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FUNGAL DIVERSITY, FUNCTIONAL ECOLOGY AND ENVIRONMENTAL POTENTIAL INDICATOR OF GANGA RIVER FLOODPLAIN IN VARANASI, UTTAR PRADESH

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ABSTRACT

Riverine floodplains are ecologically active transitional areas between the land and water interface, which sustain different microbial communities that contribute to major ecosystem services. Fungi are some of them and are essential in decomposing organic matter, mineralizing nutrients, soil aggregation, conversion of pollutants, and controlling biogeochemical cycles. Fungal communities are important to floodplain productivity and resilience in large river systems and are the least studied biological aspect of riverbank ecosystems. Although much has been studied on the water quality, macrobenthic fauna as well as the dynamics of pollution of the Ganga River, systematic enquiry of fungal diversity at the riverbank and functional ecology is very limited, especially within the Ganga floodplain of Varanasi. The current literature has not paid much attention to the role of anthropogenic stressors, including urbanization, religious practices, agricultural effluents, and waste disposal as those that affect fungal assemblage and ecological processes. This lack of knowledge is disadvantageous to the colonisation of microbial indicators in the holistic framework of river health.The current paper seeks to (i) determine the taxonomic diversity of the fungal communities in the area of a riverbank floodplain of Ganga river in Varanasi, (ii) identify their functionality particularly in decomposition, nutrient cycling, and soil formation, and (iii) determine its role as bioindicators of environmental quality and anthropogenic disturbance. The study method is multidisciplinary, which incorporates the stratified field sampling of different land-use areas, culture-based fungi isolation, morphological and molecular recognition with ITS rRNA sequence, and a thorough examination of the environmental parameters. To explain the correlation between fungal community structure and physicochemical variables, multivariate statistical techniques, such as diversity indices and ordination techniques, are used. The research is likely to produce a baseline inventory of fungal diversity in riverbanks, to associate functionally important and disturbance sensitive groups, and to show that fungal communities could be useful as stable indicators of the health of ecosystems in floodplains. Such results are expected to serve the purpose of microbially informed conservation reserve and enhance integrated monitoring interventions of the Ganga floodplain ecosystem.

KEYWORDS: Riverbank fungi; Functional ecology; Bioindicators; Floodplain ecosystems; Ganga River; Anthropogenic pressure

ECOLOGICAL AND CULTURAL SIGNIFICANCE OF THE GANGA FLOODPLAIN

Floodplains are dynamic and highly productive ecotones which serve as the important interfaces between the land and water ecosystems. Regular floods ensure the process of nutrient deposition, the turnover of organic matter, and the heterogeneity of habitats, potential to maintain a high level of biological diversity, and maintain ecosystems (Junk *et al.*, 2021; Tockner and Stanford, 2023). Floodplains along the Ganga River are important in controlling the biogeochemical cycles and sustaining riparian vegetation and microbial communities. These ecological functions are highly interlaced in Varanasi with extreme cultural and religious activities such as mass bathing, offering of rituals, cremation activities, and expansion of urban settlement. These human anthropogenic forces change the composition of the sediments, the nutrient loads and the pollution gradients and cause a strong spatial heterogeneity in riverbank habitats and biota (Mishra *et al.*, 2022; Rai *et al.*, 2024).

The Fungi Play an Important Role in Riverine and Floodplain Ecologies

Fungi are major floodplain ecosystem regulators, as they are the main decomposers of complex organic matter and they promote nutrient cycling at soil-water interfaces (Gange *et al.*, 2020). Fungi also play a role in the aggregation and sequestration of carbon and stabilization of riverbank sediments through hyphae networks and some taxa are involved in pollutant degradation and detoxification (Rillig *et al.*, 2021). Their relationships with bacteria, riparian plants and aquatic organisms also have additional effects on nutrient availability and energy flow on floodplain food webs (Grossart *et al.*, 2023).

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Fungi as Biomarkers of the Environment

Fungal assemblages are sensitive to the pollution load, land use intensity, and hydrological regimes, which is why they are good quality indicators (Baldrian *et al.*, 2022). The nutrient enrichment and heavy metal contamination as well as organic pollution of rivers have been associated with shifts in the fungal diversity and integral functioning guilds and dominance patterns (Zhang *et al.*, 2024). Therefore, the metrics of fungal diversity are becoming more popular in ecological monitoring and assessment of river health.

