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Invited Review Article

Changes in biotic diversity and environmental variables in the river Ganga: Lessons over half century and options for future research

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Abstract

India is a land of rivers, and the Ganga River is a river of national importance that acts as the lifeline of millions of people. Multitude of anthropogenic stress has impacted this river both by habitat destruction as well as by biodiversity loss. Although biodiversity loss in this river has been recognized, there is a lack of understanding about the trends in biodiversity loss under changing environmental scenarios. This review addresses this deficiency by analyzing the change trends in environmental variables and biodiversity loss in the river Ganga over the past half-century. This indicates a declining trend in fish landings, especially for major carps. The construction of dams and barrages had a negative impact on the diversity and density of plankton. However, the increasing advances and restoration strategies made over time have positively improved the water quality status in the river system, which has now also resulted in one of the best top 10 ecological restoration plans. Reviews indicate that there is a lack of scientific and systematic studies for accurate quantification of biodiversity loss, and also, better understanding is required for cause-effect interactions of environmental variables with biotic diversity with reference to the Ganga River system in India. The review also provides insights into the future directions of accurately quantifying biodiversity loss and water quality degradation.

Keywords: Fisheries, Future direction, River Ganga, Systematic review, Water quality

Highlights

- Analyses the trends of changes in environmental variables and biodiversity loss in river Ganga.
- The declining trend in fish landings, especially of major carps, was noticed.
- Construction of dams and barrages had a negative impact on the diversity and density of plankton.
- The increasing advances and restoration strategies made over time have positively improved the water quality status in the river system.

INTRODUCTION

Rivers are called the lifeline of any nation as they play a pivotal role in controlling the socio-economic and ecological values of the environment. Country's economy and social well-being directly or indirectly depend on the river water quality. This is even more important for countries like India, where two-thirds of the population is engaged in agriculture, and hence, availability of sufficient freshwater is crucial. However, the rivers are a lifeline in India due to various anthropogenic activities like water extraction, waste disposal, creation of dams and barrages, industrialization and urbanization, which resulted in habitat loss of river ecosystem and consequently, substantial changes in biotic diversity and abundance (Giri, 2021). In addition, riverine ecosystems are also affected by climate change, the greatest threat of the 21st century (Capon *et al.*, 2013). These huge anthropogenic impacts increase the vulnerability of natural freshwater systems like rivers and synergistically lead to eutrophication, freshwater pollution, biodiversity loss, the spread of invasive species and ultimately overall river health.

Ganga is the longest and largest river in India, providing ecosystem service and livelihood to millions of people. However, like other large rivers of the world, the Ganga is also under enormous natural and anthropogenic pressure, which is affecting the deliverables of this river system (Patel *et al.*, 2021). This large-scale anthropogenic stress has alarmed the life history and population dynamics of the river ecosystem. Overfishing resulted in declining fish catch and their composition. Moreover, various inorganic and organic pollutions in river Ganga notably reduce the dissolved oxygen concentration and productivity of the river regime (Kumar *et al.*, 2022a). The creation of dams and barrages in this river altered the habitat and migration pattern of the fishes (Samad *et al.*, 2022). Overfishing resulted in changes in the population dynamics of fish

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species. Fishes are also facing competition from the invasive species. This river is the treasure of the national economy, and maintaining the environment and biotic integrity can be considered the backbone of India's development.

The enormous anthropogenic pressure resulted in large variability in environmental parameters and biotic diversity in the river Ganga. In order to manage the Ganga River ecosystem, it is important to understand this variability so that appropriate action may be taken. However, to identify the unidirectional and clear changes, short-term data series may not be useful without a historical baseline against which modern observations can be compared. For this, understanding the trends in water and biotic diversity changes is important, which will provide strong signals of proximal causes that impact the overall river health. Here, based on the available literature, we documented the potential impacts of anthropogenic stress on changes in water quality and biodiversity loss in river Ganga. We have presented the basic biogeography of the river, major anthropogenic threats affecting the water quality before drawing a vivid picture of the trends of change in plankton and macro-benthic diversity and most importantly the fishes, and finally summarize the actions to be needed in future.

