RESEARCH PAPER

Seasonal and Temporal Dynamics of Diatom Communities in the Indian River: A Bioindicator

Brijveer Singh[1], Priyanka Singh[2]* and Meenakshi Mahajan[3]

[1]PhD Scholar, Amity Institute of Forensic Sciences, Amity University, Sector 125, Noida, Uttar Pradesh-201313, India
[2]Assistant Professor, Amity Institute of Forensic Sciences, Amity University, Sector 125, Noida, Uttar Pradesh-201313, India
[3]Directorate of Forensics Services, Director (Regional Forensic Science Laboratory, Northern Range, Dharamshala), Chilgari, Dharamshala, Himachal Pradesh-176215, India
[1]brijveer.singh@s.amity.edu, [2]psingh31@amity.edu and [3]mini2323@yahoo.com
[1]ORCID ID: 0009-0001-4496-5504 and [2]ORCID ID: 0000-0003-1105-1105

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ABSTRACT

Diatoms (Bacillariophyta) occur in all aquatic ecosystems, including fresh, marine, and brackish water, and contribute approximately 20% of the world's primary productivity. Due to the strong sensitivity to seasonal, physiographic, and water chemistry variations, diatoms are widely recognized as potential bioindicators of environmental changes in aquatic ecosystems. The present study aimed to investigate variations in seasonal and temporal changes in diatom diversity, species richness, and community structure across five distinct aquatic systems in India, namely the Ganga, Hindon, Masoorie Jheel, Upper Ganga, and Yamuna River. A total of 81980 diatoms ranged from 64 to 80 species, were recorded from all study sites, reflecting spatial heterogeneity and seasonal variability among sites. Among all the collection sites, Hindon River contributed the highest abundance, 27.1% of all recorded diatoms, followed by Masuri Jheel with 25.8%, Yamuna River with 22.1%, whereas Ganga River (13%) and upper Ganga River (12.1%) demonstrated a low level of abundance. The significant variation among the species composition was observed across the sites, indicating the nutritional status, anthropogenic influences, and habitat-specific hydrology. The Ganga River exhibited the highest species diversity, with a total of 80 species and the lowest in the Upper Ganga canal, only 64 species, indicating differences in hydrological condition and anthropogenic influences. Despite the variability of species richness, the community structure was demonstrated by a small number of dominant species and a large pool of rare species (<1% abundance), with species such as Coscinodiscus sps, Nitzschia sps, and Triceratium sps. consistently occurring across seasons and sites. The diatoms abundance peaked during post-monsoon (October to December), contributing 31.0% of the total annual population, followed by winter (January to March) and monsoon (July to September) accounted for 29.0% and 23.7% respectively. Bray-Curtis Similarity Indices (BCSI) values ranged from 0.12 to 0.53, demonstrating substantial temporal changes in the community composition, emphasizing the sensitivity of diatoms to hydrological and environmental fluctuations. Overall, this study makes an important contribution to the ecological knowledge of Indian river systems with a thorough seasonal and temporal examination of the community structure of diatoms and suggests that diatoms are strong bioindicators to monitor and identify the ecological status of rivers, especially in areas where there are both natural and human stressors. These relationships between the dynamics of the diatom community and spatial/temporal environmental variables can be used to implement more effective bioassessment practices and conservation programs concerning these essential aquatic ecosystems.

Keywords: *Diatoms, Bioindicator, Seasonal dynamics, Temporal variability, Bray-Curtis Similarity Indices, Indian River*

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INTRODUCTION

Diatoms (Bacillariophyta), microscopic unicellular algae, encased in a siliceous cell wall, can exist in all aquatic ecosystems, including fresh, marine, and brackish water (Smol et al, 2010; Wynne et al., 1985). Diatoms are extremely important in aquatic food web systems, accounting for 20% of the world's primary productivity. Earlier studies have reported that diatom communities are susceptible to environmental differences in diverse aquatic habitats (Smol et al, 2010; Pan et al., 1999). Diatoms are responding to seasonal, physiographic, and water chemistry variations (Leira and Sabater 2005). Worldwide research, including tropical and subtropical Africa, revealed that the assemblage of diatom communities affected by human-induced alteration to water quality (Chessman et al., 2007; Lobo et al., 2010; Potapova et al., 2002; Tan et al., 2013; Bellinger et al., 2006; Ndiritu et al.,

**Author for Correspondence: psingh31@amity*

2006; Taylor et al., 2007). In lotic systems, Anthropogenic pressure is one of the most important high-level factors driving the composition of the diatom community (Beyene et al. 2009; Bere et al. 2016 & 2018; Krajenbrink et al. 2019). Additionally, temporal variation influences diatoms by modifying key regulating factors within these systems, including hydrological features, biogeochemical processes, and precipitation-induced surface runoff (Tan et al. 2014; Yang et al. 2009; Huang et al. 2014). This suggested that diatom community dynamics depend on the function of both natural (e.g., temporal fluctuation) and anthropogenic influences (e.g., pollution release). Several studies demonstrated that the seasonal and spatial variation in diatom community compositions are shaped by the combined effects of anthropogenic and natural factors within a watershed (Shibabaw et al. 2021; Bere et al. 2016; Krajenbrink et al. 2019; Tan et al. 2014; Yang et al. 2009; Passy et al. 2007).

Diatoms exhibit high sensitivity and strong responses to biological and physicochemical changes, making them a potential indicator of the water quality of any aquatic system. Environmental changes have been investigated using the diatom assemblages, showing that fluctuation in diatom species often serves as an early warning signal of freshwater ecological problems. Their responsiveness to even minor changes in water quality makes them powerful in pollution (Sawaiker and Rodrigues 2017)

The Biological and ecological characteristics of phytoplankton communities play an important role and are considered valuable tools for indicating the environmental condition of water bodies (Lü et al. 2022; Chen et al. 2016; Gang et al. 2019; McQuatters-Gollop et al. 2019). Several factors, such as Organic pollution, flow velocity, eutrophication, and other factors, affect the distribution pattern of diatoms (Mangadze et al. 2017; Chen et al. 2019). Their short life-history and rapid response to changes in environments make them useful and effective indicators (Schneider et al. 2012; Kafouris et al. 2019). Recently, it has been proven that several environmental influences such as acidification, heavy metal contamination, land use, and eutrophication can be indicated by diatom communities and indicator indices (Bere et al. 2016; Yan et al. 2016; Petrou et al. 2019; Pillsbury et al. 2019). Earlier studies in numerous rivers highlighted the significance of diatom indicators for some anthropogenic pressure (Becker et al. 2018; Pardo et al. 2018; Karaouzas et al. 2019).

Seasonal changes significantly influence river ecology, affecting both physicochemical parameters and the composition of aquatic organisms (Yunus et al. 2020). These fluctuations strongly affect river flow, particularly in tropical rivers, reshaping the channel morphology, and consequently affect water quality (Hasan et al. 2023). This modification can further impact benthic community interactions. Diatoms are highly sensitive to changes in water quality and strongly influence the variability of river biological conditions. The seasonal dynamics of diatoms, along with the associated parameters of water, play an important role in the ecological status assessment of aquatic systems (Snell et al. 2019).

The diverse lifestyles, habitat variability, and regeneration systems of the diatom species make them an alarming agent of seasonal dynamics within the aquatic ecosystem (Ali et al. 2018)]. Diatoms are an important group of aquatic systems, rapidly respond to any fluctuation of environmental conditions. The diatoms (planktonic and benthic) exhibit seasonal variation in community composition and species richness, with assemblages of benthic diatoms being more sensitive to environmental factors. Due to the strong connection of diatoms with ecological parameters, it can be recommended as a strong bioindicator for monitoring and assessing the ecological condition of rivers (Hu et al. 2022; Yang et al. 2020).

The bioassessment evaluation of the Indian River system is limited, and most monitoring programs are still dependent on the traditional chemical and physical analysis. Naz et al. investigated the biomonitoring potential of benthic diatoms in the Sharda (Kali) river in the Himalayas, which is linked to the Yamuna River under India's National River Linking Programme (NRLP) (Naz et al. 2025). The objective of this study was to evaluate the seasonal and temporal variation in diversity, community composition, and species richness among diatoms across various aquatic systems. The study emphasizes the habitats heterogeneity and its influence on the diversity pattern, composition, and community structure. Earlier studies have demonstrated that the hydrogeomorphological alteration and human interventions influence diatom diversity in Himalayan rivers (Naz et al. 2025). Long-term investigation is essential for assessing the ecological degradation and understanding its impact on the composition of the diatom community (Bartwal & Nautiyal, 2025).

