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Science & Technology Agenda for Blue-Green Spaces Inspired by Citizen Science: Case for Rejuvenation of Powai Lake

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Abstract: Urban lakes play a major role in the socio-cultural and ecological sustainability of many cities, but are often under major development and pollution pressures. Urban decision makers are faced with a challenging task of identifying the causes of their decline and building plans for their conservation or rejuvenation. Powai Lake is a perfect example of an urban water body with historic, cultural, and ecological importance to the population of Metropolitan Mumbai, with local and regional authorities, including the Urban Development Department, Government of Maharashtra, working to identify methods for rejuvenating the Lake. In this context, characterization of pollution dynamics, hotspots, and extent is fundamental to the development of management plans and appropriate technologies for the remediation and rejuvenation of Powai Lake—the long-term goal of the present study. A two-year monitoring program at eight sampling locations on the Lake's periphery, with the engagement of citizen scientists along with environmental researchers, revealed clear seasonal and spatial dynamics that allowed for the identification of pollution drivers and the development of a three-phase rejuvenation plan. The plan represents a novel and holistic approach that recognizes Powai Lake as a complex system with multiple drivers, and aims at ecological balance and sustainable delivery of ecosystem services.

Keywords: Powai Lake; lake rejuvenation; citizen science; nature-based solution; natural treatment system; constructed wetland; water quality index; blue-green balance; capacity building

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1. Introduction

Major factors that lead to the degradation of surface water bodies are often related to progressive urbanization and the resulting imbalance between blue-green spaces within urban ecosystems. In the case of India, disposal of untreated sewage and partially treated industrial effluents into lakes, rivers, and coastal ecosystems have outpaced the pollution control systems instituted by urban local bodies and communities. This has resulted in conditions of increased turbidity, algal blooms, eutrophication, and siltation in most urban water bodies [1–3].

Given the vital role that urban lakes play in flood control, pollution mitigation, landscaping, and recreation, the Ministry of Housing and Urban Affairs, Government of India (GoI), has intervened with mission mode projects, including *Jal Shakti Abhiyan*, *Smart Cities Mission*, and *Atal Mission for Rejuvenation and Urban Transformation* [4]. These efforts are aligned with the UN Sustainable Development Goals SDG 6, SDG 11, SDG 14, and SDG 17, and demonstrate India's commitment to securing water resources and building resilient cities through multi-stakeholder partnerships [5]. Asolekar et al. [1], Arceivala and

Asolekar [6], Kumar et al. [7], and Hutchins et al. [8] have demonstrated the significance of developing new eco-niches by employing nature-based solutions (NbSs) e.g., natural treatment systems (NTSs) like constructed wetlands (CWs), polishing ponds, waste stabilization ponds, etc., and thereby revitalizing the blue-green spaces in urban ecosystems.

There are numerous examples of ecological, environmental, and social transformation actions implemented in India using innovations in treatment and reuse of wastewaters, including (a) rejuvenation of Mansagar Lake [1], (b) restoration of Kaikondrahalli Lake [9,10], (c) development of a recreational garden and female empowerment in Mhaswad Town [11,12], and (d) expansion of green spaces at a religious institution for the benefits of pilgrims in the town of Katel [13]. The transformation of Mansagar Lake in Jaipur through a public–private partnership and restoration of Kaikondrahalli Lake in Bengaluru through multi-stakeholder, socially inclusive development were cited by the NITI Aayog, GoI, and UNDP [14]. These success stories were highlighted as sustainable solutions not only for aesthetics and recreation but also for the source of revenue.

In India, lakes provide numerous ecosystem services to urban clusters if appropriately managed. Lake rejuvenation is often hindered by knowledge gaps related to pollution dynamics and pollution hotspots [1,3]. Systematic water quality monitoring and the use of aggregated water quality indices can be used to create pollution maps and identify tipping points. Various water quality indices (WQIs) have been in use to assess the overall status of a water resource with complex pollution dynamics, by combining the pollution potential of the individual parameters [15].

In recent years, citizen science has been shown to be a useful and robust scientific data collection technique [16,17] as well as supporting bottom-up environmental conservation by taking the concerns of citizens into account [18]. Further, it enhances the local communities' awareness of environmental concerns and thereby reinforces their willingness to engage in environmental conservation [19–21]. Scientists have recognized the local communities' involvement in data collection in several sectors including population dynamics of animal species [22–24], marine debris abundance in sanctuaries [25], assessment of soil characteristics in urban green spaces [26], and development of green infrastructure and urban green spaces [27]. Citizen science has been successfully applied for the creation of data sets and monitoring of water quality in river catchments [28], streams and lakes [29,30], and wetlands [31].

Powai Lake is a cornerstone ecosystem in the megacity of Mumbai with rich biodiversity [32–34], around which the suburb of Powai has rapidly developed into a residential and commercial hub in the last 3–4 decades. The developed communities of Powai are connected to a sewerage network. However, local informal settlements are not connected to a sewerage network with some portion of their wastewaters running into the Lake [35]. Recent studies indicate that poor water quality (including levels of organics and nutrients) in Powai Lake are associated with disposal of sewage and urban runoff as well as episodic pollution on account of idol immersion and religious rituals [1,36–41]. Surya et al. [42], in their study on fish ecology, linked the ecological degradation of the Lake to pollution inflows. These monitoring studies had a limited number of sampling points and were conducted over a short span of time.

The degradation of lakes, rivers, creeks, and ocean-fronts in Mumbai is likely to have large-scale impacts on the City's green spaces. For example, the prime and favored residential and institutional locations in Powai happen to be in the vicinity of the contiguous blue-green ecosystem encompassing Powai Lake, Aarey woods, and Sanjay Gandhi National Park. It is not surprising that the youth in Mumbai and the citizens of Powai area joined hands with non-governmental organizations (NGOs) to oppose construction of a rail car shed near these remaining green spaces, resulting in their conservation [43]. The continued growing attention to preserving and restoring these green spaces is key to maintaining functioning urban ecosystems.

It is increasingly evident that blue and green ecosystems are mutually dependent and often quite delicate. The selection of technological interventions for lake rejuvenation necessitates robust and continuous information on water quality and wastewater discharges. The main objective addressed in the present study was to systematically assess pollution hotspots and the temporal drivers of water quality in Powai Lake. Water quality indices were used to describe the variations in the state of the environment, as well as to communicate effectively to the community and decision makers. This study incorporated citizen science to complement data collection by the research team as well as to engage the local population as a bridge between the technical team and the civic administration. Finally, this study discusses the rejuvenation plan for Powai Lake based on the insights of professional environmental scientists, the civic administration, and the agenda articulated by the involvement of citizen scientists.

2. Methods

2.1. Study Area

Powai Lake (19°7′41.38″ N, 72°54′18.61″ E) is situated in metropolitan Mumbai and is one of its most beautiful landscapes (Figure 1). The Lake came into existence in 1891, when a 10 m tall barrage was constructed between two hillocks across Powai Basin to harvest rainwater for drinking purposes. The water was found to be unfit for drinking due to its indiscriminate use for domestic purposes by local people and also due to addition of sewage. However, a rich assortment of flora and fauna grew around Powai Lake including 50 species of birds and other aquatic species [44]. It was leased to the Maharashtra State Angling Association and is a primary angling spot in Mumbai and home to many Indian carp fish families [45].