River Ganga at a glance

The Ganga River is immensely important in Indian culture and heritage. It is the lifeline of the majority of the population in the cities, towns, and villages that lie on its banks. The major Ganga River extends from Rishikesh to Allahabad, passing through Nagal, Bijnor, Garhmukteshwar, Hasanpur, Anupshahar, Narora, Sahaswan, Kasgang, Ptiali, Kampil, Kaimgang, Fatehgarh, Kannauj, Bithur, Brahmavart, Kanpur, and ultimately Allahabad. At Allahabad, it meets a major tributary, the Yamuna, and then flows through Varanasi in Uttar Pradesh, Bihar and Jharkhand before joining the Bay of Bengal at Ganga Sagar in West Bengal, covers a total path length of 2,550 Km^2. Due to multifaceted uses of the Ganga water in various sectors like drinking water, irrigation, domestic use, transport, fisheries activities, this river consider as a lifeline for sheer number of population. However, these multiple uses resulted in the exploitation of these important natural resources, creating multiple challenges to the ecological integrity of the river system. Several researchers from various organizations have been monitoring water quality changes in this river for several decades (Richards *et al.*, 2013). Synthesis on trends of changes through literature review will provide more insight into the cause-effect interaction of environmental variables and biotic diversity.

Eutrophication and pollution in river Ganga

With the passage of time, the bursting population load has increased the pressure on the aquatic ecosystem globally. The increasing industrialization, urbanization, and chemical farming processes around the river bank have adversely affected the Ganga River ecosystem over the decades (Tiwari *et al*., 2022a). Since ancient times, maximum industrialization as well as civilization has been established across the river banks. As it has been observed that the comparative ecology and water quality status of the river system has changed accordingly with the passage of each day. There are multiple ecological stressors that have adversely affected the entire river ecosystem. The increasing contaminants and nutrient load by means of industrial effluents and agricultural wastes in the form of inorganic fertilizer in the river have also increased the eutrophication status of the river system. The rise in the eutrophication status of the river system is chiefly caused by the enhancement in nutrient loading rate, which may lead to severe river management problems such as aquatic bloom, caused by several planktonic organisms causing disturbances in the ecological niche of the entire food web. The increasing pollution level in the river can be monitored by using several ecological parameters, which can be concluded from several studies made in the river Ganga ecosystem (Tiwari *et al*., 2022a, 2022b, 2023). So, to study the several ecological variables, various essential water quality parameters such as pH, dissolved oxygen, free carbon dioxide, alkalinity, conductivity, TDS, hardness, chloride and nitrate can be assessed. However, the increasing advances and restoration strategies made over time have positively improved the water quality status in the Ganga River system, which has now also resulted in becoming one of the best top 10 ecological restoration plans. The multidecadal assessment study made by Vass *et al*. (2008) and Tiwari *et al*. (2022b) in the middle and lower freshwater stretch of the Ganga River (Kanpur to Farakka) showed that significant alterations had been observed over the last half-century in the river system. The changes can be evaluated by assessing the essential water quality parameters such as dissolved oxygen, pH and conductivity.

Dissolved oxygen: Dissolved oxygen is the essential parameter used for the assessment of any aquatic ecosystem, as it is utilized by the majority of aquatic organisms. The entire stretch of the river always receives oxygen levels more than the safe limits provided by the standard guidelines (BIS, 2012), i.e., >5 ppm. The increasing industrialization has affected the oxygen level in the river system. The major relative effect was observed during the year 1987-89. The decrease in the oxygen level in 1987-88 (Fig. 1) may be due to the amplified rate of industrialization as well as the green revolution, which reached its peak, especially across the Ganga River bank. The mean dissolved oxygen since 1960-2019 in the studied stretch was observed 6.89±0.99 ppm. The higher oxygen was observed in all the decades >7.4 ppm, although relative lowering in the dissolved oxygen was observed during 1987-89 (5.4 ppm). But after the years with the implementation of several restoration strategies and installation of sewage treatment plants the river has restored its relative status and higher oxygen levels were observed.

