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Bamboo diversity, ecological structure, and utilization in the riparian ecosystem of the upper Bengawan Solo River, Central Java, Indonesia

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Abstract. *Aprilia FN, Ardhyanti FAK, Prabowo GAS, Paramesti H, Aszar AS, Yap CK, Setyawan AD. 2025. Bamboo diversity, ecological structure, and utilization in the riparian ecosystem of the upper Bengawan Solo River, Central Java, Indonesia. Nusantara Bioscience 17: 259-276.* Bamboo plays an important ecological and socio-economic role in tropical riparian landscapes, yet its spatial structure and environmental determinants remain poorly quantified. This study analyzed the diversity, composition, ecological dominance, and utilization of bamboo communities along the upstream–midstream–downstream gradient of the upper Bengawan Solo River, Central Java, Indonesia. Field surveys recorded five species—*Bambusa spinosa*, *Dendrocalamus asper*, *Gigantochloa apus*, *G. atter*, and *G. atroviolacea*—distributed unevenly across riparian zones. Diversity, species richness, and structural heterogeneity increased downstream, shifting from monodominant *B. spinosa* stands upstream to multi-species *Gigantochloa* assemblages in lowland alluvial areas. Importance Value Index (IVI) patterns revealed strong environmental filtering in the upstream zone, mixed natural–managed dominance midstream, and cultivation-enhanced coexistence downstream. Pearson correlation analysis indicated that soil moisture, canopy openness, and soil pH were the strongest predictors of diversity, whereas species dominance was shaped primarily by ecological traits and management intensity. Utilization patterns reflected a biocultural continuum, with *D. asper* and *Gigantochloa* spp. providing multipurpose materials for construction, food, handicrafts, and cultural practices, while *B. spinosa* served chiefly as an ecological stabilizer in upland slopes. The riparian bamboo system represents a socio-ecological mosaic shaped by hydrological gradients and community management. These findings highlight bamboo's potential as a nature-based solution for riparian stabilization, biodiversity conservation, and livelihood support. Strengthening integrated, community-based bamboo management could enhance ecological resilience and sustainable riverine landscape governance in tropical regions.

Keywords: Bamboo diversity, Bengawan Solo River, ecological structure, riparian ecosystem, utilization potential

INTRODUCTION

Bamboo forests constitute one of the most ecologically and socio-economically significant vegetation components in tropical and subtropical Asia, contributing to soil stability, microclimate regulation, habitat provisioning, and rural livelihoods (Bystriakova et al. 2004; Nath et al. 2020). Indonesia is recognized as a global center of bamboo diversity, hosting more than 160 species with high endemism (Widjaja and Kartikasari 2001; Wong 2004). Across the archipelago, bamboo fulfills multifunctional roles ranging from slope stabilization and water regulation to the provision of raw materials for construction, crafts, food, and cultural practices (Silva et al. 2020; Lobovikov et al. 2007; Rani et al. 2024). In riparian ecosystems, bamboo stands are particularly important as natural buffers that protect riverbanks from erosion, enhance water quality by filtering sediments, and maintain hydrological stability. These ecological functions align with current global frameworks emphasizing nature-based solutions for watershed management and river rehabilitation (FAO 2020).

Despite the ecological importance of bamboo in riparian landscapes, research in Indonesia has been disproportionately concentrated on taxonomy, propagation techniques, and general ethnobotanical use. Relatively few studies have examined how bamboo communities are structured along river corridors, particularly in relation to environmental gradients such as slope, soil moisture, canopy openness, and anthropogenic disturbance. This represents a substantial research gap, considering that riparian ecosystems are among the most dynamic and human-impacted landscapes in the tropics. In Java, studies have focused primarily on upland bamboo assemblages (Arinasa and Sujarwo 2015), bamboo agroforestry systems (Setiawati et al. 2017), or ethnobotanical practices in rural communities (Yanty et al. 2019; Ihsan et al. 2023), but zone-based ecological assessments along riverine gradients remain largely undocumented.