To address this gap, the study was conducted across five different aquatic systems, with samples collected from July to May. The expanded sample collection and monitoring are enabled through the evaluation of seasonal variation, site-specific trends, and their effects on diatom abundance, species fluctuation, and community structure. Overall, this detailed study provides a valuable understanding of the influences of environmental factors on the diatom community structure across all diverse aquatic systems.

MATERIAL AND METHOD

Collection of Water Sample and Preservation

The water samples were collected from five distinct water systems in clean bottles to avoid bubble formation. For benthic diatoms, surface sediment or scrape of submerged substrates were also collected. The sample volume of collected water ranged from 250mL to 2L depending on the expected abundance of the diatom. Immediately after collection, samples were preserved by adding Lugol stock solution to achieve a final concentration of approximately 1% (v/v). Samples were mixed gently to ensure uniform preservation.

Extraction of Diatoms

For the extraction of diatoms, the preserved samples were centrifuged at 10000 rpm for 10 min. Following centrifugation, the supernatant was removed carefully, leaving approximately 1–5 mL pellet at the bottom of the tube. The pellet was resuspended in distilled water and centrifuged again under the same conditions to remove the preservative.

After the final wash, approximately 500µl of concentrated sample is retained with the pellet and mixed gently, and used for further analysis under the microscope.

Slide preparation and microscopic observation

A 50µl aliquot of the mixed pellet sample was placed on a clean glass slide and covered with a coverslip. Triplicate slides were prepared for each sample. Following the transfer, each slide was mounted using NaphraxTM. Microscopic observations of diatoms were performed under a light microscope manufactured by Olympus Magnus Trinocular microscope model MLX-B at various magnifications, including 10X, 40X, and 100X. The images of the respective slides were captured. The abundance of diatoms was estimated as the total count per ml.

The Microscopic slide was prepared with the extracted diatoms. The 100µl of final sample aliquot was transferred onto a 19mm coverslip using a calibrated micropipette. Following the transfer, each coverslip was inverted and mounted onto a microscope slide using Naphrax^{TM}.

Identification of Diatoms

Diatoms were identified based on standard morphological characteristics using reference databases such as the AIADC image database and the ANSP database. A repeated process was followed for all fiber samples at each respective time interval.

RESULT

Study was carried out to monitor the composition of diatoms communities across five different aquatic systems such as Ganga River, Hindon River, Masoori Jheel, Upper Ganga canal, and Yamuna River from July to May months. The data of percentage abundance highlighted a clear difference in the spatial species richness and the dominant and rare taxa abundance across the aquatic site. Variation among the diatom communities observed across all collection sites including the species richness difference, dominant pattern of species and proportion of rare taxa abundance. Among all sites the range of species richness ranged from 64 to 80 taxa which indicate heterogeneous habitat conditions. Despite the variability of species richness, a consistent abundance structure demonstrated among all aquatic system in which the majority of rare species of diatoms (<1% abundance) was observed.

The Ganga River exhibited the highest species diversity, with a total 80 species, indicated richest assemblage supports by wide hydrological range and distinguished microhabitats. Among the identified species, 29 was more than 1% abundance whereas 51 was below this level, reveling the limited dominant community of diatoms within the large pool of rare species. Overall, only 11 species accounted the 50% of total abundance among them Coscinodiscus sps with 13.1% was the most abundant followed by Triceratium sps (3.0%), Trachelomonas volvocina (3.4%), Triceratium album (3.9%), Asterionella sps (4.1%), Nitzschia sps. (4.3%), Synedra acus (8.4%) (Fig. 1).

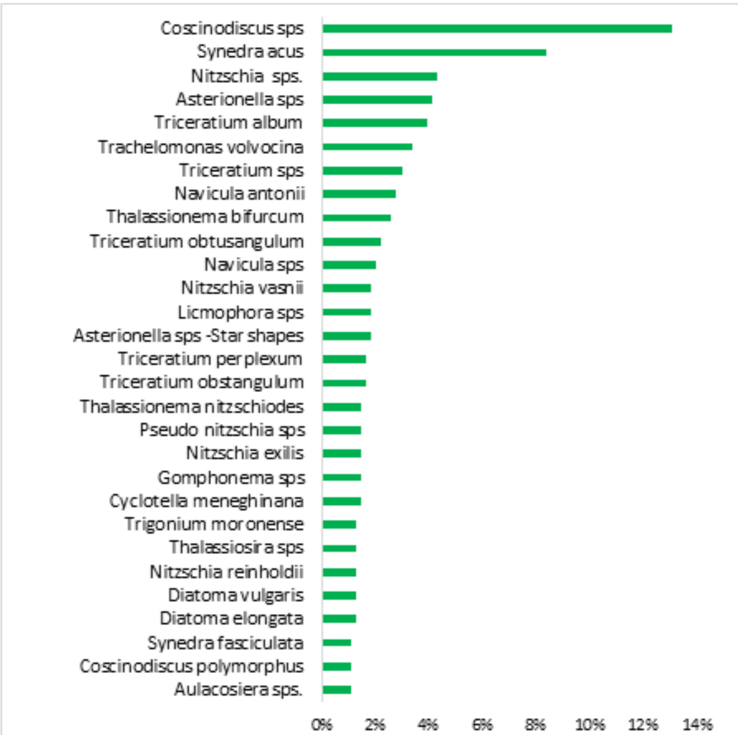

Figure 1. Abundance of diatoms greater than 1% in Ganga River from Jul to May.

The Yamuna and Hindon River exhibited a similar pattern of species abundance. With 75 identified species, the Yamuna river showed the second most species richness, followed closely by Hindon River with 74 species. The distribution of dominant and rare species was also similar between these two aquatic systems; 32 dominant species greater than 1% recorded in the Yamuna river and 33 in Hindon. Similarly, 43 rare species less than 1% were reported from the Yamuna and 41 from the Hindon (Fig 2&3).

In the Yamuna river aquatic system overall, only 13 species accounted for the 60% of total abundance. Unlike the Ganga river with 7.8% Triceratium album was most abundant and the with 6.8% Coscinodiscus sps was second most abundant species followed by Cerataulina sps (6.6%), Leptocylindrus danicus (5.8%), Diatoma elongatum (5.1%), Trachelomonas volvocina (4.7%), Trigonium moronense (4.4%), Nitzschia reversa (3.7%), Cyclostella meneghinana (3.6%), Thalassiosira sps (3.3%), Triceratium diversum (3.2%), Diatom vulgaris (2.8%), Triceratium obtusangulum (2.3%) (Fig. 2).

