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ARTICLE

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TOXIN-PRODUCING CYANOBACTERIA IN THE GANGA RIVER SYSTEM: SPATIOTEMPORAL DYNAMICS AND ENVIRONMENTAL DRIVERS

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Toxin-producing cyanobacteria have emerged as a significant global threat, impairing ecosystem services and posing risks to human, animal, and environmental health. This study investigated the seasonal distribution of harmful cyanobacteria in the Ganga River from 2021 to 2023 across 20 sites, from Harshil to Fraserganj. Notably, dense blooms of Microcystis aeruginosa, a microcystin-producing species, were observed in the river's middle stretch at Buxar, Patna, and Bhagalpur, with peak densities reaching 15.88 million cells/l during the monsoon. The proliferation of these blooms was strongly linked to anthropogenic nutrient inputs from domestic sewage, agricultural runoff, and increased levels of nitrate and phosphate. Supporting physicochemical parameters such as elevated specific conductivity and salinity further facilitated cyanobacterial growth. These findings highlight the need for targeted management strategies to mitigate bloom formation and protect water quality, offering critical insights into the seasonal ecology of harmful cyanobacteria in the Ganga River system.

Introduction

Cyanobacteria, among the oldest known prokaryotic organisms on Earth, are photoautotrophs commonly referred to as blue-green algae[1]. They typically form extensive colonies or filaments in freshwater ecosystems[2] and contain chlorophyll-a along with accessory pigments such as phycoerythrin and phycocyanin[3]. These pigments enable adaptation to varied light conditions[4], contributing to their ecological success. Physiological adaptations such as buoyancy regulation via gas vesicles[5,6] and high-temperature tolerance[7] further allow cyanobacteria to thrive in diverse aquatic environments. Additionally, they can fix atmospheric nitrogen and form dormant cells under stress conditions[8,9]. In recent decades, cyanobacterial proliferation has increased globally, including in India, primarily due to climate change and eutrophication driven by agricultural runoff, industrial discharge, and urban sewage[10]. These nutrient-rich conditions promote harmful algal blooms (HABs) that degrade water quality[11]. Cyanobacteria produce a range of toxins harmful to plants, animals, and humans[12], outcompeting other algal groups and disrupting aquatic food webs[13]. Moreover, blooms reduce dissolved oxygen levels and alter pH, resulting in hypoxic conditions and fish mortality[14,15], thereby destabilizing aquatic ecosystems.

The Ganga River, revered as a sacred river throughout India, spans approximately 2,550 kilometers and flows through five major states. It serves as a critical source of drinking water for nearly 43% of India's population[16] and supports the livelihoods of thousands residing along its banks. Despite its cultural and economic importance, the Ganga has been ranked among the world's most polluted rivers, highlighting an urgent need for sustainable conservation and pollution control measures. The present study aims to investigate the spatiotemporal

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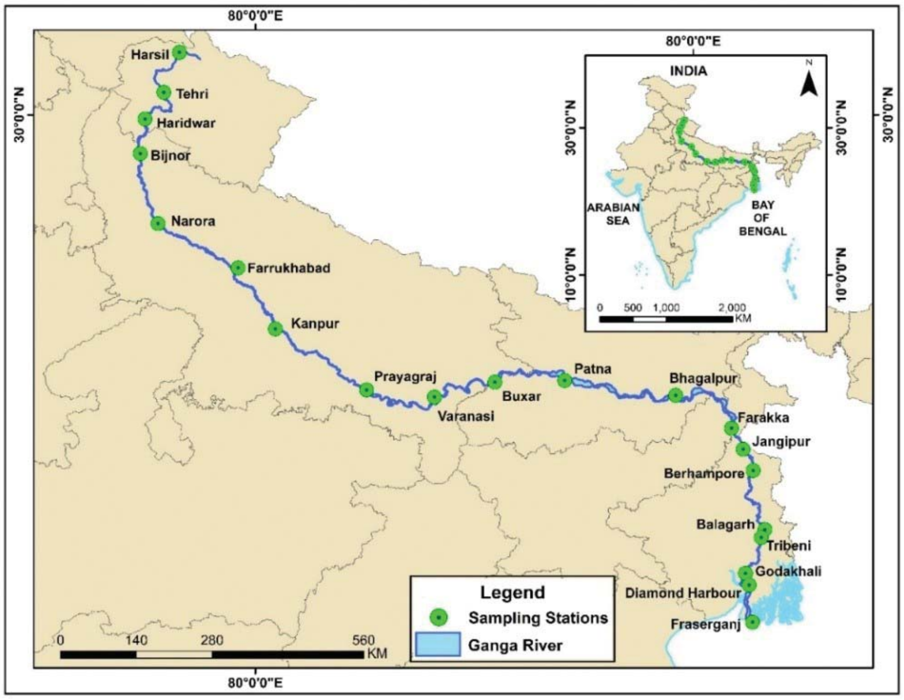