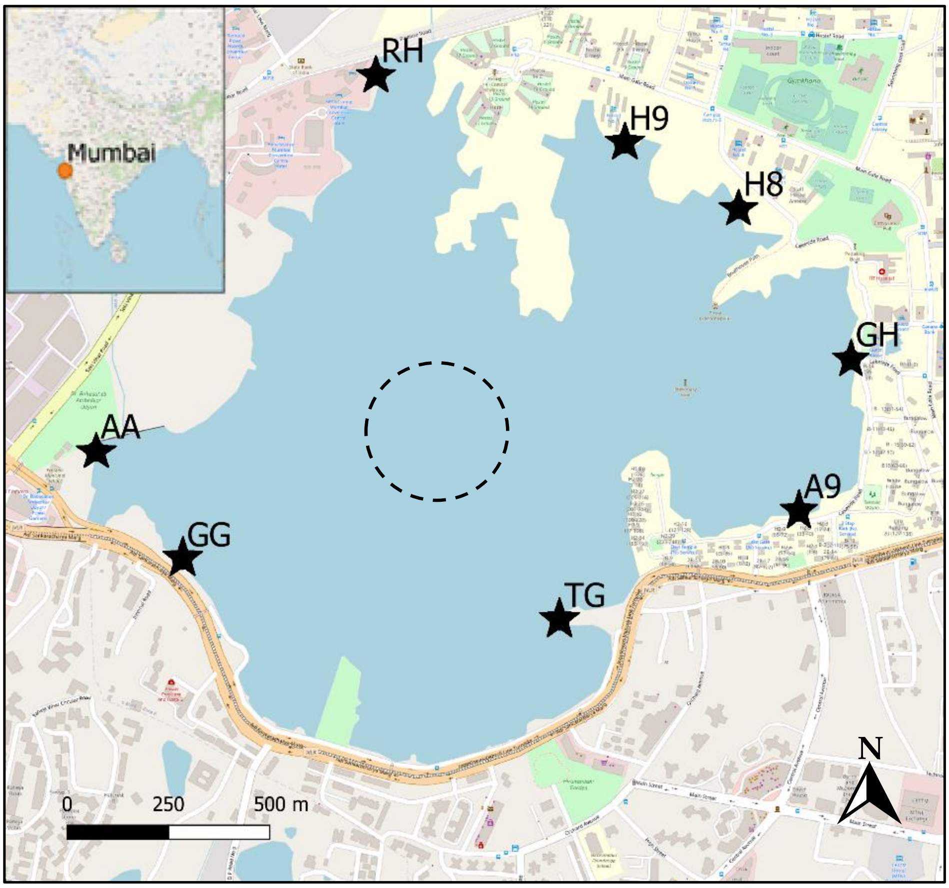

Figure 1. The study area in this research is the Powai Lake (19°7′41.38″ N, 72°54′18.61″ E) in the City of Mumbai, State of Maharashtra, India. The eight designated sampling stations are indicated by black stars on the Lake periphery and the approximate location for occasional sampling in the central zone of the Lake is indicated by the black dotted circle.

Powai Lake has approximately 3 m depth along the periphery and 10 m in the middle [37]. Located at an altitude of 58.5 m above sea level, the Lake has an extension of 2.2 km^2 with a catchment area of 6.61 km^2. It is surrounded by IIT, NITIE, Vihar Lake, Powai Garden, and residential as well as commercial complexes. The rapid urbanization of the surrounding areas has led to siltation of the lake, encroachment by builders, disposal of sewage, and deforestation in the surrounding regions [35].

2.2. Recruitment and Training of Citizen Scientists and Their Engagement in Data Collection

In the present study, multiple training events (6) were organized for citizen scientists in relation to the HSBC sustainability training programs (STPs) and conducted by Earthwatch India in coordination with IITB Research Scientists. In each event, new community and HSBC volunteers were trained to become citizen scientists and engaged in water quality monitoring for Powai Lake. These citizen scientists were residents of Mumbai and were highly motivated and encouraged to participate in the monitoring activities for Powai Lake.

In each training event, citizen scientists were introduced to the significance of water quality, and the need for rejuvenation of the lake and ecosystem through successful case studies [1,11–13]. This was followed by a one-hour brainstorming session that addressed queries of citizen scientists relating to the science behind water quality monitoring, treatment of wastewater using NTSs, economic and social implications of lake rejuvenation, etc. Training on monitoring methods, parameters, and monitoring instruments required two hours.

It was envisaged that participants will benefit from increased scientific knowledge, empowerment related to potential solutions, awareness of the city's environmental problems, and satisfaction by being connected to nature and people. In each STP, citizen scientists were also given hands-on experience at the pilot-scale constructed wetland, which treats domestic wastewater, at the IITB research station. Research scientists and citizen scientists actively discussed its potential for treating and reusing municipal wastewater and the significance of such an intervention in a given community towards the implementation of concepts of the circular economy. Subsequently, volunteers dispersed to sampling stations for collection of water quality data. Three sampling stations were designated for citizen scientists for sample collection and analysis of water quality. Research scientists worked closely with the citizen scientists and ensured that water quality monitoring was carried out following determined measurement and quality control protocols.

2.3. Organization of Water Quality Monitoring and Data Analyses

Monthly water quality monitoring by citizen scientists and professional scientists was conducted between April 2018 and March 2020. An initial reconnaissance survey was conducted along the entire periphery of Powai Lake, and by combining the information on the pollution potential of land use along the periphery, the eight sampling locations were designated (Table 1, Figure 1). Land use activities identified were fishing, cattle rearing, and religious events. Potential wastewater discharges were identified and geolocated. The selection of sampling locations was also conditioned by their accessibility and safety of the citizen scientists and based on experience of the Powai Lake Rejuvenation Committee. As the Lake is a habitat for reptiles and crocodiles [46], sampling could not be conducted at the center of the Lake. However, given these safety concerns, efforts were made to collect samples occasionally with the help of local fishermen. Although the exact GPS locations of those sampling spots could not be recorded, the approximate zone can be seen as the black dotted circle in Figure 1. In all, four sampling campaigns were conducted during the study period and two nearby locations were chosen for collecting samples in the central zone of the Lake during each campaign.

Table 1. The details of eight designated stations for sampling campaigns for the study in Powai Lake.

Sr. No.	Sites	Coordinates	Description
1	AA	19°7′35.37″ N, 72°53′45.06″ E	Observed angling activities
2	GG	19°7′26.78″ N, 72°53′52.47″ E	Idol immersion and occasional fishing noticed
3	TG	19°7′22.58″ N, 72°54′24.08″ E	Recreational spot and idol immersion observed
4	A9	19°7′31.25″ N, 72°54′44.53″ E	Box culvert for stormwater drains
5	GH	19°7′43.48″ N, 72°54′48.77″ E	Idol immersion and recreation were noticed
6	H8	19°7′56.56″ N, 72°54′40.21″ E	Stormwater drain
7	H9	19°8′1.80″ N, 72°54′30.27″ E	Site receiving runoff from Vihar Lake water
8	RH	19°8′6.75″ N, 72°54′7.96″ E	Stormwater drain

As per the CPCB's classification of surface waters [47], 'Class A' water quality is typically considered the most suitable water resource for feeding the water works (responsible for production of drinking water by treating the surface water). Vihar Lake has been a Class A resource and feeds into the water works for the mega-city of Mumbai. Therefore, H9 station receiving water from Vihar Lake was taken as a reference station to study the variations in pollution in Powai Lake.

Fifteen sampling campaigns were conducted between April 2018 and March 2020 by the IITB Research Team and 6 sampling campaigns were by citizen scientists. Citizen scientists collected water samples from three predetermined sampling locations (GG, TG, and H9) and monitored water quality parameters temperature, pH, total dissolved solids (TDS), and dissolved oxygen (DO) using portable real-time instruments. Samples were transported at 4 °C to a research laboratory for further analyses following the *Standard Methods for the Examination of Water and Wastewater*.

A portable HACH USA (HQ40d) multi-meter was used for in situ analyses of pH, temperature, TDS, DO, ammonia nitrogen (NH_3-N), and nitrate nitrogen (NO_3-N). Further, chemical oxygen demand (COD) was determined using the closed reflux method, and biochemical oxygen demand (BOD_5) was measured after incubation for five days at 20 °C. For total kjeldahl nitrogen (TKN) estimation, digestion and distillation were carried out using a block digestion unit and a semi-automatic steam distillation unit, respectively. The ammonium molybdate spectrophotometric method was used to determine total phosphorous (TP). Fecal coliforms (FC) were estimated by membrane filtration followed by incubation at 44.5 °C [48].

For the assessment of seasonal variations in each sampling location, the 21 sampling events were grouped in seasons, namely monsoon (June to September), post-monsoon (October to January), and summer (February to May). In each season, eight observations for each parameter were recorded for each station. Pollutant concentrations recorded at the Lake's center were not numerous enough to establish seasonal variations, hence they were represented with mean values and standard deviation (SD). Data were analyzed using Student's *t*-test (0.05% level of significance) for evaluating differences in seasonal changes and spatial variations. All statistical analyses were carried in Microsoft Excel (2016). QGIS 3.4.3 was used to create maps of the study area and the water quality index.

