Wetland on Ventilator: Ecological collapse of Satpura reservoir caused by invasive weeds, with a comprehensive checklist of aquatic plants

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Wetland on Ventilator: Ecological collapse of Satpura reservoir caused by invasive weeds, with a comprehensive checklist of aquatic plants

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Abstract

Aquatic macrophytes are integral to the structure, productivity, and ecological functioning of freshwater ecosystems; however, comprehensive floristic assessments remain scarce for Indian reservoirs. This study presents the first systematic evaluation of aquatic macrophyte diversity and community structure in the Satpura Reservoir - formerly the most productive reservoir of the state. The survey in 21 sites of four zones resulted in 24 aquatic plants, representing five growth forms; dominated by two families (Hydrocharitaceae and Polygonaceae) - indicative of meso-eutrophic conditions and pronounced mesohabitat variability. Multivariate analyses revealed significant spatial variation in community composition. The F1 zone supported a distinct flora (~25% similarity to other zones). Downstream zones exhibited greater species overlap, associated with topographical confinement. Diversity indices identified F2 and F3 as biodiversity-rich in contrary to L3 and T3, with invasives' dominance. *Salvinia molesta* and *Pontederia crassipes*, two globally most invasive species, occurred in all zones except F1, indicating serious ecological and socio-economic risks. Ordination analyses showed clear zonal clustering, linking native species such as *Najas kurziana, Hydrilla verticillata,* and *Ipomoea aquatica* with more diverse sites. Co-occurrence patterns reflect niche complementarity and potential competitive exclusion. This study offers critical insights into ecological zonation, invasion dynamics, and conservation management in Indian reservoir.

Keywords: Aquatic macrophytes, Invasive species, *Pontederia crassipes, Salvinia molesta*, Satpura reservoir, Species diversity

Introduction

Aquatic macrophytes are photosynthetic plants visible to the naked eye, occurring in free-floating, submerged, or emergent forms. Globally, approximately 2,614 macrophyte species are known, representing about 1% of all vascular plants (Chambers et al., 2007), while India supports around 730 species of aquatic angiosperms, including 114 endemics (Botanical Survey of India, 2019). These plants underpin freshwater ecosystem functioning by contributing to primary production, nutrient cycling, and habitat structure for diverse aquatic biota (Chambers et al., 2007; Bornette & Puijalon, 2011). However, the proliferation of invasive species has increasingly disrupted native biodiversity, altered ecosystem processes, and deteriorated water quality (Strayer, 2010; Hussner et al., 2017). The spatial and compositional distribution of macrophytes is influenced by multiple environmental and anthropogenic factors, including water depth, physical and chemical conditions, substrate characteristics, and disturbance regimes (Bornette & Puijalon, 2011; Hussner et al., 2017). Studies from the Chilika Lagoon (Kumar & Pattnaik, 2013), Loktak Lake (Devi et al., 2024), and the Western Ghats (Kumar et al., 2011) have documented high macrophyte diversity across varied freshwater habitats in India.

In the Anthropocene, nutrient enrichment, hydrological alteration, pollution, and species translocation have accelerated the spread of invasive aquatic plants in freshwater systems (Gallardo et al., 2016). Baseline data on macrophyte diversity are therefore essential for biodiversity monitoring, conservation planning, and early detection of invasions (Kohli et al., 2006; Vilà et al., 2011). Despite these concerns, systematic floristic inventories remain limited for Indian reservoirs. The Satpura Reservoir, a key medium-sized water body in Madhya Pradesh, lacks comprehensive documentation of its aquatic vegetation. Given its ecological and economic importance, establishing a baseline inventory of macrophytes is crucial for detecting temporal floristic changes and managing invasive species. This study provides the first detailed assessment of aquatic macrophyte diversity and composition in the Satpura Reservoir, offering foundational data to support long-term ecological monitoring and sustainable management strategies.

Materials and Methods

Study area

The study was conducted in the Satpura Reservoir (22°08′21″ N, 77°11′14″ E) (Fig. 1), a medium-sized impoundment constructed across the Tawa River in Madhya Pradesh - central India. The Tawa River, the longest tributary of the Narmada - the state's principal river and the fifth longest in India - serves as a major hydrological lifeline for the region. The area experiences a tropical monsoon climate with hot summers (March–June), substantial monsoon rainfall (July–October), and mild winters (November–February). The reservoir encompasses diverse aquatic habitats, including littoral shelves, submerged banks, floating vegetation mats, and marshy spill zones, providing suitable conditions for macrophyte colonization.

Data collection and analysis

Field surveys were conducted from April 2020 to March 2021 across the Satpura Reservoir. The reservoir was divided into four hydrological zones based on water flow characteristics: fluvial ($\geq$0.5 m s^{-1}), transitional (0.05 – 0.5 m s^{-1}), lacustrine ($\leq$0.05 m s^{-1}), and spill zones (isolated water bodies), comprising a total of 21 sampling sites. Stratified random sampling was employed following the method of Mueller-Dombois & Ellenberg, 1974. Aquatic macrophytes were photographed in situ from a boat, and specimens accessible for collection were uprooted for detailed examination and photographic documentation. Species identification was carried out using standard taxonomic references (Bentham & Hooker, 1862; Cook, 1996).

Local stakeholders (n=187) were interviewed using semi-structured questionnaires to document the utilization and local knowledge of aquatic plants. Degree of Invasiveness (DI) were measured through the respondents' perception by following (Khan et al., 2011).Data were tested for normality using the Shapiro-Wilk test, and non-parametric comparisons were made using the Wilcoxon rank-sum test. All statistical analyses were performed in R ("R Core Team," 2025).

Results

Aquatic floral diversity

A total of 24 aquatic macrophyte species were recorded from the Satpura Reservoir (Fig. 2), representing a single phylum (Tracheophyta), three classes, ten orders, and twenty genera (Table 1). The species were classified into five ecological growth forms: emergent (10), submerged (5), floating (4), submerged with floating leaves (4), and floating-semi-emergent (1) (Fig. 3). Several species have local uses as medicinal resources, food, fodder, and fuel (Table 2).

The most species-rich families in the Satpura Reservoir were Hydrocharitaceae (6 species) and Polygonaceae (3 species), followed by Salviniaceae and Convolvulaceae (2 species each) (Fig. 4).

Cluster analysis based on Jaccard similarity (Fig. 5) revealed distinct zonal segregation of macrophyte assemblages. The fluvial zone (F1) showed the greatest dissimilarity from all other zones (~25% similarity; Jaccard height ≈ 0.85), indicating unique species composition and hydrological conditions. Subsequent sub-clusters displayed moderate similarity between zones L5 and T4, T3, T2, L3 (~40%; Jaccard height ≈ 0.6). Zones T3 and L3 exhibited the closest floristic resemblance, whereas F4 and S3 were relatively distinct from their respective clusters. Spill zones S6 and S7 demonstrated higher internal similarity compared with the L2, L4, L6 cluster, reflecting shared ecological characteristics and species composition.

Diversity indices and species richness

The Shannon diversity index indicated highest macrophyte diversity in zones F3 and F2 ($H' = 2.7–2.9$), reflecting rich and evenly distributed assemblages (Fig. 6, 9). Zones F4, L1, L2, L4, L6, S1, S2, S4, S5, S6, S7, and T1 exhibited moderate diversity ($H' = 2.1–2.5$), whereas F1, L5, and S3 showed intermediate values ($H' = 1.8–2.0$). Lowest diversity occurred in L3, T2, T3, and T4 ($H' = 0.6–1.8$), indicating species-poor and unstable habitats.

Simpson's diversity index also showed clear spatial variation (Fig. 7, 9). Zones F2, F3, F4, L1, L2, L4, L6, S1, S2, S3, S4, S5, S6, S7, and T1 had high diversity ($D > 0.85$), suggesting relatively even community structure. Intermediate diversity was observed in F1, L5, T2, and T4 ($D = 0.6–0.8$), while L3 and T3 exhibited the lowest values ($D \approx 0.5$).

Species richness varied from 2 to 18 across zones (Fig. 8, 9). The highest richness was recorded in F2 (15 species) and F3 (18 species), followed by intermediate richness (8–12 species) in F4, L1, L2, L4, L6, S1, S2, S4, S5, S6, S7, and T1. Low richness (2–7 species) occurred in F1, L3, L5, S3, T2, T3, and T4, with L3 and T3 showing the minimum (2–3 species).

Based on the heatmap of species presence (Fig. 10), it shows that *Pontederia crassipes, Salvinia molesta* were the most abundant species (found in all the zones except F1), whereas *Najas marina* was the least found species (found only in T1).

Invasion of the species

Notably, two globally recognized invasive species - *Salvinia molesta* and *Pontederia crassipes* - were recorded from the reservoir, in which *Salvinia molesta* is reported for the first time. Their widespread occurrence poses significant ecological threats to native biodiversity and adverse socio-economic impacts on local fisheries and industrial operations, including the Satpura Thermal Power Station (Fig. 11).

Degree of invasiveness (DI)

DI was determined based on the respondent's perception and categorised in 5 categories. Category 1 indicates 'Naturalised' (self sustaining but don't hamper other plant's growth); category 2 indicates 'Introduced' (species are planted and confused to be naturally established); category 3 indicates 'Possibly Invasive' (locally regenerating but the extent limit is confused); category 4 indicates 'Moderately Invasive' (spreading at moderate densities and have some immediate problem); category 5 indicates 'Highly Invasive' (dominant or co-dominant and are threat to the native flora and biodiversity). *Salvinia molesta* got in the category 5 based on the respondent's perception as well as personal observation. Prior to infestation of *S. molesta*, *Pontederia crassipes* was in category 5 but afterwards *S. molesta* dominated over *P. crassipes* and now it is coming uder category 4. Whereas *Ipomoea carnea* placed in category 3.

Co-occurrence analysis of aquatic plants

Co-occurrence analysis (Fig. 12) revealed 209 valid species pairs after excluding 67 (24.28%) with expected co-occurrence <1. Of these, 18 pairs (8.6%) showed significant non-random patterns - 17 positive and one negative - while 188 were random and three unclassified.

Zonal distribution of aquatic plants

Fluviatile, transitional, lacustrine and spill zones are having 8, 1, 1, 3 exclusive plant species, respectively. In case of two-way intersection of fluviatile & spill; fluviatile & transitional, and spill & lacustrine 2, 1 and 1 species are found, respectively. In three-way intersection among fluviatile, spill and lacustrine 5 species are found and 2 species are reported from all the zones (Fig. 13).

Multivariate analysis of aquatic faunal diversity

Non-metric Multidimensional Scaling (NMDS) reveals clear pattern of species composition across the sampled zones. Spatial clustering is associated with the associated species. F1, F2, F3, T1 and L1 shows strong association with *Najas kurziana, Najas graminea, Ipomoea aquatic, Nymphoides indica, Aponogeton natans, Hydrilla verticillata, Vallisneria spiralis, Ottelia alismoides.* T2, T3, T4 and L3 are although having significant distance with *Najas mariana,* but the closest as compared to other zones. F4, L2, L4, L5, L6, S1, S2, S3, S4, S5, S6, S7 shows close association with the remaining plants (Fig. 14).

On Principal Component Analysis (PCA) (Fig. 15), the Principal Component 1 (PC1) and Principal Component 2 (PC2) represent 26.1% and 20.7% of variance respectively, totaling to 46.8%. The sites are clustering into 5 and the aquatic plants are forming cluster except *Najas marina* (Fig. 15).

