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RESEARCH PAPER

Vascular flora and ecological resilience of the Ganga River watershed: a study from Gomukh to Gangasagar

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Abstract
This study investigates the vascular plant diversity of the Ganga River watershed, a 2600 km-long vital water system extending from the Himalayas to the Bay of Bengal. The study was conducted along the Ganga River in 2023, with 26 selected sites covering a 10 km area on both sides and a 100 km distance between each site. Field surveys during pre-monsoon and post-monsoon seasons collected 13,000 plant specimens and identified 1117 species from 660 genera and 152 families. Among these, 876 species were native, and 241 were exotic. Dominant families include Poaceae, Fabaceae, Asteraceae, Malvaceae, and Lamiaceae, with herbaceous species prevalent along the riverbanks. Life-form analysis revealed a "thero-chamaeo-phanerophytic" phytoclimate, with therophytes, chamaephytes, and phanerophytes comprising a significant proportion of documented plants. A comprehensive systematic enumeration of each species' habit, nativity, and life-form is provided. This study highlights the adaptive resilience of the Ganga River ecosystem, shaped by its diverse flora, but underscores pressing conservation challenges, particularly habitat destruction and fragmentation due to urbanization and industrialization. Targeted conservation strategies, addressing habitat degradation, and promoting sustainable biodiversity management, are critical to safeguarding this ecologically and culturally significant watershed for future generations.

Keywords Floristic diversity · Ganga River · Life-from · Nativity · Vascular plants

Introduction

Water is the key resource required to sustain life on this planet. It is found in most of the earth as in the ocean, rivers, ponds, streams, ice, etc. The river Ganga is an important source of water in India, forming a major river system that stretches from the Himalaya to the Bay of Bengal. The Indian civilization and economy depend on this river system due to its water availability throughout the year (Paul and Sinha 2013). Ganga alone accounts for 25% of India's total water resources (Paul 2017). Globally, more than 300 million people from India, Nepal, and Bangladesh depend on the river Ganga (Gopal 2000). The Ganga River originates from Gomukh (30°36′ N, 79°40′ E) at the Gangotri Glacier in the Uttarkashi district of Uttarakhand, where it is initially known as the Bhagirathi. Another major tributary, the Alaknanda River, originates from the Bhagirath-Kharak (30°49′ N, 79°17′ E) and Satopanth (30°45′ N, 79°21′ E) glaciers. These two tributaries converge at Devprayag, marking the point where the river officially takes the name Ganga. Up to Haridwar, the Ganga River flows through the Himalayan terrain. Upon reaching Haridwar, it enters the Indo-Gangetic plains. From this point, the river flows southward, traversing the plains of Uttar Pradesh. Upto the Ballia, it continuously flows in Uttar Pradesh through different districts, after here it enters Bihar near Chausa of Buxar district. It flows up to Katihar district in Bihar and enters the Sahebganj district of Jharkhand. Then it turns southwards and enters West Bengal from the Murshidabad district. About 40 km from

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Farakka, it divides into two streams; the left stream flows eastwards toward Bangladesh, while the right stream which is known as Hooghly, continues to flow south through West Bengal. Its name changes to Bhagirathi when it flows west and southwest of Kolkata and finally reaches the Bay of Bengal. The river has a total length of 2600 km from its main source, Gomukh. People from all over the world are drawn to the Ganga River because of its variety, species richness, and unique qualities. The Ganga River's surrounding forest ranges from alpine meadows in its source regions to coniferous, mixed-oak, pine, scrub-and-bushes, monsoon deciduous, and mangrove forests. There are dense forests across the Delta and the Himalayan area. From ancient times, plant communities have been a key source of interest for researchers. An area's vegetation assemblages and composition create an important habitat that supports the growth and maintenance of these ecosystems. The Ganga's vegetation pattern is subject to seasonal variations, topogeography, flood levels, and species composition influenced by various soil types and water supply functions. These factors have a significant impact on the distribution of plant species. The Ganga River falls under all the vegetation types like tropical, sub-tropical, temperate, alpine, and mangrove types. Various earlier works have been done on the floristic diversity of the Ganga basin. A description of several plants of the Upper Ganga Plain has been reported by Duthie (1903–1929) in his three volumes of "Flora of the Upper Gangetic Plain and of the Adjacent Siwalik and Sub-Himalayan Tracts". According to Biswas and Calder (1994), a list of 171 species of aquatic angiosperms that grow commonly in freshwater, brackish water, as well as marshy areas has been reported in "Handbook of Common Water and Marshy Plants of India and Burma". Subramanyam (1962), in "Aquatic Angiosperms," gives a detailed description and distribution of 117 taxa belonging to 32 families of the commonly found aquatic and halophytic flowering plants of the Indian Sub-continent. The systematic account of 1230 species of Angiosperms belonging to 624 genera distributed over 115 families, which includes records of some aquatic angiosperms in this information is recorded by Babu (1977) in his book "Herbaceous Flora of Dehradun". Naskar described the aquatic plants in two volumes: "Aquatic and Semi-Aquatic Plants of the Lower Ganga Delta: Its Taxonomy, Ecology and Economic Importance" (Naskar 1990) and "Plant Wealth of the Lower Ganga Delta: An Eco-Taxonomical Approach" (Naskar 1993). Cook (1996) provides a detailed description of vascular angiosperms and wetland plants of the Indian Sub-continent in his book 'Aquatic & Wetland Plants of India'. Recently, Shruti et al. (2019) described 289 plant species belonging to 219 genera and 88 families from the mangrove delta region in the lower Gangetic plain. Despite these contributions, floristic studies along the Ganga remain fragmented. The need for a comprehensive vegetation analysis from its source in Gomukh to the Gangasagar has become imperative. The current study addresses this gap by systematically documenting vascular plants along the river's continuum, categorizing species by their habits, nativity, and life forms. Thus, it contributes to a holistic understanding of the Ganga's ecological heritage.