pH: Similar to oxygen, pH also plays an important role in balancing the aquatic environment as well as aquatic organisms, as this affects the majority of physical and biological processes. The assessment showed that in all the decades, the mean pH level in the river had obtained the optimum pH standards, i.e., 7.7 to 8.5 (BIS, 2012). However, relatively lower pH values were observed during the year 1987-89 (Fig. 2). The mean pH in the entire stretch during the last half-century was 8.03±0.21. In all the stretches, the pH values were observed to be optimum for the majority of the aquatic organisms (Fig. 2). The lowering in the pH in the river system is mainly due to the industrial wastes, which can be effectively observed during the years 1987-89, however with the implementation of the various strategies like Ganga action plan has helped the river to rejuvenate it and attain its earlier status.

Conductivity: The conductivity in the river water is due to presence of inorganic salts of sulphur, sodium, calcium, nitrate, magnesium ions etc. This is an important parameter, and its assessment indicates the level of pollution in the aquatic ecosystem. The trend showed that with the passage of time, the conductivity of the river Ganga has increased (Fig. 3). However, with the construction of various sewage treatment plants and other rejuvenation strategies, the conductivity level was maintained to its limits. A rise in the conductivity level was observed from 1960 onwards, and the mean conductivity was 281.6 µS/cm. This raised consecutively to 401.2 µS/cm, 402.84 µS/cm and 424.17

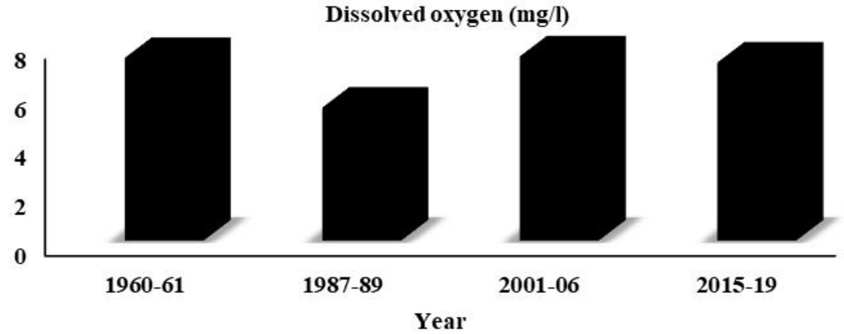

Fig. 1. Relative variation in the dissolved oxygen status across the decade (1960-2019)