Species-site association and interspecific relationship of aquatic plants

Bonnaya ciliate, *Phyla nodiflora*, *Ottelia alismoides*, *Najas graminea*, *Najas kurziana*, *Vallisneria spiralis*, *Aponogeton natans*, *Nymphoides indica*, *Ipomoea aquatica* and *Hydrilla verticillata* are better represented by sites L1, T1, F2, and F3. *Persicaria hydropiper*, *Azolla pinnata*, *Persicaria glabra*, *Colocasia esculenta*, *Ipomoea carnea*, *Polygonum plebeium*, *Cyperus articulatus*, *Ludwigia adscendens*, *Typha domingensis* and *Pontederia crassipes* are better represented by sites S1, S2, S4, and S5. *Salvinia molesta, Acmella paniculata* and *Nelumbo nucifera* are better represented by sites L4, S7, L2, S6, and L6. *Bonnaya ciliate, Phyla nodiflora*, *Najas graminea*, *Najas kurziana*, *Ottelia alismoides*, *Aponogeton natans*, *Vallisneria spiralis*, *Nymphoides indica*, *Ipomoea aquatica*, *Hydrilla verticillata*, *Persicaria hydropiper*, *Azolla pinnata*, *Persicaria glabra*, *Colocasia esculenta*, *Ipomoea carnea*, *Polygonum plebeium* and *Cyperus articulatus* are positively correlated species. *Najas kurziana*, *Najas graminea*, *Bonnaya ciliata* are unrelated to *Ludwigia adscendens*, *Typha domingensis. Najas marina* and *Ipomoea carnea*, *Colocasia esculenta; Najas kurziana*; *Najas graminea*, *Bonnaya ciliata* and *Nelumbo nucifera*, *Acmella paniculata*, *Salvinia molesta* are mutually negatively correlated or very weakly related to each other.

Discussion

This study represents the first comprehensive documentation of aquatic macrophytes in the Satpura Reservoir. Earlier records by Shrivastava et al., (2003) noted the presence of *Nymphaea*, *Hydrilla*, *Vallisneria*, *Potamogeton*, and *Eichhornia* (=*Pontederia*) *crassipes*, but provided no species-specific information except for *E. crassipes*. The present survey identified 24 species, confirming *E. crassipes* and excluding *Potamogeton* from the earlier list. The dominance of Hydrocharitaceae and Polygonaceae aligns with observations from comparable freshwater ecosystems (Thakur et al., 2017; Rasal et al., 2020), reflecting the broad ecological tolerance and adaptive versatility of these families.

The fluvial zone (F1) was distinct from all other zones due to continuous inflow, which limited the accumulation of invasive species and reduced anthropogenic disturbance. Its species composition showed only ~25% similarity with other zones, reflecting unique hydrological and ecological conditions. The L5 zone formed a separate cluster from T4, T3, T2, and L3 (~38% similarity), likely influenced by differences in water depth, substrate, and adjacent terrestrial habitats. L5 is shallower with muddy sediments, whereas T4, T3, T2, L3 are deeper, hill-encircled zones with contrasting hydrodynamics.

Zones along the left bank (T1, F2, F3, and L1) exhibited high inter-zonal similarity, possibly due to comparable sediment characteristics and higher anthropogenic and industrial influence. Spill zone S3 showed ~32% similarity with other spill and lacustrine zones (L2, L4, L6), attributed to its peripheral location and reduced human activity. Within the spill zones, S5 shared 65% similarity with S1, S2 and S4, while S1, S2 and S4 exhibited ~88% similarity among themselves, indicating stable floristic composition in deeper sections and sediment accumulation effects in S5. The S6 and S7 pair shared 90% species similarity, reflecting close proximity and similar substrate and water quality. L2 shared 70% similarity with L4 and L6, while L4 and L6 were more similar (~80%), likely due to their spatial contiguity and absence of physical barriers, whereas combination of this with L2 is having barrier of high land, which may be the reason of 10% lesser similarity than L4 and L6 with L2. The decreasing similarity from L2, L4 and L6 corresponds with gradual transition toward agricultural landscapes.

Zones F3 and F2 exhibited the highest Shannon diversity values, likely due to their variable depth range, sediment heterogeneity, and periodic flooding, which create diverse microhabitats for macrophytes. Wind- and flow-mediated dispersal of *Salvinia molesta* may also contribute to the moderate and intermediate diversity observed in adjacent zones. High- and moderate-diversity sites were characterized by greater species richness and evenness, whereas zones L3, T2, T3, and T4, located downstream and partially enclosed by hills, showed reduced diversity, richness, and evenness. The accumulation and competitive dominance of *S. molesta* in these areas, combined with limited water circulation and increased depth, likely suppressed submerged vegetation.

Simpson's index further indicated low dominance and higher evenness across most zones, except L3 and T3, which were overwhelmingly dominated by *S. molesta* and *P. crassipes*. The near-monoculture of these invasive species rendered these zones least diverse and potentially least productive. In contrast, the species-rich F2 and F3 zones experience reduced competition from invasives and support varied sediment types - from sandy to silty substrates - providing favorable conditions for macrophyte establishment. Conversely, L3, T3, T2, and T4 remain heavily infested by *S. molesta* and *P. crassipes*, whose dense mats restrict light penetration and impede water movement. Their persistence is further reinforced by topographical confinement and limited hydrodynamic exchange in the downstream sections of the reservoir.

Invasion by these two species are the reason of socio-economic loss of the fishers, industrial operation of Satpura Thermal Power Station and biodiversity loss. Because of the invasion of *Salvinia*, it is very difficult to navigate and do fishing as the vertical dense interlocking mat ranges from 90–120 cm. Both of the invasive species are free floating, so even when favorable fishable sites are spread with gill net in the evening, if the wind flows towards the gear site, it is difficult to locate the spread net and haul it back. In this case the gill nets are moving with the weeds and are the reason of ghost fishing. It causes double economic loss to the fisher (loss of caught fish and gear). The thick interlocking mat hinders the light penetration and reduces the primary productivity and depletes the dissolved oxygen of the reservoir, which is critical for the productivity of the reservoir. The trials were done to get rid of *Salvinia* by manual removal, which didn't have any impact on its infestation (Fig. 16).

DI of *Salvinia molesta* (DI=5) is higher than *Pontederia crassipes* (DI=4) than *Ipomoea carnea* (DI=3). *S. molesta* is having the latest invasion before which *P. crassipes* was the most dominant. The reason of highest DI may be climate change, no natural competitor, wide range of environmental tolerance, vegetative propagation, outcompeting for light and nutrients etc. or combination of them.

In species co-occurrence matrix, most of the species are randomly occurring. 17 pairs are showing positive correlation which provides information that occurrence of one supports another or vice-versa. These 17 pairs are - *Hydrilla verticillata - Salvinia molesta; Hydrilla verticillata - Persicaria hydropiper; Hydrilla verticillata - Najas kurziana; Hydrilla verticillata - Ipomoea aquatica; Hydrilla verticillata - Nymphoides indica; Polygonum plebeium*

- Persicaria hydropiper; Polygonum plebeium - Typha domingensis; Polygonum plebeium - Colocasia esculenta; Polygonum plebeium - Ipomoea carnea; Vallisneria spiralis - Najas kurziana; Vallisneria spiralis - Aponogeton natans; Persicaria hydropiper - Persicaria glabra; Cyperus articulatus - Persicaria glabra; Cyperus articulatus - Ludwigia adscendens; Typha domingensis - Ludwigia adscendens; Ipomoea aquatica - Najas graminea; Salvinia molesta - Pontederia crassipes. This positive occurrence shows same kind of habitats shared between them. There is a single pair of *Hydrilla verticillata - Nelumbo nucifera*, which shows negative correlation, so presence of one inhibits or retard the occurrence of other. It is because of the totally different habitats and conditions. Whereas *Phyla nodiflora, Bonnaya ciliate, Ottelia alismoides, Najas marina, Azolla pinnata, Acmella paniculata* occurs randomly, which don't show any relationship with other species. It may be because of wide range of habitats and occurs with more than one species.

The widespread occurrence of *Pontederia crassipes* and *Salvinia molesta* across all zones except F1 indicates their strong establishment within the reservoir. Their absence in F1 is attributable to continuous water flow, which prevents the settlement of floating vegetation. The restriction of *Najas marina* to the T1 zone is likely related to the dominance of these surface-floating invasives in other areas, where their dense mats limit light penetration and suppress submerged macrophytes.

Non-metric multidimensional scaling (NMDS) analysis revealed a strong association of *Najas kurziana*, *Najas graminea*, *Ipomoea aquatica*, *Nymphoides indica*, *Aponogeton natans*, *Hydrilla verticillata*, *Vallisneria spiralis*, and *Ottelia alismoides* with zones F1, F2, F3, T1, and L1, reflecting similar ecological, and physical and chemical conditions along with moderate anthropogenic influence. In contrast, *Najas marina* showed limited association with T2, T3, T4, and L3, consistent with low light availability and invasive dominance in these deeper downstream zones. Zones F4, L2, L4–L6, and the spill zones clustered together, indicating comparable habitat features and macrophyte composition.

In PCA plot, *Hydrilla verticillata* has strong influence is describing variability of cluster 4. Similarly, *Persicaria hydropiper, Nelumbo nucifera* and *Najas marina* better describes variability of cluster 1, 5 and 2 & 3. *Phyla nodiflora, Bonnaya ciliate, Pontederia crassipes* are the species with doesn't strongly influence the separation. These are evenly and sporadically distributed species. *Bonnaya ciliate, Phyla nodiflora*, *Najas graminea*, *Najas kurziana*, *Ottelia alismoides*, *Aponogeton natans*, *Vallisneria spiralis*, *Nymphoides indica*, *Ipomoea aquatica*, *Hydrilla verticillata*, *Persicaria hydropiper*, *Azolla pinnata*, *Persicaria glabra*, *Colocasia esculenta*, *Ipomoea carnea*, *Polygonum plebeium* and *Cyperus articulatus* are positively correlated species. *Najas kurziana*, *Najas graminea*, *Bonnaya ciliata* are unrelated to *Ludwigia adscendens*, *Typha domingensis. Najas marina* and *Ipomoea carnea*, *Colocasia esculenta; Najas kurziana*. *Najas graminea*, *Bonnaya ciliata* and *Nelumbo nucifera*, *Acmella paniculata*, *Salvinia molesta* are mutually negatively correlated or very weakly related to each other. These relationship statuses may be because of habitat, water depth, anthropogenic impact and invasion of the species or combination of them.

Among the macrophytes recorded in this study, *Salvinia molesta* and *Pontederia crassipes* are listed among the world's 100 most invasive species ("Global Invasive Species Database," 2025). Their proliferation threatens both floral and faunal diversity within the reservoir. Although Sugunan (1995) described the Sarni (Satpura) Reservoir as the most productive in Madhya Pradesh, the present decline in fish catches, fishers' migration, and deteriorating socio-economic conditions indicate a loss of fisheries potential. The dense macrophyte cover also interferes with the operation of the Satpura Thermal Power Station, underscoring the broader ecological and industrial implications of these invasions.

Conclusions

The results of this study highlight a clear need for focused management actions in the Satpura Reservoir to slow the spread of invasive macrophytes and protect the reservoir's ecological balance and the livelihoods it supports. The widespread dominance of *Salvinia molesta* and *Pontederia crassipes*, particularly in downstream lacustrine and spill zones with slow water movement, indicates that these areas should be treated as priority sites for intervention. Effective control will require a mix of approaches, including consistent monitoring of macrophyte populations through permanent observation plots, repeated field surveys, and remote-sensing tools; hydrological adjustments where possible, such as temporary drawdown or enhanced flushing to break up floating mats; and targeted mechanical removal in fishing grounds, navigation channels, and industrial intake points.