From an ecological perspective, bamboo species exhibit growth strategies that allow them to rapidly colonize and dominate riparian zones. Rhizomatous root systems, rapid culm regeneration, and tolerance to disturbance enable certain taxa—such as *Bambusa spinosa*, *Dendrocalamus asper*, and *Gigantochloa apus*—to establish monospecific or co-dominant stands following flooding, erosion, or human intervention (Xu et al. 2020; Nath et al. 2020). However, these adaptive advantages may also suppress diversity in harsher upstream environments, whereas higher moisture and nutrient availability downstream often support more heterogeneous assemblages. Understanding how these ecological processes translate into spatial changes in diversity indices (H′, R, E) and Importance Value Index (IVI) is essential for predicting ecosystem function and resilience.

Equally important is the socio-ecological dimension of bamboo in Javanese landscapes. Local communities extensively utilize species such as *G. apus*, *G. atter*, and *D. asper* for construction materials, woven products, agricultural tools, and edible shoots (Widjaja and Kartikasari 2001; Ekawati et al. 2022). However, quantitative analyses linking ecological dominance with documented and potential utilization categories remain scarce, especially in riparian habitats where ecological function and cultural utility overlap. This gap limits our understanding of how community preferences and management practices influence bamboo distribution, regeneration, and long-term ecological stability.

The Bengawan Solo River, the longest river in Java, Indonesia, traverses diverse ecological and socio-economic zones. Its upper stretches are characterized by steep slopes, mixed agroforestry mosaics, and rapidly transforming riparian vegetation (Maulana et al. 2019). Habitat alteration through land conversion, sedimentation, selective cutting, and patchy replanting has led to shifts in bamboo species composition and structural integrity (Ferreira et al. 2019). Yet, no prior study has analyzed how bamboo diversity, IVI-based dominance, and environmental variables jointly structure bamboo communities along the upper Bengawan Solo riparian gradient. Moreover, the integration of ecological metrics with utilization data has not been attempted in this region, despite its importance for community-based conservation and watershed management.

Accordingly, this study was designed to (i) document the composition and diversity of bamboo species across the upstream, midstream, and downstream segments of the upper Bengawan Solo River; (ii) analyze ecological structure and dominance patterns based on density, frequency, and IVI; and (iii) assess documented and potential uses of each species to identify socio-ecological linkages relevant for management. By combining ecological indicators with ethnobotanical relevance and environmental drivers, this research provides the first spatially explicit, socio-ecologically integrated assessment of riparian bamboo communities in Central Java. The findings are expected to strengthen the scientific basis for bamboo-based riparian restoration and sustainable landscape management within tropical river systems.

MATERIALS AND METHODS

Study area

This study was conducted in March 2025 in the riparian landscape of the upper Bengawan Solo River, Central Java, Indonesia, which flows through the upland catchments of Wonogiri before entering the agricultural lowlands of Klaten and Sukoharjo Districts (JICA 2007). Three sampling sites representing distinct hydrological and land-use segments were selected: Giriwono (upstream), Sidowarno (midstream), and Gadingan (downstream). These locations were chosen to capture ecological variability along the longitudinal gradient of the river—an approach commonly used in riparian ecology (Naiman and Décamps 1997)—and to represent natural, semi-natural, and intensively managed riparian conditions. The spatial configuration of the study area is shown in Figure 1.

The upstream area at Giriwono (~135 m asl) is characterized by hilly terrain, steep riparian slopes, and mixed dryland agriculture interspersed with remnant forest patches. As part of the Bengawan Solo upland catchment, this zone contributes perennial water flow to the river despite seasonal climate variation (Whitten et al. 1997). Riparian vegetation is relatively wide and buffered, with bamboo occurring naturally near the boundaries of the Alas Kethu protected forest.