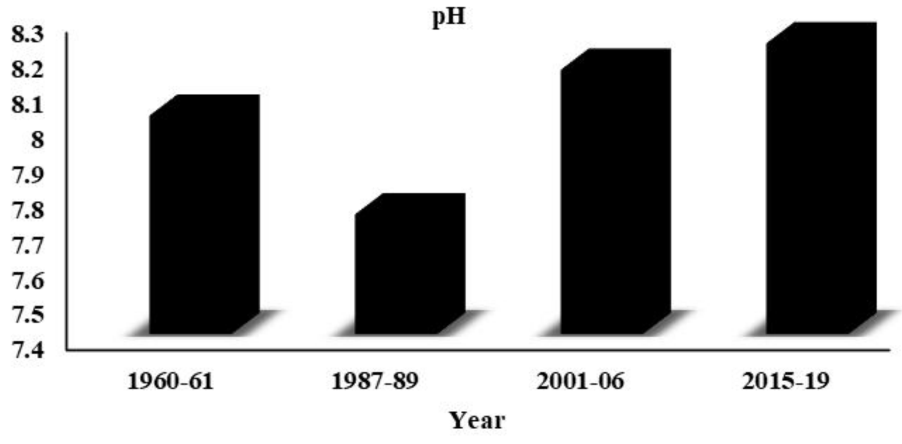

Fig. 2. Changes of the pH in the river Ganga from 1960-2019

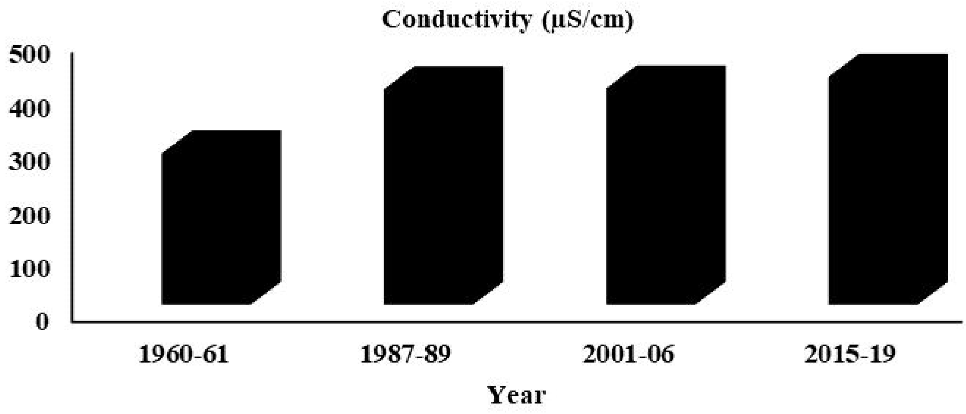

Fig. 3. Variation of the conductivity during the year 1960-2019

µS/cm during the years 1960-61, 1987-89, 2001-06 and 2015-19, respectively (Tiwari *et al*., 2022b). However, the range of conductivity was within the safe limits as per standards of the Bureau of Indian Standards (BIS, 2012). The rise in the conductivity level in all the decades is a matter of concern, and a few more stereological changes are required for proper management of the river system.

Other than these essential parameters, significant variations were also observed for other parameters over the decades in this river system (Tiwari *et al*., 2022b). The rise in pollution and eutrophication levels also raises serious concern for the ecological habitat of the majority of organisms. Nowadays, it has been observed that many aquatic organisms such as fishes, plankton and other aquatic organisms are becoming extinct with the increasing anthropogenic activities. However, with the implementation of various conservation and rejuvenation programs along with awareness activities, the riverine water quality is maintained in many places.

Changes of benthic community in river Ganga

Recent years have shown that bio-monitoring is an effective method for establishing an action plan to reduce river pollution and measure water quality improvement (Sharma and Behera, 2022). The benthic macro-invertebrate fauna is among the most susceptible to changes in the water quality of all biotic elements of rivers. They are among the first populations to suffer due to habitat deterioration. Due to several factors including elevation, the substructure of the river bed, the confluence of tributaries, depth, flow velocity, and others. River Ganga traverses a range of habitats from its upstream to downstream reaches, including riffles, slacks, runs, depositing, eroding, and turbulent and pool conditions. Benthic macro-invertebrates are believed to be the best biological parameter for assessing water quality.

The ability of communities to support species, or functional groupings, capable of differential responses, is a prerequisite for ecosystem stability, and the lower the species diversity of a biological community, the lower the danger of ecological collapse (Palmer *et al*., 2010; Mellin *et al*., 2014). Additionally, researchers have discovered a favorable correlation between ecoregional species richness and riverine production (Duffy *et al*., 2007; McIntyre *et al*., 2016). A reduction in biodiversity leads to reduced ecological stability and production and ultimately, ecological collapse, which would have a significant negative impact on human well-being (Mellin *et al*., 2014). Changes in water quality, river's physical habitat, land use pattern, temperature and precipitation patterns, alterations in the flow regime of the river, introduction of invasive species and efforts to restore and rehabilitate the river are some of the potential factors contributing to decadal changes in the macrobenthic community of the Ganga River.

In total, 69 macrobenthic species from three different phyla: Mollusca, Arthropoda, and Annelida were found in the Ganga River. Of the 31 gastropod species found there, 19 are freshwater species, and 12 are estuary species. As for the different types of species, the gastropod population predominated throughout the middle and lower portion of the river, followed by bivalves and insects (Shreya *et al*., 2022). In the Ganga River, the annual production of macrobenthos ranged from 14 to 2,312 U/m^2, primarily dominated by gastropods. Benthic organisms are a major source of pollution indicators. Out of 69 benthic species, 13 species have been designated as the pollution indicator in the Ganga River. Shreya *et al.* (2022) observed a declining pattern in the abundance of the macrobenthic community by comparing the data from 1958–1959 of taxon abundances (U/m^2) and diversity across multiple decades.