Fig. 1. Study Area of different sites of river Ganga

plankton net was used to filter 100 litres of river water at each site. The concentrated plankton samples were collected in clean, dry, airtight containers, fixed with 4% formalin, and stored for quantitative analysis. Microscopic examination was performed using a trinocular microscope (Scope.A1 AXIO Zeiss) at 40× and 63× magnifications. Taxonomic identification was based on standard keys[17,18], with nomenclature verified via AlgaeBase.

For physicochemical analysis, sub-surface water samples (0.5 m depth) were collected in 1 L HDPE bottles and transported to the laboratory. Parameters such as temperature, pH, salinity, and turbidity were measured in situ using an Aquaread 7000 AP multi-parameter probe. Dissolved oxygen, total hardness, and alkalinity were estimated using titrimetric methods. Nutrients—including total nitrogen, total phosphate, nitrate-nitrogen, phosphate-phosphorus, and chloride—were analyzed following APHA protocols[19].

Data were analyzed using one-way ANOVA to assess seasonal variation in water quality parameters. Karl Pearson correlation was applied to examine relationships between physicochemical variables and plankton groups using PAST software.

variation of harmful cyanobacterial species along the Ganga River system. It also seeks to identify the key environmental drivers that influence the growth and proliferation of these toxin-producing organisms.

Materials and Methods

Study Sites: Twenty sites were selected along the Ganga River, covering a 2,525 km stretch from its origin in India to its confluence with the Bay of Bengal. The study was conducted over three years, from March 2021 to December 2023, with seasonal sampling performed at each site. Geographic coordinates were recorded using a handheld GPS device (Garmin, USA), and a map of the study area was prepared using QGIS 2.18 (Fig. 1). Sampling followed the seasonal classification of the Indian Meteorological Department: winter (December–February), pre-monsoon (March–May), monsoon (June–August), and post-monsoon (September–November).

Sampling and Data Analysis: Seasonal sampling was conducted from 2021 to 2023 between 8:00 and 9:00 A.M. at selected sites along the River Ganga. A conical