2.4. Water Quality Index

The National Sanitation Foundation Water Quality Index (WQI) [49,50] was used to classify changes in lake water quality. This widely used index is based on nine parameters: DO, fecal coliform (CFU), pH, BOD_5, temperature, total phosphate, nitrate, turbidity, and total solids (TS). The provision to add or eliminate any parameter as and when required is also allowed considering the significance of monitored water quality. In the present study, WQI was calculated based on the eight parameters for twenty-one sampling months. As an alternative to TS, TDS was used in the calculations. The results of WQI had no considerable variations when non-original parameter TDS was used in place of TS [51]. The WQI is calculated based on Equation (1) [50]:

$$\text{NSFWQI} = \frac{\sum_{i=1}^{N} W_i Q_i}{\sum_{i=1}^{N} W_i}, \quad (1)$$

where Q_i is the sub-index and W_i is the weight coefficient for ith water quality parameter. The number of water quality parameters is represented as N, and the quality is reported as per the values shown in Table 2. To convert the water quality parameters from concentration metrics to new units of pollution level or sub-indices, a set of sub-index rating curves was used [52]. This single index of pollution was calculated and expressed on a normalized pollution scale, and the overall WQI was then reported as the weighted geometrical average of individual parameters. Thus, weight coefficients of these parameters were 0.17 (DO), 0.16 (FC), 0.11 (BOD_5), 0.11 (pH), 0.1 (NO_3N), 0.1 (temp), 0.1 (TP), and 0.07 (TDS).

Table 2. Interpretation of WQI values as reported by Brown et al. [50].

NSFWQI	Description of Quality
91–100	Excellent
71–90	Good
51–70	Medium
26–50	Bad
0–25	Very Bad

2.5. Development of a Rejuvenation Plan for Powai Lake

The National Environment Policy (NEP) [53] recommends that action plans for lake restoration integrate conservation strategies along with poverty alleviation, livelihood improvement, and eco-tourism. Present and future generations should receive ecological, social, and economic benefits of a well-managed lake [54], and therefore strategies should be based on multi-stakeholder partnerships and regulatory enforcement [39,55]. Successful lake rejuvenation case studies in India that provided local communities with aesthetic and recreational spaces, and a source of revenue, are very limited. One such example was the Mansagar Lake rejuvenation in the City of Jaipur, State of Rajasthan. Environmental conservation, heritage restoration, and business promotion were all addressed while executing the restoration plan in Mansagar Lake. A successful public–private partnership model for rejuvenation through NbS was completed in eight years, and the lake returned to full health [1,14]. Similarly, a multi-stakeholder socially inclusive restoration of Kaikondrahalli Lake in the City of Bengaluru, State of Karnataka, was carried through the local administrative body, with community maintenance employed by an NGO and funding for maintenance provided by another NGO, along with the Revenue Department providing administrative and legal support [9,10,14].

In the past two decades, several attempts have been made to reduce pollution loads to the Powai Lake by the municipality as well as the Government of Maharashtra and Ministry of Environment, Forest and Climate Change (MoEF&CC), GoI, New Delhi, India. Their efforts were limited to “direct interventions in Powai Lake”. While these efforts had some success, the underlying problem remained unaddressed. The limitations of these non-integrated approaches were addressed while developing the present rejuvenation plan, which was prepared from scientific evidence gathered from water quality monitoring, a growing experience on lake rejuvenation, and also through the engagement of stakeholders. Along with citizen scientists’ participation in water quality monitoring, capacity building workshops and round-table conferences were conducted to provide a shared knowledge of the concepts in urban and rural ecological restoration of blue-green spaces through water reuse and community engagement. Stakeholders included regulatory agencies, NGOs, industry, municipality, and faculty members, graduate, post-graduate, and doctoral students from educational institutions in India especially Mumbai, Nepal, Uganda, and three universities from the European Union; namely, Norwegian University of Science and Technology from Ålesund, Instituto Superior Técnico from Lisbon, and TU Delft from The Netherlands [56]. The action plan for Powai Lake rejuvenation was prepared employing inputs from panel discussions with a wide range of local and non-local stakeholders.

3. Results and Discussion

3.1. Data Collection

A total of 544 data points were collected by citizen scientists in the course of six sampling campaigns during few summer and post-monsoon months (Table 3). Data collected by citizen scientists in summer and post-monsoon months were significantly correlated with research scientists' data in the months in corresponding seasons.

Table 3. Details of water sampling campaigns at Powai Lake by the citizen scientists in collaboration with IITB research scientists.

Sr. No.	Dates of Sampling Campaigns	Sampling Stations	Sample Size	Maximum No. of Parameters Monitored	Total Data Points Collected
1	12–13 April 2018	3 (GG, TG, H9)	27	4	140
2	11–12 October 2018	3 (GG, TG, H9)	42	4	168
3	21–22 February 2019	3 (GG, TG, H9)	29	4	116
4	4–5 April 2019	1 (H9)	10	4	40
5	7–8 November 2019	1 (H9)	10	4	40
6	28–29 November 2019	1 (H9)	10	4	40
				Total Data Sets	544

Water quality monitoring of Powai Lake conducted by IITB Research Scientists expanded and validated the monitoring conducted by citizen scientists (Table 4).

Table 4. Details of twenty-one sampling campaigns at Powai Lake conducted by the IITB research scientists.

Sampling Location	No. of. Months Sampled	No. of. Sampling Stations	Sample Size in One Campaign	Total Samples Collected	Maximum No. of Parameters Monitored
Lake Periphery	21	8	8	168	11
Lake Centre	4	2	2	16	11

Capacity building and awareness creation was successfully carried out during citizen scientist training through the classroom interaction and walk-the-talk during the sampling campaigns. The interaction helped cultivate the 'environmental conscience' of the participants, a key benefit from the incorporation of citizen science in environmental monitoring [18,21]. The questions and comments of the citizen scientists indicated that they recognized the potential importance of NTSs for lake rejuvenation. The incorporation of citizen science facilitated not only scientific knowledge gain and empowerment for local communities, but also helped in setting the scientific agenda for technological intervention for the Powai Lake rejuvenation plan.

3.2. DO, pH, and TDS

Lake temperature recorded in the present study ranged between 26 °C and 31 °C, with no significant spatial or temporal variations. Drastic temperature variations that could affect aquatic life [57] were not observed in the study. These observations were comparable with the values reported by Usman et al. [40] and Kadu et al. [58]. It is also to be noted that one of the previous studies reported water temperature values in the range of 20 °C to 34 °C in Powai Lake [39]. This disparity could be due to the difference in the location of the sampling sites, depths of sampling, and the temperatures of incoming wastewaters, as well as the differences in sampling periods of the studies as compared to this study. Water temperature was not monitored in the center of the Lake.

pH varied between 6.97 and 8.07, (Figure 2), with no significant spatio-temporal variations. pH values were on the higher side of the permissible tolerable alkaline pH (<8), especially during the summer season at sampling stations GG, TG, GH, and H9. Usman et al. [40] reported a similar range of pH values in Powai Lake during a one-year study period between 2016 and 2017. A prime factor for the high pH levels in Powai Lake might be the increased assimilation of carbonates and bicarbonates triggered by immersion of idols year-after-year in large numbers in Powai Lake. These changes in pH levels can affect the aquatic flora and fauna in the Lake.

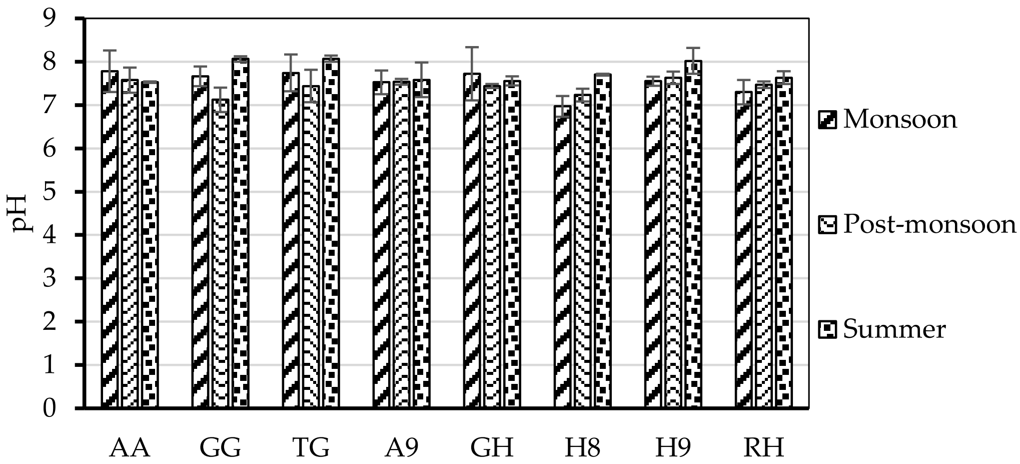

Figure 2. Seasonal variation of pH in Powai Lake represented as mean at different sampling locations. Error bars represent standard deviation.