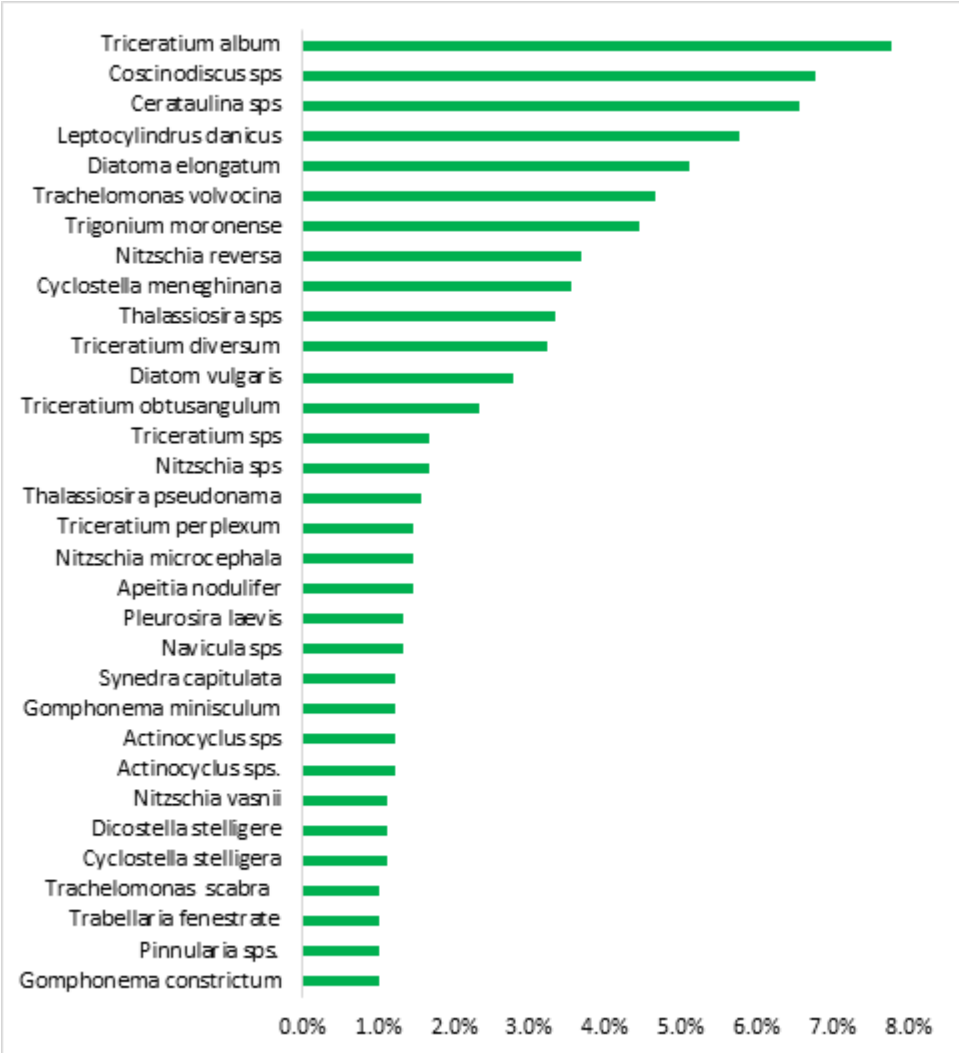

Figure 2. Abundance of diatoms >1% in Yamuna River from Jul to May.

In the Hindon river aquatic system overall, only 11 species accounted for the 45% of total abundance. Like the Ganga river Coscinodiscus sps was most abundant accounting for 7.7% followed by Triceratium obtusangulum (5.7%), Pleurosira laevis (4.5%), Triceratium album (4.2%), Cerataulina sps. (3.8%), Actinocyclus sps (3.6%), Leptocylindricus danicus (3.5%), Flagillaria biceps (3.2%), Thalossiosira sps (3.2%), Trachelomonas volvocina (2.9%), Cocconeis pediculus (2.7%) (Fig. 3).

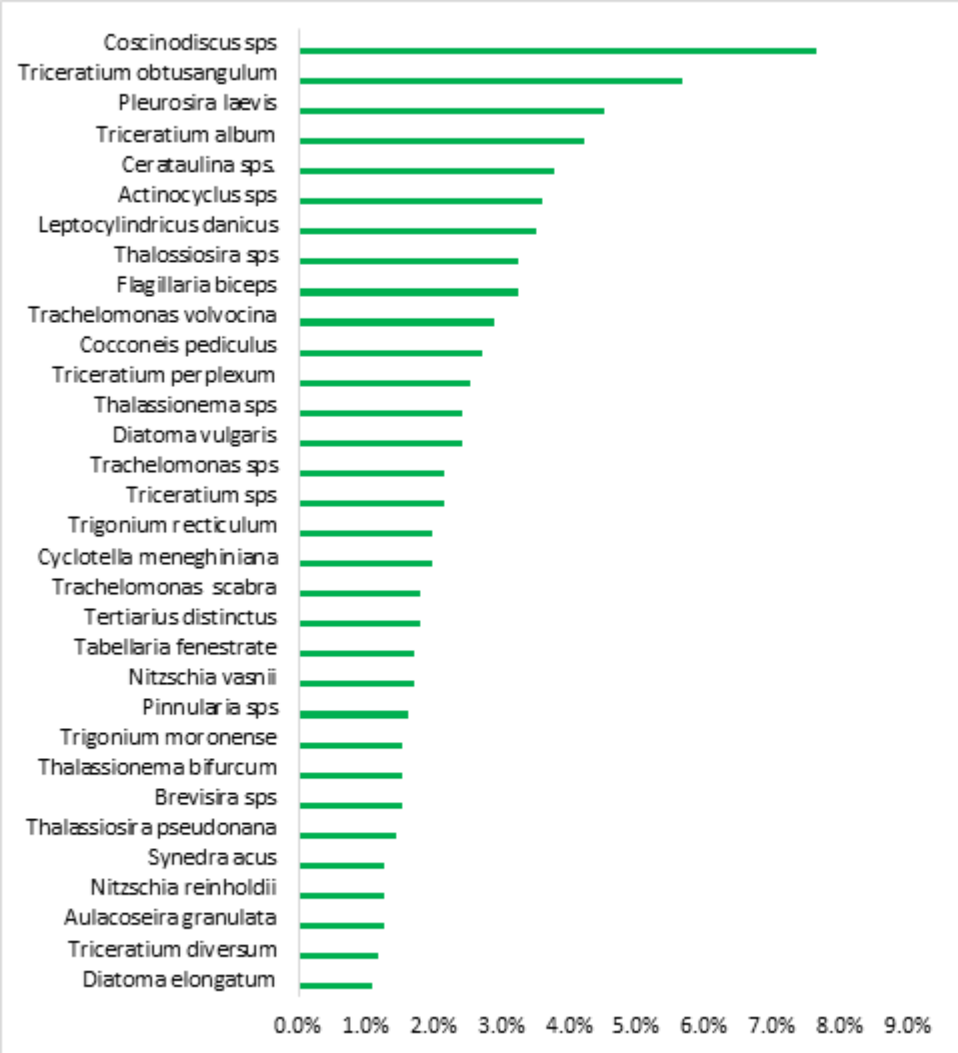

Figure 3. Abundance of diatoms >1% in Hindon River from Jul to May.

A total 71 species were reported from the lentic system, Masoori Jheel, among them 28 were dominant species greater than 1% whweras 43 species were rare less than 1%. In this ecosystem only 11 species accounted for more than 50% of abundance. Unlike the Ganga and other ecosystem, the with 6.4% Coscinodiscus sps comes at third position however, Trachelomonas volvocina (8.6%) was most abiundant and Diatoma vulgaris (7.4%) was most abiundant followed by Ceartaulina sps (5.4%), Cyclostella meneghinana (3.6%), Triceratuim obtusangulum (3.6%), Trigonium moronense (3.5%), Surirella sps (3.1%), Thalassiosira pseudonana (3.0%), Nitzschia vasnii (2.9%), Triceratium moronense (2.6%) (Fig 4).

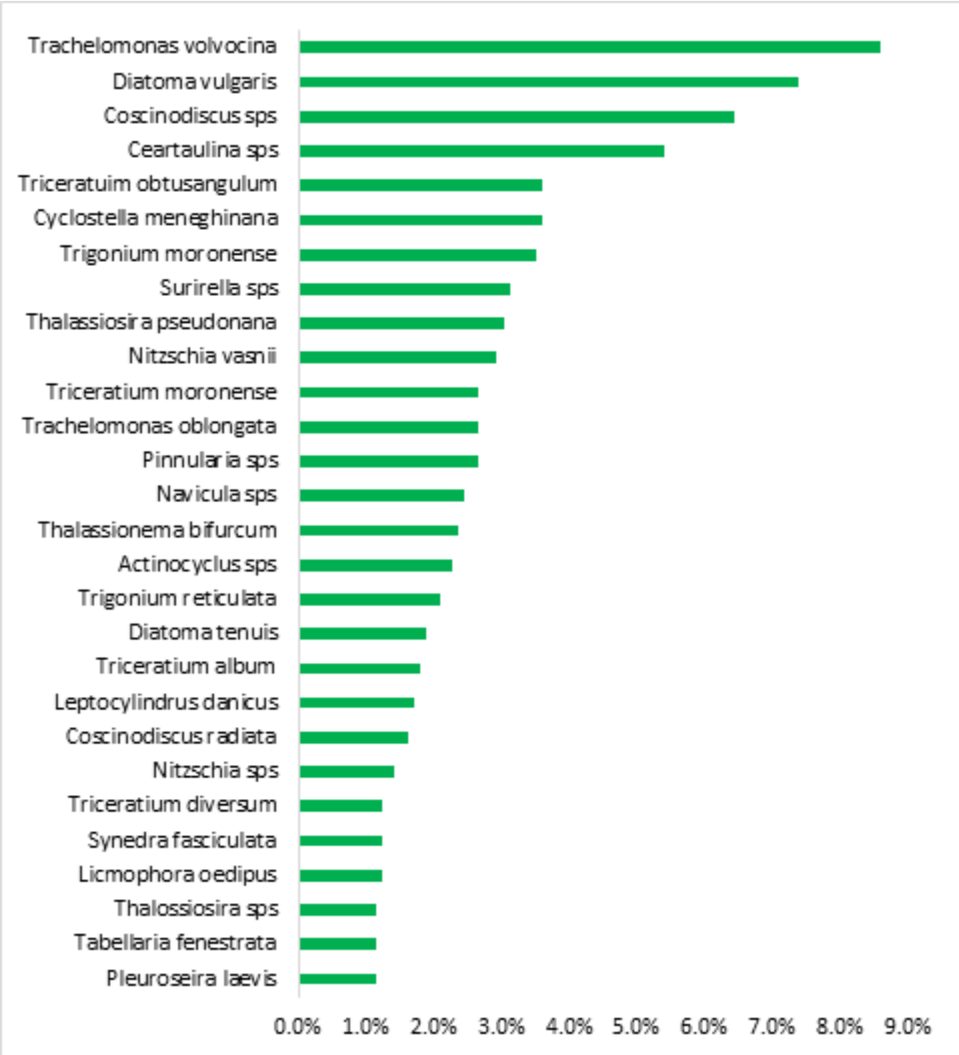

Figure 4. Abundance of diatoms >1% in Masoori Jheel from Jul to May.