Materials and methods

Study area

The current study was carried out along the Ganga River between Gomukh (4023 m) and Gangasagar (4 m). A detailed description of each site and site selections is described in the previous study (Balkrishna et al. 2025). Briefly, a total of 26 sites were selected, with two sites ranging between around 100 km in distance. This selection was based on the ecological variability of the Ganga River, which changes significantly from its source to its endpoint. The river Ganga flows through five states, *i.e.*, Uttarakhand, Uttar Pradesh, Bihar, Jharkhand, and West Bengal. Among all the twenty-six sites, five (S1–S5) were in Uttarakhand, ten (S6–S15) in Uttar Pradesh, five (S16–S20) in Bihar, one (S21) in Jharkhand, and five (S22–S26) in West Bengal (Fig. 1). For the study purpose, around 10 km areas on both sides of each site were covered.

Data collection

A comprehensive survey of the floristic diversity along the Ganga River was conducted during the pre-monsoon season (March to May 2023) and post-monsoon season (October to November 2023). Approximately 13,000 plant specimens were collected, processed, and mounted on herbarium sheets following the standardized methods (Jain and Rao 1977). These specimens were deposited in the Patanjali Research Foundation Herbarium (PRFH) for future reference and record. The identification of the plants were purely morphological and their authentication were carried out using extensive literature, including seminal works such as those by Hooker (1872–1897), Duthie (1903–1929), Osmaston (1927), Gupta (1968), Babu (1977), Raizada and Saxena (1978), Stainton (1988), Polunin and Stainton (1988), Naskar (1990, 1993), Cook (1996), Gaur (1999), Kehimkar (2000), Singh and Prakash (2002), Uniyal et al. (2007), Pusalkar and Srivastava (2018), Singh et al. (2019), Sinha et al. (2019), Dash and Mao (2020) and Mao and Dash (2020a,b). The habit types and nativity statuses of the plants were determined based on literature from Gerber et al. (2004), Reddy (2008),