According to the results of the decadal comparative study, the macro-benthic density in the middle and lower sections of the Ganga has significantly decreased. When examining the macro-benthos along the middle and lower stretches of the Ganga, Khan *et al*. (1999) found that the densities were 500–3,636 U/m^2 in Kanpur, 220-800 U/m^2 in Allahabad, and 204–2,432 U/m^2 in Varanasi. But in recent study, the number of benthic species varied from 30 to 335 U/m^2 in Ghazipur, 140 to 145 U/m^2 in Prayagraj, 5 to 140 U/m^2 in Narora and Varanasi, 5 to 125 U/m^2 in Chunar, and 18 to 168 U/m^2 in Bijnor (Shreya *et al*., 2022). These researchers also noticed an increase in the diversity and abundance of benthic macro invertebrates between 1982 and 1995. Benthic macro-invertebrate production rose from 728 U/m^2 in the years 1985–87 to 4,514 U/m^2 in 1995 at Buxar and from 1,669 U/m^2 in 1991 to 12,825 U/m^2 in 1995 at Farakka. Recent research by Shreya *et al*. (2022) on macro-benthic communities in the Ganga's Patna to Farakka stretch found a range of 5-168 U/m^2 between Kanpur and Varanasi and 15-375 U/m^2 there, showing a reduction in the benthic population with time. A change in dominance of mollusk species was also noted in Patna. In accordance with the findings of the current study, *Melanoides lineatus* was the dominant group (94.3%) in Patna in 1959, when the abundance of *Filopaludina bengalensi* speaked at (96%) in 2022. A new distribution of microbenthic invertebrates has been recorded from river Ganga, namely *Cybister* spp., *Sigara* spp. and *Antocha* spp. from Narora and Haridwar, respectively. Such information is valuable for making informed decisions about river management and conservation efforts (Shreya *et al*., 2022).

Changes in fish biodiversity and fish production

Hamilton (1822) described the comprehensive accounts of the fish fauna of the Gang River with a total of 260 fish species. Subsequently, Day (1988) has enlisted 1,340 fishes under the 342 genera from India, where most of the fishes are found in the river Ganga. To modify Hamilton's works in 1822, extensive research was also urged by Hora (1929). Menon (1974) also made a concerted attempt and enlisted 207 fish species covering the upper Ganga to Gangetic (Hooghly) estuary. However, Talwar and Jhingran (1991) reported 266 fish species from the entire Gangetic River basin, consisting of 158 freshwater and 108 marine species. Sarkar *et al*. (2012) provided the most recent complete description and biogeographical distribution of 143 fish species (belonging to 72 genera and 32 families), focusing on the freshwater zone of the river.

The recent study conducted by ICAR-CIFRI from 2016 to 2023 in the river Ganga recorded 190 fish species, of which 182 species were native, and 8 were exotics. Of these, Cyprinidae (28 species, 14.28%) was the most dominant species rich family. This was followed by Danionidae (19 species, 9.69%), Sisoridae (10 species, 5.10%) and Bagridae (9 species, 4.59%), respectively. The study further indicates that most of these species are food fish (60.84%), followed by ornamental (35.44%) and sport fish (3.7%). As per the IUCN Red List (2020), 10% of the species fall into the threatened species category. Whereas, about 73.68% of the recorded species are under the 'Least Concern' category.

Commercial fishing activity in the Ganga begins below Haridwar at Anupshahar while the middle stretches of the river support major fishery resources. Commercial fishes in the Ganga are broadly categorized into 7 major groups as trout, mahseer, major carps, other carps, large catfish, small catfish and shads. The study revealed 74 commercially valuable species belonging to 12 orders, 27 families and 59 genera. The river supports various commercially important fish species including Indian major carps (*Labeo rohita*, *Labeo catla*, *Cirrhinus mrigala* and *Labeo calbasu*), minor carps (*Labeo bata*, *Labeo fimbriatus*, *Labeo gonius*, *Cirrhinus reba*, etc.), catfishes (*Sperata aor*, *Sperata seenghala*, *Wallago attu*, *Rita rita*, *Pangasius pangasius*, *Bagarius bagarius*, *Eutropiicthys vacha*, *Clupisoma garua*, *Mystus* spp., etc.) and several other small indigenous fishes.