With only 64 species, the Upper Ganga River demonstrated the lowest species diversity. However, exhibited a comparatively higher proportional of dominant species, with 31 species exceeding 1% abundance and 33 falling below this level. Similar to the Ganga and Hindin river ecosystem, Coscinodiscus sps (11.9%) was the most abundant and Cerataulina sps was second most followed by Diatoma vulgaris (5.4%), Nitzschia sps (4.4%), Synedra acus (4.0%), Trachelomonas volvocina (3.8%), Triceratium album (3.8%), Actinocyclus sps (3.2%), Tertiarius distinctus (3.0%). In this ecosystem the species dominance was high compared to other and these 9 species together accounted for approximately 50% of total diatom abundance.

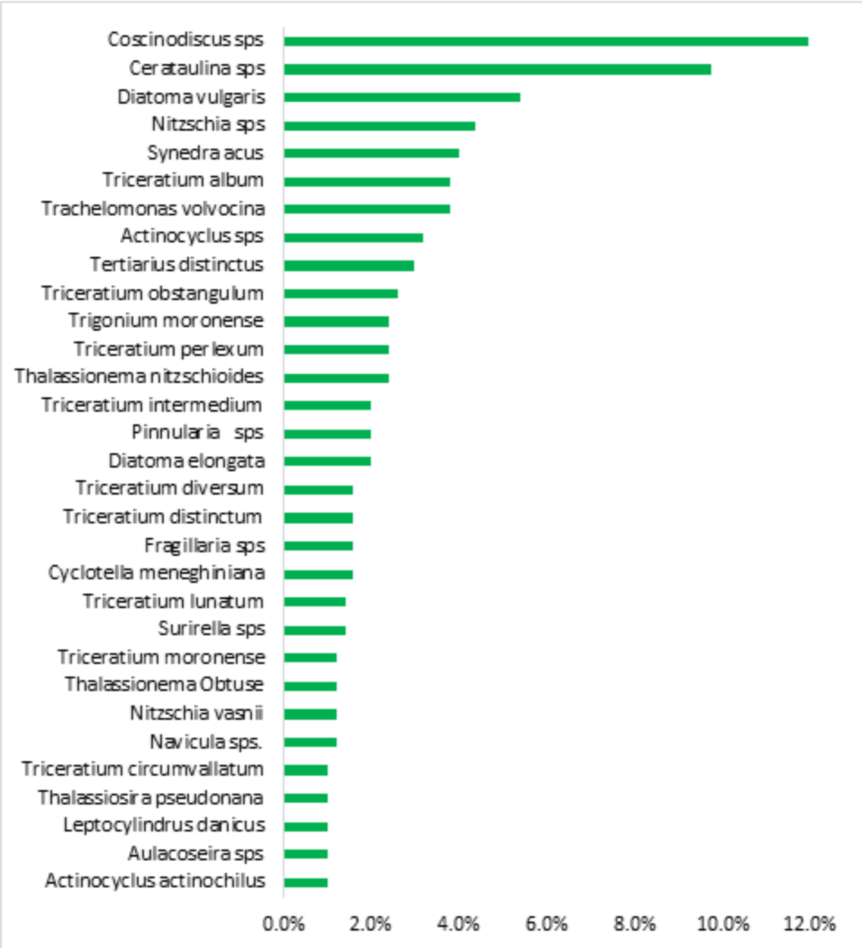

Figure 5. Abundance of diatoms >1% in Upper Ganga Canal from Jul to May.

Seasonal Dynamics and Site-Specific Patterns of Diatom Communities

During the study period from July to May, a total of 81980 diatoms were recorded from all five aquatic habitats demonstrated the seasonal and site-specific dynamics of communities of diatoms. Among all the collection sites Hindon river contributed highest abundance, 27.1% of all recorded diatoms followed by Masuri Jheel with 25.8%, Yamuna river with 22.1%, whereas Ganga River (13%) and upper Ganga River (12.1%) demonstrated low level of abundancy (Fig. 6). The significant variation among the species composition were observed across the sites indicating the nutritional status, anthropogenic influences and habitat specific hydrology.

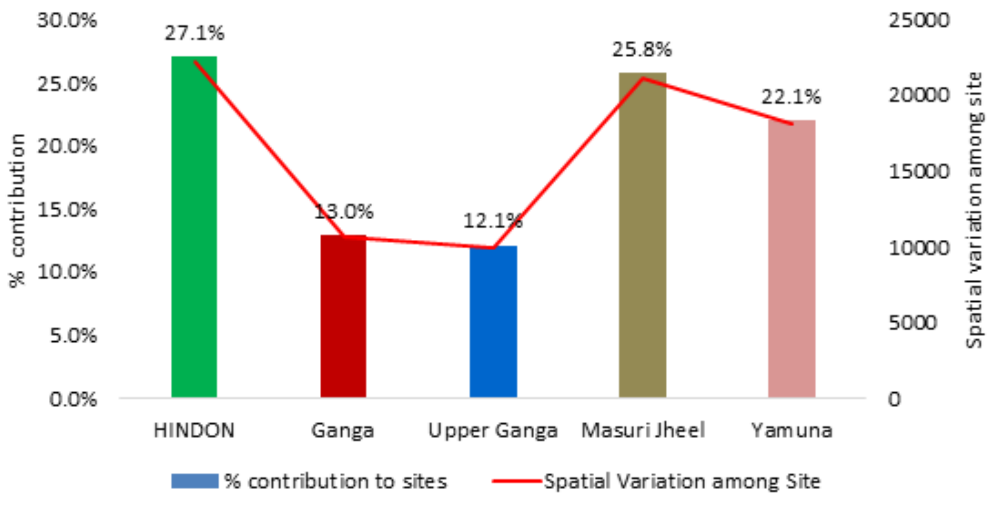

Figure 6. Spatial variation among the collection sites.

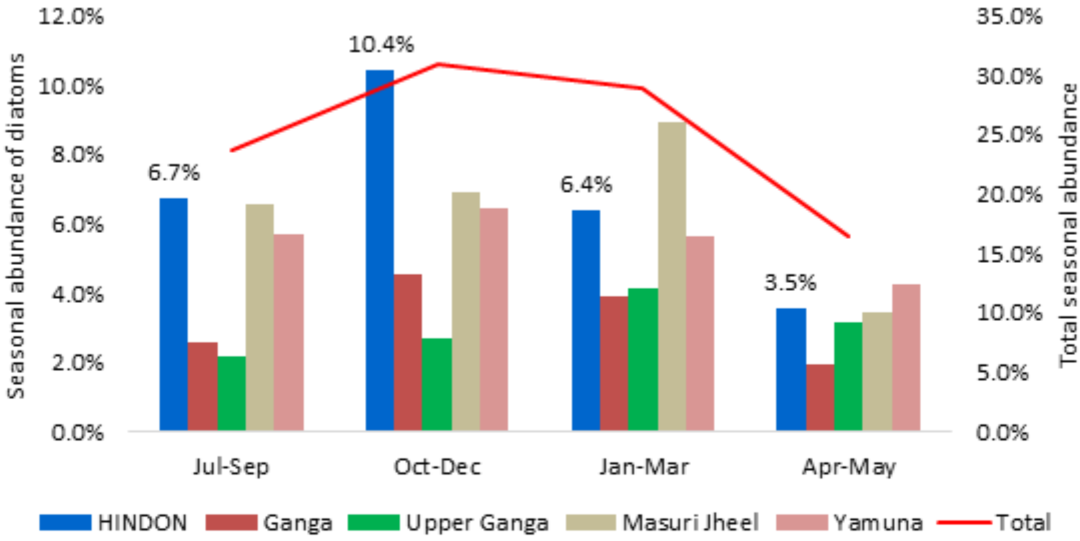

Figure 7. Seasonal abundance of diatoms number.