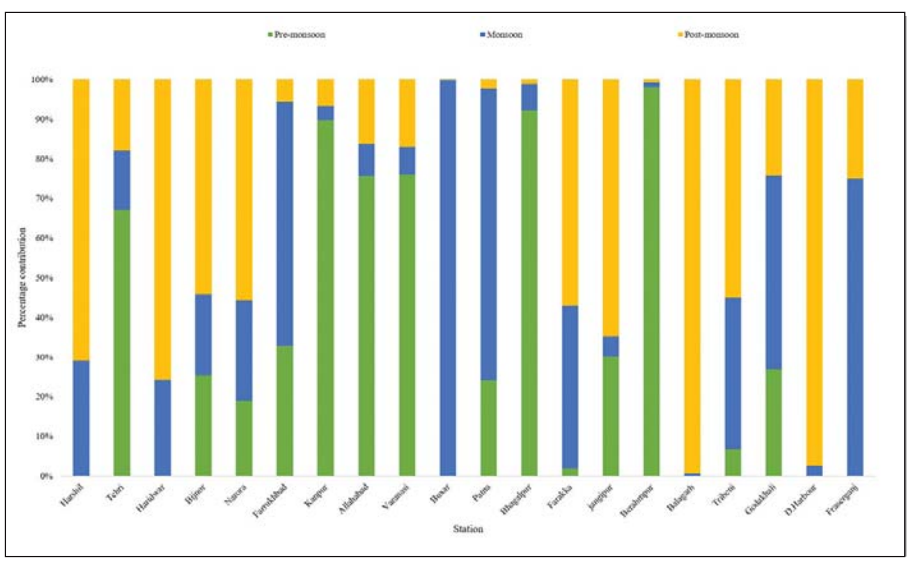

Fig. 2. Percentage contribution of Cyanobacteria in different sites of river Ganga in different seasons