The midstream zone in Sidowarno (~95 m asl) represents a transitional agricultural landscape dominated by rice, sugarcane, tobacco, and agroforestry mosaics. Volcanic-derived regosol soils form the dominant substrate, supporting intensive farming. Human disturbance is more substantial here, with riparian strips managed directly by farmers for fencing, scaffolding, and soil stabilization (Radnawati and Fatmala 2020).

The downstream site at Gadingan (~85 m asl) lies on alluvial floodplains formed by long-term deposition from upstream erosion and volcanic sediments. These fertile substrates support extensive rice cultivation and settlement development. Riparian buffers are narrow or fragmented, and bamboo communities are dominated by cultivated stands planted along irrigation channels or field boundaries.

The region experiences a tropical monsoon climate with annual rainfall of 2,000-2,500 mm and temperatures generally ranging from 23-30 °C (BMKG 2023a, b). These climatic conditions facilitate rapid bamboo growth and continuous culm production, as commonly observed in monsoonal Southeast Asia (Sembada et al. 2025).

Sampling design

A stratified–systematic sampling design (Mueller-Dombois and Ellenberg 1974; Kent and Coker 1992) was implemented to represent ecological variation across the upstream, midstream, and downstream segments of the Bengawan Solo River. Each segment was treated as an independent ecological stratum reflecting differences in topography, land use, and hydrological influence. Within each stratum, 10 vegetation plots were systematically established, resulting in 30 plots across all sites.

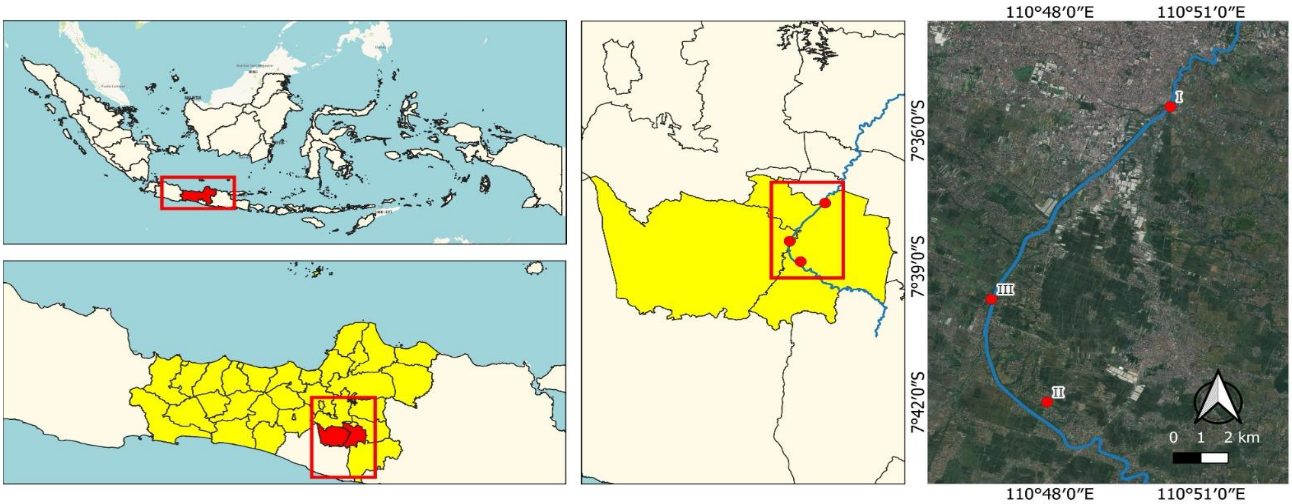

Figure 1. Map of the research locations along the upper Bengawan Solo River, Central Java, Indonesia: I. Gadingan Village, Mojolaban Sub-district, Sukoharjo District (7°34'37.1"S 110°50'45.0"E); II. Giriwono Village, Wonogiri Sub-district, Wonogiri District, (7°47'48.1"S 110°56'08.4"E); and III. Sidowarno Village, Wonosari Sub-district, Klaten District (7°38'34.2"S 110°47'31.3"E)