Table 1. Seasonal and Spatial abundance of diatoms number.

	HINDON	Ganga	Upper Ganga	Masuri Jheel	Yamuna	Total
Jul-Sep	5520	2120	1780	5380	4660	19460
Oct-Dec	8540	3720	2200	5640	5280	25380
Jan-Mar	5240	3180	3380	7300	4640	23740
Apr-May	2900	1600	2580	2820	3500	13400
Total	22200	10620	9940	21140	18080	81980

Across all study sites, the highest diatoms abundance was reported during October to December contributing 31.0% of total annual population, followed by during January to March and July to September accounted for 29.0% and 23.7% respectively. From Hindon, Ganga and Yamuna River highest contribution of diatoms consistently reported during October to December whereas from Upper Ganga and Masuri Jheel exhibited their peak diatoms abundance during January to march indicting a distinct monthly response at these sites (Table 1 and Fig 7).

Hindon River

The Hindin river exhibited one of highest diatoms abundance among all sites, contributed 27.1% of total diatom population from all studied sites. The population ranged from 2900 during April and May to a peak of 8540 during October-December. The highest population contribution was recorded during the October to December accounting for 10.4% of total diatom count, followed by 6.7% during July-Sepetember, 6.4% during January-March and only 3.5% from April and May (Fig. 6 & 7 and Table 1).

During July to September, a total of 5520 diatoms were recorded, with Pleurosira laevis being the most dominat speies, contributing 4.4% of total population followed by Triceratium obtusagulum, Coscinodiscus sps, Thalassionema sps, Trachelomonas volvocina, Thalassiosira sps., Triceratum sps. The abundance of diatoms increased subsiquently during October-December up to 8540 where Triceratium album was most abundant contributing 2.5% of total recovered isolates followed by Thalossiosira sps., Trigonium recticulum, Coscinodiscus sps, Trachelomonas volvocina, Actinocyclus sps, Cerataulina sps, and Leptocylindrus danicus.

A gradual decline in population was observed in January to March and April to May with counts of 5240 and 2900 respectively. During January to March Cerataulina sps and Flagillaria biceps was dominate and contributed 2.2% of total population followed by Coscinodiscus sps, Triceratium perlexum, Brevisira sps, Diatoma elongata. In April and May, Coscinodiscus sps was most abundant, contributed 2.4% followed by Cyclostella meneghinana, Actinocyclus sps., Leptocylindricus danicus, Trachelomonas pisciformis, Thalassionema bifurcum.

Overall, the diatom communities in Hindon river were consistently dominated by Coscinodiscus sps, and Actinocyclus sps, occurred across all seasons, representing a stable core group of diatoms. Other species such as Trachelomonas volvocina, Thalossiosira sps and Thalassionema sps were also recorded in multiple seasons, indicating broad ecological tolerance and adaptability.

Ganga River

A moderate diverse diatom communities were recorded from the Ganga River across all season with abundance range from 1600 to 3720 and contributed only 13.0% of total population across all sites, including 2.6% during July to September, 4.5% during October to December, 3.9% during January to March and 2.0% during April and May (Fig. 6 & 7 and Table 1).

During July to September, the community comprised 2120 individuals, dominated by Thalassionema nitzschiodes, Trachelomonas volvocina, Triceratium album, Cyclotella meneghinana, Coscinodiscus polymorphus, Nitzschia vasnii, Aulacoseira sps., Trigonium moronense, and Leptocylindrus danicus. The abundance of diatoms increased to 3720 during October to December and to 3180 during January to March before declined during April to May. From October to December, the community shifted to dominant species Asterionella sps, Coscinodiscus sps, Navicula antonii, Triceratium obstangulum, Licmophora sps, Nitzschia exilis, Trachelomonas volvocina, Thalassiosira sps. In January to March, the major contribution was given by Coscinodiscus sps, Nitzschia sps., Synedra acus, Navicula sps, Triceratium oblongatum, Triceratium sps, and Triceratium perlexum. By April and May the community was dominated by Synedra acus, Coscinodiscus sps, Triceratium sps, Diatoma vulgaris, Triceratium album (Fig. 8 and Table 1).

It was observed that certain species such as Coscinodiscus sps, Nitzschia sps, and Triceratium sps. was consistent dominant across all season, indicating their broad ecological tolerance, strong adaptability and persistence establishment in this aquatic system.

Masuri Jheel

Similar to the Hindon river, Masuri Jheel also supported a high overall diatom and ranking second among all study sites and contributing 25.8% of total recorded diatoms from all studies sites. Maximum number of diatoms was recorded during January to March (7300), accounting 8.9% followed by October to December (5640), and July to September (5380) both contributed almost equal 6.9 and 6.6% respectively. Least number, only 3.4% of diatoms was recorded during summer, April to May. The lowest abundance (2820) was recorded during April- May, contributing 3.4%.

During July-September, Triceratium obtusagulum and Trigonium moronense were dominant species contributing 2.8% of total diatom population followed by Trachelomonas volvocina, Trigonium reticulata, Thalassiosira pseudonama, and Thalassionema bifurcum, In October to December, Diatoma vulgaris emerge as the most abundant species (2.4%) followed by Trachelomonas volvocina, Nitzschia vasnii, Coscinodiscus sps, Actinocyclus sps and Cerataulina sps. January to March seasons was favourable for diatoms growth at this site, resulting in highest diatoms was reported across the season. Coscinodiscus sps (3.1%) was dominant species followed by Trachelomonas volvocina and Cerataulina sps, each contributing 2.4%, other frequ

ently occurring species included Cyclotella meneghiniana, Triceratium moronense, Diatoma vulgaris and Nitzschia sps. Least abundance was reported during April-May, during which Diatoma tenuis (2.4%) was dominant followed by Ceartaulina sps (2.2%), Cyclostella meneghinana, Trachelomonas volvocina and Diatoma vulgaris each contributed 1.8% of total abundancy, while Trachelomonas oblongata and Surirella sps, each contributed 1.2%

Upper Ganga Canal

Upper Ganga canal recorded lowest abundance of diatoms was recorded among all studied sites, with a total of only 9940, contributing 12.1% of total population. Similar to Masuri Jheel highest diatoms was recorded during January-March accounting for 4.1% of total population across sites. The July-September 2.2% and October-December 2.7% was contributed almost similar population. Unlike other studied sites, the second highest diatoms were recorded during April-May (3.1%).

During July-Sepetember, Diatoma vulgaris was most abundant species however contributing only 1.1% of total population followed by other species such as Trachelomonas volvocina, Coscinodiscus sps, Thalassiosira pseudonama, Nitzschia sps each accounting <1%. In October to December Coscinodiscus sps (1.5%) emerged as most abundant, however similar to Julu-September, other species such as Cerataulina sps, Thalassionema nitzschioides, Thalassionema obtuse, Triceratium album, Triceratium perplexum, Aulacoseira sps are also <1%.

During the January to March Coscinodiscus sps (1.7%) remained dominate followed by Nitzschia sps and Tertiarius distinctus, each contributing 1.0%, while all others recorded <1%. Highest species-specific abundance of diatoms recorded across all season of Upper ganga canal was Ceartaulina sps (4.3%), followed by Synedra acus (2.4%), Coscinodiscus sps (1.9%), Diatoma vulgaris and Fragillaria sps, each contributed 1.2%.

Yamuna River

With a total 18080 recorded diatoms, Yamuna River ranked third in diatoms abundance among all sites, contributing 22.1% of all total diatom population across all sites. Similar to Hindon river, the highest number was recorded during October-December (5280), accounting for 6.4% of total population, whereas almost similar individuals were recorded during July-October (4660) and January- March (4640). The lowest abundance was observed during the April-May (3500), contributing 4.3% of total diatom population.

During July-September, Cerataulina sps was most dominant species, accounting 3.7% of total diatom population, followed by Triceratium album (2.1%) and Coscinodiscus sps (2.0%). Other species such as Diatoma elongatum, Thalassiosira sps., Thalassiosira pseudonama was found abundantly.

A comparatively lower abundance was recorded during October-December, with Triceratium album (1.7%) remained dominant species, followed by Nitzschia sps, Triceratium obstangulum, Triceratium sps, Diatoma elongata, Diatom vulgaris. During January-March, Triceratium album (2.0%) continued to dominant accompanied by Triceratium diversum, Leptocylindrus danicus, Cyclotella meneghiniana and Trabellaria fenestrate.