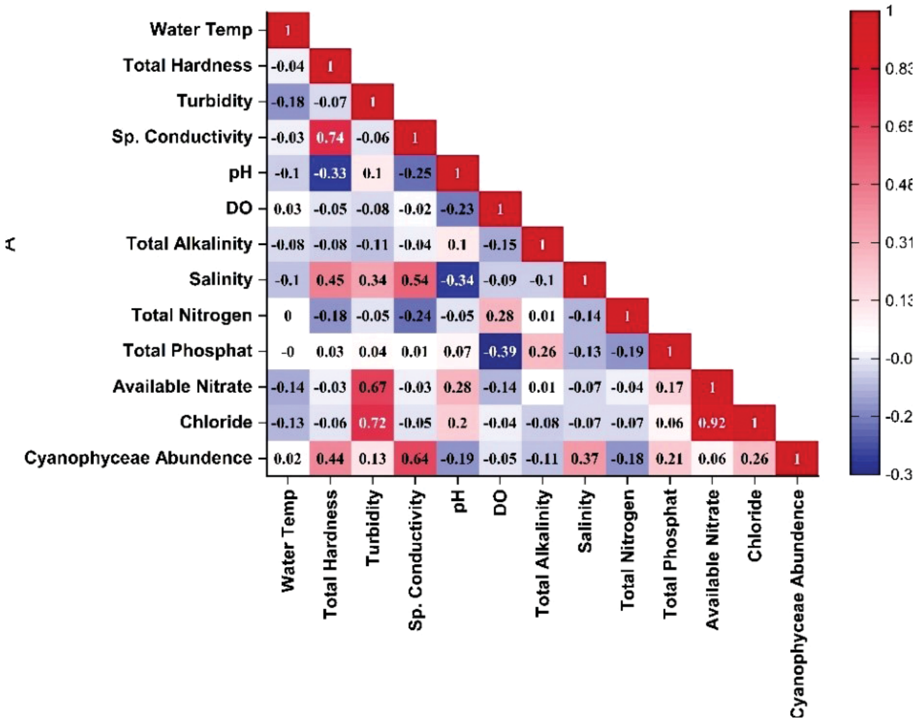

Fig. 3. Correlation between Cyanophyceae density and physico-chemical parameter

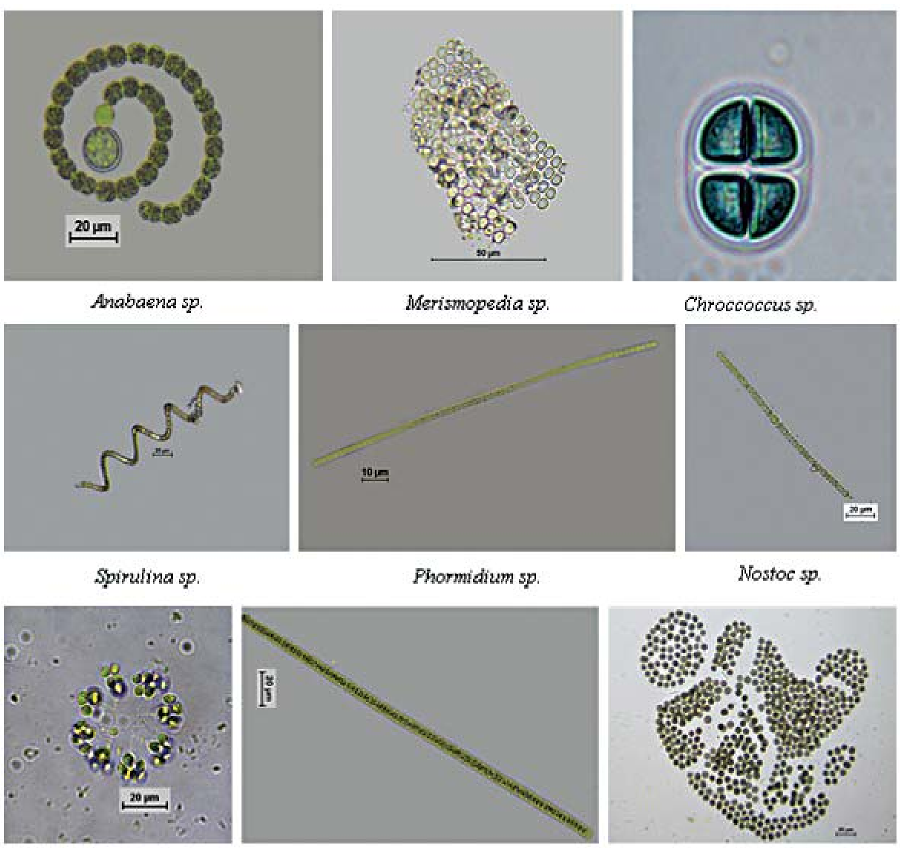

Fig. 4. Picture of Some recorded genera of Cyanophyceae

Result and Discussion

The seasonal distribution of Cyanobacteria across different sites is presented in Fig. 2. The highest density was recorded during the monsoon season (15,881,687 cells/l), while the lowest was observed in the post-monsoon period (282,484 cells/l). This variation is largely influenced by seasonal environmental changes. Monsoon rainfall increases surface runoff, leading to elevated nutrient inputs—particularly nitrogen and phosphorus—along with rises in water temperature and turbidity, all of which favour cyanobacterial proliferation[20,21]. Conversely, post-monsoon conditions are characterized by nutrient dilution, reduced runoff, and altered light availability, which collectively limit cyanobacterial growth[22].

Regionally, the highest cyanobacterial density was recorded in Bihar, dominated by blooms of *Microcystis aeruginosa*, a microcystin-producing species known for its hepatotoxic and neurotoxic effects[23]. The lowest abundance occurred between Harshil and Farrukhabad, likely due to minimal anthropogenic influence in these upper stretches. In contrast, high densities of Cyanophyceae from Kanpur to Diamond Harbour may be attributed to intensive agriculture and industrial activity along the riverbanks.

The density of Cyanophyceae showed positive correlations with salinity (0.371) and total hardness (0.436), suggesting that higher concentrations of these parameters are linked to increased cyanobacterial prevalence. Salinity is a key factor controlling the

Table 1: Water quality values of different parameters of different sites (Average value ± Standard Deviation)