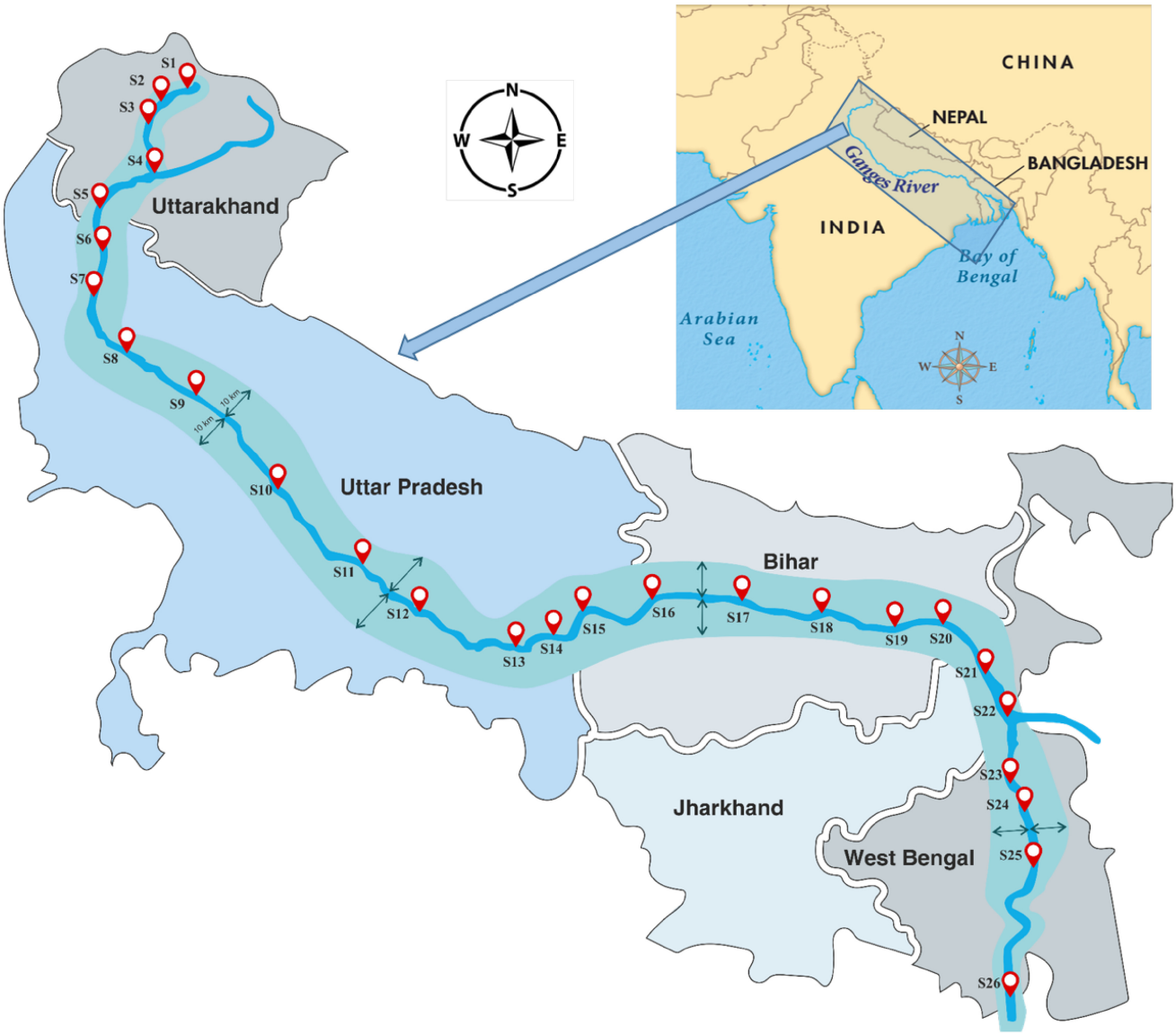

Fig. 1 A map of the study area showing various study sites. The highlighted area around 10 km on either side of the Ganga River was the surveyed region

Singh et al. (2010), and Khuroo et al. (2012). For life form analysis, Raunkiaer's life-form classification (Raunkiaer 1934), modified by Ellenberg and Mueller-Dombois (1974), was adopted. The field study meticulously recorded plant characteristics, including habit, height, and the nature of perennating buds, classifying the plants into various life-form categories: Chamaephytes (Ch), Geophytes (G), Therophytes (Th), Hemicryptophytes (H), Lianas/Climbers (L), Macro-phanerophytes (M), Nanophanerophytes (N), Hydrophytes (HH), and Epiphytes (E). The botanical nomenclature of all identified plants was standardized using the *Plants of the World Online* database (POWO 2024), ensuring accuracy and alignment with global taxonomic standards.

Results

During the survey for floristic diversity around the Ganga River, 1117 plant species representing 660 genera and 152 families were identified and documented with their habits, nativity, and life-form status (Supplementary file). Among these, 1072 species belong to the Angiosperms, 12 to the Gymnosperms, and 33 to the Pteridophytes. The plant specimens were collected from five states where the Ganga River flows. The highest species diversity was recorded in Uttarakhand, with 637 species from 112 families, followed by Uttar Pradesh (536 species, 94 families), West Bengal (357 species, 82 families), Bihar (314 species, 74 families), and Jharkhand (159 species, 58

families). Site-wise analysis revealed the highest species richness in site S5, with 375 species across 76 families, followed by S4 (212 species, 70 families) and S11 (183 species, 60 families). The lowest species diversity was recorded at sites S1 (34 species, 22 families) and S19 (32 species, 19 families) (Fig. 2).

Plants habit

The documented plants were categorized into different habits including epiphytic, climbers, herbs, shrubs, and trees. Among all the habits, a maximum of 606 plants belong to the herbaceous forms followed by shrubs (215 plants), trees (190 plants), climbers (101 plants), and epiphytes (5 plants). Among the 606 herbacious plants, 26 plants (*Coix aquatic*, *Enydra fluctuans*, *Hydrilla verticillata*, *Hydrolea zeylanica*, *Ipomoea aquatic*, *Lemna minor*, *Limnophila indica*, *Marsilea minuta*, *Nymphaea alba*, *N. nouchali*, *N. pubescens*, *Nymphoides hydrophylla*, *N. indica*, *Pistia stratiotes*, *Pontederia crassipes*, *P. hastate*, *P. vaginalis*, *Potamogeton crispus*, *P. natans*, *Sagittaria guayanensis*, *S. montevidensis*, *S. sagittifolia*, *Stuckenia pectinate*, *Trapa natans*, *Utricularia stellaris*, *Vallisneria spiralis*) are aquatic and 4 plants namely *Bambusa bambos*, *B. tulda*, *Dendrocalamus strictus*, *Saccharum officinarum* are woody in nature. 5 epiphytic plants namely *Asplenium nidus*, *Drynaria quercifolia*, *Dendrophthoe falcate*, *Vanda tessellate*, *Viscum articulatum* were identified among them *Asplenium nidus* belongs to the pteridophytic group. Among all the climbers, 6 plants exhibited woody habit *i.e.* they belong to the lianas category, such as *Combretum indicum*, *Hiptage benghalensis*, *Phanera vahlii*, *Telosma pallida*, *Tiliacora acuminate*, *Ventilago denticulate*.