Similar to the Upper Ganga canal, April-May represented the season with the highest species-specific abundance in Yamuna River. Despite having lowest overall population, this period recorded the highest population abundance of Coscinodiscus sps (4.3%) followed by Trachelomonas volvocina, Ceartaulina sps, Leptocylindricus danicus, Actinocyclus sps., Diatoma elongatum, Cyclostella meneghinana, and Triceratium perplexum.

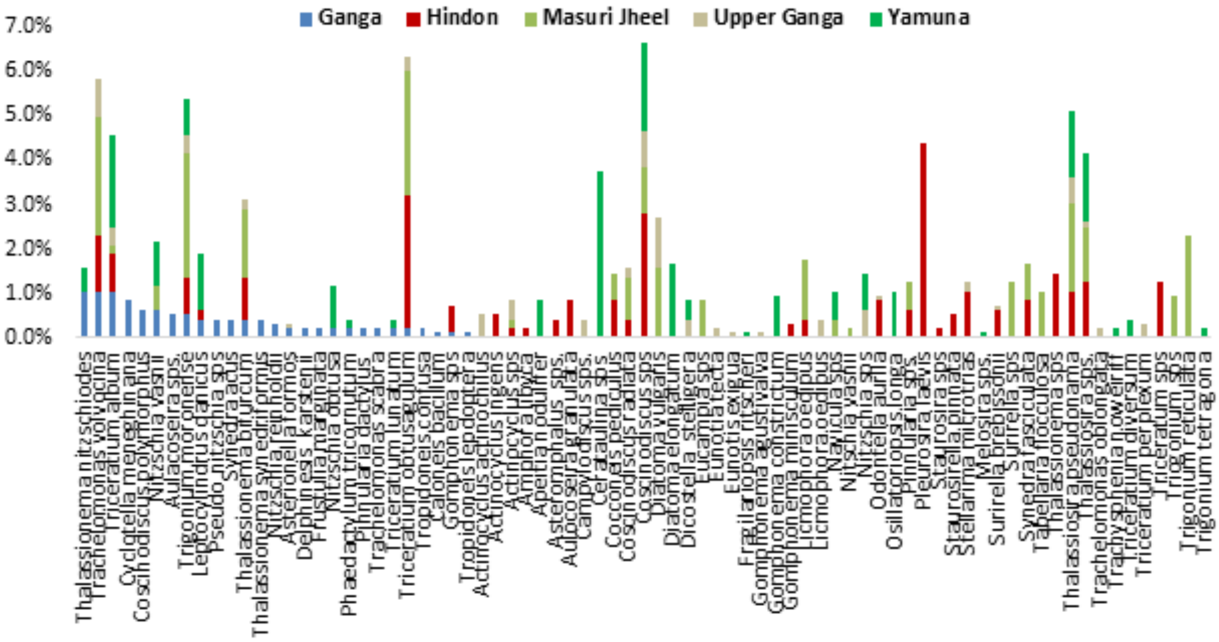

Figure 8. Population abundance during July to September.

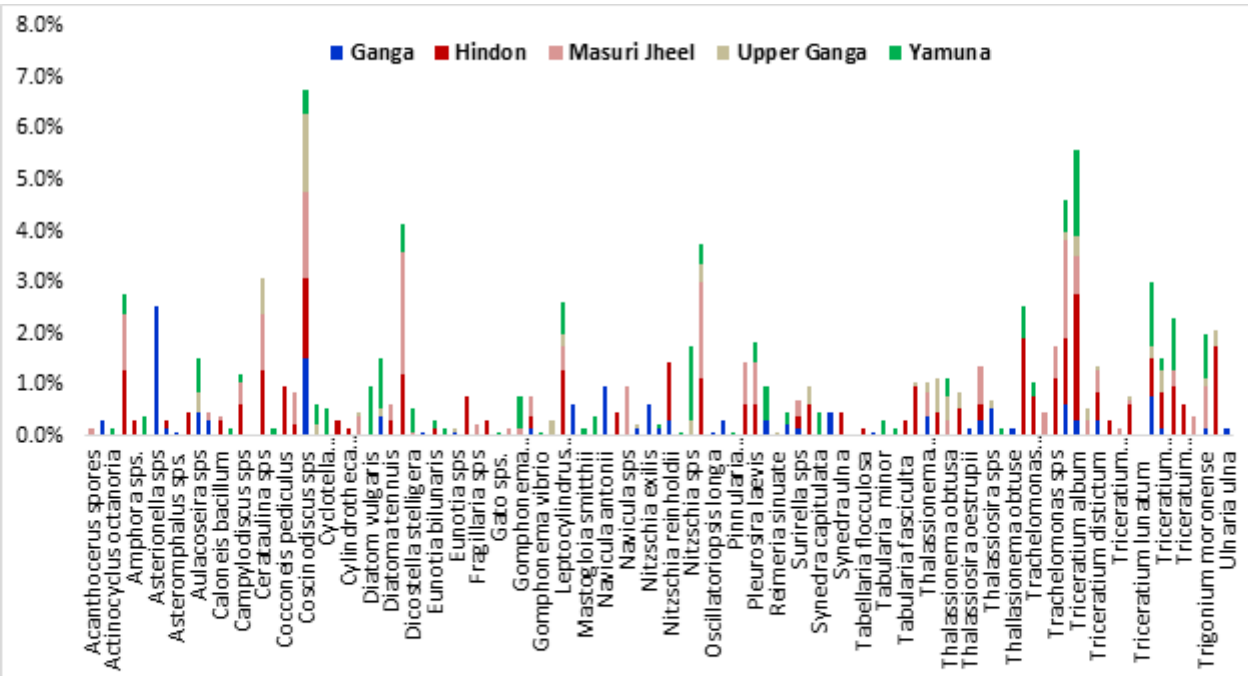

Figure 9. Population abundance during October to December.

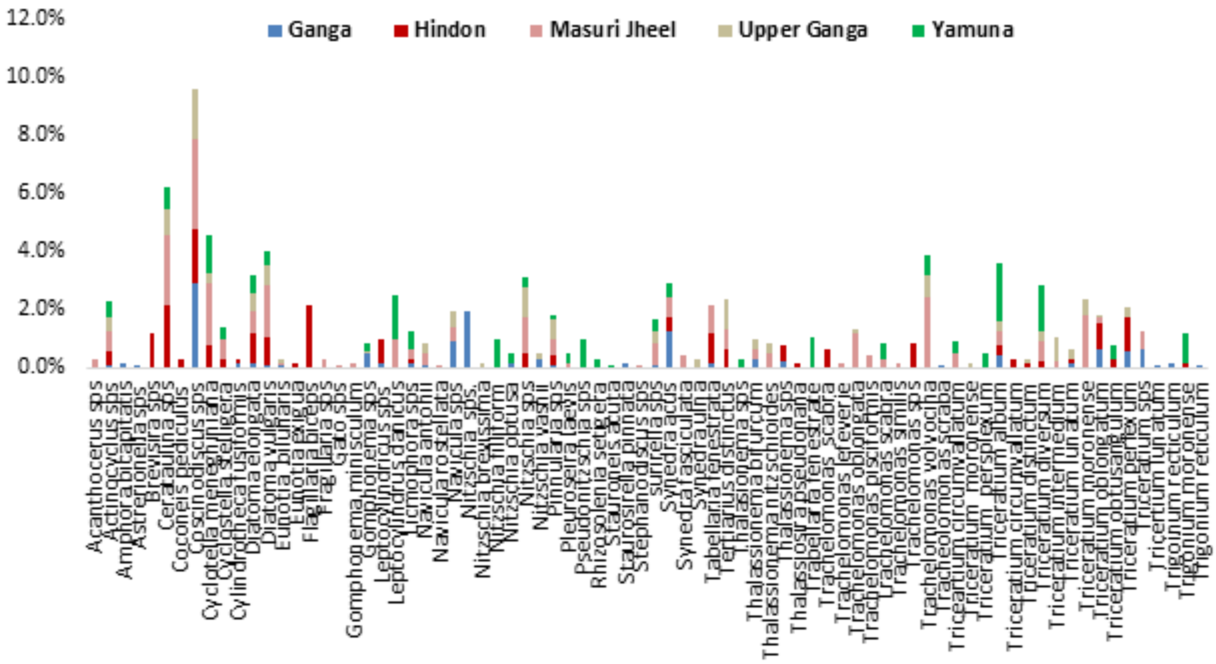

Figure 10. Population abundance during January to March.