The average DO concentrations at A9, RH, H8, and GH stations were below 4 mg/L, which is the minimum required DO concentration for healthy aquatic life in freshwater [59] (Figure 3). The lowest DO (<2 mg/L) was observed in sampling stations A9 and RH. All seasons evidenced similar DO concentrations at GH and H8, implying unvarying pollution. The DO concentrations at AA, GG, TG, and A9 stations exhibited significant variation between monsoon and post-monsoon seasons ($p < 0.05$), with lower concentrations in post-monsoon. Similarly, significant differences in the DO concentrations were observed between summer and monsoon seasons at sampling stations GG, TG, AA, RH, and A9 with the lowest DO concentrations during the summer ($p < 0.05$). The decrease in DO concentrations from monsoon to summer season could be due to the pollution loading, together with excessive hyacinth growth with eutrophic conditions.

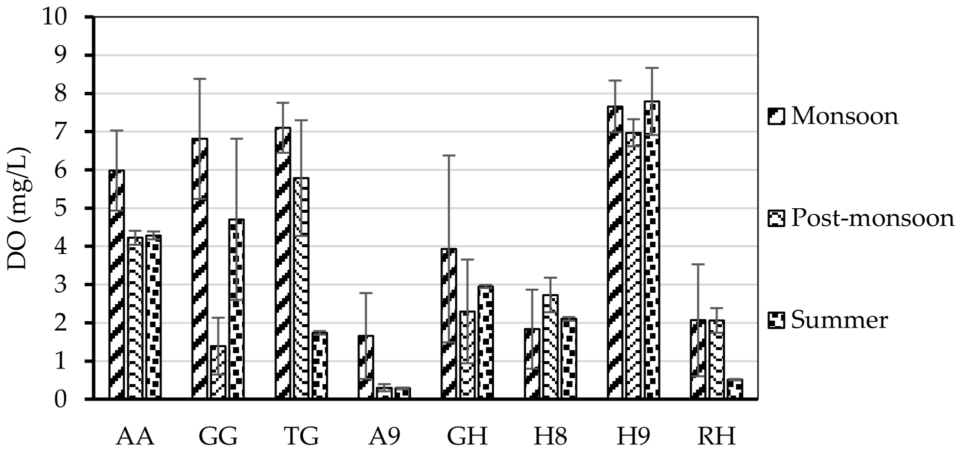

Figure 3. Seasonal variation of DO in Powai Lake represented as mean at different sampling locations. Error bars represent standard deviation.

Unlike other sites, no significant seasonal variation in DO concentrations was observed at H9 as there was no pollution loading at the site. The comparison of DO levels reported by Ratheesh et al. [38] (3.58–7.19 mg/L), Salaskar and Muley [39] (3.9–6.3 mg/L), and Surya et al. [42] (2.8–8 mg/L) with the DO levels in the present study clearly suggests that the DO concentrations have drastically altered in recent years.

From the littoral and limnetic zones monitored in Powai Lake, it was observed that the mean TDS concentration in the Lake was, respectively, 223 ± 110 mg/L (n = 143) and 157 ± 10 (n = 16), with significant differences ($p < 0.01$) between the two zones. These high levels of TDS can interfere with the mineral content of water and induce high osmotic pressure, which can harm aquatic species [60]. As depicted in Figure 4, the highest TDS concentrations (>500 mg/L) at more than desirable limits [61], were observed at A9 and RH sampling stations during all seasons, an indication of the continually higher pollution inflows through these sites. In addition, stations AA, GG, and GH had significantly ($p < 0.05$) high TDS concentrations during the summer months. From the present study, it is evident that in Powai Lake there was an increase in TDS through 2018–2020 when compared to concentrations of 50–220 mg/L, 185–238 mg/L, and 257 ± 116 mg/L reported, respectively, by Usman et al. [40] in 2017–2018, Kadu et al. [58] in 2014–2015, and Salaskar and Muley [39] in 2010–2012.

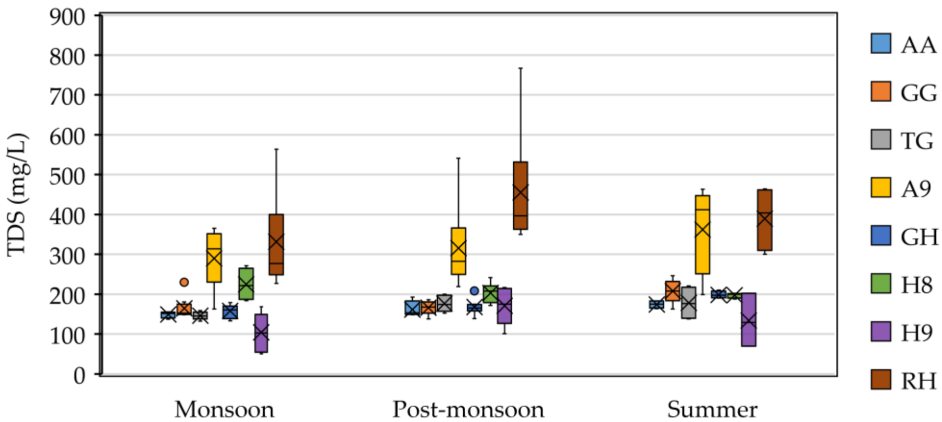

Figure 4. Seasonal variation of TDS in Powai Lake at different sampling locations shown as box plots. The top and bottom of the box indicate the 75th and 25th percentiles, line within the box represents median, cross represents mean, range bar represents the maximum and minimum values, and dots represent the outliers.

3.3. Organic Pollution

In the course of this study, at least one incidence of high COD (>50 mg/L) was observed in all the stations, except for H9, with the highest concentrations observed during summer and post-monsoon months. Figure 5 shows the seasonal variation in COD at the eight sampling locations in Powai Lake. COD concentrations were significantly higher during the post-monsoon season compared to the monsoon season at sampling stations GG, TG, and A9 ($p < 0.05$). However, no significant variations in COD concentrations were observed between post-monsoon and summer seasons at these stations, implying a similar pollution load. These observations also confirm that sources of pollution at these sites were more anthropogenic in nature.

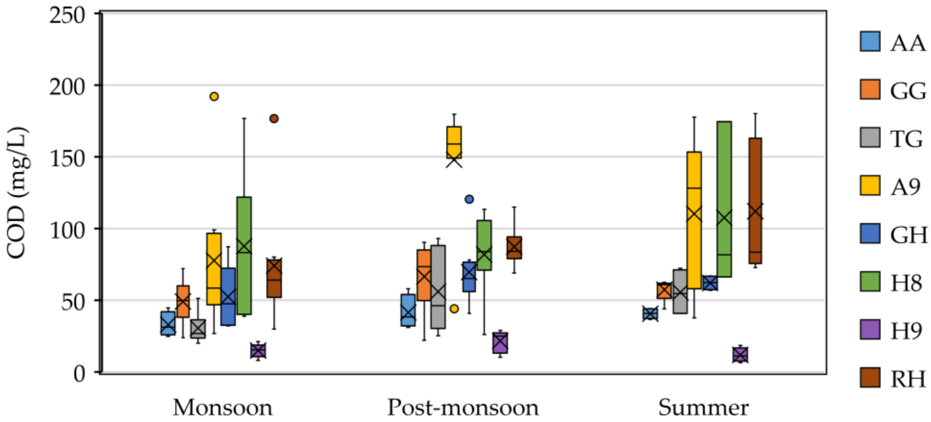

Figure 5. Seasonal variation of COD in Powai Lake at different sampling locations shown as box plots. The top and bottom of the box indicate the 75th and 25th percentiles, line within the box represents median, cross represents mean, range bar represents the maximum and minimum values, and dots represent the outliers.

The RH station had the highest COD (140–180 mg/L) in two sampling campaigns. However, at RH, temporal variations were not markedly different as compared to other stations (AA, GH, and H8) receiving major pollution loads. The H9 station had the highest COD in the post-monsoon months; significant COD variations were also observed between monsoon and post-monsoon ($p < 0.05$) as well as post-monsoon and summer ($p < 0.05$) months. COD in the limnetic zone of 6.3–28.8 mg/L (mean 16.1 $\pm$ 6.3; $n = 16$) was significantly different compared to the periphery ($p < 0.05$).

Bhateria and Jain [62] reported that natural sources like precipitation can bring nutrients, organic loading, and base-metal cations into the lake. There is runoff and erosion during monsoon season and subsequently these inputs were evident post-monsoon with increased COD at the H9 site. The Indian Meteorological Department reported that Mumbai City received 2239 mm and 3475 mm rainfall during 2018 and 2019, respectively [63]. The decreased trend in pollution during monsoon may be attributed to the dilution of lake water receiving elevated precipitation. Compared to previous studies [39,40,58], COD values in the present study were the highest (>150 mg/L) observations in past six years.