Plants nativity

The nativity status of all documented plant species in the Ganga watershed was assessed. The analysis revealed that a majority of 876 species, representing approximately 78.51%, are native to India and are classified as native plants. In contrast, the remaining 241 species, accounting for 21.49%, are identified as exotic. Among the exotic species, the majority originated from the America, followed by regions such as Europe, Australia, Madagascar, Brazil, and Tropical Africa. These findings indicate that the Indo-Gangetic plain harbors a significant diversity of flora introduced from tropical and subtropical regions.

Plant families analysis

An analysis of plant families revealed distinct patterns of diversity across major groups. The Pteridophytes were represented by 9 families, encompassing 18 genera and 33 species. The Gymnosperms were recorded with 5 families, 10 genera, and 12 species. In contrast, the Angiosperms showed the highest diversity, with 138 families comprising 632 genera and 1072 species. Among all families, Poaceae, Fabaceae, and Asteraceae emerged as the most dominant, with the highest number of genera and species. In terms of generic richness, the top 10 dominant families were Poaceae (69 plants), Fabaceae (57 plants), Asteraceae (52 plants), Lamiaceae (29 plants), Malvaceae (23 plants), Apocynaceae (21 plants), Amaranthaceae & Acanthaceae (14 plants each), Euphorbiaceae & Rubiaceae (13 plants each). Regarding species richness, the leading families included Poaceae (131 species), Fabaceae (105 species), Asteraceae (74 species), Malvaceae (48 species), Lamiaceae (46 species), Cyperaceae (36 species), Solanaceae (28 species), Convolvulaceae & Rosaceae (27