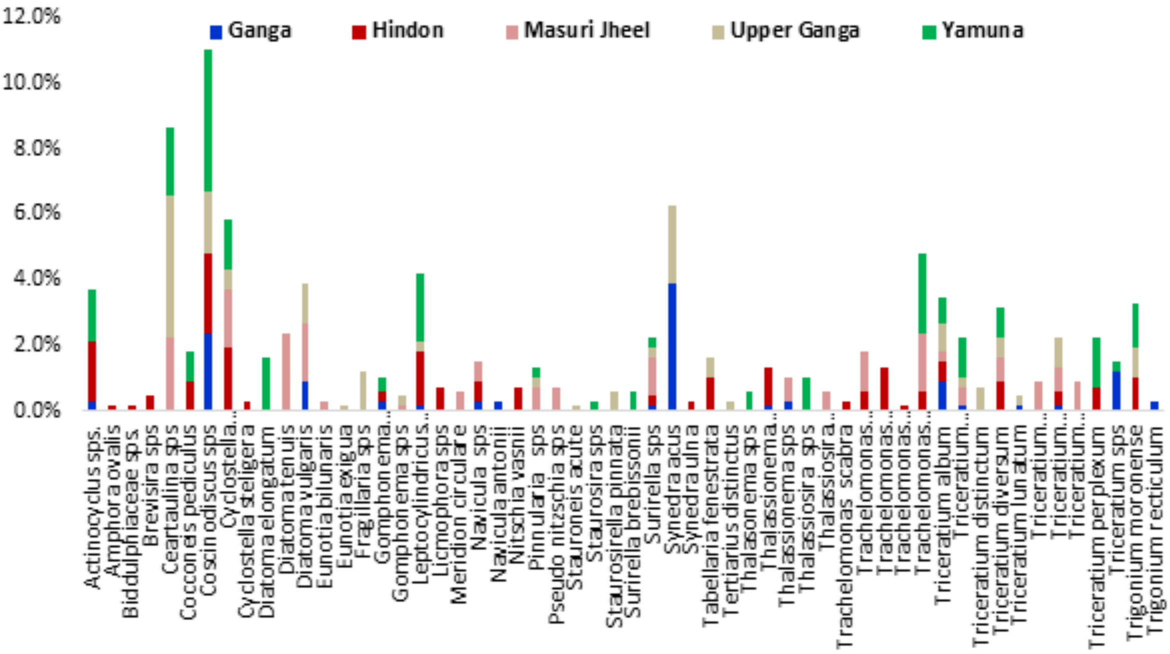

Figure 11. Population abundance during April to May.

Temporal stability and seasonal variation

The coefficient of variation (CV%) was used to access the temporal stability and seasonal variation of diatom abundance across the sampling sites, and result revealed distinct difference in differences among aquatic systems (Fig.). With 23% Coefficient of variation, Masuri Jheel exhibited lowest temporal variability among the diatom population indicating the most stable temporal pattern with relative uniform diatom abundance throughout months. Yamuna river also exhibited moderate stability with 28.6% Coefficient of variation while Hindon river demonstrate comparatively greater fluctuation due to high Coefficient of variation (39.6%).

In contrast, highest variability recorded in Ganaga and Upper Ganga Canal with Coefficient of variation 44.1 and 49.2% respectively, indicating high temporal fluctuation among the diatom's population. These finding indicates that the downstream or lentic-influenced sites such as Masuri Jheel, Yamuna River and to some extent the Hindin river maintain stable ecological conditions, compare to the upstream lotic system such as Ganga and Upper Ganga Canal which experiencing greater temporal variability in population.

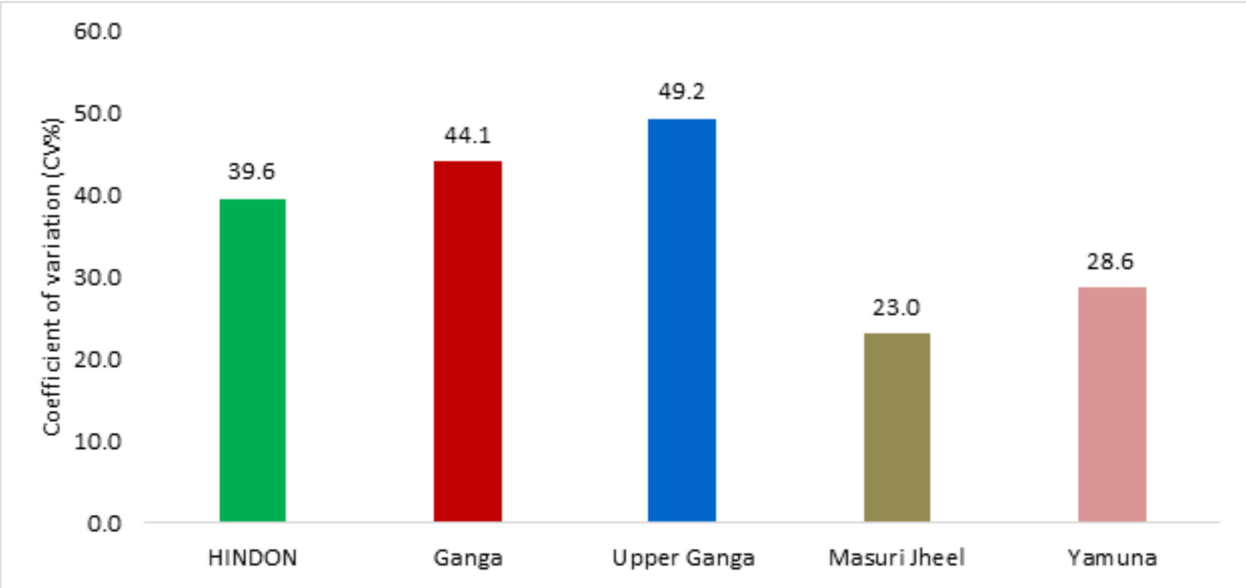

Figure 12. Coefficient of variation (CV%) across collection sites.

Bray-Curtis Similarity Indices (BCSI) for whole sample species composition

Bray-Curtis Similarity Indices (BCSI) were used to calculate relative similarity of species assemblages across all five aquatic sample collection sites (Ganga, Hondon, Masuri Jheel, Upper Ganga Canal and Yamuna River) using the PAST software (Table 1). The BCSi values represent the degree of similarity or dissimilarities in diatom species composition, where lower value indicates greater dissimilarities, while higher value reflects stronger similarities among the species composition. Across all seasons, the BCSi values ranged from 0.12 to 0.53, demonstrating substantial temporal changes of diatoms communities.

During the July-September, the highest value was recorded between Hindon and Masuri Jheel (0.44), while Ganga River exhibited low similarity with Masuri Jheel (0.15) and Hindon river (0.17). In the October-December, the value ranged from 0.20-0.47, with Masuri Jheel again showing strongest similarity with Hindin (0.47) and Ganga exhibited low value with Hindon (0.20), and Masuri Jheel (0.22). The highest overall inter site similarity was observed in January-March among all seasons with the range from 0.12-0.51. With the 0.51, the Masuri Jheel and Upper Ganga River exhibited strongest similarity, while Ganga and Yamuna River showed lowest (0.12). During the April-May, the values ranged form 0.14-0.53, with the highest similarities between Hindon and Yamuna River, representing the maximum similarity recorded among all aquatic sites and seasons. In contrast, Masuri Jheel exhibited the low similarity with Ganga (0.14) and Hindon river (0.25).

Table 2. The Bray-Curtis similarity (BCsi) values calculated for all reference samples for Jul to Sep.

	Ganga	Hindon	Masuri Jheel	Upper Ganga	Yamuna
Ganga	1.00				
Hindon	0.17	1.00			
Masuri Jheel	0.15	0.44	1.00		
Upper Ganga	0.21	0.24	0.27	1.00	
Yamuna	0.22	0.24	0.22	0.21	1.00

Table 3. The Bray-Curtis similarity (BCsi) values calculated for all reference samples for Oct to Dec.

	Ganga	Hindon	Masuri Jheel	Upper Ganga	Yamuna
Ganga	1.00				
Hindon	0.20	1.00			
Masuri Jheel	0.22	0.47	1.00		
Upper Ganga	0.31	0.26	0.29	1.00	
Yamuna	0.23	0.31	0.28	0.25	1.00

Table 4. The Bray-Curtis similarity (BCsi) values calculated for all reference samples for Jan to Mar.

	Ganga	Hindon	Masuri Jheel	Upper Ganga	Yamuna
Ganga	1.00				
Hindon	0.31	1.00			

Masuri Jheel	0.31	0.44	1.00		
Upper Ganga	0.32	0.42	0.51	1.00	
Yamuna	0.12	0.28	0.38	0.30	1.00

Table 5. The Bray-Curtis similarity (BCsi) values calculated for all reference samples for Apr to May.