Temporal BOD_5 differences were observed to follow a similar trend as that of COD (Figure 6). BOD_5 concentrations were much higher than the limits (<3 mg/L) recommended by the ISI Standard [61] for the intended use of the water resource. During the study, at least one incidence of very high BOD_5 (>20 mg/L) was observed at all stations, except for H9, with the highest concentrations observed during summer and post-monsoon months. Similar to the COD trend, stations A9, H8, and RH had the highest BOD_5 (>60 mg/L), indicating the presence of discharges of partially treated domestic wastewaters to the Lake. BOD_5 values at the center of the Lake were 3–13 mg/L (mean 8.1 $\pm$ 3.1; $n = 16$) significantly different from the periphery ($p < 0.05$). Compared to the previous studies in the limnetic zones [38–40,58] and littoral zone [58] of Powai Lake, a clear increase in BOD_5 was observed, particularly in the littoral zone.

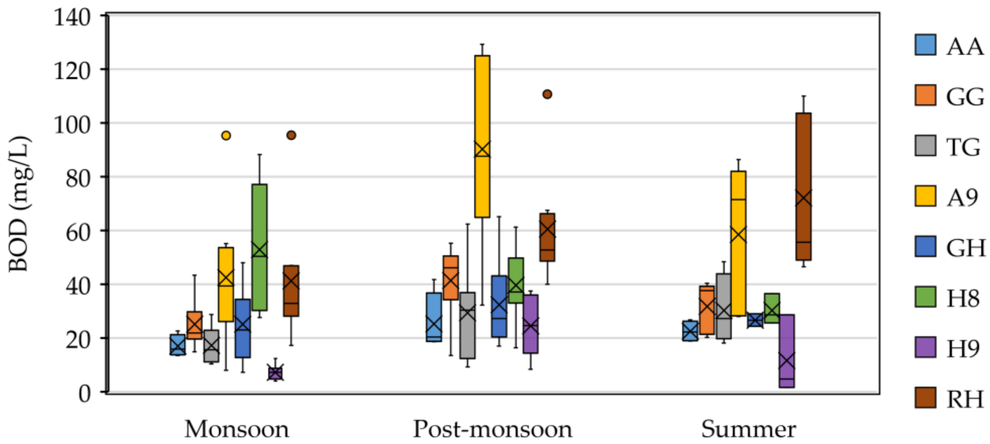

Figure 6. Seasonal variation of BOD_5 in Powai Lake at different sampling locations shown as box plots. The top and bottom of the box indicate the 75th and 25th percentiles, line within the box represents median, cross represents mean, range bar represents the maximum and minimum values, and dots represent the outliers.

3.4. Nutrients and Pathogens

Spatio-temporal variations in organic nitrogen, NO_3-N, and NH_3-N were significant (Figures 7–9). The highest concentrations of TKN were recorded at stations A9 (50.4 ± 19.3 mg/L) and RH (34.4 ± 12.3 mg/L) during the summer months. At TG, significant variations ($p < 0.05$) in TKN were observed post-monsoon in comparison with summer and monsoon, with higher TKN observations in the post-monsoon season.

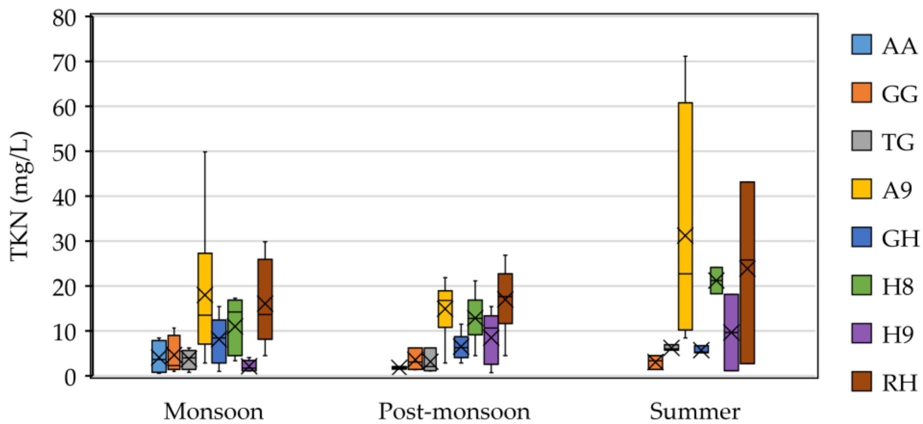

Figure 7. Seasonal variation of TKN in Powai Lake at different sampling locations shown as box plots. The top and bottom of the box indicate the 75th and 25th percentiles, line within the box represents median, cross represents mean, range bar represents the maximum and minimum values, and dots represent the outliers.

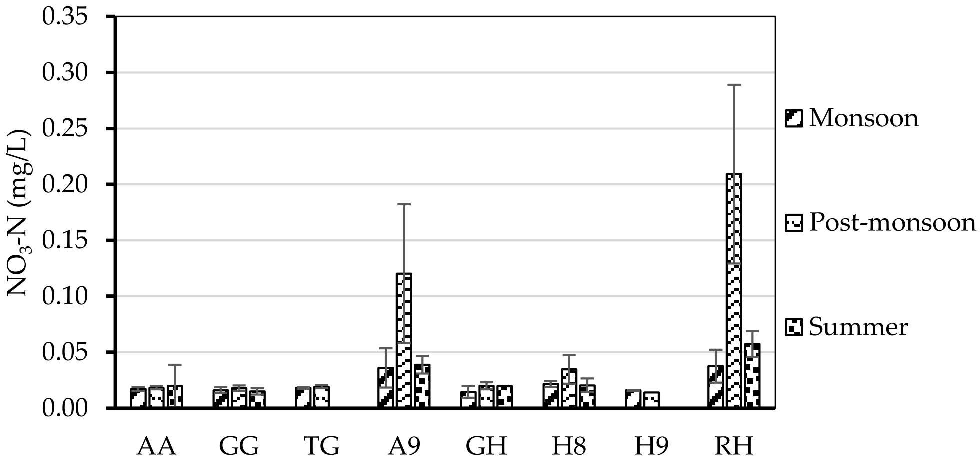

Figure 8. Seasonal variation of NO_3-N in Powai Lake represented as mean at different sampling locations. Error bars represent standard deviation.

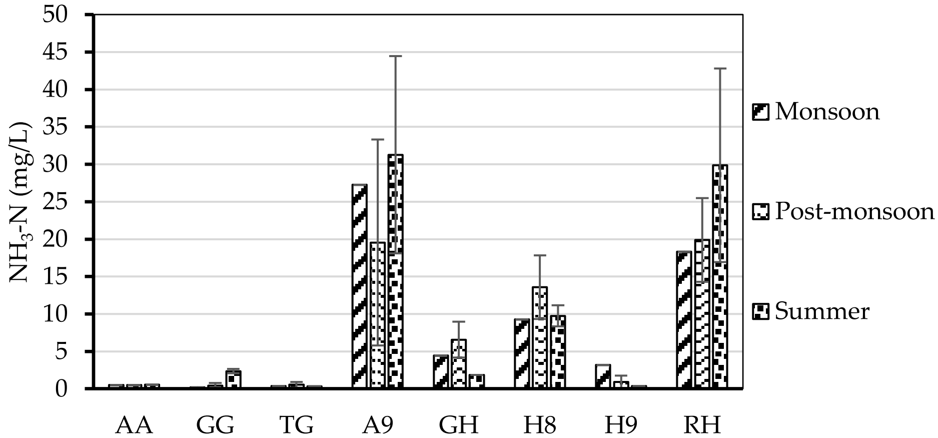

Figure 9. Seasonal variation of NH_3-N in Powai Lake represented as mean at different sampling locations. Error bars represent standard deviation.

Similar to COD and BOD_5 observed in the post-monsoon season at TG, organic nitrogen was also observed to be the highest in the post-monsoon season. Similarly, at station H9, TKN dynamics were comparable to COD and BOD_5, with post-monsoon months witnessing higher concentrations and variations significantly ($p < 0.05$) differing from monsoon season. This is attributed to the natural sources bringing pollutants through runoff and erosion. TKN was not detected at AA station during summer months. Further, stations GG, A9, GH, H8, and RH did not exhibit any significant variations in TKN for the three seasons, implying similar nutrient loading. At the center of the Lake, lower concentrations (1.87 ± 0.77 mg/L) were observed. The enrichments of nitrogen species in water bodies eventually induces anoxic conditions, toxicity in invertebrates, fish mortality, and algal blooms, resulting in habitat and biodiversity loss [64,65].