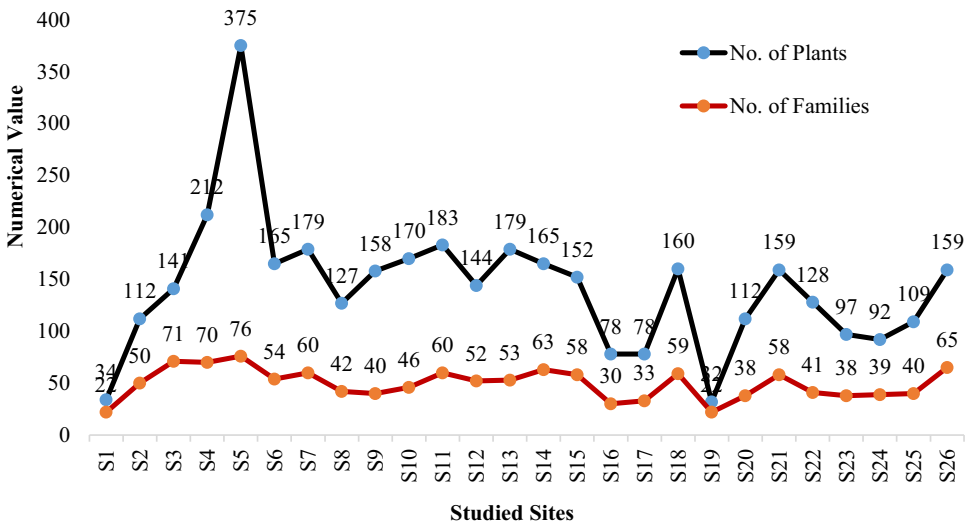

Fig. 2 Plants and their families' distribution in various stidied sites

species each), Amaranthaceae & Euphorbiaceae (26 species each). Apart from these families, the most species-rich families were Moraceae (20 plants), Cucurbitaceae (18 plants), Rubiaceae (17 plants), Polygonacaeae (14 plants), Brassicaceae (12 plants), and Plantataginaceae (10 plants); Several families shared similar species counts as two families (Acanthaceae and Apocynaceae) each having 25 plants, two families (Apiaceae and Urticaceae) each having 11 plants, five families (Boraginaceae, Lythraceae, Phyllanthaceae, Ranunculaceae and Rutaceae) each having 9 plants, three families (Araceae, Asparagaceae, and Commelinaceae) each having 8 plants, three families (Menispermaceae, Myrtaceae, and Rhamnaceae) each having 7 plants, seven families (Anacardiaceae, Bignoniaceae, Capparaceae, Nyctaginaceae, Onagraceae, Salicaceae, and Verbenaceae) each having 6 plants, seven families (Annonaceae, Arecaceae, Combretaceae, Meliaceae, Oleaceae, Sapindaceae, and Scrophulariaceae) each having 5 plants, seven families (Amaryllidaceae, Berberidaceae, Cactaceae, Caryophyllaceae, Crassulaceae, Dioscoreaceae, and Linderniaceae) each having 4 plants, sixteen families (Alismataceae, Araliaceae, Betulaceae, Cannabaceae, Cleomaceae, Molluginaceae, Nymphaeaceae, Oxalidaceae, Papaveraceae, Passifloraceae, Pontederiaceae, Potamogetonaceae, Primulaceae, Smilacaceae, Tamaricaceae, and Vitaceae) each having 3 plants, twenty three families (Campanulaceae, Caprifoliaceae, Cornaceae, Ebenaceae, Ericaceae, Fagaceae, Geraniaceae, Hydrocharitaceae, Hypericaceae, Juglandaceae, Juncaceae, Lauraceae, Mazaceae, Menyanthaceae, Orchidaceae, Orobanchaceae, Piperaceae, Portulacaceae, Typhaceae, Ulmaceae, Viburnaceae, Violaceae, and Zingiberaceae) each having 2 plants, and remaining fourty six families (Acoraceae, Aizoaceae, Asphodelaceae, Basellaceae, Bixaceae, Bromeliaceae, Buxaceae, Calophyllaceae, Cannaceae, Caricaceae, Casuarinaceae, Celastraceae, Coriariaceae, Costaceae, Dipterocarpaceae, Elatinaceae, Gentianaceae, Grossulariaceae, Hydrangeaceae, Hydroleaceae, Iridaceae, Lentibulariaceae, Linaceae, Loranthaceae, Magnoliaceae, Malpighiaceae, Martyniaceae, Moringaceae, Muntingiaceae, Musaceae, Myricaceae, Paeoniaceae, Pedaliaceae, Petiveriaceae, Plumbaginaceae, Proteaceae, Putranjivaceae, Salvadoraceae, Santalaceae, Sapotaceae, Saxifragaceae, Simaroubaceae, Sphenocleaceae, Symplocaceae, Tropaeolaceae, and Zygophyllaceae) each was represented by a single plant (Fig. 3). This data highlights the significant contribution of specific families to the floristic diversity in the study region.

Life-forms and biological spectrum

In the Ganga River watershed, therophytes were the dominant life form, accounting for 34.02% (380 species), followed by chamaephytes (18.17%, 203 species), macrophanerophytes (17.01%, 190 species), geophytes (8.86%, 99 species), lianas/climbers (8.42%, 94 species), hemicryptophytes (5.82%, 65 species), nano-phanerophytes (4.48%, 50 species), and hydrophytes (2.78%, 31 species). Epiphytes represented the least common life form, comprising only 0.45% (5 species) (Table 1). The study revealed that therophytes, chamaephytes, and phanerophytes collectively constituted a significant portion of the documented plants, indicating a "thero-chamaeo-phanerophytic" phytoclimate in the study area. A comparison between the floristic life-form spectrum of the studied region and Raunkiaer's normal spectrum showed notable deviations, despite a strong positive correlation between the two ($p < 0.005$, $r^2 = 0.8269$) (Figs. 4, 5). The major deviations were observed in the proportion of therophytes (− 21.02%), hemicryptophytes (+ 20.18%), macro-phanerophytes (+ 10.99%), and nano-phanerophytes (+ 10.52%) (Table 1), reflecting a biological spectrum that differs significantly from Raunkiaer's standard model.

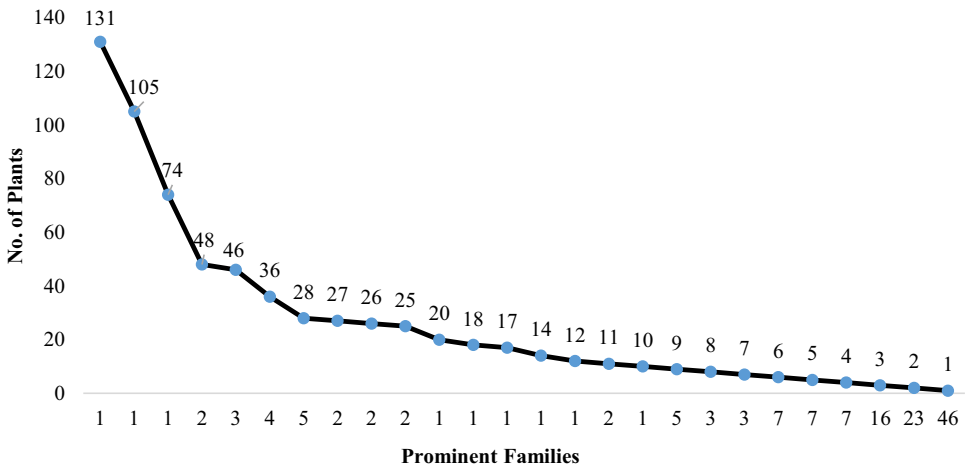

Fig. 3 Number of plants and their prominent families

Table 1 Comparison among life-form spectra and Raunkiaer's normal spectrum in the Ganga River watershed