The principal fish production in the Ganga River always occurs in the middle stretch of the river. The annual landings at the middle stretch varied between 59.02 to 243.25 tonnes during 1955-1966, with the highest landing at Prayagraj (193.58 to 243.25 tonnes) (Jhingran, 1991). The fish production of major carp and other groups of commercial fishes from selected stretches during the period of 1975 to 2020 is shown in Table 1. Hilsa fishery was the mainstay in the middle stretch during the 1950s and 60s, contributing to the tune of 29-62% and 33% from the Prayagraj and Buxar stretch, respectively, while the fishery of Hilsa totally collapsed in the middle stretch, especially in the Prayagraj stretch after the commissioning of Farakka Barrage. The maximum fish landing (47.5% of the total) was recorded in the middle stretch (Prayagraj to Farakka) during 2019-20. The study indicated that the contribution from small-sized miscellaneous fish groups increases manifold from the Buxar to Bhagalpur stretch of the river Ganga (Das *et al*., 2023) due to the gradual decline in valuable major carp catches in these regions (Payne *et al*., 1996). This

Table 1. Production of major carp and other major groups of fish (in tonnes) from selected stretches of river Ganga (1975-2020)

Stretch	Groups	Period		
		1975-1980	1980-1985	2016-2020
Buxar	IMC	5.81	14.44	4.03
	Catfish	36.36	36.98	9.9
	Hilsa	3.42	4.95	0
	Exotic	NA	NA	19.6
	Misc.	72.6	97.71	13.79
	Total	**118.19**	**154.08**	**47.32**
Patna	IMC	NA	16.51	2.16
	Catfish	NA	33.87	8.06
	Hilsa	NA	0.27	0
	Exotic	NA	0	0.08
	Misc.	NA	80.03	17.69
	Total	**NA**	**130.65**	**27.99**
Bhagalpur	IMC	43.12	22.49	1.98
	Catfish	90.39	83.57	6.49
	Hilsa	0.72	2.16	0
	Exotic	NA	0	0
	Misc.	191.83	193.94	11.45
	Total	**326.06**	**302.16**	**19.92**
Farakka	IMC	9.18	1.62	1.34
	Catfish	19.73	2.11	7.9
	Hilsa	45.41	15.98	10.39
	Exotic	NA	0	0
	Misc.	67.51	17.65	25.53
	Total	**141.83**	**37.36**	**45.16**
		Jhingran, 1991	Jhingran, 1991	NMCG, 2021

also indicates the declining trends in major carps landing sites in river Ganga. The substantial decrease in the production of major carps was also noticed in Prayagraj region of river Ganga during the period of 1981-90 (35.82 tonnes) to 2016-19 (5.97 tonnes). However, the contribution of catfish groups to the total catch remains uniform in all the centers, with the total catch ranging from 6.49 to 9.9 tonnes. Amongst the catfishes, *E. vacha* (0.93%), *H. fossilis* (0.90%), *Ailia coila* (0.44%) and *C. garua* (0.16%) were the most abundant. The fishery of *Wallago attu*, *Sperata aor* and *S. seenghala* were one of the major fisheries in the Ganga River system during 1958-1966. The total catch of *S. aor* and *S. seenghala* was to the tune of 72.79 tonnes, and the catch of *W. attu* was 59.85 tonnes during these years from the middle stretch, i.e., between Kanpur and Bhagalpur. Hilsa fishery was the mainstay at the Buxar stretch of the Ganga during the 1960s, contributing 33.48% (22.35). However, after the construction of the Farakka barrage in the 1980s, the population gradually declined in post-barrage, and there was a sudden drop in the catches of prized Hilsa from 160 to 9 kg/km in the middle stretches of the river Ganga. However, the abundance was found below Farakka. A drastic decline in major carp landing was also noticed in Patna stretch during the period of 1981-90 (23.35 tonnes; 21.48%) to 2016-19 (2.16 tonnes; 7.88%). The present investigation revealed that among the threatened fish species, *Harpadon nehereus* was found to be dominant and abundant in the estuarine zone of the river Ganga, as this species is primarily a marine fish species. The abundance of high-value endangered species *viz. Clarias magur* and *Tor putitora* are negligible due to habitat alteration by dam construction, pollution, overfishing/illegal fishing, and the introduction of exotic fishes into the Ganga River.