	Ganga	**Hindon**	**Masuri Jheel**	**Upper Ganga**	**Yamuna**
Ganga	1.00				
Hindon	0.27	1.00			
Masuri Jheel	0.14	0.25	1.00		
Upper Ganga	0.44	0.31	0.33	1.00	
Yamuna	0.24	0.53	0.32	0.36	1.00

DISCUSSION

This study aimed to assess the variations in seasonal and temporal changes in diatom diversity, species richness, and community structure across five distinct aquatic systems in India, namely the Ganga, Hindon, Masoorie Jheel, Upper Ganga, and Yamuna River. We observed that spatial heterogeneity and seasonal variation play a critical role in the community development of diatoms and also support their potential as sensitive bioindicators of the health of aquatic systems (Kafouris et al., 2019; Schneider et al., 2012; Smol et al, 2010; Wynne et al., 1985). The study is one of the solutions to the mentioned limitation of bioassessment studies of the Indian river systems that were traditionally based mostly on classic chemical and physical analyses (Naz et al., 2025).

Spatial Patterns in Diatom Diversity and Community Composition

The result of our study revealed considerable differences among the community structure of diatoms across all aquatic systems, with variations among the species richness, their dominant structures patter along with the proportion of rare organisms. The highest species diversity, with 80 species were recorded from the Ganga River, indicating a rich and diverse community supported by a large hydrological range accompanied by heterogeneous microhabitats. This finding is supported by earlier studies indicating that ecoregional variations in India, such as climatic and geological processes, play a significant role in determining the quality of water, resulting in variation in the community of diatoms (Bhatt et al., 2025). On the other hand, the Upper Ganga Canal exhibited the lowest species diversity with 64 species, reflected more constrained or modified environment. The earlier study demonstrated that human interventions and hydrogeomorphological changes cause a significant reduction in the diversity of diatoms in the riverine systems (Naz et al., 2025). The effects of human activity, including urbanization, agricultural activity, and industrial effluents on the water quality and the resulting diatom community structure in rivers are well-reported (Clayton et al., 2025; Richards et al., 2022).

Among all aquatic systems, a consistent abundance of diatom species was observed, with a large pool of rare species and only limited dominant species. As an example, in the Ganga River, only 29 species constituted more than 1% abundance of total reported species, and 51 were below this level. A similar pattern was also observed in the Yamuna River (75 species, 32 dominant) and Hindon River (74 species, 33 dominant), suggesting a small number of highly adaptable species among all species with a broader, rarer community. Coscinodiscus sps, Nitzschia sps, and Triceratium sps were commonly reported from multiple seasons and locations. This control of a few species is a typical process of ecological dynamics of the environment, in which taxa are characterized by a wide ecological tolerance and adaptability to the existing conditions (Ferrari et al., 2020). The water quality parameters, such as turbidity, iron, and potassium, have been demonstrated to have a profound effect on the assemblage of the diatoms at the local level in the Indian rivers and played an important role in the structures of the community observed (Bhatt et al., 2025). Furthermore, significant organic pollution induced by anthropogenic influences might result in the predominance of particular diatom species such as Cyclotella striata, Nitzschia linearis, and Navicula (Achyuthan, 2017).

Seasonal Dynamics and Temporal Variability of Diatom Abundance

Our findings revealed that seasonal dynamics play a crucial role, influencing the abundance of diatom species, and we observed the highest population of diatoms during the post-monsoon season. Across all aquatic systems, site-specific response was also observed where the Hindon, Ganga, and Yamuna rivers exhibited the highest diatom abundance in post monsoon season, while the Upper Ganga canal and Masoori Jheel showed abundance peak during the winter season. The temporal fluctuation aligned with the fact that seasonal changes have a significant impact on the river flow, water quality, and consequently, the composition and abundance of aquatic life, including the diatoms. The short life cycle and high sensitivity to environmental variations make them potential indicators of these temporal variations (Kafouris et al., 2019; Schneider et al., 2012). The effects of hydrology caused by precipitation and upstream inflow plays important role in determining the composition of diatom communities, especially in rivers, where they can dominate physicochemical variables in determining diatom traits and biomass (Guo et al., 2020; Sun et al., 2021). In temperate and subtropical rivers, regular seasonal cycles of algal activity are generally common, usually associated with light, nutrient and water temperature (Álvarez-Cobelas et al., 2019; Jakovljevic et al., 2021; Snell et al., 2019; Wang et al., 2022).

Further investigation by the coefficient of variation showed that there were unique variations in the temporal stability of the aquatic systems. The lowest temporal variability (23%), observed at Masoori Jheel, indicated stable ecological conditions during the study period. There was moderate stability in the Yamuna River (28.6%). On the contrary, the Ganga River and the Upper Ganga Canal exhibited the greatest variability (44.1% and 49.2%, respectively), indicating that they underwent more significant changes in their diatom populations over time. It implies that the sites, which are affected by lentic forces or are downstream, such as Masoorin Jheel and the Yamuna River, would tend to have more stable environmental conditions compared to more lotic systems, like the Ganga River and the Upper Ganga Canal, which have a higher tendency towards environmental change and hydrological disturbance (Mora et al., 2017). Diversity and tolerance to nutrient fluctuations can influence the diatom community stability, with more diverse communities frequently demonstrating greater stability (Lavoie et al., 2008). Environmental variability, including water temperature and dissolved oxygen, has been found to have a high effect on the temporal variability of phytoplankton communities (Bhatt et al., 2025; Tian et al., 2016).

Spatial-temporal variation and similarity in Diatom community structure

Bray-Curtis Similarity Indices were used to study the spatiotemporal correlation and they also explained the dynamic correlation in the diatom communities. The mean of our BCSi values varied between 0.12 and 0.53 in all sites and seasons and exhibited a significant variation in the community of diatoms with time and locations. Such changes in similarity indices are characteristic of dynamic aquatic systems, in which assemblages of species are dynamically responding to environmental-related factors (Hu et al., 2025). As an example, Hindon and Masoori Jheel (BCSi = 0.44) showed the highest similarity during the monsoon season (July-September), whereas the Hindon and Yamuna Rivers (BCSi = 0.53) had the highest similarity in the summer season (April-May). The winter season (January-March) recorded the lowest inter-site similarity between the Ganga and Yamuna Rivers (BCSi = 0.12), and Masoori Jheel and the Upper Ganga River recorded the highest similarity (BCSi = 0.51) of similarity. These differences indicate that diatom is vulnerable to even relatively slight alterations in climate regulation and hydrological connectivity, which cause patchy distributions and abundance of widespread taxa (Beltrones, 2017a, 2017b; Minelgaite et al., 2020). The structure of the diatom community is also influenced by the complexity of the environmental factors and their interaction with the chemical properties, substrate, flow rate, light, and temperature (Jakovljević et al., 2021; López-Mejia, 2022).

This research makes an important contribution to the ecological knowledge of Indian river systems with a thorough seasonal and temporal examination of the community structure of diatoms that goes beyond the conventional chemical evaluation (Naz et al., 2025). Our results support the suggestion of diatoms as strong bioindicators to monitor and identify the ecological status of rivers, especially in areas where there are both natural and human stressors (Becker et al., 2018; Bere et al., 2016; Karaouzas et al., 2019; Naz et al., 2025; Pardo et al., 2018; Petrou et al., 2019; Pillsbury et al., 2019; Tan et al., 2017; Yan et al., 2016). These relationships between the dynamics of the diatom community and spatial/temporal environmental variables can be used to implement more effective bioassessment practices and conservation programs concerning these essential aquatic ecosystems. It also offers a more mechanistic interpretation of how these important primary producers react to the conditions in complex water bodies by correlating the community processes observed with a set of environmental drivers and a set of general ecological principles.

Although this study has given useful information, some limitations must be acknowledged. The effect of anthropogenic pressure on ecological degradation and its consequences on the diatom communities, especially with increasing pressure, requires long-term investigation (Bartwal and Nautiyal, 2025). Future studies would be able to focus more on the major physicochemical parameters and anthropogenic stressors, such as land-use change, nutrient runoff, heavy-metal contamination, and habitat degradation, which cause the observed variations. These activities would help to create more specific management and conservation plans (Chen, Zhang, et al., 2019; Eriksen et al., 2020; Mangadze et al., 2017). Furthermore, a combination of diatom-based measurements with highly sophisticated hydrological models and overall water-quality control would facilitate predicting the ecosystem reaction to environmental alteration.

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