Involving local communities can greatly strengthen management efforts. Inputs from fishers and other stakeholders - translated into simple DI-based assessments - can provide valuable early warnings for emerging invasions. At the same time, broader catchment-level actions are needed to limit nutrient enrichment, shoreline disturbance, and the introduction of propagules from ornamental or aquaculture sources. Developing a dedicated invasive-species management plan for the reservoir, with clearly identified priority zones, response thresholds, and coordinated action among fisheries, irrigation, power-generation, and conservation departments, would enable a more adaptive and evidence-driven approach to safeguarding both biodiversity and fisheries productivity in the Satpura Reservoir.

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Mohammad Nadim: Data curation, Investigation, Resource, Formal analysis, Software, Visualization, Writing – Original draft, review and editing; **Jyothi PV:** Conceptualization, Methodology, Validation, Writing – Review and editing; **Anvar Ali PH:** Conceptualization, Supervision, Validation, Writing – Review and editing.

Data availability:

Data will be made available on request.

References

Bentham, G., & J. D. Hooker, 1862. Genera plantarum :ad exemplaria imprimis in Herberiis Kewensibus servata definita. A. Black, Londini.

Bornette, G., & S. Puijalon, 2011. Response of aquatic plants to abiotic factors: a review. Aquatic Sciences 73: 1–14. https://doi.org/10.1007/s00027-010-0162-7.

Botanical Survey of India, 2019. Aquatic wetland plants of India.

Chambers, P. A., P. Lacoult, K. J. Murphy, & S. M. Thomaz, 2007. Global diversity of aquatic macrophytes in freshwater. Hydrobiologia 595: 9–26.

Cook, C. D. K., 1996. Aquatic and wetland plants of India: a reference book and identification manual for the vascular plants found in permanent or seasonal fresh water in the subcontinent of India south of the Himalayas. Oxford University Press, Oxford.

Devi, R. S., K. B. Satapathy, & S. Kumar, 2024. Loktak Lake of the state Manipur: A review to educate the intellectuals and awareness on its biowealth. Educational Administration: Theory and Practice, 30: 6936–6947.

Gallardo, B., M. Clavero, M. I. Sánchez, & M. Vilà, 2016. Global ecological impacts of invasive species in aquatic ecosystems. Global Change Biology 22: 151–163. https://doi.org/10.1111/gcb.13004.

Global Invasive Species Database, 2025. http://193.206.192.138/gisd/search.php.

Hussner, A., I. Stiers, M. J. J. M. Verhofstad, E. S. Bakker, B. M. C. Grutters, J. Haury, J. L. C. H. Van Valkenburg, G. Brundu, J. Newman, J. S. Clayton, L. W. J. Anderson, & D. Hofstra, 2017. Management and control methods of invasive alien freshwater aquatic plants: A review. Aquatic Botany 136: 112–137. https://doi.org/10.1016/j.aquabot.2016.08.002.

Khan, M. A. S. A., F. Sultana, Md. H. Rahman, B. Roy, & S. I. Anik, 2011. Status and ethno-medicinal usage of invasive plants in traditional health care practices: a case study from northeastern Bangladesh. Journal of Forestry Research 22: 649–658. https://doi.org/10.1007/s11676-011-0174-8.

Kohli, R. K., D. R. Batish, H. P. Singh, & K. S. Dogra, 2006. Status, invasiveness and environmental threats of three tropical American invasive weeds (Parthenium hysterophorus L., Ageratum conyzoides L., Lantana camara L.) in India. Biological Invasions 8: 1501–1510. https://doi.org/10.1007/s10530-005-5842-1.

Kumar, R. B., K. Anitha, A. Watve, S. Mani, S. Rehel, & W. Arisdason, 2011. The status and distribution of aquatic plants of the Western Ghats. IUCN, Cambridge, UK and Gland, Switzerland.

Kumar, R., & A. K. Pattnaik, 2013. Chilka: An integrated management planning framework for conservation and wise use. Chilka Development Authority and Wetlands International - South Asia.

Mueller-Dombois, D., & H. Ellenberg, 1974. Aims and methods of vegetation ecology. Wiley, New York, NY.

R Core Team, 2025. https://www.R-project.org/.

Rasal, V. M., S. G. Yadre, S. Shukla, P. M. Ravi, M. K. Mishra, & S. Dasgupta, 2020. Diversity and Distribution of Aquatic Macrophytes in Bargi Reservoir on River Narmada in Madhya Pradesh, India. Journal of the Bombay Natural History Society (JBNHS) 117: 79. https://doi.org/10.17087/jbnhs/2020/v117/149777.

Shrivastava, N. P., B. L. Pandey, & A. K. Das, 2003. Ecology and Fisheries of Selected Reservoirs of Madhya Pradesh. Central Inland Fisheries Research Institute (Indian Council of Agricultural Research), Barrackpore, Kolkata - 700 120, West Bengal.

Strayer, D. L., 2010. Alien species in fresh waters: ecological effects, interactions with other stressors, and prospects for the future. Freshwater Biology 55: 152–174. https://doi.org/10.1111/j.1365-2427.2009.02380.x.

Sugunan, V. V., 1995. Reservoir fisheries of India. Food and Agriculture Organization of the United Nations, Rome.

Thakur, M. K., R. K. Pandey, & S. Kourav, 2017. Inventory of aquatic macrophytes from Johila Reservoir of Sanjay Gandhi Thermal Power Plant, Birsinghpur, Umaria (M.P.). Online International Interdisciplinary Research Journal, {Bi-Monthly} 07: 29–32.

Vilà, M., J. L. Espinar, M. Hejda, P. E. Hulme, V. Jarošík, J. L. Maron, J. Pergl, U. Schaffner, Y. Sun, & P. Pyšek, 2011. Ecological impacts of invasive alien plants: a meta-analysis of their effects on species, communities and ecosystems: Ecological impacts of invasive alien plants. Ecology Letters 14: 702–708. https://doi.org/10.1111/j.1461-0248.2011.01628.x.

Table 1 Checklist of aquatic plants in Satpura Reservoir, Madhya Pradesh, India

Phylum	Class	Order	Family	Genus	Scientific name	Origin
Tracheophyta	Magnoliopsida	Caryophyllales	Polygonaceae	Polygonum L.	*Polygonum plebeium* R.Br.	I
				Persicaria (L.) Mill.	*Persicaria hydropiper* (L.) Delarbre	I
					Persicaria glabra (Wild.) M. Gómez	I
		Lamiales	Verbenaceae	Phyla Lour.	*Phyla nodiflora* (L.) Greene	I
			Linderniaceae	Bonnaya Link & Otto	*Bonnaya ciliata* (Colsm.) Spreng	I
		Solanales	Convolvulaceae	Ipomoea L.	*Ipomoea carnea* Jacq.	E
					Ipomoea aquatica Forssk	I
		Asterales	Menyanthaceae	Nymphoides Hill	*Nymphoides indica* (L.) Kuntze	I
			Asteraceae	Acmella Rich. Ex Pers.	*Acmella paniculata* (Wall. ex DC.) R.K.Jansen	I
		Myratales	Onagraceae	Ludwigia L.	*Ludwigia adscendens* (L.) H. Hara	I
		Proteales	Nelumbonaceae	Nelumbo Adans.	*Nelumbo nucifera* Gaertn.	I
	Liliopsid	Alismatales	Araceae	Colocasia Schott	*Colocasia esculenta* (L.) Schott	I

		Aponogetonaceae	Aponogeton L.f.	*Aponogeton natans* (L.) Engl. & K. Krause	I
		Hydrocharitaceae	Hydrilla Rich.	*Hydrilla verticillata* (L.f.) Royle	I
			Ottelia Pers.	*Ottelia alismoides* (L.) Pers.	I
			Vallisneria P. Micheli ex L.	*Vallisneria spiralis* L.	I
			Najas L.	*Najas kurziana* Rendle	I
				Najas graminea Delile	I
				Najas marina L.	I
	Commelinales	Pontederiaceae	Pontederia L.	*Pontederia crassipes* Mart. ex Schult. & Schult.f.	E*
	Poales	Typhaceae	Typha L.	*Typha domingensis* Pers.	I
		Cyperaceae	Cyperus L	*Cyperus articulatus* L.	I
Polypodiopsida	Salviniales	Salviniaceae	Azolla Lam.	*Azolla pinnata* R. Br.	I
			Salvinia Ség.	*Salvinia molesta* D.S. Mitch.	E*

* Invasive species, I – Indigenous, E – Exotic

Table 2 Aquatic macrophytes of the Satpura Reservoir with common names, categories, and local uses

Scientific name	Common English name	Category	Local use
Polygonum plebeium	Small knotweed	Emergent / Amphibious	Edible as a leafy vegetable and used as medicinal plant too.
Persicaria hydropiper	Water pepper	Emergent / Amphibious	Used as medicinal plant for knee pain and ichthyotoxins too.
Persicaria glabra	Smooth smartweed	Emergent / Amphibious	No use.
Phyla nodiflora	Frog fruit	Emergent / Amphibious	Used as medicinal plant.
Bonnaya ciliata	Bonnaya	Emergent / Amphibious	Used as medicinal plant.
Ipomoea carnea	Pink morning glory	Emergent / Semi-aquatic Shrub	Used for cooking fire, when dried. Used as medicine as well as in local rituals as a substitute of sacred plants.
Ipomoea aquatica	Water spinach	Floating / Semi-emergent	Edible as a leafy vegetable and medicinal plant.
Nymphoides indica	Water snowflake	Submerged with Floating Leaves	Leaves and roots are used as a medicine.
Acmella paniculata	Toothache plant	Emergent / Wetland herb	Used for mouth remedies (toothache and mouth ulcers and gum infection).
Ludwigia adscendens	Water primrose	Floating	Edible as a leafy vegetable, cattle fodder and as a medicinal plant.

Nelumbo nucifera	Sacred lotus	Submerged with Floating Leaves	Sacred plant. Rhizomes are edible. Seeds are eaten either raw or roasted or made into sweet offering in the temples. Flower is used in *Pooja* (worship in the temple) offering. Leaves used plate.
Colocasia esculenta	Taro	Emergent	Used as vegetable in the form of curry, fry or boiled.
Aponogeton natans	Floating-leaf pondweed	Submerged with Floating Leaves	Used as medicinal plant.
Hydrilla verticillata	Hydrilla	Submerged	Used as fodder for cattle. Local community predict water quality by its growth.
Ottelia alismoides	Duck lettuce	Submerged with Floating Leaves	Used as a leafy vegetables and medicinal plant.
Vallisneria spiralis	Tape grass	Submerged	No use.
Najas kurziana	Najas	Submerged	No use. Regarded as indicator species for water quality.
Najas graminea	Slender waternymph	Submerged	No use. Regarded as indicator species for water quality.
Najas marina	Spiny naiad	Submerged	No use. Regarded as indicator species for water quality.
Pontederia crassipes	Water hyacinth	Floating	No use.
Typha domingensis	Southern cattail	Emergent	Leaves and stems are used to make roof of the home, mats and baskets.

Cyperus articulates	Jointed flatsedge	Emergent	Used as a medicinal plant by tribal.
Azolla pinnata	Mosquito fern	Floating	Fed to cattle for better milk production.
Salvinia molesta	Giant salvinia	Floating	No use.