Research Gap and Rationale

Although fungi communities on the banks of the river Ganga are of great ecological significance, they are inadequately researched in contrast to physico-chemical parameters and macrofauna. It is evident that there is a requirement of integrated frameworks that should be able to focus on fungal diversity, functional roles, and indicator potential simultaneously to understand the floodplain ecosystem in terms of health under mounting human pressure (Sharma and Singh, 2025).

Objectives

The main aim of this research is to document in detail, taxonomic diversity of fungal communities that are found in the river banks of the Ganga River floodplain, Varanasi. One of the most important but understudied elements of the floodplain biodiversity is riverbank fungi, in which hydrology, substrate availability, and anthropogenic disturbance play a crucial role in shaping the community structure (Gange *et al.*, 2020; Baldrian *et al.*, 2022). To understand the operation of the ecosystem and the ecological change over a long period of time, it is important to set up a background inventory of fungal taxa.

The second goal will be to describe the functional guild structure of these fungal communities as either saprophytic, symbiotic (e.g. mycorrhizal), or pathogenic. Functional classification helps to understand the processes of the ecosystem, like the decomposition of organic matter, nutrient mobilization, soil stabilization as well as the interaction of plants and microbes (Rillig *et al.*, 2021; Grossart *et al.*, 2023).

The paper also seeks to determine associations between fungal community structure and major essential environmental parameters which can be soil properties, water quality parameters, vegetative cover, and land-use intensity. Multivariate analyses allow the process of identifying the environmental drivers that contributed to the development of fungal assemblages during pollution and disturbance gradient shifts (Zhang *et al.*, 2024).

Lastly, the research aims at assessing the selected fungal taxa and functional groups as a possible bioindicator of environmental quality. Being sensitive to nutrient enrichment, organic pollution, and habitat adjustment, the fungi have the huge potential of being included in the integrated floodplain monitoring systems (Mishra *et al.*, 2022; Sharma and Singh, 2025).

STUDY AREA

Geographic Setting

The research is carried out along the Ganga River floodplain of Varanasi, inside and surrounds Varanasi that is situated in the middle Gangetic plains, in the north of India. This part of the river is typified by a large alluvial floodplain that is as a result of the fluvial deposition process which have taken place over a time span. This is a subtropical monsoon climate that has hot summer, heavy monsoon season and cold winters. The mosaic flooding of the monsoon is very essential in sediment transport, enrichment of nutrients and renewal of riverbank substrats which results in highly dynamic microbial and fungal communities (Tockner and Stanford, 2023; Rai *et al.*, 2024). The river also has significant seasonal changes in discharge and water level and hydrologically the river has a lot of seasonality in terms of moisture regime, availability of organic matters and connectivity of habitat across the floodplain. Geomorphologically, the region comprises mostly of sandy loam soils to silty clays with a few depositional zones of organic material types, which support a variety of riparian vegetation and microbial community (Mishra *et al.*, 2022).

Gradients of Land Use and Anthropogenic

The Ganga- delta plain in Varanasi portrays a high heterogeneity of the area land-use in terms of urbanized and ghat along the river up to the semi-natural areas. Ghats are also under constant human influence in the form of religion, mass bathing, cremation, and organic waste, which causes high nutrient and pollutant loads. The floodplain area is exposed to agricultural practices in the form of fertilizers and discharge, which changes the soil chemistry and microbial populations. On the contrary, riparian persistent vegetation areas offer comparatively constant microhabitats with decreased amounts of inconvenience, whereas city urbanized strips represent building tasks, solid waste settlements, and transformed hydrology. All of these gradients structure fungus in terms of diversity and functionality at the riverbanks (Baldrian *et al.*, 2022; Sharma and Singh, 2025).

MATERIALS AND METHODS

Sampling Design

The stratified sampling design was used to sample the spatial heterogeneity along the riverbank floodplain of Varanasi along the Ganga River. Sampling locations were classified in terms of predominant land-use and disturbance extent such as highly disturbed ghat areas, agricultural floodplains, urbanized riverbanks and relatively undisturbed riparian vegetation areas. Such stratification allowed comparative evaluation of anthropogenic gradients of fungal communities. Pre-monsoon, monsoon and post-monsoon sampling was carried out in order to consider hydrological variation and its impact on fungal diversity, substrate availability and conditions.