Life-forms	No. of species	Biological spectrum (%)	Normal spectrum (%)	Deviations (%)
Chamaephytes (Ch)	203	18.17	9.00	– 9.17
Geophytes (G)	99	8.86	4.00	– 4.86
Therophytes (Th)	380	34.02	13.00	– 21.02
Hemicryptophytes (H)	65	5.82	26.00	20.18
Lianas/Climbers (L)	94	8.42	–	– 8.42
Macro-phanerophytes (M)	190	17.01	28.00	10.99
Nano-phanerophytes (N)	50	4.48	15.00	10.52
Hydrophytes (HH)	31	2.78	2.00	– 0.78
Epiphytes (E)	5	0.45	3.00	2.55
Total	1117	100	100	

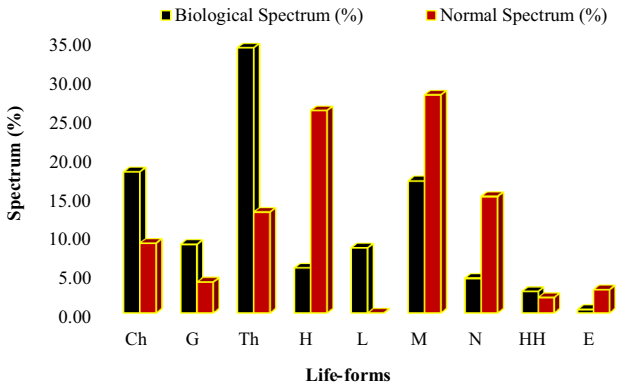

Fig. 4 Comparison of Biological spectrum with Raunkiaer's normal spectrum

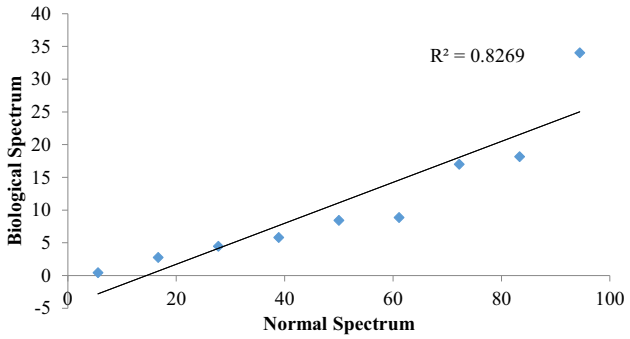

Fig. 5 Corelation between Biological spectrum and Raunkiaer's normal spectrum

Plants diversity

In the Ganga River watershed, a rich diversity of tree species was observed. The tree species such as *Abies spectabilis*, *Acacia dealbata*, *Acer cappadocicum*, *Alnus nepalensis*, *Betula utilis*, *Cedrus deodara*, *Cornus macrophylla*, *Cupressus torulosa*, *Engelhardia spicata* var. *integra*, *Lyonia ovalifolia*, *Pistacia chinensis* subsp. *integerrima*, *Populus ciliata*, *Quercus floribunda*, *Q. leucotrichophora*, *Rhododendron arboreum*, *Salix oxycarpa,* and *Wigandia urens* were reported from Uttarakhand. In contrast, *Acacia auriculiformis*, *Aegle marmelos*, *Ailanthus excelsa*, *Alstonia scholaris*, *Bauhinia racemosa*, *Butea monosperma*, *Cassia fistula*, *Dalbergia sissoo*, *Ficus benghalensis*, *Holoptelea integrifolia*, *Mallotus nudiflorus*, *M. philippensis*, *Melia azedarach*, *Oroxylum indicum*, *Syzygium cumini*, *Tectona grandis,* and *Vachellia nilotica* subsp. *indica* were commonly found throughout the entire watershed. Shrub diversity was also notable, with species such as *Astragalus himalayanus*, *Berberis chitria*, *B. lycium*, *B. pseudumbellata*, *Coriaria napalensis*, *Cotinus coggygria*, *Cotoneaster lindleyi*, *Cotoneaster microphyllus*, *Deutzia staminea*, *Ephedra gerardiana*, *Himalrandia tetrasperma*, *Hypericum oblongifolium*, *Rosa sericea* var. *glandulosa*, *Rosmarinus officinalis*, *Viburnum cotinifolium,* and *Zanthoxylum acanthopodium* reported from Uttarakhand. Meanwhile, species such as *Abutilon indicum*, *Calotropis gigantea*, *C. procera*, *Clerodendrum infortunatum*, *Datura stramonium*, *Helicteres isora*, *Jatropha gossypiifolia*, *Mesosphaerum suaveolens*, *Murraya koenigii*, *Pogostemon benghalensis*, *Urena lobata,* and *Ziziphus nummularia* were widespread across the river watershed. In terms of herb diversity, species such as *Alliaria petiolata*, *Clinopodium umbrosum*, *Crepidium acuminatum*, *Erysimum hieraciifolium*, *Fragaria nubicola*, *Paeonia emodi*, *Podophyllum hexandrum*, *Potentilla argyrophylla*, *P. atrosanguinea*, *Primula denticulata*, *Rheum webbianum*, *Rhodiola heterodonta*, *Valeriana jatamansi*, *Viola betonicifolia* subsp. *jaunsariensis,* and *V. pilosa* were recorded in temperate and alpine regions of Uttarakhand. Common herbs across the Ganga River watershed included *Acalypha indica*, *Achyranthes aspera*, *Ageratum houstonianum*, *Argemone mexicana*, *Boerhavia diffusa*, *Cirsium arvense*, *Eclipta prostrata*, *Euphorbia hirta*, *Gomphrena celosioides*, *Lepidium didymum*, *Nicotiana plumbaginifolia*, *Oxalis corniculata*, *Polygonum plebeium*, *Rumex dentatus*,