	Water temp	Sp.Con	T.Hardness	Chloride	Salinity	Nitrate-N	Phosphate-P	Silicate
Harsil	8.42±3.23	39.9±85.67	73.49±40.81	2.1±2.16	0.02±0.03	0.l2±0.08	0.93±2	2.27±2.97
Tehri	9.73±4.65	39.88±85.67	80.34±40.63	2.52±3.06	0.02±0.03	0.l2±0.08	0.92±2.01	2.34±2.92
Haridwar	11.25±5.81	39.93±85.65	71.34±37.77	2.32±3.14	0.02±0.02	0.28±0.29	0.92±2.01	2.34±2.92
Bijnor	13.01±5.12	26.32±51.9	68.63±36.53	2.32±3.14	0.02±0.02	0.28±0.29	0.92±2.01	2.13±2.5
Narora	14.57±6.6	26.33±51.9	68.63±36.53	3.71±4.41	0.02±0.02	0.23±0.26	0.92±2.01	2.38±2.38
Farrukhbad	15.61±6.77	26.33±51.9	69.78±34.32	4.13 ±4.16	0.02±0.02	0.22±0.26	0.92±2.01	2.37±2.39
Kanpur	17.4±7.97	25.86±51.04	69.78±34.32	4.13±4.16	0.02±0.02	0.22±0.26	0.92±2.01	2.5±2.55
Prayagraj	18.66±7.32	25.85±51.05	58.92±27.03	4.7I±4.04	0.02±0.02	0.21±0.27	0.l5±0.l6	2.47±2.58
Varanasi	20.5±6.08	25.86±51.05	59.2±26.95	4.99±3.72	0.02±0.02	0.17±0.25	0.l5±0.16	2.22±2.49
Buxar	22.26±3.48	25.85±51.05	57.78±26.42	4.29±3.87	0.02±0.02	0.17±0.25	0.l4±0.16	2.22±2.49
Patna	22.13±3.66	25.87±51.04	60.63±32.2	4.79±4.58	0.04±0.06	0.17±0.25	0.16±0.16	2.17±2.53
Bhagalpur	22.01±3.72	25.83±51.06	0.92±40.52	5.29±4.28	0.05±0.06	0.07±0.06	0.45±0.88	2.18±2.52
Farakka	21.75±4.08	38.05±81.47	77.06±44.32	5.29±4.28	0.05±0.06	0.07±0.06	0.45±0.88	2.49±3.13
Jangipur	21.65±3.98	38.06±81.46	77.06±44.32	4.99±3.89	0.O7±0.06	0.07±0.06	0.4±0.83	2.67±3.26
Berahmpur	21.55±4.02	38.06±81.46	8.09±42.68	4.63±4.21	0.05±0.06	0.11±0.13	0.45±0.82	2.66±3.26
Balagarh	20.65±2.91	45.02±90.34	78.09±42.68	4.63±421	0.05±0.06	0.11±0.13	0.45±0.82	2.86 ±3.5
Tribeni	20.54±2.95	45.04±90.34	88.95±42.23	4.85±429	0.05±0.06	0.11±0.13	0.47±0.81	2.92±3.46
Godakhali	20.34±2.76	45.06±90.33	95.52±39.36	5.42±4.11	0.05±0.06	0.11±0.l3	0.49±0.81	3.19±3.32
D.Harbour	20.41±2.84	45.07±90.32	101.81±36.53	5.45±4.04	0.05±0.06	0.12±0.13	0.53±0.79	3.19±3.32
Fraserganj	20.63±2.66	45.06±90.33	102.52±36.99	4.1±3.26	0.04±0.03	0.l2±0.13	0.52±0.8	3.21±3.3

blooms of nitrogen-fixing cyanobacteria[24] such as *Anabaena* sp. and *Nodularia* sp. Urrutia et al.[25] found that higher salinity can favor cyanobacterial taxa by displacing other phytoplankton genera. Chia and Bako[26] also noted a positive association between cyanobacterial growth and total hardness, while a negative correlation was observed with pH levels.

Cyanobacteria exhibited positive associations in Fig. 3. with accessible nitrate (0.057), total phosphate (0.213), and specific conductivity (0.639). The increased discharge of agricultural runoff and industrial effluents enhances nutrient levels and specific conductivity, creating anthropogenic conditions that promote the formation of harmful[16,27]. Additionally, turbidity had a positive influence on cyanobacterial abundance (0.126). Many Cyanophyceae species, such as *Microcystis* and *Anabaena*, possess gas vesicles that provide buoyancy, allowing them to remain near the water surface where light is more available despite high turbidity[5]. Turbidity can also suppress the growth of competing algal groups like diatoms and green algae, which require clearer water and stronger light penetration, thereby giving cyanobacteria a competitive advantage[28]. Furthermore, turbidity is often associated with increased nutrient loading from sediment resuspension and runoff, leading to eutrophic conditions that favor cyanobacterial growth. Overall, the data indicate that the abundance of Cyanophyceae is not strongly influenced by nitrogen, pH, or oxygen levels, but is primarily regulated by water quality indicators, particularly conductivity and hardness.

