sundarbans.

oil pollution, etc.) and consequences to the sustainable management of the Sundarbans have already been identified (Ranjan et al., 2018; Mahmood et al., 2021). These issues may have impacted the Sundarbans' ecosystem. In recent times, ecological monitoring is becoming an effective tool for monitoring the health of an ecosystem around the Globe. There must be a system or set of key indicators to monitor the soil quality of the Sundarbans.

Mangrove soil is a critical component that shapes forests' floral and faunal composition. Conversely, floral and faunal composition positively influences the parameters of soil. The soil quality improvement enhances plants' growth, changes the site to a more diversified one, and improves the environmental quality (Rosa & Sobral, 2008). Therefore, the soil is the most important abiotic component of a forest ecosystem. Maintaining and improving the soil quality ensures the environmental sustainability of a forest ecosystem. Soil quality assessment helps guide soil research planning and conservation policy (Rosa & Sobral, 2008). Unlike water and air quality, the single parameter of soil appears insufficient to monitor the soil quality. A trade-off must be considered when selecting soil parameters for the ecological monitoring of soil components. However, a complex integration of static and dynamic parameters of soil's chemical, physical, and biological components needs to be understood before selecting them as indicators of ecological monitoring (Braimoh & Vlek, 2008; Cherubin et al., 2016). Setting indicators for field monitoring and quality assessment of soil parameters takes time and effort. However, this study has reviewed a good number of recent literature on the ecological monitoring of soil parameters, soil quality assessment, ecosystem monitoring, and their assessment methods for mangroves and non-mangroves ecosystems. A good number of physical, chemical, and biological parameters can identify as soil components of a terrestrial ecosystem, and they significantly influence each other (Rosa & Sobral, 2008). Biological productivity, biodiversity, regulating water flow, storing and cycling of nutrients and carbon, filtering, buffering and transforming organic and inorganic materials, regulation and partitioning of water and solute flow are the significant functions of the soil of a mangrove ecosystem (Clough, 1982; Hutchings & Saenger, 1986; Mahmood et al., 2004).

The primary assessment of mangrove soil quality is necessary to evaluate the degradation status and changing trends with time and natural and anthropogenic activities. Soil properties sensitive to changes in management operations and natural and anthropogenic activities can be used as field and laboratory assessment indicators. The physical, chemical and biological parameters can serve as indicators for soil quality assessment. It is challenging to select an appropriate set of soil parameters/indicators to monitor the soil quality of a particular forested ecosystem. It is only possible to develop a single shortlist suitable for some purposes. It is advised to use a range of likely indicators/ parameters in designing an MDS (Minimum Data Set) rather than a single indicator covering the soil's physical, chemical, and biological properties (Rosa & Sobral, 2008; Maurya et al., 2020). The MDS of a particular site varies with site and land use pattern (agriculture to forested land) (**Table 4**).

The selection of field indicators/parameters is difficult to cover the soil's physical, chemical, and biological parameters considering the site condition and level of interferences. The field indicators/ parameters can be called visual indicators obtained from observation or photographic interpretation. The field indicators indicate that soil quality is threatened or changing. Sundarbans mangrove forest is a vast coastal wetland that experiences natural and human-induced harmful activities. Several threats have been identified to the Sundarbans mangrove forest (Mahmood et al., 2021). There is a need to develop an ecological monitoring scheme for the Sundarbans' soil component.

MDS for monitoring the soil component of the Sundarbans requires the incorporation of some field indicators along with physical, chemical, and biological parameters. The possible list indicators/parameters (MDS) for monitoring the Sundarbans soil has been presented in Table 5, which may help select MDS for monitoring the Sundarbans soil from the permanent sample plots. However, we need to set standards for the visual indicators before implementing in the field.

Table 4. Minimum datasets (MDS) used for soil quality assessment.

Proposed MDS	Sites types	References
N:P ratio, carbon, enzyme	Alkaline soil	Yu et al. (2018)
pH, total nitrogen, available phosphorus, potassium, soil organic matter, soil salinity	River delta soil	Wu et al. (2019)
Alkali hydrolysable nitrogen, soil organic matter, microbial biomass nitrogen: total nitrogen, available zinc	White and maize cropping system	Li et al. (2019)
pH in water, exchangeable calcium, available phosphorus, bulk density, soil organic carbon	Shifting cultivation	Yemefack et al. (2006)
Soil organic matter, top soil depth, infiltration, aggregation, pH, electrical conductivity, suspected soil pollutants, soil respiration	Agro-ecosystem	Arshad & Martin (2002)
Soil texture, content coarse material, available water capacity, organic matter content, potentially mineralizable nitrogen, pH, available phosphorus	Remediation sites	Volchko et al. (2014)
Organic matter, organic carbon, bulk density, aggregate stability, pH, salinity, forms of nitrogen, microbial biomass, microbial respiration	Agricultural	Kruse (2007); Bastida et al. (2008)
Electrical conductivity, bulk density, exchangeable magnesium, available phosphorus	Tropical moist deciduous forest	Mishra et al. (2019)
Soil texture, depth of ground water table, soil organic matter, pH, sodium, available potassium, phosphorus, zinc	Arable soil	Juhos et al. (2019)

Table 5. List of indicators/parameters for the ecological monitoring of the Sundarbans soil.