Unlike organic pollutants and other nutrients, merely a few incidences of elevated NO_3-N were measured (Figure 8). NO_3-N concentrations in the Lake varied between <0.06 mg/L, 0.06–0.63 mg/L, and 0.06–0.08 mg/L, in monsoon, post-monsoon, and summer seasons respectively. Stations A9 and RH recorded the highest NO_3-N in all seasons, though no seasonal variations were observed. The concentrations measured at A9 and RH imply the high NO_3-N loadings due to wastewater inputs in monsoon season, and subsequent reduction owing to uptake by weeds and water hyacinths in summer.

The observed low NO_3-N concentrations in the littoral zones of the present study compared to past studies in the limnetic zones [38–40] were attributed to nutrient retention by weeds and algal blooms in the Lake's littoral zone, converting NO_3-N to NH_3-N or elemental nitrogen. Further, the prevalence of NO_3-N is reportedly highest in summer and post-monsoon seasons owing to fertilizer inputs, livestock rearing, and sewage inlets [59], and is recognized by concentrations in the range 0.5–1.5 mg/L in eutrophic lakes [65] as witnessed in the present study.

At least one incidence of elevated NH_3-N was observed in all eight sampling stations, indicating the deposition of organic wastes at these sites (Figure 9). The highest concentrations of NH_3-N were observed in A9, H8, and RH. Levels of NH_3-N > 1.2 mg/L strongly compromise wildlife and fisheries in surface water bodies [66]. Such concentrations were observed at sampling stations A9, GH, H8, and RH during all sampling months, with the highest recorded concentration of 48.7 mg/L at RH station during summer. Other stations with very high NH_3-N (10–45 mg/L) recorded include A9, GH, and H8. Further, NH_3-N > 1.2 mg/L was also observed at GG during the summer season and at H9 during monsoon and post-monsoon seasons.

Moreover, ammonia nitrogen toxicity on fish is ten times more detrimental at pH 8 as compared to pH 7 [66]. As detailed earlier, in at least one of the sampling campaign months, lake water at sampling stations AA, GG, TG, GH, and H9 was observed with $\geq$pH 8. Alarmingly, these concentrations of NH_3-N in the littoral zones were 30–40 times higher than the variations in the limnetic zone reported in past studies [35,37]. These high concentrations in the Lake's littoral zone may be attributed to the photosynthetic activities of weeds and algal blooms converting NO_3-N to NH_3-N.

Seasonal variation of TP is shown in Figure 10. At the center of the Lake, average TP was 0.93 $\pm$ 0.61 mg/L (n = 16), with a maximum of 1.7 mg/L in the monsoon and post-monsoon seasons. TP concentrations in the Powai Lake periphery ranged between BDL—2.78 mg/L, BDL—1.49 mg/L, and 0.05–2.45 mg/L in monsoon, post-monsoon, and summer seasons, respectively. These values were 10 times higher than the reported concentrations in the limnetic zones over the past decade [37,38] and TP concentrations reported in 2016–2017 [40] were similar to the present study. TP is a limiting factor for algal growth [65,67] and should remain below 50 µg/L to reduce the risk of algal blooms [59]. At least one incidence of high TP (>0.05 mg/L) was observed in all the stations, with the highest concentrations detected during summer and post-monsoon months.

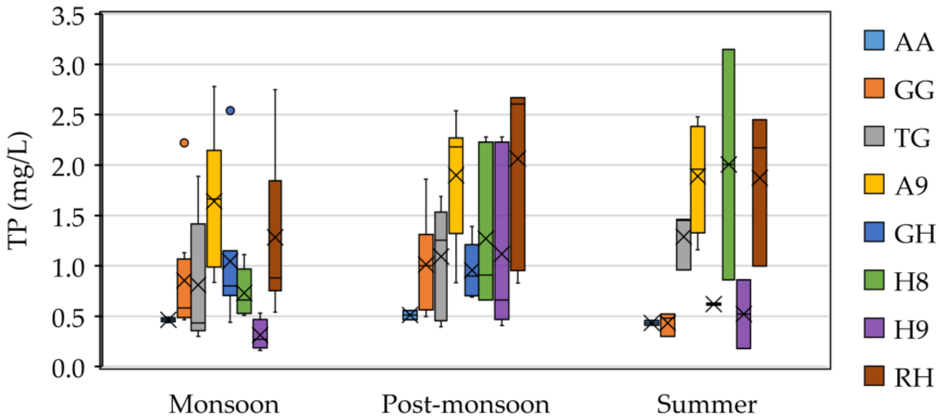

Figure 10. Seasonal variation of TP in Powai Lake at different sampling locations shown as box plots. The top and bottom of the box indicate the 75th and 25th percentiles, line within the box represents median, cross represents mean, range bar represents the maximum and minimum values, and dots represent the outliers.

No significant temporal variations were observed in any of the sampling stations and H9 had the lowest concentration in all seasons (p < 0.05). The few incidences of elevated TP concentrations (up to 0.53 mg/L) at H9 were attributed to internal phosphorous loading. Phosphorous accumulated in lake sediments, particularly those bound to iron compounds, which are redox sensitive, are mobile in nature and eventually released into water [68]. The nutrient sources of the lake can be examined through the N:P ratios in the pelagic zone of the water resource. N:P ratios in lakes ranging from 20 to >200 have been associated with precipitation, groundwater, and nutrient export from lands and soils. N:P between 10 and <1 is often associated with sediments, sewage, and urban runoff [67]. From the present study, N:P ratios in the littoral and limnetic zones range between 2 and 11, evidencing nutrient loads from sediments, sewage, and urban runoff. Likewise, the evidence of organics and nutrients at the Lake's center highlights the chronic nature of pollution in Powai Lake.

In the present study, all the eight sampling stations in the Lake periphery showed fecal coliform contamination; no significant variations were identified due to insufficient data points (Figure 11). Maximum fecal coliform densities reached up to 2×10^4 CFU/100 mL during summer months at station RH, followed by H8 with 1.6×10^4 CFU/100 mL, inferring that the highest sewage contamination occurred at these sites. Fecal coliforms were not detected for the samples collected from the center; however, the contamination of pathogens at the center of the Lake cannot be ruled out. The sampling events at the center of the lake were insufficient to establish a statistically significant result.

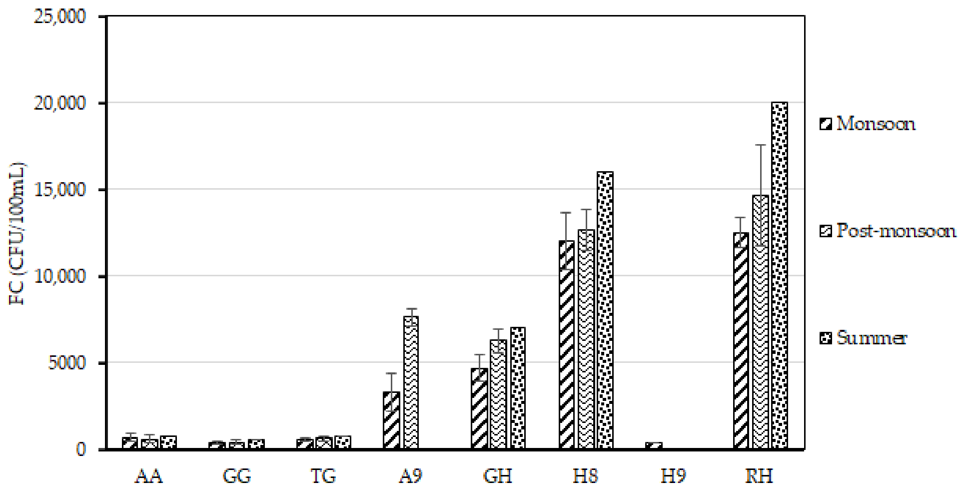

Figure 11. Seasonal variation of fecal coliform in Powai Lake represented as mean at different sampling locations. Error bars represent standard deviation.

As per USEPA [69], <410 CFU/100 mL is the recommended maximum statistical threshold value for total coliforms in recreational water bodies. All eight locations in the Lake periphery had FC concentrations that made them unfit for recreational purposes. Threshold values for pathogens (total coliform/100 mL) in water bodies used as Class A (drinking water source), Class B (outdoor bathing), or Class C (drinking water source after conventional treatment) by CPCB [47] are <50, <500, and <5000 respectively. Thus, Powai Lake water does not qualify as a source for Class A, Class B, or Class C use.