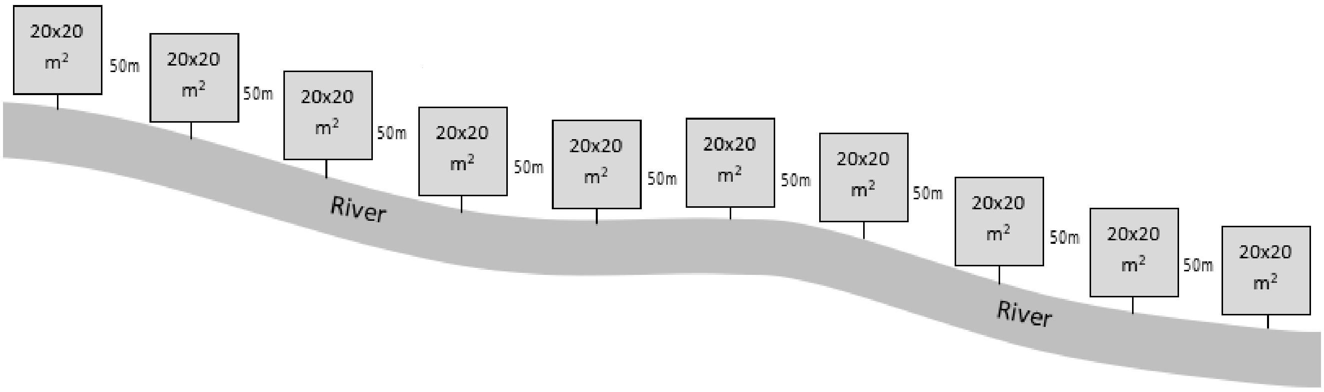

Figure 2. Diagram showing the sampling layout design for vegetation plots (10 plots per site) along the riparian gradient

Each plot measured 20 × 20 m (400 m²), providing 0.4 ha of sampling area per site (1.2 ha total). Plots were positioned at approximately 50 m intervals along a single riverbank to ensure consistent representation of riparian vegetation, following best practices in riparian vegetation sampling (Sutherland 2006), with the linear arrangement of the ten plots at one site illustrated in Figure 2. Plot placement began near the river edge, where hydrological influence is strongest, and extended toward adjacent agricultural or settlement zones. Plot boundaries were marked with stakes, and GPS coordinates of plot centers were recorded using a Garmin eTrex 32x (±3 m accuracy).

This sampling design captured both natural and managed bamboo stands while reflecting spatial heterogeneity associated with hydrological gradients and anthropogenic pressures (Naiman and Décamps 1997).

Vegetation data collection

Within each plot, all bamboo clumps (culm clusters) were identified to species level and treated as individual sampling units. Structural measurements followed standard procedures for Southeast Asian forest and bamboo vegetation (Soerianegara and Indrawan 2002; Liese and Köhl 2015). For each clump, species identity, culm count, average height, and diameter were recorded. Culm diameter was measured at breast height (1.3 m above ground), while height was estimated using a graduated pole or laser rangefinder.

Vegetative morphological characteristics were documented to support identification, including culm color, internode length, sheath morphology, wall thickness, and branching pattern—traits widely used in bamboo taxonomy (Ohrnberger 1999; Widjaja and Kartikasari 2001). Field assistants received prior training on bamboo recognition and measurement techniques to reduce observer bias.

Representative photographs were taken to support post-field verification.

Environmental variables

A suite of environmental variables was measured within each plot to contextualize bamboo community variation. Soil pH was measured with a portable pH meter, soil moisture using a soil moisture probe, and soil temperature using a soil thermometer, following standard ecological soil measurement protocols (Allen 1989).