Figure captions:

Fig. 1 Satpura reservoir

Fig. 2 Representative aquatic macrophytes recorded from the Satpura Reservoir **(a)** *Polygonum plebeium* **(b)** *Persicaria hydropiper* **(c)** *Persicaria glabra* **(d)** *Phyla nodiflora* **(e)** ***Bonnaya ciliata*** **(f)** *Ipomoea carnea* **(g)** *Ipomoea aquatica* **(h)** *Nymphoides indica* **(i)** *Acmella paniculata* **(j)** *Ludwigia adscendens* **(k)** *Nelumbo nucifera* **(l)** *Colocasia esculenta* **(m)** *Aponogeton natans* **(n)** *Hydrilla verticillata* **(o)** *Ottelia alismoides* **(p)** *Vallisneria spiralis* **(q)** *Najas kurziana* **(r)** *Najas graminea* **(s)** *Najas marina* **(t)** *Pontederia crassipes* **(u)** *Typha domingensis* **(v)** *Cyperus articulatus* **(w)** *Azolla pinnata* **(x)** *Salvinia molesta*

Fig. 3 Aquatic macrophytes in the Satpura Reservoir showing species number and percentage contribution

Fig. 4 Family-wise species richness and percentage contribution of aquatic macrophytes in the Satpura Reservoir

Fig. 5 Jaccard dendrogram of aquatic macrophyte similarity across sites in Satpura Reservoir

Fig. 6 Shannon diversity index of aquatic macrophytes across sampling sites in the Satpura Reservoir

Fig. 7 Simpson diversity index of aquatic macrophytes across sampling sites in the Satpura Reservoir

Fig. 8 Species richness of aquatic macrophytes across sampling sites in the Satpura Reservoir

Fig. 9 Comparative diversity indices of aquatic macrophytes across sampling sites in the Satpura Reservoir

Fig. 10 Heatmap of species presence across sites in Satpura Reservoir

Fig. 11 Exotic flora of Satpura reservoir **(a), (b), (c)** Invasion by *Salvinia molesta* and **(d)** Invasion by *Pontederia crassipes* **(e)** *Ipomoea carnea*

Fig. 12 Species co-occurrence matrix of aquatic plants (1 - *Polygonum plebeium*; 2 - *Persicaria hydropiper*; 3 - *Persicaria glabra*; 6 - *Ipomoea carnea*; 7 - *Ipomoea aquatic*; 8 - *Nymphoides indica*; 9 - *Ludwigia adscendens*; 10 - *Nelumbo nucifera*; 11 - *Colocasia esculenta*; 12 - *Aponogeton natans*; 13 - *Hydrilla verticillata*; 15 - *Najas kurziana*; 16 - *Najas graminea*; 18 - *Pontederia crassipes*; 20 - *Cyperus articulates*; 21 - *Azolla pinnata*; 22 - *Salvinia molesta*; 23 - *Vallisneria spiralis*)

Fig. 13 Venn diagram of the species presence across zones in Satpura Reservoir

Fig. 14 NMDS plot **(**POPL - *Polygonum plebeium*; PEHY - *Persicaria hydropiper*; PEGL - *Persicaria glabra*; PHNO - *Phyla nodiflora*; BOCI - *Bonnaya ciliate*; IPCA - *Ipomoea carnea*; IPAQ - *Ipomoea aquatic*; NYIN - *Nymphoides indica*; LUAD - *Ludwigia adscendens*; NENU - *Nelumbo nucifera*; COES - *Colocasia esculenta*; APNA - *Aponogeton natans*; HYVE - *Hydrilla verticillata*; OTAL - *Ottelia alismoides*; NAKU - *Najas kurziana*; NAGR - *Najas graminea*; NAMA - *Najas marina*; POCR- *Pontederia crassipes*; TYDO - *Typha domingensis*; CYAR - *Cyperus articulates*; AZPI - *Azolla pinnata*; SAMO - *Salvinia molesta*; VASP - *Vallisneria spiralis*; ACPA- *Acmella paniculata*)

Fig. 15 PCA of the species and sites **(**A - *Polygonum plebeium*; B - *Persicaria hydropiper*; C - *Persicaria glabra*; D - *Phyla nodiflora*; E - *Bonnaya ciliate*; F - *Ipomoea carnea*; G - *Ipomoea aquatic*; H - *Nymphoides indica*; I - *Ludwigia adscendens*; J - *Nelumbo nucifera*; K - *Colocasia esculenta*; L - *Aponogeton natans*; M - *Hydrilla verticillata*; N - *Ottelia alismoides*; O - *Najas kurziana*; P - *Najas graminea*; Q - *Najas marina*; R - *Pontederia crassipes*; S - *Typha domingensis*; T - *Cyperus articulates*; U - *Azolla pinnata*; V - *Salvinia molesta*; W - *Vallisneria spiralis*; X - *Acmella paniculata*)

Fig. 16 Manual removal of the *Salvinia* **(a)** Collection of *Salvinia* **(b)** Loading *Salvinia* to tranctor to dump away from water.

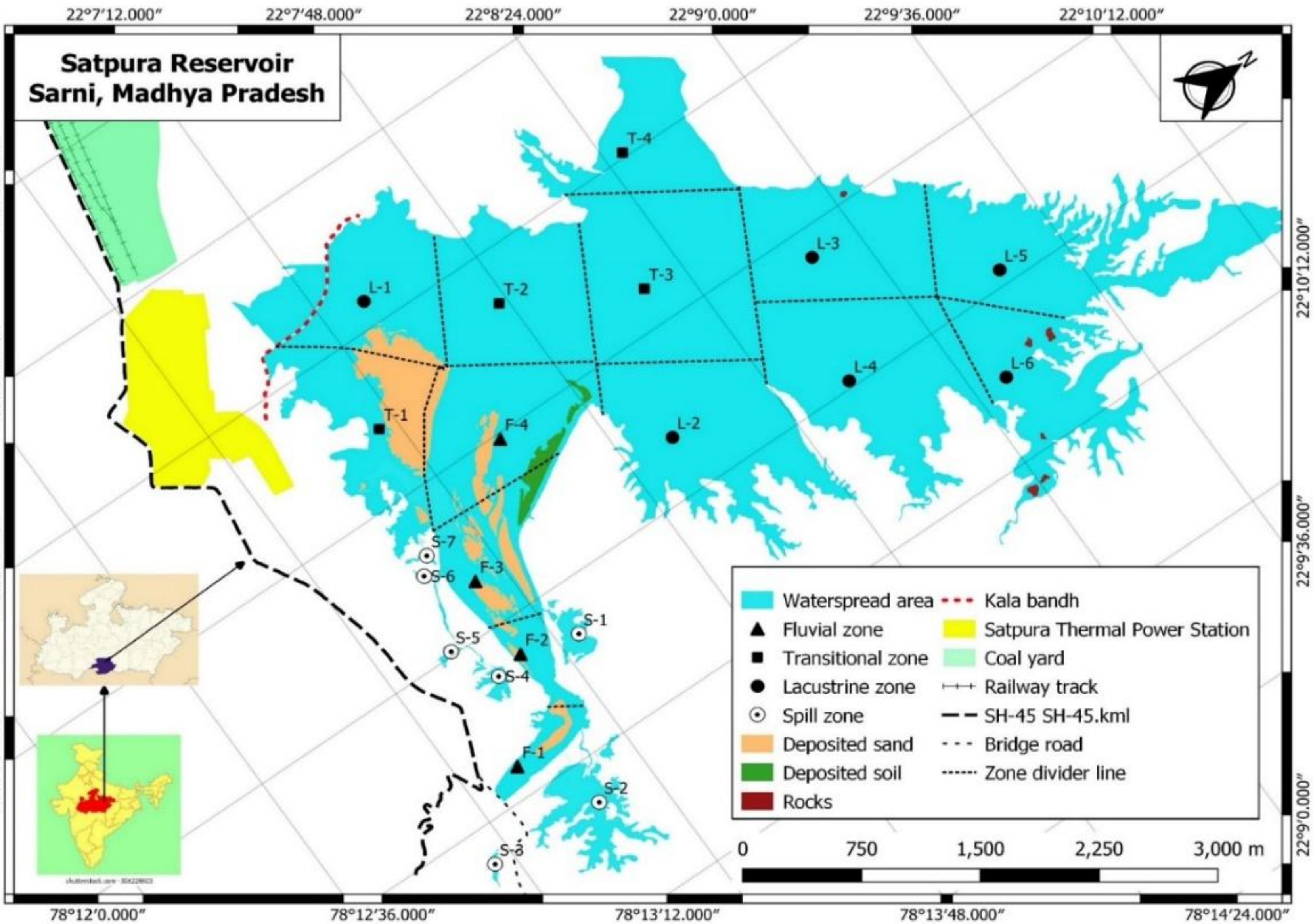


Fig. 1 Satpura reservoir

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

(i) (j)

(k) (l)

(m)

(n)

(o)

(p)

(q)

(r)

(s)

(t)

(u) **(v)**

(w) **(x)**

Fig. 2 Representative aquatic macrophytes recorded from the Satpura Reservoir **(a)** *Polygonum plebeium* **(b)** *Persicaria hydropiper* **(c)** *Persicaria glabra* **(d)** *Phyla nodiflora* **(e)** *Bonnaya ciliata* **(f)** *Ipomoea carnea* **(g)** *Ipomoea aquatica* **(h)** *Nymphoides indica* **(i)** *Acmella paniculata* **(j)** *Ludwigia adscendens* **(k)** *Nelumbo nucifera* **(l)** *Colocasia esculenta* **(m)** *Aponogeton natans* **(n)** *Hydrilla verticillata* **(o)** *Ottelia alismoides* **(p)** *Vallisneria spiralis* **(q)** *Najas kurziana* **(r)** *Najas graminea* **(s)** *Najas marina* **(t)** *Pontederia crassipes* **(u)** *Typha domingensis* **(v)** *Cyperus articulatus* **(w)** *Azolla pinnata* **(x)** *Salvinia molesta*