The presence of potentially pathogenic bacteria (indicated by FC of 4×10^2 CFU/100 mL) at station H9 was unexpectedly observed in the 2018 monsoon. Reportedly, fecal coliforms and *Escherichia coli* can possibly survive even in nonhost habitats in aquatic ecosystems such as algae, zooplankton, turtles, and fish. In addition to sewage disposal, other predominant sources of fecal indicator bacteria identified were birds, dogs, seabirds, and waterfowl [70]. The habitat in the vicinity of station H9 in Powai Lake has, in fact, been frequented by many of such species that might have contributed to fecal contamination. Few other lakes in India have been studied with respect to the influence of urban settlements. Fecal coliforms reported in Nainital Lake in Dehradun with 14×10^4 MPN/100 mL [71], and Kankaria Lake and Chandola Lake in Ahmedabad with 15×10^5 CFU/100 mL and 34×10^4 CFU/100 mL, respectively [72], are comparable to the present study.

3.5. Water Quality Index for Powai Lake

Powai Lake's WQI (Figure 12) indicated that no station monitored in Powai Lake could be considered of 'excellent quality' or 'good quality'. The 'bad quality' of water at stations GG, TG, and GH could be attributed to the religious events and other activities such as recreation, fishing, bathing, and cattle rearing. Further, water quality monitoring reveals that stations A9, H8, and RH observed very high organic, nutrient, and pathogen loadings indicating that urban runoff primarily discharges from informal settlements at these sites. AA and H9 were observed with a 'medium quality' (51–70) index, owing to relatively lower pollution loads. The improved water quality at H9 is an implication of overflow water received from Vihar Lake. Similarly, occasional fishing was the only major anthropogenic activity observed at station AA, though urban surface runoff bringing pollutants at the site is likely. There was discrete seasonal variation in water quality at AA station as described in Sections 3.3 and 3.4; however, the index value (51) for AA reflects enhanced water quality. This may be attributed to the annual average concentrations considered for all pollutants while calculating WQI at AA station.

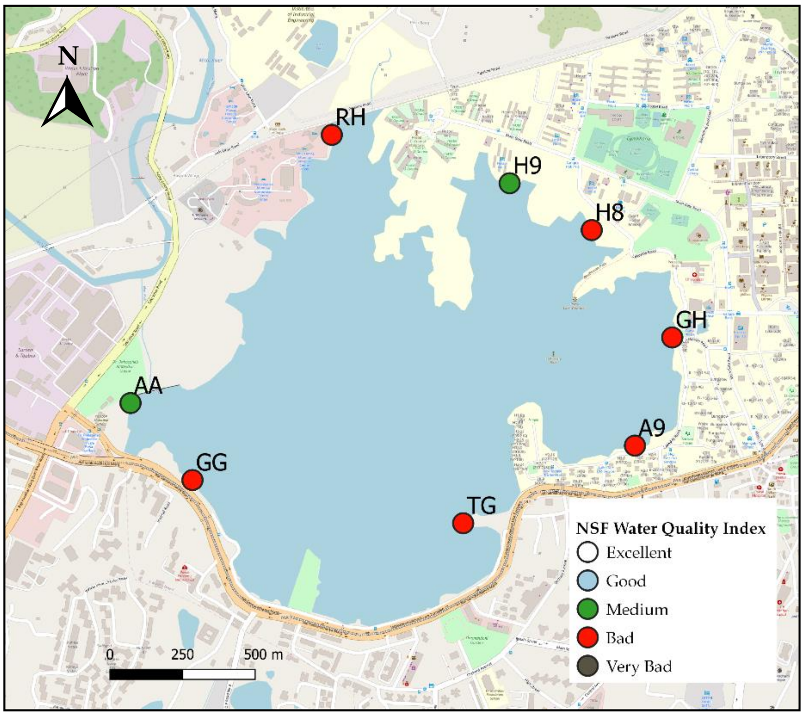

Figure 12. Water quality indexes mapped at different sampling locations along the periphery of Powai Lake.

4. Rejuvenation Plan for Powai Lake

The key issues identified in the present study for degradation of Powai Lake include anthropogenic activities occurring in and around the Lake, including idol immersion, discharge of solid wastes, sewage discharge from domestic and commercial sources, presence of water hyacinth and weeds, slit deposition, etc. The fundamental objective of a rejuvenation strategy should not only be to attain regulatory compliance but also to maintain a high quality of water suitable for recreation, performing religious rituals, process water for industry, and irrigation [1]. A summary rejuvenation plan (Figure 13) for Powai Lake was prepared using the inputs received from water quality monitoring data and through the capacity building of other accountable stakeholders, especially the citizen scientists. The plan was structured in three phases.

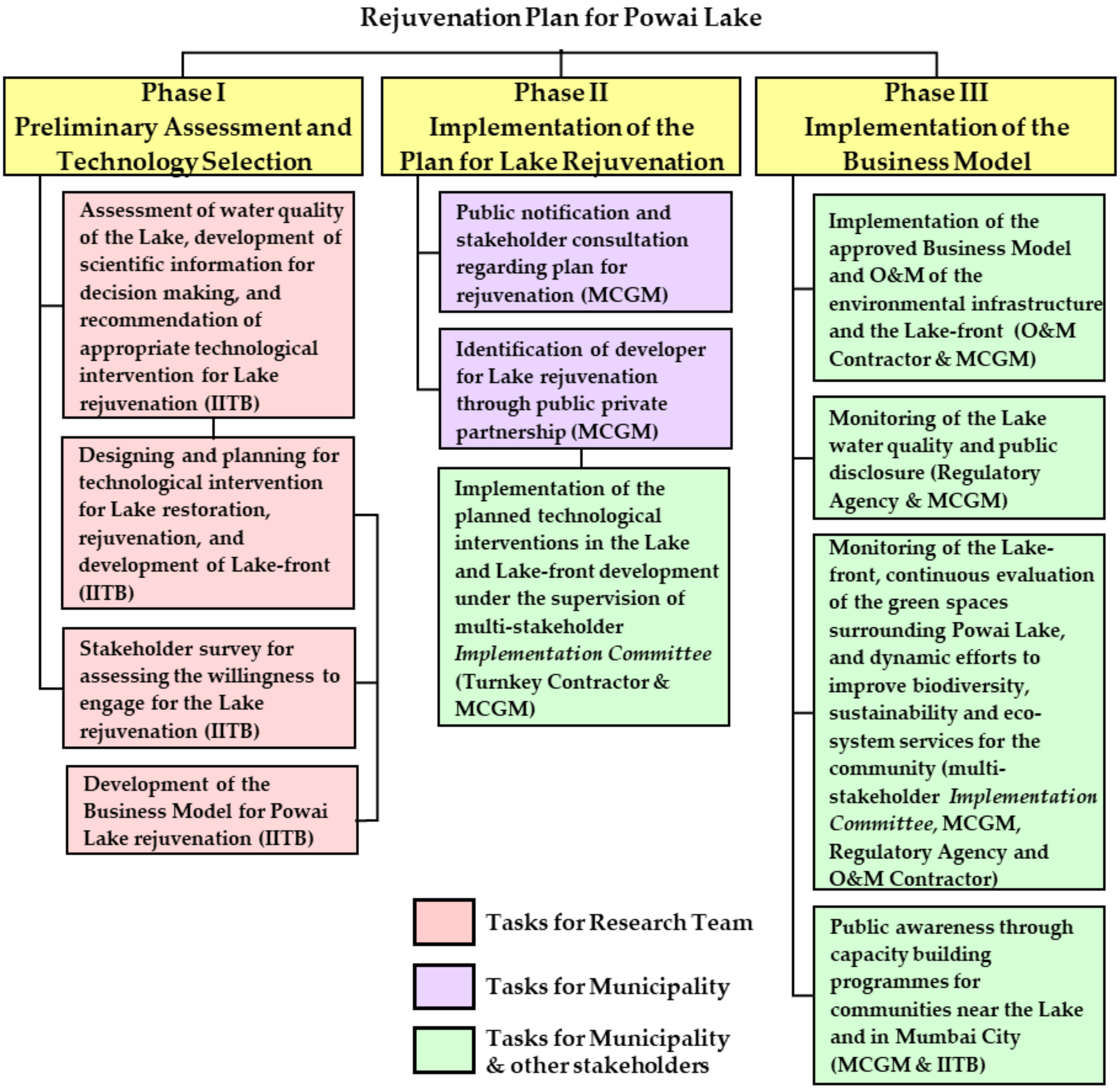

Figure 13. The proposed phase-wise plan for rejuvenation of Powai Lake and the associated tasks.

4.1. Phase I: Preliminary Assessment and Technology Selection

Phase I focuses on creating the groundwork and information flows to facilitate a sustainable rejuvenation and provide support for an appropriate technological intervention. This phase was initiated in the present project, with the support of the citizen scientists. This phase also includes an evaluation of potential technological actions to achieve lake rejuvenation and a stakeholder survey, which will help in the development of a Business Model.