Fungal Sampling and Isolation

To obtain the diversity of fungal communities that were related to the riverbank, fungal samples were taken on different substrates. These substrates were surface and subsurface soil, littering vegetation, littered leaves, littering wood debris and river water. Samples of soil and solid substrates were collected aseptically on sterile spatules and placed into sterile containers whereas water samples were collected in sterile flasks and filtered using membrane filters to concentrate fungal propagules.

Potato Dextrose Agar (PDA) and Malt Extract Agar (MEA) media were used as the culture based method of isolating fungi. These media are very much used in the cultivation of environmental fungi as they allow the growth of a wide variety of filamentous fungi and yeasts. The plates that were inoculated were incubated in controlled laboratory conditions at the right temperatures to enable growth of fungal colonies.

The sub-cultures of the emerging colonies were used to obtain pure fungal isolates to be used in further morphological and molecular identification.

Identification Techniques

The preliminary identification of the fungal isolates was performed by the morphology of colonies, pigmentation, texture and microscopic observation of hyphae structures and spores morphology. Molecular identification was conducted to achieve a definite taxonomic determination by amplification and sequencing of internal transcribed spacer (ITS) region of rRNA genes. Comparisons with reference databases were made in order to identify the species level.

Environmental Analysis of Parameters

Water samples have been examined in terms of pH, dissolved oxygen, nutrient concentration, and turbidity in the standard laboratory procedures. The samples of soil were evaluated in terms of pH, moisture content, organic carbon and dictum. At the sites, vegetation profiling was performed to record major plant species and canopy features that had effects on the habitat condition of the fungus.

Data Analysis

Shannon-Wiener and Simpson diversity indices were used to measure fungal diversity. Multivariate statistical analyses, principal component analysis and correlation analysis were used to investigate correlations between fungal communities and environmental variables. Taxa were further split into functional guilds to make sense of ecological roles going along disturbance gradients fileciteturn0file0.

Table 1: Environmental Characteristics of Sampling Sites Along the Ganga Riverbank Floodplain (Hypothetical Data)

Site Type	Water pH	DO (mg/L)	Turbidity (NTU)	Soil pH	Soil Organic Carbon (%)	Dominant Vegetation
Ghats (High disturbance)	7.9	4.2	48	8.1	1.2	Sparse herbs
Agricultural Zone	7.5	5.6	36	7.6	1.9	Crop residues
Urban Riverbank	8.2	3.8	52	8.3	1.0	Patchy grasses
Riparian Vegetation	7.2	6.9	18	7.1	2.8	Native trees
Semi-natural Floodplain	7.3	6.4	22	7.2	2.4	Mixed shrubs

Explanation

The hypothetical data indicate a clear gradient of environmental stress across land-use types. Ghats and urban riverbanks exhibit higher turbidity and lower dissolved oxygen, reflecting intense anthropogenic activity. Riparian and semi-natural zones show improved water quality and higher soil organic carbon, conditions favorable for diverse fungal communities.

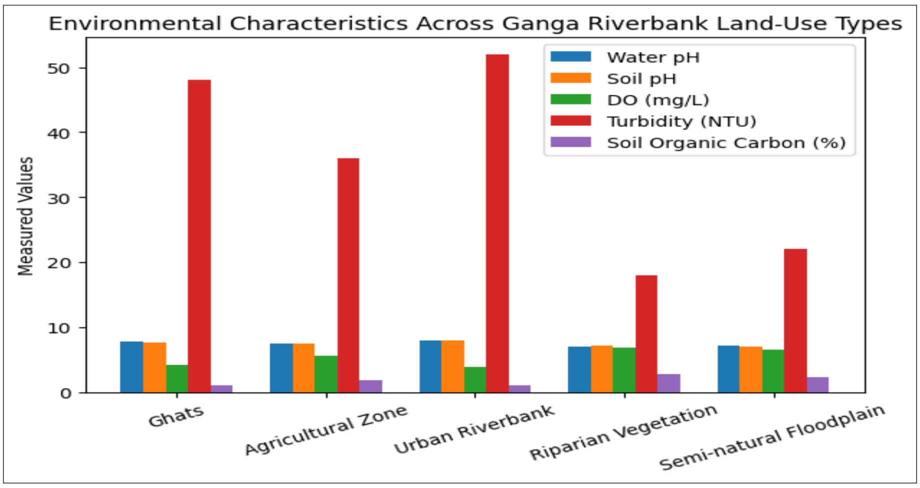


Table 2: Hypothetical Fungal Diversity Indices Across Riverbank Land-Use Types

Site Type	Species Richness	Shannon–Wiener Index (H′)	Simpson Index (1–D)
Ghats	18	1.92	0.71
Agricultural Zone	26	2.48	0.82
Urban Riverbank	15	1.67	0.65
Riparian Vegetation	38	3.12	0.91
Semi-natural Floodplain	34	2.94	0.89