Solanum nigrum, and *Youngia japonica*. Grasses were widely distributed, including species such as *Arundo donax*, *Bothriochloa pertusa*, *Capillipedium assimile*, *Dactyloctenium aegyptium*, *Eragrostis tenella*, *Imperata cylindrica*, *Neyraudia arundinacea*, *Phragmites karka*, *Saccharum spontaneum*, *Tripidium bengalense*, and *Urochloa ramosa* being common. Among sedges, species such as *Bulbostylis barbata*, *Cyperus rotundus*, *Fimbristylis bisumbellata*, and *F. dichotoma* were widespread across the river watershed.

Discussions

The Ganga River watershed is characterized by exceptional plant diversity, with distinct patterns of species richness across its regions. In this study, a total of 876 plants were identified as native to India, while 241 were classified as exotic. Naskar (1993) conducted a floristic study of the middle and lower Ganga River basin using available secondary data (IIT Report 2012). Similarly, in the report prepared by IITs, 861 plants were considered indigenous, while 314 were categorized as exotic in the middle and lower Ganga basin (IIT Report 2012). The Ganga River watershed is rich in plant diversity, with representation from nearly all plant families. Families such as Poaceae, Fabaceae, Asteraceae, Malvaceae, and Lamiaceae dominate the flora in these areas, reflecting their adaptability to the region's diverse ecological conditions. These findings align with previous studies emphasizing the dominance of these families in similar ecological contexts (Hua 2012; Mehraj et al. 2018; Shruti et al. 2019; Nafeesa et al. 2021). The Uttarakhand which falls in the Himalayan regions exhibits the highest species richness, attributed to a wide range of climatic zones, from sub-deciduous (Shivalik) to temperate (Tehri, Uttarkashi) to alpine (Gangotri-Gomukh). A similar pattern of plant distribution with high diversity in Uttarakhand was reported by Shruti et al. (2019). The Ganga River is home to numerous grasses and sedges, with the Poaceae family and *Cyperus* genus being the most prominent in the present study. In Uttarakhand, maximum plant diversity was recorded in Haridwar, which serves as a transition zone between the Gangetic plain and the Shivalik hills, acting as a natural barrier for seed dispersal from the plains to the hills.

In contrast, species richness diminishes in Gomukh (S1) due to phylogenetic constraints associated with elevation (Sekar et al. 2024), and in Jharkhand (S21) due to the river's limited flow in the state. The study region's vegetation is highly diverse, shaped by ecological zonation, microhabitats, and topographic features. Various factors, including elevation, climate, topography, competition, species pool, species dynamics, and human activity, influence regional patterns of species richness (Rahman et al. 2020; Mitchell et al. 2023). The study also highlights the uneven distribution of plant species across families, identifying 46 families as monotypic. The diverse flora reflects variations in microhabitats, morphological features, life spans, and ecological niches (Haq et al. 2021; Khoja et al. 2022). Herbaceous species dominate due to frequent flooding and waterlogging along the riverbanks, which disrupt vegetation. Examining floristic diversity in a geographical area provides critical insights for conservation strategies and biodiversity management (Khan et al. 2014; Nafeesa et al. 2021). The conservation of plant diversity along the Ganga River requires a multi-faceted approach, including *in-situ* strategies like establishing protected areas, community-led afforestation, and riparian zone restoration, alongside *ex-situ* measures such as botanical gardens, seed banks, and tissue culture for rare species. Pollution control through strict industrial regulations, organic farming, and phytoremediation can mitigate environmental damage, while awareness campaigns, legal frameworks, and sustainable development policies ensure long-term protection. Integrating these strategies will help preserve the rich biodiversity of the Ganga River ecosystem.

The study found that 21.49% of recorded species were exotic, thriving primarily in anthropogenic habitats as opposed to slightly fragmented ones (Winfree et al. 2011; Ahmad et al. 2018). The interplay of abiotic conditions and biotic interactions significantly shapes vegetation patterns in the region (Klanderud et al. 2015). Employing a functional diversity approach to study species traits can enhance ecosystem service assessments. Therophytes were the dominant life form, followed by mega-phanerophytes and hemicryptophytes. The prevalence of therophytes, adapted to disturbed habitats, underscores the ecological impact of human activities such as grazing, agriculture, urbanization, and road construction (Vakhlamova et al. 2016; Haq et al. 2023). Their survival strategy, characterized by adaptability to unfavorable dry conditions, allows them to thrive in low-precipitation environments and short growing seasons along rivers, roadsides, and disturbed habitats (Schulze et al. 2019). The presence of alien weedy species such as *Alternanthera ficoidea*, *A. pungens*, *Amaranthus blitum*, *A. caudatus*, *Argemone mexicana*, *Dicliptera paniculata*, *Erysimum hieraciifolium*, *Heliotropium indicum*, *Ludwigia hyssopifolia*, *Mirabilis jalapa*, *Oenothera* spp., *Parthenium hysterophoru*, *Phyllanthus amarus*, *Rivina humilis*, *Soliva anthemifolia*, *Sonchus arvensis*, *S. oleraceus*, *Taraxacum officinale*, *Tridax procumbens*, *Verbesina encelioides,* etc. further illustrates the influence of human activity on the ecosystem (Aubin et al. 2007; Haq et al. 2023).