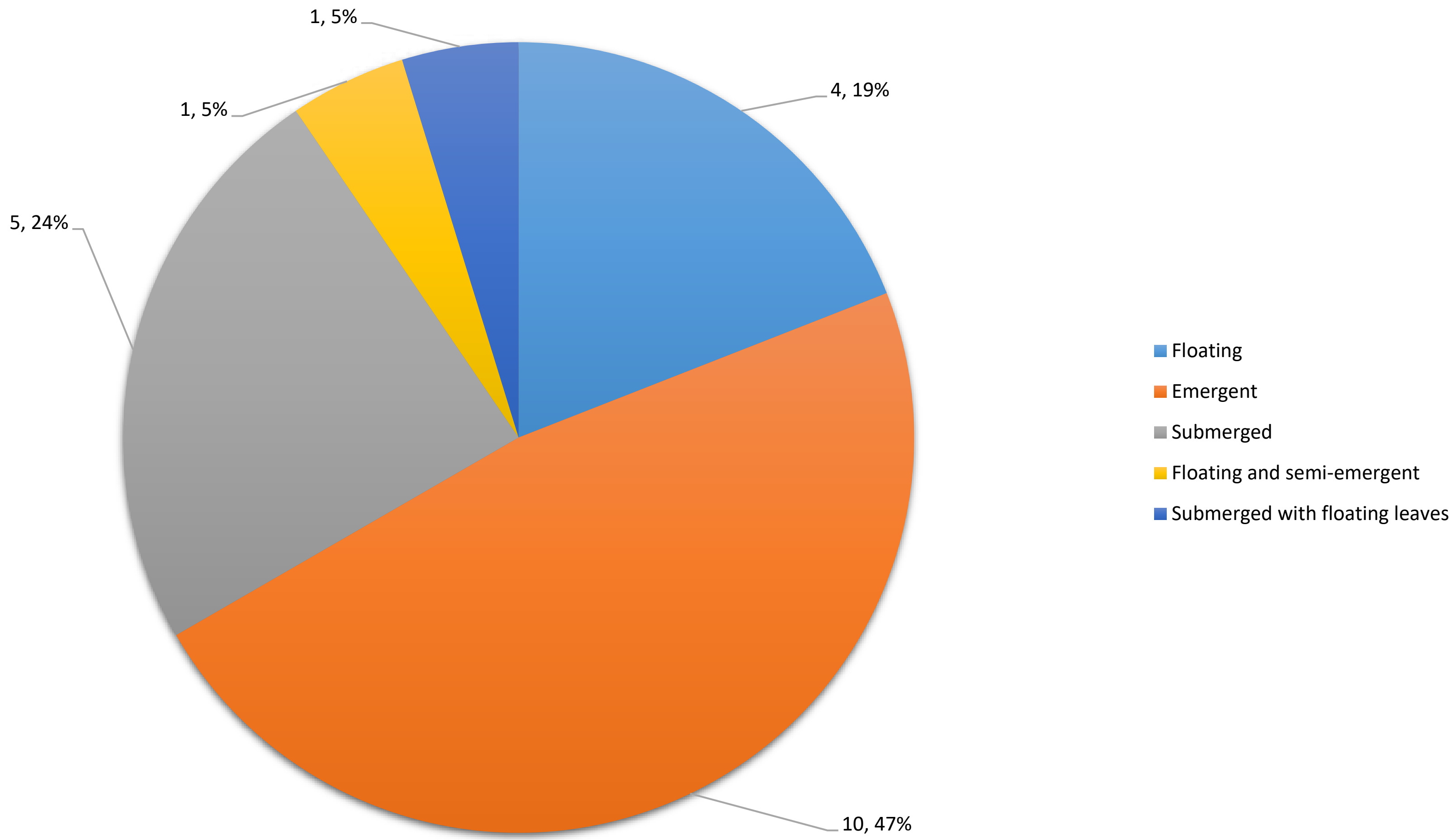
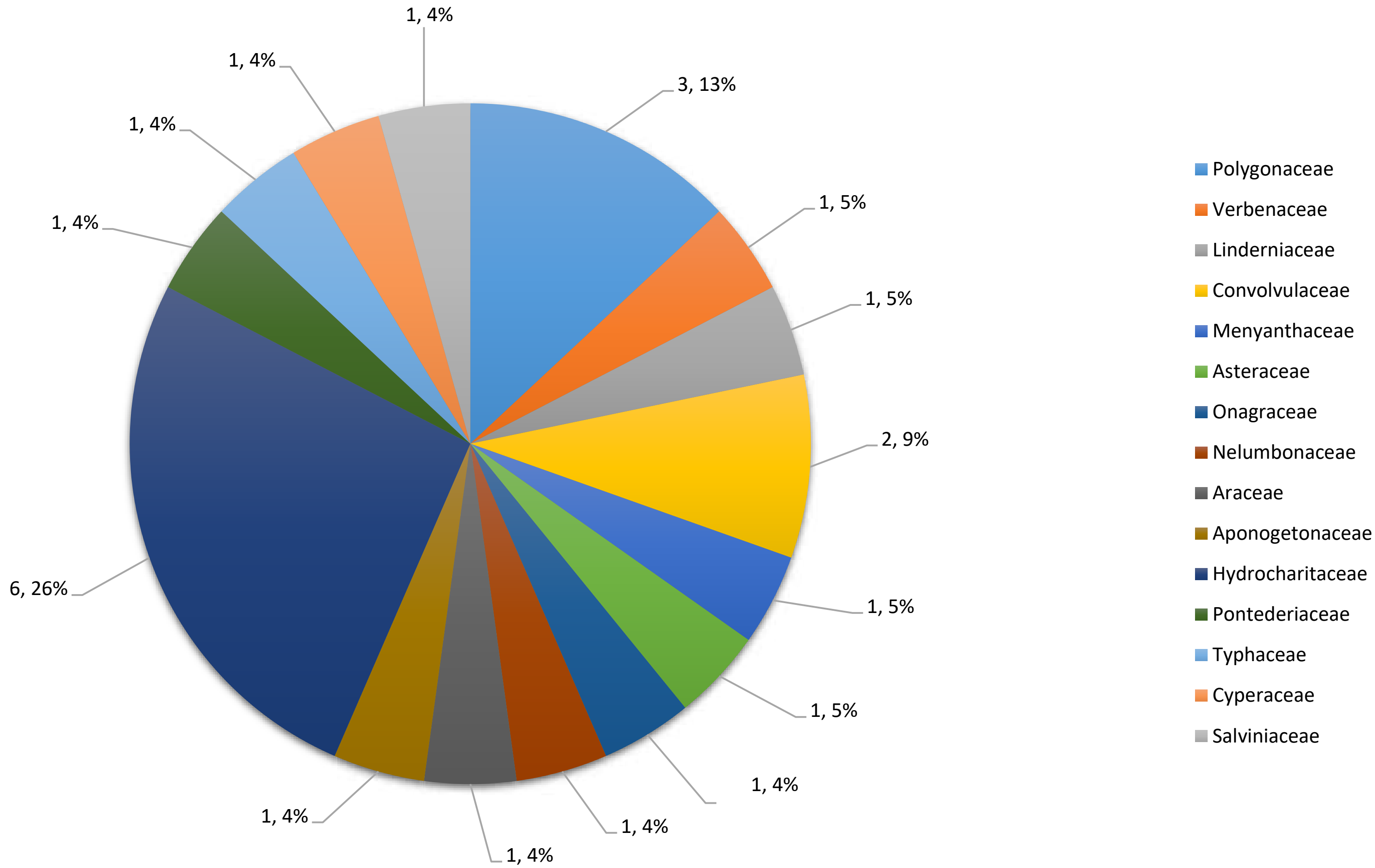


Fig. 3 Aquatic macrophytes in the Satpura Reservoir showing species number and percentage contribution



516

517 **Fig. 4** Family-wise species richness and percentage contribution of aquatic macrophytes in the Satpura Reservoir

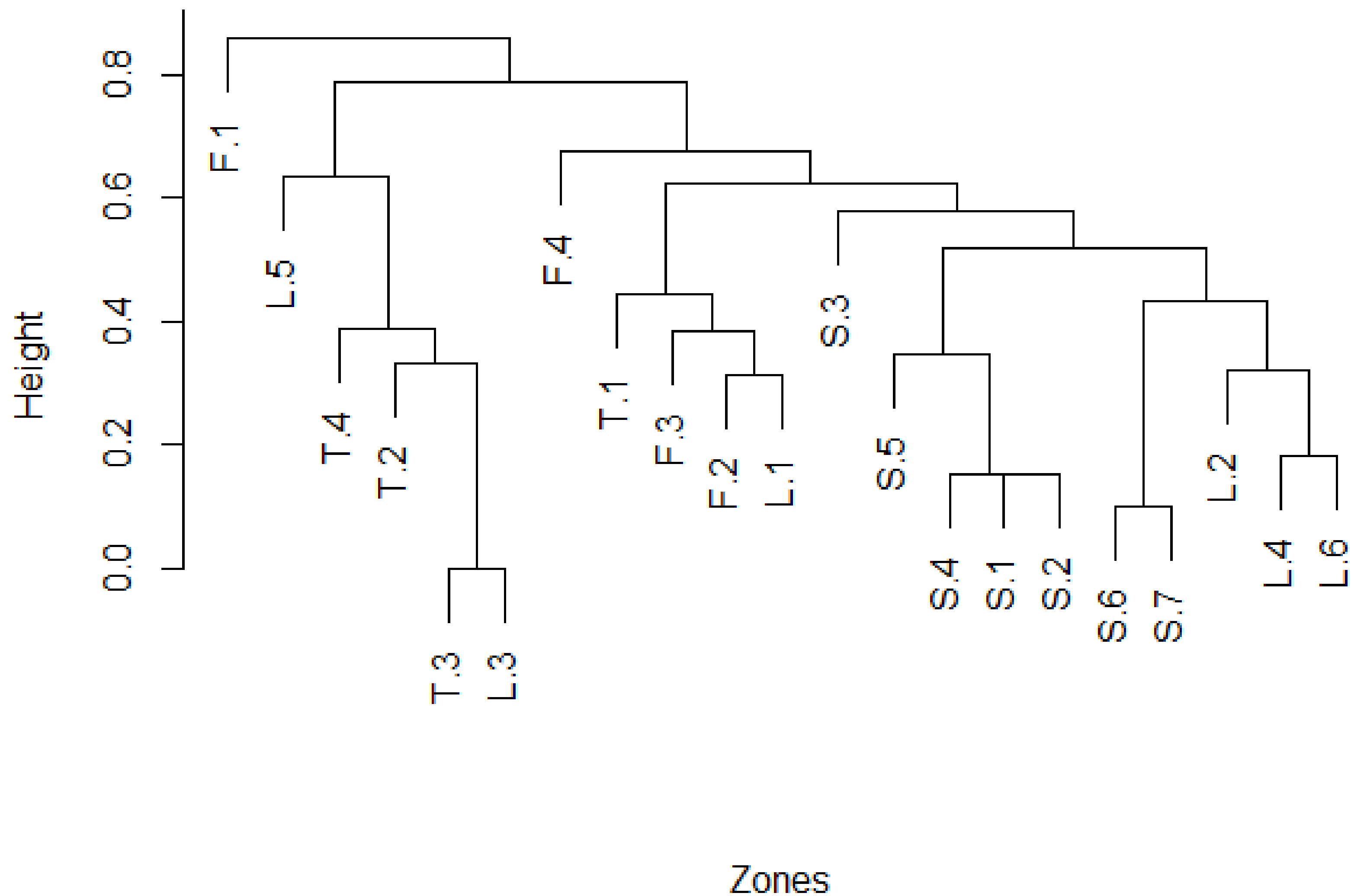


Fig. 5 Jaccard dendrogram of aquatic macrophyte similarity across sites in Satpura Reservoir