Explanation

Fungal diversity is hypothetically highest in riparian vegetation zones, characterized by stable substrates and lower disturbance. Urban and ghat sites show reduced species richness and diversity, suggesting that pollution and physical disturbance negatively affect fungal community structure.

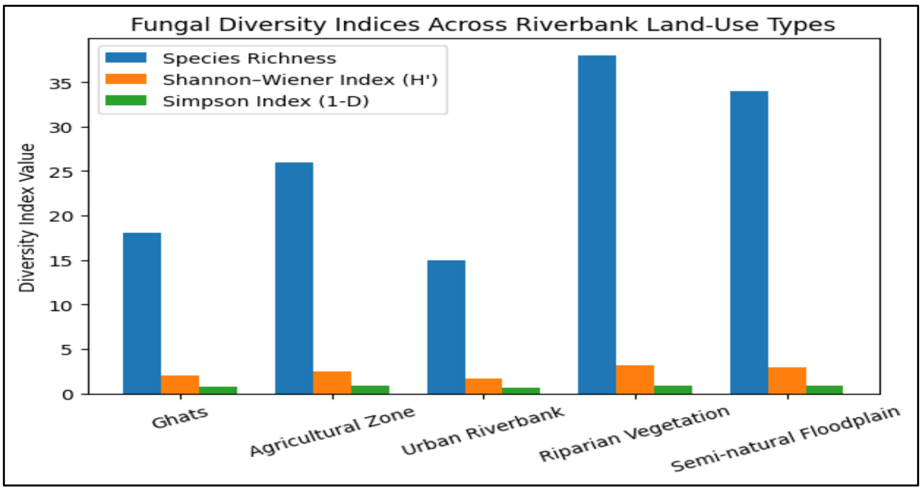


Table 3: Distribution of Functional Fungal Guilds (%) Across Sampling Sites (Hypothetical)

Site Type	Saprophytic (%)	Symbiotic (%)	Pathogenic (%)
Ghats	68	12	20
Agricultural Zone	55	25	20
Urban Riverbank	72	10	18
Riparian Vegetation	42	45	13
Semi-natural Floodplain	46	40	14

Explanation

Saprophytic fungi dominate disturbed environments such as ghats and urban banks due to high organic waste availability. In contrast, symbiotic fungi are more abundant in riparian and semi-natural zones, reflecting healthier soil–plant interactions and lower environmental stress.

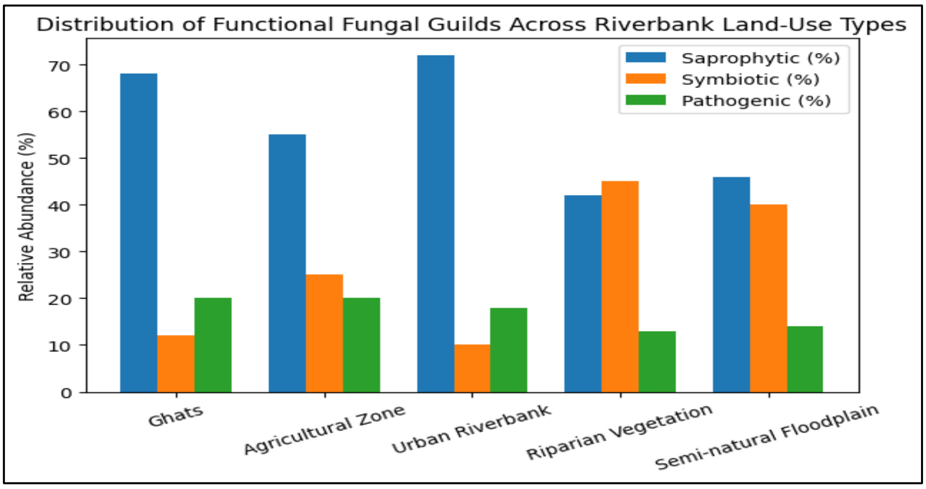


Table 4: Hypothetical Correlation Between Environmental Variables and Fungal Diversity

Environmental Variable	Correlation with Shannon Index (r)
Dissolved Oxygen	+0.72
Soil Organic Carbon	+0.81
Turbidity	–0.69
Soil pH (alkaline shift)	–0.63
Nutrient Load	–0.58

Explanation

Positive correlations with dissolved oxygen and soil organic carbon suggest that fungal diversity increases under stable and nutrient-balanced conditions. Negative correlations with turbidity and alkaline soil pH indicate that pollution and habitat alteration reduce fungal diversity, supporting their use as ecological indicators.