NTSs are eco-technologies that enable the reestablishment of natural processes for pollution control with improved efficacy. A variety of NTSs recognized for wastewater treatment comprise CWs, natural wetlands, algal ponds, duckweed ponds, sewage-fed fish ponds, hyacinth ponds, etc. [6]. Among these NTSs, CW is one of the promising technologies that utilize plants and associated rhizospheric microorganisms for removal of pollutants from wastewater, and their applications in India have been investigated by many researchers [1,2,6,7,73]. CWs are gaining attention due to their extensive applicability all over the world, India in particular, owing to their simple construction and easy operation and maintenance in tropical climates, as well as cost effectiveness [2,6,7,11–13,74–77]. In India, CWs have been considered to be the most appropriate technology for wastewater treatment among the 108 NTSs studied in operation [7].

The decentralized eco-centric technology titled 'CW4Reuse', which is a variant of horizontal subsurface flow constructed wetland (HSSF-CW) has been developed to treat domestic wastewaters [11–13,76]. This NbS is capable of achieving climate change mitigation, pollution control in air, land, and water, conservation of biodiversity, restoration of ecosystem services, and re-naturing the urban environment, thereby creating resilient landscapes and cities leading to socio-economic transformation of rural and peri-urban areas. Other benefits of this approach have been associated to empowerment of women and creation of green jobs [78–80]. Owing to the sub-surface flow of water in the constructed wetland bed, this technology also eliminates the possibility of breeding of disease vectors, including mosquitoes.

By assessing the pollution sources in the present study, three zones of pollution were divided as Area-I (i.e., A9, GH, H8, and RH), Area-II (i.e., AA, GG, and TG), and Area-III (i.e., H9). Area-I was identified as stations receiving the highest pollution through the discharge of partially treated wastewaters, Area-II represents stations influenced by anthropogenic activities (e.g., fishing, religious rituals, cattle rearing), and Area-III was recognized for receiving natural sources of pollution. Specific actions for pollution control for Area-I include the interception, diversion, and treatment of inlets using 'CW4Reuse'. Restrictions on anthropogenic activities in Area-II are identified in conjunction with appropriate riparian-zone treatment. Area-III can be revitalized in situ using floating constructed wetlands.

In Powai Lake and its surrounding urban area, the blue-green balance needs to be improved; therefore, CW4Reuse technology was identified as the most suitable not only for the improvement of lake water quality but also for the expansion of green patches on the landward side of the lake-front. Further, surface runoff can also be reduced due to its natural filtering effects. The final task of Phase 1 was the stakeholder survey for the assessment of the willingness to participate in Powai Lake rejuvenation (manuscript in progress). Lastly, the development of a comprehensive Business Model for the technological intervention selected for rejuvenation has to be undertaken in Phase I.

4.2. Phase II: Implementation of Plan for Rejuvenation

The second phase of the rejuvenation plan comprises the implementation of the selected technology. The initial task involved in Phase II to be undertaken by the municipality (MCGM) is the public notification and stakeholder consultation regarding the plan for rejuvenation, followed by identification of a developer and implementation of a rejuvenation plan for the Lake and lake-front.

At the outset of Phase II, a multi-stakeholder 'Implementation Committee' will be set up to supervise the action plan, selecting members from the Departments of Environment, Water Resources, Public Works, Public Health, Tourism, Regulatory Agencies, and Revenue, as well as representatives from NGOs and community-based organizations (CBOs). Such a committee would be convened by the Lake Protection Authority and advised by IITB as the knowledge partner to monitor the stages of the restoration of Powai Lake. The progress of the tasks in this phase would be reported to the 'Implementation Committee' and their feedback would have to be addressed.

The first task in Phase II is to communicate the rejuvenation plan of Powai Lake to the surrounding community and other citizens of Mumbai. Such disclosures are typically disseminated through the formal municipal orders as well as via newspapers, public forums, magazines, and television news. This will help in educating the public and thereby create a sense of responsibility towards the Lake and their ownership in the rejuvenation process.

Subsequently, the second task is the identification of the developer and financing sources, optimally through a public–private partnership. CPHEEO [54] recommended a tripartite arrangement between a funding agency (private or a public source), implementing agency (public trust or private entity), and the State Government, as the most transparent and efficient. A comprehensive SWOT analysis is also suggested [81].

The third task is the planned technological intervention and lake-front development. One of the initial steps in lake-front development is the precise mapping and demarcation of the Lake's boundary with the direction of the Revenue Department to identify potential lake encroachers and manage their relocation and resettlement. Reconstruction of inlets and outlets, dredging, de-silting and de-weeding, construction of silt traps in the inlet points, setting up of low-cost sanitation provisions in and around the Lake, construction of lake fence and shore-line, building embankments, and construction of greenways for walking and leisure, fountains, and lighting are the lake-front development considerations. Separate artificial ponds can be constructed for citizens to conduct their religious activities near the Lake. Unauthorized activities and management of solid waste littering is also essential to the execution of the rejuvenation plan.

4.3. Phase III: Implementation of the Business Model

Current breakthroughs in sustainable development models have shifted the paradigm from traditional approaches of lake restoration as a 'potential cost to economic production' to an 'ecosystem service function' to be derived from revitalized urban green-blue spaces [82–84]. A multidimensional approach of a 'Circular Business Model' is recommended [85] and other studies demonstrate that place-led and nature-led solutions are the hallmarks of circular territorial projects. With the same spirit, the Business Model developed for Powai Lake should deliver a multifunctional strategy that addresses Powai Lake restoration and revitalizes the urban landscape through ecotourism. The implementation of the Business Model for rejuvenation of Powai Lake that provides for the operations of the environmental infrastructure is the primary focus in Phase III (Figure 13). Biodiversity, sustainability, and ecosystem services for the community should be the overall objectives of the Business Model where the user will pay for utilities derived from the ecosystem.

The environmental and regulatory responses of the ecosystem restoration of Lake Rotorua used the drivers-pressures-state-impact-response framework and a lack of awareness of environmental issues and social lag times in responding to ecosystem decline were the factors that led to regulatory response failures of lake restoration. To overcome these shortcomings, ecological factors, economic interests, and societal limitations should follow an interdisciplinary approach [86].

Phase III will also include capacity building for the local communities, monitoring of lake water quality, and periodic public disclosures by the regulatory agency and municipality. These are long-term tasks that need to be functionalized by the multi-stakeholder 'Implementation Committee'. For a successful implementation of the restoration tasks, Powai Lake and the periphery should be declared an 'eco-sensitive area' through a formal notification to rule out detrimental real-estate development on the lake-front. The capacity building workshops for the local community and other residents in Mumbai would involve major stakeholders such as members from the 'Implementation Committee', municipal authority, and all partners of the funding agency.

The Powai Lake rejuvenation plan not only focuses on reviving the quality of water but also directs the restoration through the transformation of its entire locale by adopting eco-centric technologies in partnership with the community, and is in line with UN Sustainable Development Goals 6, 11, and 17 [5].

5. Conclusions

Powai Lake is threatened by the ingress of untreated domestic wastewaters from informal settlements and surface runoff. The present study shows that these conditions continue to degrade the lake ecosystem. The capacity building of citizen scientists and other stakeholders is the first key step in a phased rejuvenation plan. Importantly, there is no time to waste; public awareness has risen, also thanks to the present project, and the condition of the Lake should not deteriorate any further.

The water quality of the Lake was assessed in a large number of sites for 21 months. These results underline the chronic pollution nature in the Lake. Organic pollutant loading, nutrient enrichment, and pathogenicity characterized much of the littoral zone with significant spatial and temporal variations. Their impacts are extended to the limnetic zone evidenced by infestation of weeds including water hyacinth.

Based on this evidence, a three-phase rejuvenation plan aims at restoration through employing environmentally and socially sustainable technology. If one aims at restoration of Powai Lake and its ecological niche, one will have to reverse the decades of pollution and the ecological degradation of the aquatic ecosystem and the surrounding green spaces. Clearly, unless the waste management system in the surrounding community is upgraded, the rejuvenation efforts of the Lake will not succeed.

In summary, the rejuvenation of Powai Lake can only be achieved through adopting an integrated approach, in which the disconnect between the need for conservation of environment and ecology of the Lake and the development in the green space around the Lake should be addressed with priority. Ensuring the participation of the stakeholder community residing around the Lake is equally important in implementing the rejuvenation plan. The management plan is a holistic approach that understands and recognizes the Lake as a system, not only focusing on the improvement of water quality; but also on the associated ecosystem services delivered to the local and larger community.

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