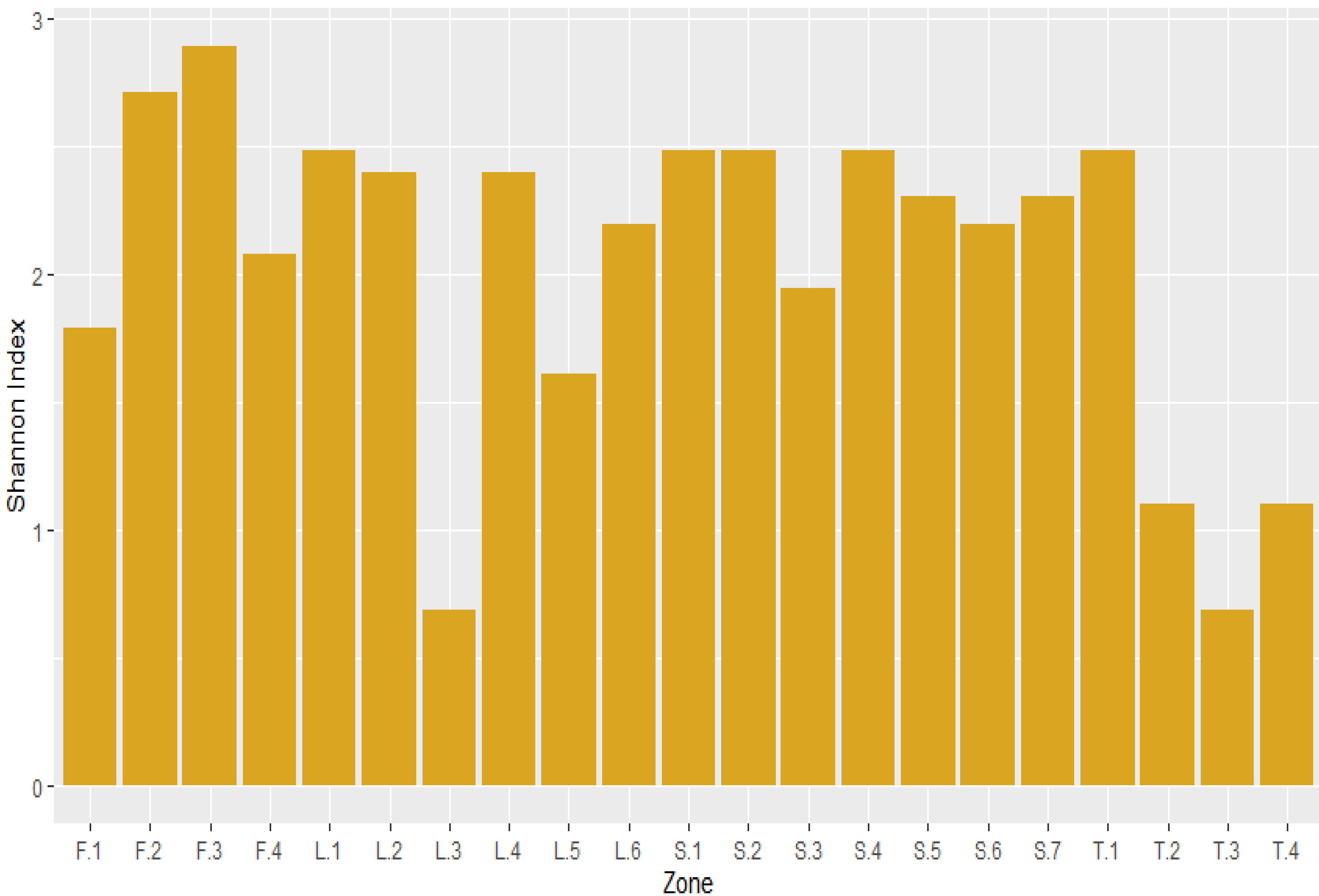
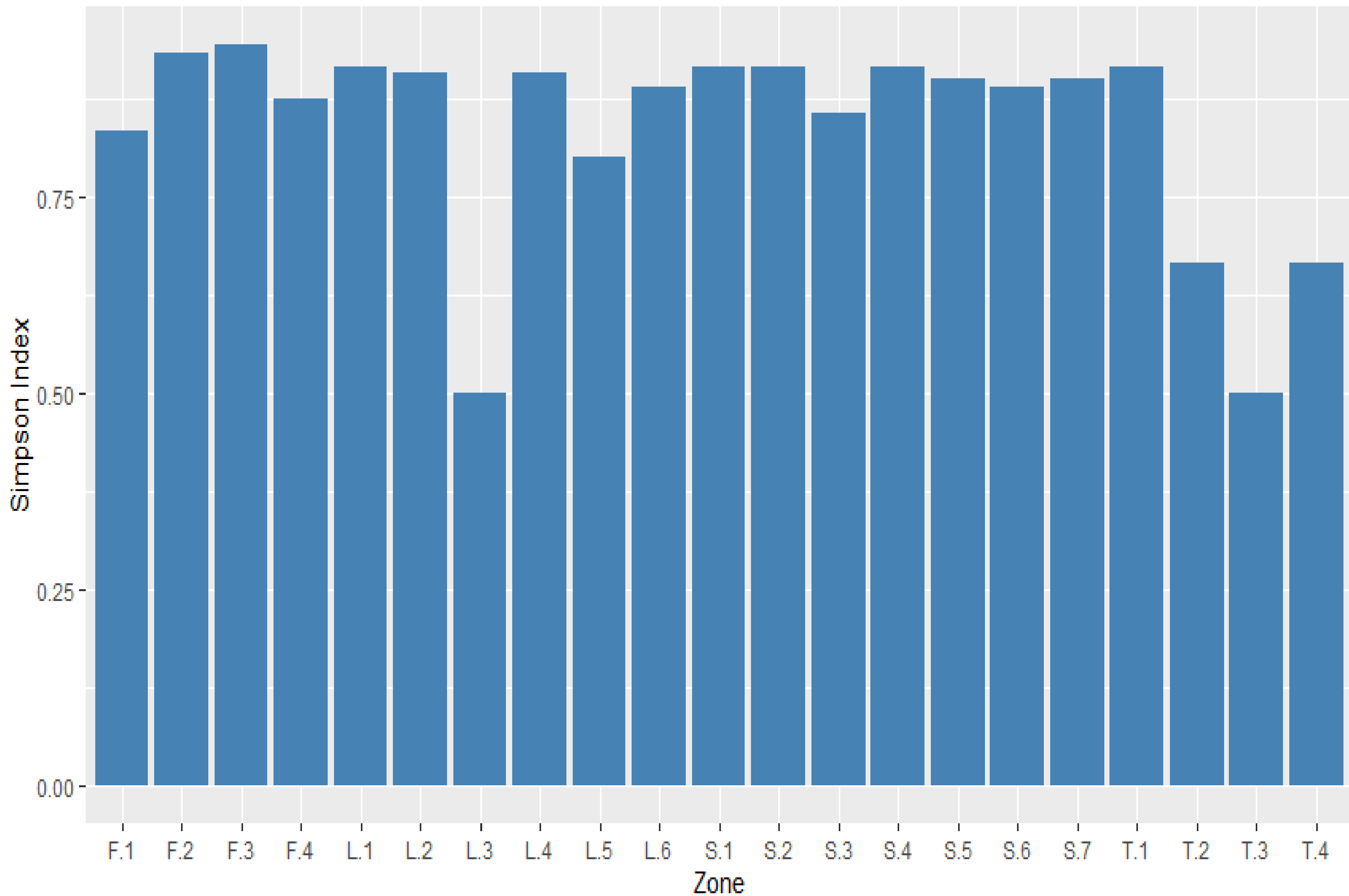


Fig. 6 Shannon diversity index of aquatic macrophytes across sampling sites in the Satpura Reservoir



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523 **Fig. 7** Simpson diversity index of aquatic macrophytes across sampling sites in the Satpura Reservoir

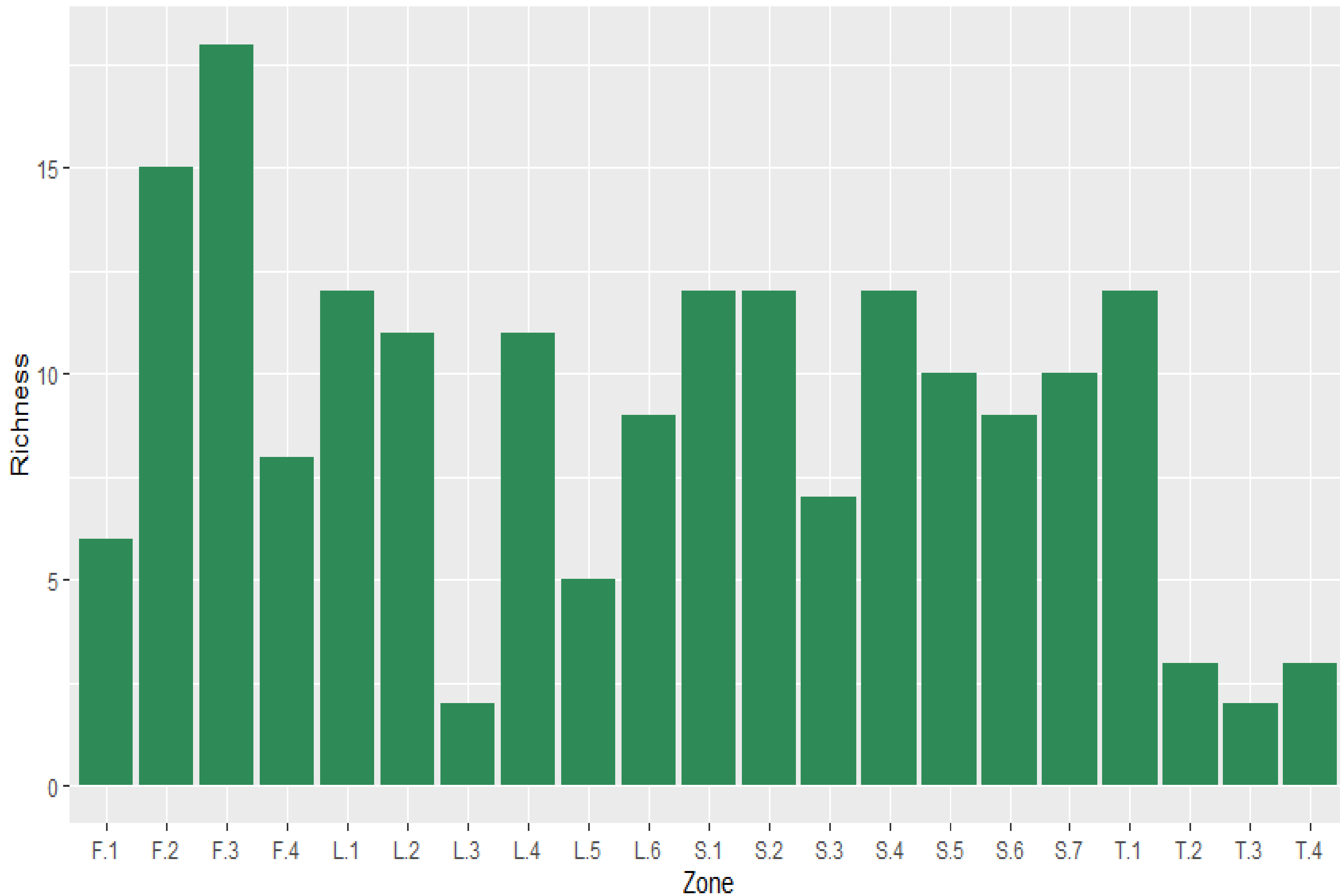

Fig. 8 Species richness of aquatic macrophytes across sampling sites in the Satpura Reservoir