Indicator category	Indicators	Functions	Field/Lab
Physical indicator	Bulk density	Soil compaction Limitations to root growth Movement of water within the soil profile	Lab
	Texture	Movement of water within the soil profile Retention and mobility of water and nutrients Habitat for macro and micro fauna Water holding capacity, rate of water and air movement	Lab
Chemical indicator	pH	Influence the activities of soil bacteria, Influence the mobility and availability of nutrient, toxic elements, and soil structure	Field/Lab
	Electrical conductivity	It measures the soil salinity Affect the productivity Availability nutrients for plant uptake Influence the soil microorganism activity Influence several soil physical and chemical properties like availability of nutrients, soil texture, cation exchange capacity, etc.	Field/Lab
	Available Nitrogen	Productivity and plant growth	Lab
	Available Phosphorus	Productivity and plant growth	Lab
	Available Potassium	Productivity and plant growth	Lab
	Heavy metals (As, Cr, Co, Cu, Hg, Pb)	Ecological health risk	Lab

Continued

Biological indicator	Organic matter	Soil structure Nutrient retention Carbon sequestration Microbial population	Lab
	Organic carbon	Carbon sequestration	Lab
Visual indicator	Snail on the forest floor and tree trunk	Habitat quality	Field
	Crab burrow density	Soil aeration condition Crab mount facilities natural regeneration Consumption and mechanical breakdown of the mangrove litter that accelerate the decomposition of litter Enhance microbial decomposition of litter that support nutrient cycling and adding of organic matter to the mangrove soil and supply of detritus to the aquatic ecosystem	Field
	Natural drainage ways after any event	Indication of changing the surface hydrology	Field
	Burial and exposing of pneumatophores	Evidence of sediment accretion and erosion	Field
	Occurrence and coverages of weed species (Tiger fern)	Less tidal inundation due to sediment accretion	Field
	Occurrence of oil of the forest floor	Oil pollution cause rapid destruction of the habitats of soil microorganism and organisms living among the roots and branches of mangroves.	Field
	Collection of plastic material on the forest floor	Indicator of urban pollution. The micro-plastic from the degradation of the plastic compound may carry disease-causing organisms and act as a vector for diseases. Micro-plastics can also interact with soil fauna, affecting their health and soil functions.	Field
	Leaf litter on forest floor	High amount of organic matter Less tidal inundation	Field

5. Challenges and Outlook in Monitoring the Pollution in the Sundarbans Ecosystem

Monitoring the pollution level for different components (Air, Water and Soil) of the Sundarbans ecosystem is a complex task with several challenges. The challenges are categorized as technological, logistic, human resources, extreme weather and local community. Technical challenges include the selection of key monitoring parameters for the specific ecosystem component, using high-tech instruments and their maintenance in the remote areas in the Sundarbans, data storage and transmission systems. The remote and swampy habitat of the Sundarbans makes it challenging to establish and maintain pollution monitoring stations around the year, especially during the monsoon season and extreme weather conditions. The availability of a skilled workforce is another challenge for operating the pollution monitoring equipment, data recording and interpretation of the collected data. Extreme weather events (cyclones, heavy monsoons, and tidal surges) damage the monitoring equipment, permanent sample plots and field infrastructure and pose safety risks to field researchers. These may cause discontinuation of collecting a time series data. Human-wildlife conflict (particularly with the Bengal tiger) can influence the monitoring activities in the Sundarbans. Balancing the needs of local communities, who depend on the

Sundarbans for their livelihoods, with conservation and monitoring efforts can be challenging. The challenges of monitoring pollution in the Sundarbans are substantial. Selection of appropriate key indicators, technological advancements, interdisciplinary collaborations and research, disaster preparedness, government initiatives, and community engagement may provide better solutions for improving monitoring and safeguarding this invaluable ecosystem.

6. Conclusion

Properly assessing and interpreting the different properties of the Sundarbans' air, water, and soil is the key to monitoring the pollution level. The Sundarbans' air, water, and soil quality are within the range of good quality except for very few water parameters (TDS, Pb and PO_4). It will be wise to rely on something other than visual indicators and field measurements to monitor the soil quality. It requires some laboratory measurements for nutrients and heavy metal concentration in soil. This study proposed some visual indicators for soil quality assessment. However, it requires setting standard values for each visual indicator before implementation in the field. Detailed research is needed to develop a monitoring mechanism to identify the pollution level for air, water, and soil of the Sundarbans mangrove forest of Bangladesh.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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