The annual fish yield per kilometer stretch of the river was maximum at Patna (1.80 tonnes per km) and minimum at Bhagalpur (0.78 tonnes per km). A genuine structural variation has been noted in fisheries of the river in different stretches with major carp domination in Kanpur to Prayagraj stretch. Similarly, the other sites of the river such as Varanasi, Patna, and Bhagalpur also showed considerable variations.

Qualitative changes of plankton in the Ganga River

The Ganga River is home to a variety of aquatic organisms, including plankton. These organisms play an essential role in determining the river's ecology with its contribution to the food web. These are considered as primary producers and are a source of food for different aquatic creatures (Kumar *et al*., 2017, 2020a, 2022b; Surya *et al*., 2018). Further, plankton is divided into phytoplankton and zooplankton, which are tiny, microscopic plant and animal creatures that float in the aquatic ecosystem. The size of phytoplankton varies from 1 µm to 2000 µm, while size of zooplankton varies from 5 µm to 3500 µm. Picoplankton (0.2-2 µm), nanoplankton (2-20 µm), microplankton (20-200 µm), and macroplankton (more than 200 µm) are the four sizes into which planktons can be divided. Biological organisms are widely recognized for their capacity to forecast the ecological health scenario of any aquatic habitat and their adaptability to environmental changes. Due to their short lifespan, they are strongly impacted by a variety of environmental conditions.

However, like many other aspects of the river Ganga's biodiversity, the plankton community also faces challenges due to pollution and other human-induced impacts. Besides pollution from untreated sewage, industrial effluents, and agricultural runoff, several constructions dams and barrages disrupt the balance of the planktonic community (Srivastava *et al*., 2020a; Kumar *et al*., 2023). Changes in plankton populations can reflect environmental changes and pollution levels, which, in turn, can have cascading effects on the entire aquatic ecosystem (Shukla *et al*., 2015; Malik *et al*., 2021). Pahwa and Mehrotra (1966) estimated the density of plankton at different stretches of river Ganga, i.e. Kanpur, Allahabad, Varanasi, Buxar, Patna, Bhagalpur and Rajmahal. Sinha and Khan (2001) reported lower plankton density in 1956-66 as compared to 1960 in the middle to lower stretches of the Ganga. The population density of pollution indicating the genera of plankton (*Ankistrodesmus* spp., *Coelastrum* spp., *Fragillaria* spp., etc.) increased in the year 1960. However, there was a small change in the qualitative composition. Srivastava *et al*. (2020b) reported that plankton taxa such as *Melosira* spp. (Diatom), *Scenedesmus* spp. (green Algae), *Merismopedia* spp. (blue-green Algae), and *Brachionus* spp. (Rotifer) are resistant to changing climatic circumstances. According to this report, the abundance of plankton increased from 2002 to 2016 (from 30 u/L to 800 u/L) and then started to decline at the Kanpur stretch of river Ganga. Sarkar *et al*. (2019) have reported decreases in the density of phytoplankton due to barge movements compared to normal conditions. The study was carried out from Bandaragar to Lalbag in river Ganga, and the abundance of phytoplankton was 3,513 u/L under normal conditions and 1,997 u/L during barge movement. Srivastava *et al*. (2020a) documented the density of plankton varies from 1,060 u/L to 1613 u/L in the upper stretch of river Ganga (Chinyalisaur to Rishikesh). The authors also highlighted that the diversity and density of plankton were mainly affected by the construction of dams and barrages, which had a negative impact on water variables. The changes in the diversity of plankton were made by different researchers at Kanpur and Hooghly estuary of river Ganga has been given in Table. 2.