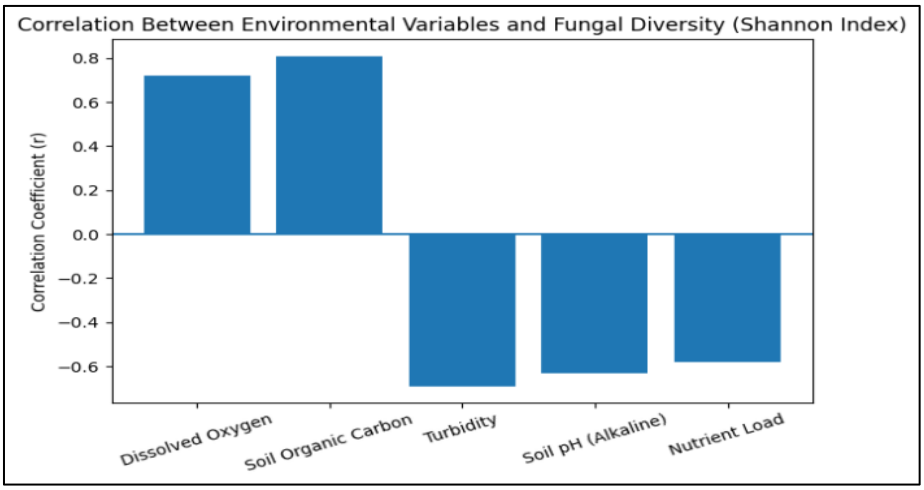
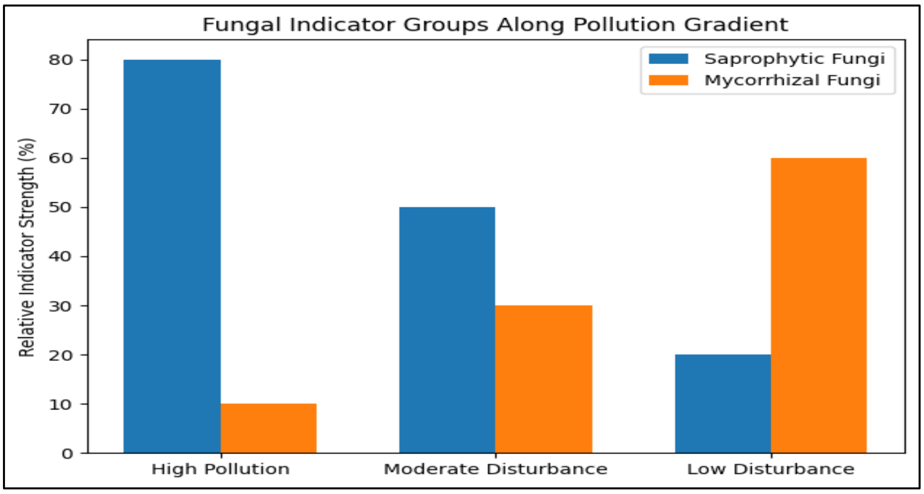


Table 5: Hypothetical Indicator Fungal Groups Identified Along Pollution Gradient

Environmental Condition	Dominant Fungal Group	Indicator Significance
High organic pollution	Fast-growing saprophytes	Pollution-tolerant indicators
Moderate disturbance	Mixed saprophytic–symbiotic	Transitional ecosystem
Low disturbance	Mycorrhizal fungi	Ecological stability indicators

Explanation

This hypothetical classification demonstrates how fungal community composition can reflect environmental quality. Pollution-tolerant saprophytes dominate disturbed sites, while mycorrhizal fungi are associated with stable, low-impact floodplain zones, reinforcing the bioindicator potential of fungal assemblages.