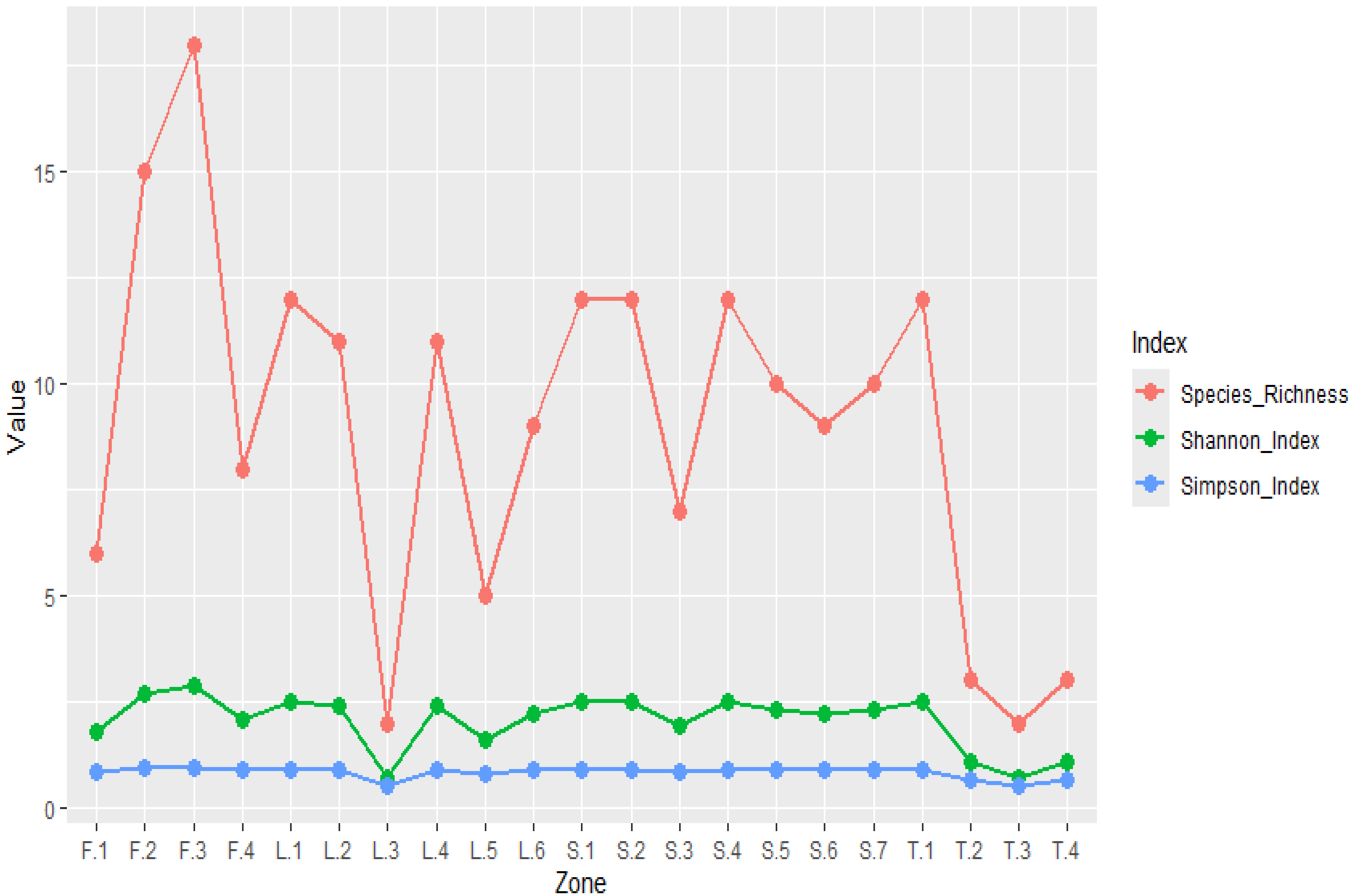

Fig. 9 Comparative diversity indices of aquatic macrophytes across sampling sites in the Satpura Reservoir

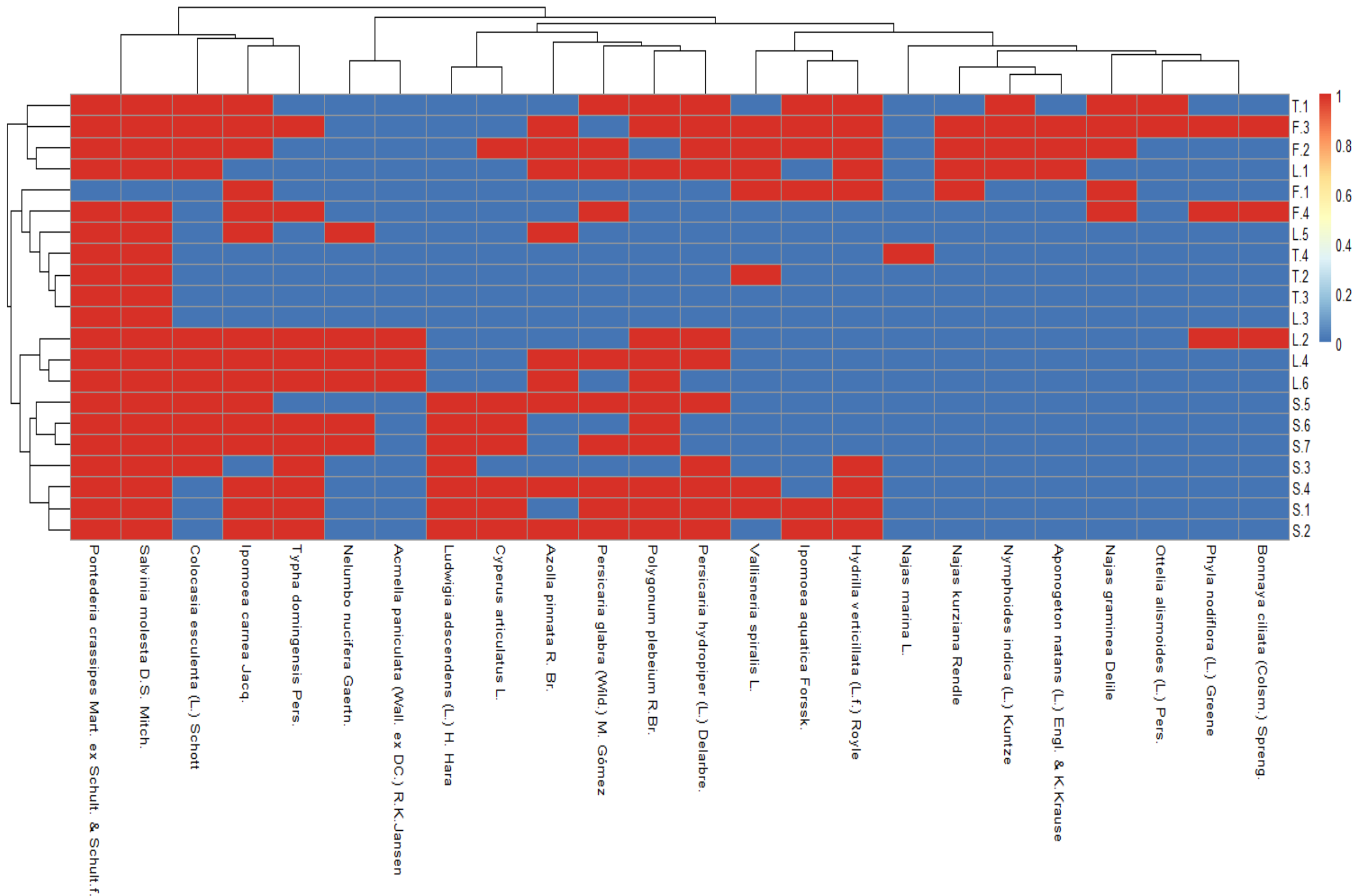

Fig. 10 Heatmap of species presence across sites in Satpura Reservoir

(a) **(b)**

(c)

(d)

(e)

Fig. 11 Exotic flora of Satpura reservoir **(a), (b), (c)** Invasion by *Salvinia molesta* and **(d)** Invasion by *Pontederia crassipes* **(e)** *Ipomoea carnea*

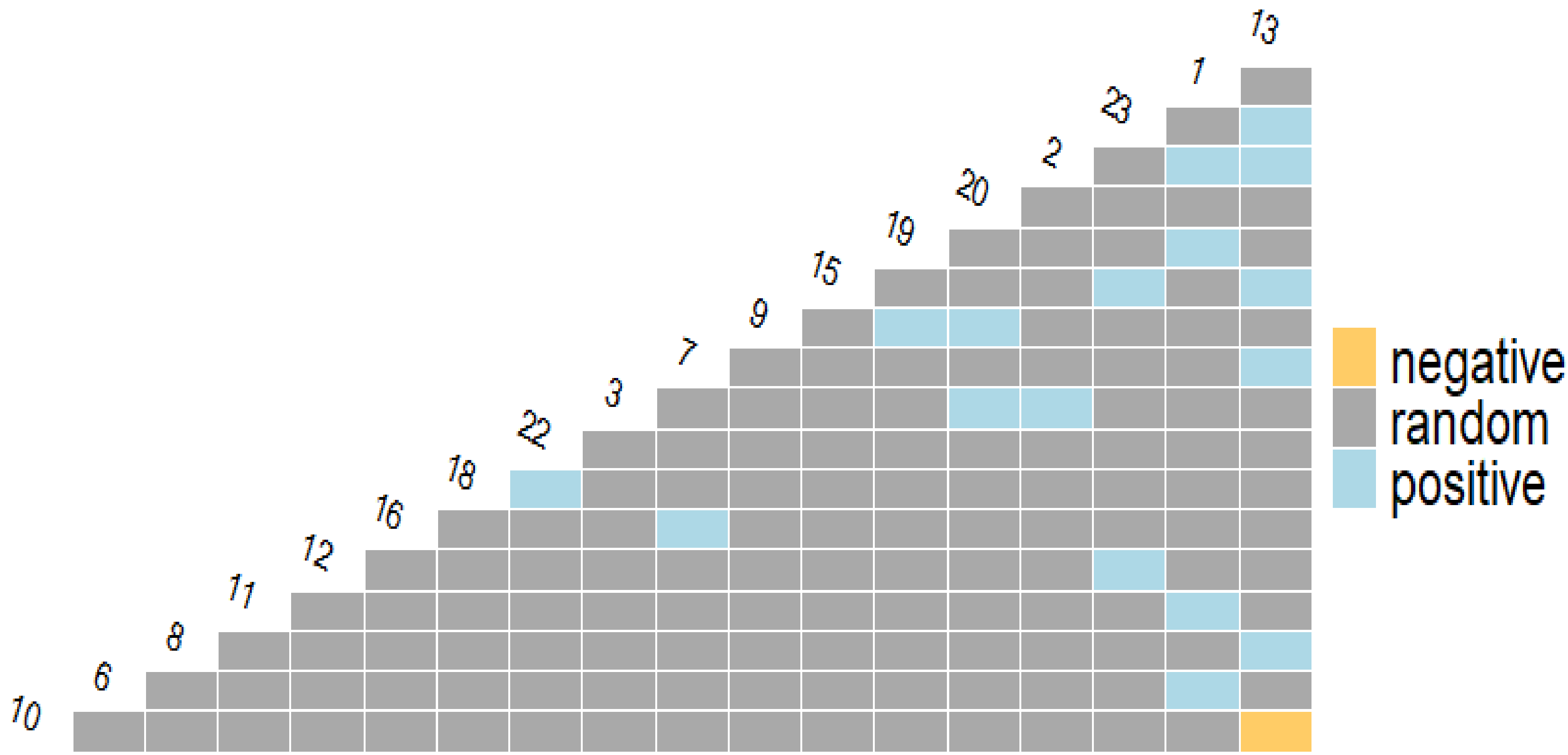

Fig. 12 Species co-occurrence matrix of aquatic plants of Satpura Reservoir (1 - *Polygonum plebeium*; 2 - *Persicaria hydropiper*; 3 - *Persicaria glabra*; 6 - *Ipomoea carnea*; 7 - *Ipomoea aquatic*; 8 - *Nymphoides indica*; 9 - *Ludwigia adscendens*; 10 - *Nelumbo nucifera*; 11 - *Colocasia esculenta*; 12 - *Aponogeton*

natans; 13 - *Hydrilla verticillata*; 15 - *Najas kurziana*; 16 - *Najas graminea*; 18 - *Pontederia crassipes*; 20 - *Cyperus articulates*; 21 - *Azolla pinnata*; 22 - *Salvinia molesta*; 23 - *Vallisneria spiralis*)