Table 2. Changes in plankton in the Ganga (Hooghly) estuary

Stretch	Year	Density of plankton	Source
Kanpur	1966	Plankton = 76 species, Bacillariophyceae = 17 species, Chlorophyceae = 15 species, Cyanophyceae = 10, Dianophyceae = 2 species, Rotifera = 16 species, Crustecea = 11 species, Protozoa = 4 species,	Srivastava *et al*. (2020b)
	2002 - 2020	Plankton = 147 species	
Chinyalisaur, Ghansali, Koteshwar, Srinagar, Devprayag, Vyasghat, Kaudalaya, Rishikesh	2018 - 2020	Phytoplankton = 31 genera, Bacillariophyceae = 14 genera, Chlorophyceae = 11 genera, Cyanophyceae = 4 genera, Euglenophyceae = 1 genera, Xanthophyceae = 1 genera	Malik *et al*. (2021)
Palta to Diamond Harbour	1949 - 1951	Phytoplankton = 105 species, Diatom = 72 species, Chlorophyceae = 18 species, Cyanophyceae = 9 species, Dinophyceae = 3 species, Euglenoid = 3 species	Dutta *et al*. (1954)

Cont. Table 2.

Table 2., Cont. ...

Stretch	Year	Density of plankton	Source
Nabadwip to estuarine mouth, the Rupnarain and the Matla regions	1956 - 1958	Phytoplankton = 106 species, Diatoms = 50 species, Chlorophyceae = 30 species, Cyanophyceae = 18 species, flagellates = 8 taxa	Shetty *et al.* (1961)
Hooghly-Matla estuarine system		Phytoplankton = 378 species, Coscinodiscop hyceae = 108 species, Bacillariophyceae = 70 species, Fragilariophyceae = 17 species, etc.	Gopalakrishnan (1971)
Sundarban region	2011	Phytoplankton = 166 species	Sarkar (2011)
Nabadwip to Godakhali	2018	Phytoplankton = 96 species	Roshith *et al.* (2018)
Baranagar to Lalbag	2019	Phytoplankton = 52 species	Sarkar *et al.* (2019)

Synthesis and recommendations

Since rivers play a pivotal role in governing the economy of countries like India, it is our duty to quantify anthropogenic pressures and their impacts on river health. Based on our thorough bibliographic search and synthesis, it is evident that there is a need for research in some areas that will help understand the link between environmental variables and the associated biodiversity loss in the Ganga River. The pollution in the river has to be looked upon in the border view with more stakeholder participation and a detailed approach. This border area will be able to fill knowledge gaps by determining the cause-effect relationship. There is an urgent need to develop predictive models that help to integrate the interaction of environmental variables with biotic communities. In this aspect, a microcosm study may be more meaningful for predicting the environmental impacts. There is an urgent need for effective implementation of river basin management actions, which will not only address the present problem but also help reduce the likelihood of devastation in upcoming happenings in the river regime. Accurately mapping and quantifying biodiversity loss and water quality depletion could be an important step toward identifying the key riverine stretches impacted by anthropogenic pressure. Research priorities should include different taxa, consisting of amphibians, birds and mammals as well as their influence by environmental variables. Some online monitoring systems can be implemented at the field level so that continuous data can be generated for better output and application in future studies. This will help to understand the river health status at micro-level throughout the river stretch. Future development in the management of these river basins should combine the socio-economic, climatic and environment-related indicators for the management of the Ganga River.

Conclusion

The review indicates that increasing advances and restoration strategies made over time have positively improved the water quality status in the river system, which has now also resulted in it being one of the top 10 ecological restoration plans. However, there should be continuous monitoring of the implemented programmers, and the programmes must be decentralized by involving various stakeholders residing in the bank of the river. The declining trend in fish diversity and the abundance of various other biota is of concern. Hence, there is an urgent need to develop species-specific conservation planning, landscape profiling and riverine habitat fingerprinting for effective conservation of threatened biota.

Conflict of interest: Authors have no conflict of interest in this study.

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