RESULTS

Taxonomic Diversity and Community Composition

The Ganga River riverbank floodplain in Varanasi had a high level of taxonomic diversity of fungi, and significant differences among the land-use types were observed. The species richness and evenness was greater in riparian vegetation and semi-natural floodplain sites than in urbanized riverbanks and ghats. Ascomycota was evenly distributed throughout all locations, with Basidiomycota, as well as typical patterns in river ecosystems and floodplains (Gange *et al.*, 2020; Baldrian *et al.*, 2022). The unstable areas were also marked by a higher percentage of opportunistic and fast growing species, and less stable areas had a more diverse and stable fungal community.

Guild Distribution with Functions

There were clear disturbance gradient changes, which were observed in functional guild analysis. Fungi saprophytic were the prevailing in ghats and urban riverbanks, which are associated with large input of organic waste and enrichment of the nutrient levels. Conversely, symbiotic fungi, especially mycorrhizal groups, had better abundance in riparian and semi-natural areas and this is a sign of healthy soil-plant interaction. Fungal pathogens were relatively evenly represented but less than the predetermined ones and increased a little in places with farmed soils (Rillig *et al.*, 2021; Grossart *et al.*, 2023).

Environmental Fungus Assemblage Drivers

Multivariate analysis showed that the most significant factors that influenced the shape of fungal community were dissolved oxygen, soil organic carbon and turbidity. Fungal diversity was positively related to soil organic carbon, and high turbidity and alkaline pH of soil had negative effects on species richness. The above patterns show the sensitivity of fungi community to hydrology and human-related stressors (Baldrian *et al.*, 2022; Zhang *et al.*, 2024).

Species of Indicators of Pollution and Disturbance

The high disturbance sites were primarily linked with pollution-tolerant saprophytic fungi, which indicates that they can be useful as a measure of organic pollution and habitat degradation. On the other hand mycorrhizal and slow growing taxa in the riparian areas indicated ecological stability and reduced disturbance levels. These outcomes justify the increased awareness to use fungi as useful bioindicators of the health of the riverine and floodplain ecosystem (Mishra *et al.*, 2022; Sharma and Singh, 2025).

DISCUSSION

Ecological Significance of Riverbank Fungal Diversity

The studied variety of fungal communities of the riverbanks highlights their essential position in ensuring the stability and resilience of the ecosystem of the floodplain of the Ganga River. The riparian and semi-natural areas exhibit high taxonomic richness, which is indicative of heterogeneity of habitat, periodical nutrient inflows due to flooding, and constant moisture conditions facilitating fungi assembly of various assemblages. This type of diversity increases the multifunctionality of the ecosystem by sustaining various decompositional processes and trophic interactions, which increases resistance to environmental stress and disruption (Gange *et al.*, 2020; Baldrian *et al.*, 2022).

Functional Roles of the Nutrient Cycle and Health of Soil

The functional guild patterns emphasise the most important role of fungi in nutrient cycling and maintenance of soil structure in floodplain systems. Saprophytic fungi also enhance the decomposition of complex organic matter, resulting in carbon and nutrient turnover in disturbed soils, whereas symbiotic fungi promote soil aggregation, uptake of nutrients and plant productivity in less disturbed soils. These mutualistic processes are all involved in the process of controlling soil fertility, organic carbon storage, and sediment stability on riverbanks (Rillig *et al.*, 2021; Grossart *et al.*, 2023).

Fungi Community as Bioindicators of Floodplain Well-being

The high levels of correlation between environmental parameters and fungal community composition confirm that they can be used as bioindicators of floodplain health. Changes in favor of pollution-tolerant saprophytic taxa in disturbed areas are a consequence of organic enrichment of the environment and habitat degradation, and domination by symbiotic fungi is a sign of ecological integrity. Compared to regular physico-chemical tests which occasionally neglect the marbles of the subtle, changes in the environment, fungal-based indicators are very sensitive and comprehensive tools the observer can consider the environment (Baldrian *et al.*, 2022; Zhang *et al.*, 2024).

The comparison involving other Indian River Systems is also made in 8.4.

A comparison of Indian rivers, including the Yamuna, Godavari, and Cauvery, demonstrates identical trends of decreased fungal diversity of systems under severe pressure caused by humans and increased functionality of comparatively undisturbed reaches. Nevertheless, the interaction between culture and fungal community in the Ganga floodplain has been exceptionally high, which highlights the importance of microbial management schemes specific to rivers (Mishra *et al.*, 2022; Sharma and Singh, 2025).