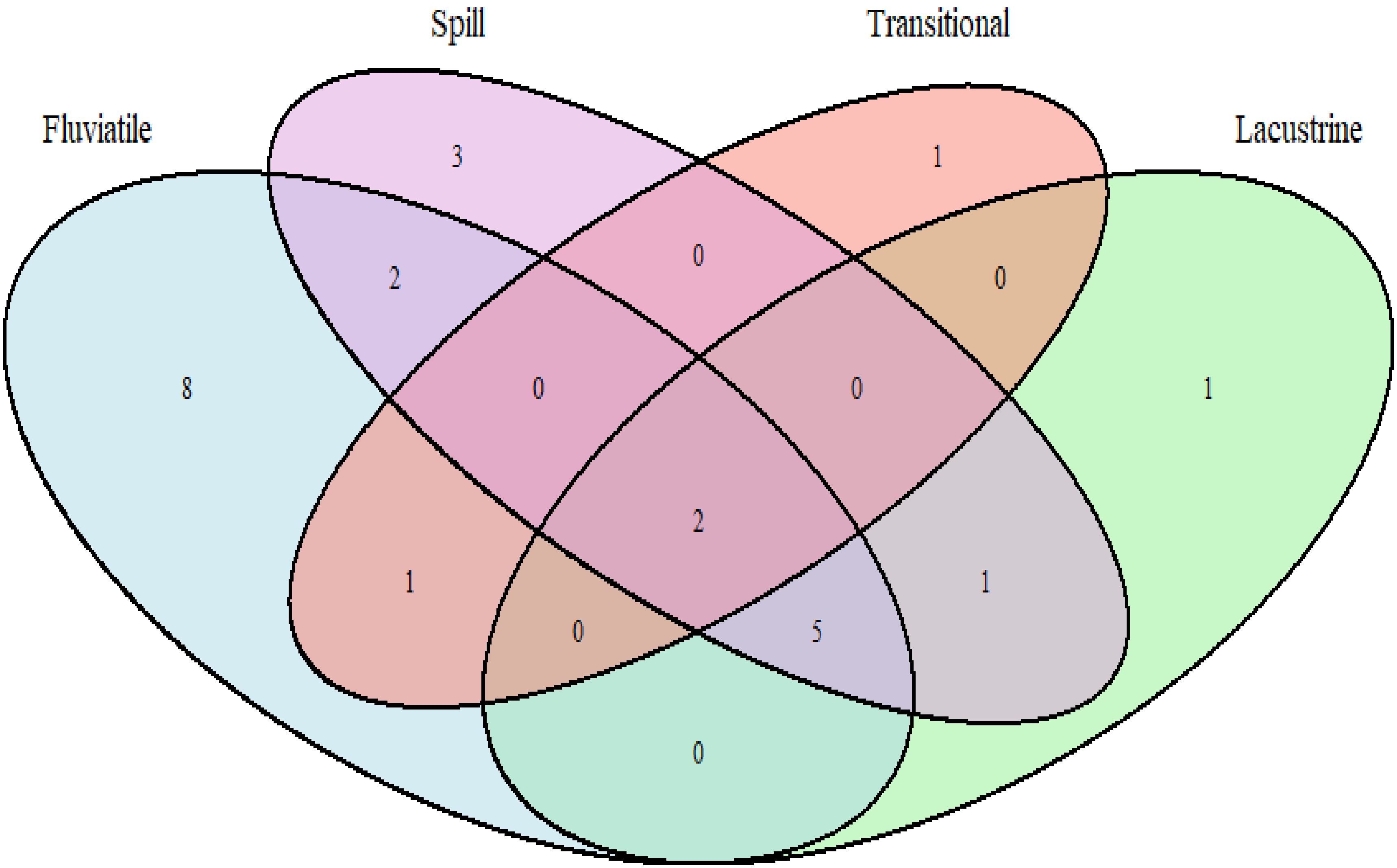

Fig. 13 Venn diagram of the species presence across zones in Satpura Reservoir

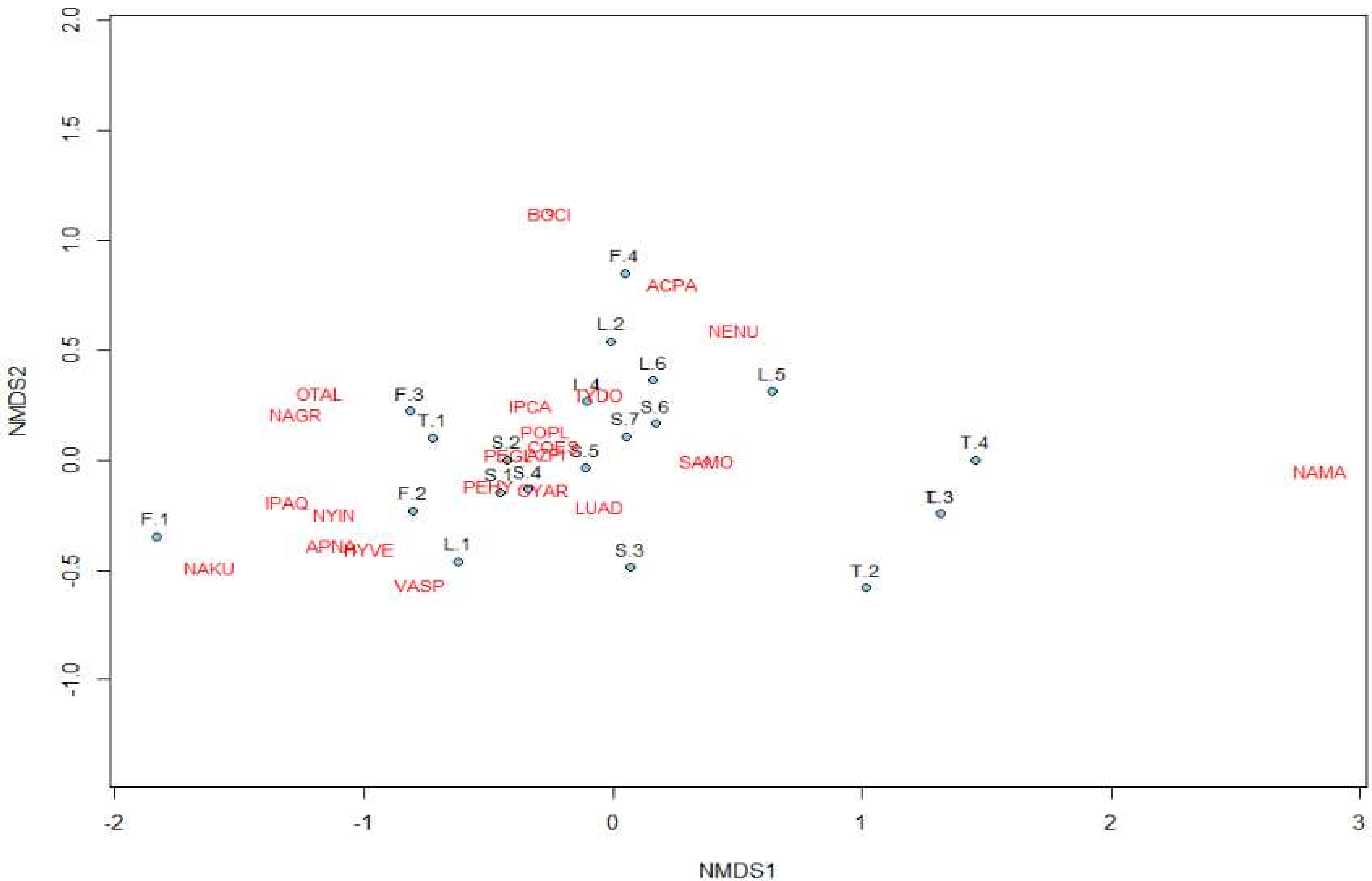

Fig. 14 Non-metric Multidimensional Scaling (NMDS) ordination illustrating the relationship between aquatic macrophyte species and sampling sites in Satpura Reservoir **(**POPL - *Polygonum plebeium*; PEHY - *Persicaria hydropiper*; PEGL - *Persicaria glabra*; PHNO - *Phyla nodiflora*; BOCI - *Bonnaya ciliate*; IPCA -

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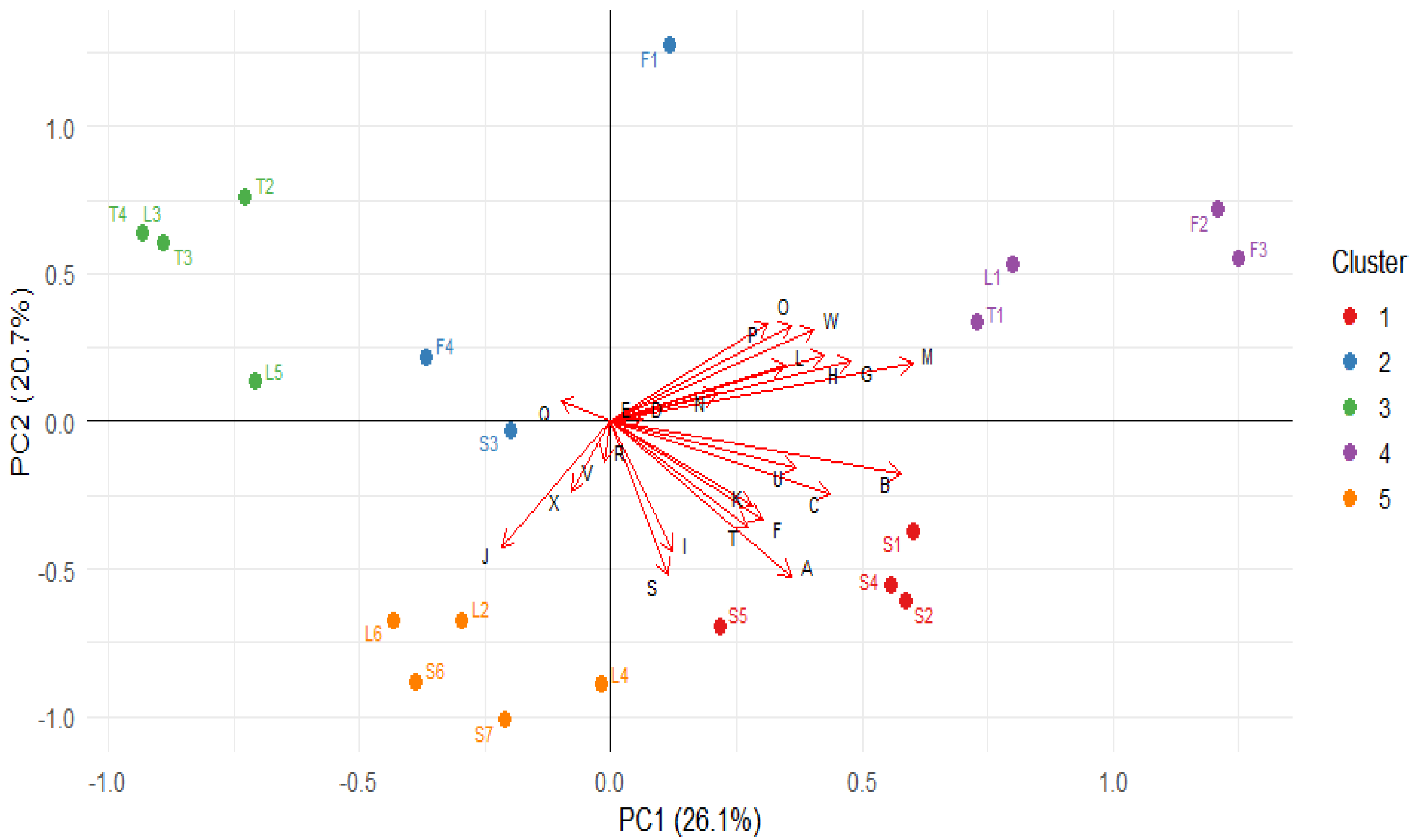

Fig. 15 Principal Component analysis (PCA) ordination of aquatic macrophyte species and sampling sites in Satpura Reservoir **(**A - *Polygonum plebeium*; B - *Persicaria hydropiper*; C - *Persicaria glabra*; D - *Phyla nodiflora*; E - *Bonnaya ciliate*; F - *Ipomoea carnea*; G - *Ipomoea aquatic*; H - *Nymphoides indica*; I - *Ludwigia adscendens*; J - *Nelumbo nucifera*; K - *Colocasia esculenta*; L - *Aponogeton natans*; M - *Hydrilla verticillata*; N - *Ottelia alismoides*; O - *Najas*

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