Physico-chemical Parameter

Water quality parameters were analyzed across 20 sites along the River Ganga, focusing on water temperature, specific conductivity, total hardness, chloride, salinity, and nutrients such as nitrate-nitrogen, phosphate-phosphorus, and silicate as given in Table 1. Water temperature ranged from 8.42°C at Harshil to 22.26°C at Buxar, reflecting altitudinal differences—Harshil lies in the higher Himalayas, while Buxar is in the lower Gangetic plain—and increased anthropogenic influence downstream. Specific conductivity varied from 39.9 µS/cm at Harshil to 45.07 µS/cm at Diamond Harbour, with the higher value at Diamond Harbour attributed to its estuarine setting[29]. Elevated chloride and salinity levels at coastal sites like Fraserganj suggest saltwater intrusion[30]. Nutrient concentrations remained generally low across all sites, indicating limited enrichment despite varying land-use pressures.

Harmful Effect of Cyanobacteria

Cyanobacteria are particularly harmful due to their ability to produce toxins, a trait linked to the presence of the *mcy* gene[23]. Some cyanobacterial species we observed in all over the Ganga River as shown in Fig. 4. The *mcy* gene encodes peptide synthetases that play a key role in the synthesis of microcystins[31]. Major toxin-producing cyanobacterial genera include *Microcystis* sp., *Dolichospermum* sp., *Aphanizomenon* sp., and *Oscillatoria* sp.[32]. Consequently, the World Health Organization (WHO), along with various national agencies, has classified cyanobacterial metabolites—such as cyanotoxins, geosmin, and 2-methylisoborneol (MIB)—as emerging pollutants that pose serious public health risks[33]. Persistent ingestion of or contact with contaminated water can lead to long-term health effects, including damage to vital organs such as the liver and kidneys[34,35]. Several toxin-producing Cyanophyceae species identified during the study are listed in Table 2.

Table. 2 Recorded Cyanobacterial species produce Toxin[36]

Toxic genus/species	Cyanotoxin
Anabaena circinalis	Microcystins, Anatoxin-a, Saxitoxins
Anabaena flos-aquae	Microcystins, Anatoxin-a
Anabaena variabilis	Microcystins
Aphanizomenon sp.	Cylindrospermopsin
Aphanizomenon flos-aquae	Cylindrospermopsin, Saxitoxins
Cylindrospermum sp.	Anatoxin-a
Lyngbya sp.	Deoxycylindrospermopsin Cylindrospermopsin
Microcystis aeruginosa	Microcystins
Microcystis flos-aquae	Microcystins
Nodularia spumigena	Nodularin
Nostoc sp.	Microcystins
Oscillatoria agardhii	Anatoxin-a, homoanatoxin-a
Oscillatoria limosa	Microcystins
Oscillatoria princeps	Anatoxin-a, homoanatoxin-a
Oscillatoria sp.	Microcystins
Phormidium ambiguum	Microcystins
Phormidium fragile	Homoanatoxin-a, anatoxin-a
Phormidium sp.	Microcystins
Synechococcus aeruginosus	Microcystins
Planktothrix rubescens	Microcystins

Conclusion

The River Ganga, a vital freshwater resource supporting diverse uses—including drinking water and rich aquatic biodiversity is increasingly threatened by the proliferation of toxin-producing cyanobacteria. Species such as *Microcystis aeruginosa*, capable of releasing harmful microcystins, were found in high densities, particularly in the middle and lower stretches of the river. Their growth is driven by anthropogenic pressures such as nutrient enrichment, increased salinity, and altered physicochemical parameters. The seasonal peaks during the monsoon further underscore the role of environmental factors in bloom dynamics. The cyanobacterial taxa linked to hepatotoxins and neurotoxins highlights serious risks to public and ecological health. Continuous, systematic monitoring and the implementation of effective water quality management strategies are essential to mitigate these risks and ensure the sustainability of this culturally and ecologically significant river system.

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