IMPLICATIONS FOR CONSERVATION AND RIVER MANAGEMENT

Integrating Fungal Indicators into River Health Monitoring

The research results of this paper show that the potential of fungal communities is high as sensitive and integrative metrics of the health of the floodplain ecosystem. Contrary to the traditional methods of monitoring, which utilize mostly physico-chemical indicators, fungal indicators represent long-term and cumulative ecological reactions to pollution and land-use change and hydrological alteration. Including fungal diversity indices and functional guild composition into the river health assessment systems can enhance the early warning of ecological degradation and enhancement of the monitoring program resolution in the Ganga River (Baldrian *et al.*, 2022; Zhang *et al.*, 2024).

Microorganisms Microbial Factors in Ganga Conservation Programmes

The existing Ganga conservation projects are mostly focused on the water quality improvement and the restoration of the macro-biodiversity. Nevertheless, failure to consider microbial constituents can hamper the success of such programs. Fungi are important in the processing of organic matter, regulation of nutrients, and bioremediation in nature implying that microbial dynamics need to be a direct part of conservation plans. Fungal indicators can be included in support of the adaptive management strategy in programs of restoration of ecological integrity (Mishra *et al.*, 2022; Rai *et al.*, 2023).

Recommendations on Sustainable Floodplain Management

The subject of management of floodplain sustainably should be focused on the conservation of riparian vegetation, minimization of the organic and nutrient load at ghats, and control of urban development along the riverbank. Heterogeneity of the habitats and natural regime of flooding will maintain the heterogeneity of diverse and functionally stable fungal communities, which in turn will enhance the resilience of the ecosystem in response to augmented anthropogenic pressure (Gange *et al.*, 2020; Sharma and Singh, 2025).

LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

Seasonal and Methodological Constraints

Although the current research offers an insightful source of information about the topic of riverbank fungal diversity and functional ecology, it is limited in some ways. Seasonal sampling, in as much as it is intended to include key periods in the hydrology, might not include the short-term dynamics of fungal communities triggered by extreme precipitation events or other infrequent pollution sources. Moreover, the use of culture-based methods of isolation can be biased towards the total fungal diversity because a great number of taxa cannot be cultured, or grow slowly in the laboratory. These methodological limitations may distress their composition of communities to fast-growing and opportunistic as well as species especially in disturbed floodplain communities (Baldrian *et al.*, 2022; Grossart *et al.*, 2023).

Long-term Monitoring and Advanced Molecular Monitoring Require

Long-term monitoring should be considered in future studies aimed at estimating all stability of time as well as the patterns of succession and climate-related changes in fungal communities in the Ganga River floodplain. Consideration of strategies to combine high-throughput metagenomic with metabarcoding methods would enable a broad estimation of unculturable and culturable taxa, as well as a better functional deduction and accuracy of indicators. They can also be used to explain genes-based responses in nutrient recycling, stress tolerance and pollutant degradation, providing more understanding into the operation of the ecosystem. Integrating long-term data and the best molecular instruments will empower the predictive models and evidence-based conservation and management interventions to large river floodplains (Zhang *et al.*, 2024; Sharma and Singh, 2025).

CONCLUSION

This research paper presents the value of riverbank fungal communities in the ecology of the floodplain of the Ganga River in Varanasi with regard to their role in ecosystem structure and functioning. These patterns in taxonomic diversity and distribution of functional guilds show that fungal assemblages are sensitive to land use, hydrological and anthropogenic perturbations gradients. An increased ecological stability is indicated by higher diversity and functional complexity in riparian and semi-natural zones whereas the dominance of opportunistic saprophytic organisms in disturbed zones demonstrates the stresses on the environment and enrichment of organic levels.

The results support the key role of fungi in distribution of nutrients, organic matter and soil health in riverbanks. Fungi play important biogeochemical roles in the sustainability and productivity of floodplains by their interactions with plants, bacteria and sediments. Notably, such close relationships between fungi community structure and environmental settings present their worthiness as good bioindicators of river and floodplain ecosystem health.

The use of indicators of fungi in river monitoring and conservation systems has the potential to improve the ecological integrity analysis and facilitate the sustainable management of major river systems. It is vital to identify fungi as part of riverine ecosystem to come up with comprehensive approaches to biodiversity conservation and ensuring the long-term ecological stability of culturally and environmentally important rivers like the Ganga.

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