The ecological implications of these findings are significant. Plant species distribution in the Ganga watershed is shaped by altitude, climate, and habitat variability. Microhabitats support diverse species, with therophytes thriving in environments characterized by low precipitation, short growing seasons, and frequent disturbances. In urbanized

and industrialized areas, therophyte prevalence reflects the ecosystem's adaptive response to changing environmental conditions (Vakhlamova et al. 2016). Habitat remains a crucial factor for plant growth and development at the micro-scale (Sørensen et al. 2001). The study found maximum species richness in natural forest habitats, particularly in Uttarakhand. However, these habitats face threats from habitat destruction, fragmentation, and degradation due to anthropogenic disturbances, altering forest communities in this part of the Himalayas (Haq et al. 2019a,b). Similar findings were reported by Haq et al. (2019c) in the Keran Valley forests, India, and by Nafeesa et al. (2021) in the Bhimber hills of the Kashmir Himalayas. In other states, urbanization and industrialization have significantly impacted the Ganga River's biodiversity, resulting in lower plant richness compared to Uttarakhand. Despite its rich biodiversity, the Ganga River watershed faces substantial conservation challenges. Habitat destruction, fragmentation, and degradation, especially in urban and industrial areas, have adversely affected plant richness.

Conclusions

The study underscores the remarkable floristic diversity along the Ganga River watershed, highlighting its ecological significance and the richness of its plant species. The documentation of 1117 plant species spanning 660 genera and 152 families provides a comprehensive understanding of the area's floristic diversity, with Angiosperms dominating the plant groups. The Uttarakhand region exhibited the highest species richness due to its varied climatic zones, while species diversity diminished in the higher elevation zone of Gomukh and the limited river flow area of Jharkhand. The dominance of herbaceous plants, particularly therophytes, reveals the adaptability of vegetation to the dynamic and disturbed habitats along the riverbanks. The presence of native and exotic species reflects the ecological interactions influenced by human activity and natural factors, further enriched by the region's unique climatic and topographical conditions. The study emphasizes the prominence of families like Poaceae, Fabaceae, and Asteraceae, demonstrating their adaptability across diverse habitats. This study provides valuable insights for biodiversity management, conservation planning, and ecological studies. Understanding the life-form spectrum and the ecological roles of dominant species can inform strategies to mitigate human impact, preserve native flora, and manage invasive species. The findings contribute significantly to the broader ecological understanding of the Ganga River watershed, emphasizing its role as a vital hotspot for plant biodiversity and a critical area for ecological conservation efforts.

This study paves the way for future research focused on long-term monitoring of floristic diversity along the Ganga River to evaluate the impacts of climate change, habitat fragmentation, and anthropogenic pressures. Advanced ecological niche modeling can aid in predicting species distribution shifts under future climate scenarios. Expanding investigations into soil–plant interactions, hydrological dynamics, and nutrient cycling will provide a deeper understanding of ecosystem functioning. Additionally, assessing the influence of invasive species on native flora and evaluating conservation strategies through community-driven ecological restoration projects will be essential. The integration of molecular techniques, such as DNA barcoding and phylogenetic analysis, will refine species identification and evolutionary relationships. Furthermore, collaborative research employing remote sensing, GIS-based habitat mapping, and ecological modeling will facilitate data-driven conservation planning and sustainable biodiversity management across the Ganga River watershed.

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Author contribution Acharya Balkrishna: Conceptualization, Funding acquisition, Investigation, Methodology. Ishwar Prakash Sharma: Data curation, Formal analysis, Resources, Software, Writing—original draft, Writing—review & editing. Bhasker Joshi: Data curation, Formal analysis, Methodology, Resources. Amit Kumar: Data curation, Resources. Arun Kumar Kushwaha: Data curation, Resources. Rajesh Kumar Mishra: Data curation, Resources, Validation, Inam Mohammad: Data curation, Resources. Vedpriya Arya: Conceptualization, Investigation, Methodology, Project administration, Supervision. Rama Shankar: Data curation, Resources, Writing—review & editing. Anupam Srivastava: Data curation, Resources, Writing—review & editing.

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Declarations

Conflict of interest Authors declared there is no conflict of interest.

Ethical approval None of the authors have experimented on humans or animals for this study.

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