Microclimatic variables—including air temperature and relative humidity—were measured using a digital hygrometer. Canopy openness was estimated using a spherical densiometer (Lemmon 1956) and categorized into open, moderate, or closed canopy classes. Topographic parameters such as slope gradient and elevation were recorded visually or with a clinometer. Distance to the river channel was measured to capture varying degrees of riparian influence. Environmental measurements were carried out between 08:00 and 11:00 a.m. to minimize diurnal variability, as recommended in standard ecological monitoring guidelines (Sutherland 2006).

Species identification and taxonomic verification

Species identification followed the taxonomic keys and field guides of Ohrnberger (1999) and Widjaja and Kartikasari (2001). Diagnostic vegetative features—including sheath characteristics, culm coloration, leaf morphology, branching pattern, and internode dimensions—were used due to the infrequent flowering of most bamboo species (Liese and Köhl 2015). Scientific names were validated using international databases: the GBIF Backbone Taxonomy (2024), International Plant Names Index (IPNI 2024) and Plants of the World Online (POWO 2024) ensuring nomenclatural accuracy. Voucher specimens were collected and deposited in the Herbarium of Universitas Sebelas Maret, Central Java. Metadata included plot number, GPS coordinates, and habitat characteristics.

Data analysis

Community structure

Phytosociological parameters were calculated following standard procedures (Mueller-Dombois and Ellenberg 1974; Soerianegara and Indrawan 2002). Density (D) was expressed as clumps per hectare. Frequency (F) represented the proportion of plots in which a species occurred. Dominance (Do) was estimated using basal area based on mean culm diameter (Liese and Köhl 2015). Relative values—Relative Density (RD), Relative Frequency (RF), and Relative Dominance (RDo)—were calculated and summed to obtain the Importance Value Index (IVI), a robust indicator of species ecological significance (Kent and Coker 1992).

Diversity indices

Bamboo community diversity was calculated using the Shannon–Wiener index (H′), Margalef richness index (R), and Pielou's evenness index (E) (Pielou 1975; Magurran 2004). Interpretation of H′ values followed Junaedi and Mutaqien (2010), where H′ <1.0 indicates low diversity, 1.0-3.0 indicates moderate diversity, and ≥3.0 denotes high diversity.

Comparative analysis

Ecological differences among upstream, midstream, and downstream sites were assessed by comparing species richness, abundance, IVI, and diversity indices and relating them to observed environmental variation (Naiman and Décamps 1997). Visual comparisons were generated through bar and line charts.

Correlation analysis

To evaluate associations between environmental conditions and bamboo community attributes, Pearson's correlation analysis was conducted after normality testing with the Shapiro–Wilk test. This approach follows established ecological statistical practices (Magurran 2004). Analyses were performed in IBM SPSS Statistics 26, with visualization in Microsoft Excel 2021.

Utilization assessment

Utilization categories—construction, handicraft, agriculture/forestry, food, medicine, culture, and landscape—follow established classifications of bamboo uses (Widjaja and Kartikasari 2001; Irawan et al. 2025). Documentation included literature review and field observations near study sites. Utilization profiles were interpreted in relation to ecological dominance (IVI) to identify multifunctional species supporting riparian ecosystem stability and local livelihoods (Bystriakova et al. 2004).

RESULTS AND DISCUSSION

Species composition across riparian zones

A total of five bamboo species belonging to three genera were recorded across the riparian zones of the upper Bengawan Solo River (Table 1). These species—*B. spinosa*, *D. asper*, *G. apus*, *G. atter*, and *G. atroviolacea*—showed uneven distribution among the upstream, midstream, and downstream segments, indicating strong zonation along the river gradient.

The upstream zone (Giriwono) contained only two species, *B. spinosa* and *D. asper*. *Bambusa spinosa* was particularly dominant, contributing 35 of the 53 clumps recorded in this segment, while *D. asper* was present in smaller numbers (18 clumps). The absence of *Gigantochloa* species in this zone (Table 1) reflects the drier, steeper upland conditions that limit the establishment of species requiring moister substrates.

In the midstream zone (Sidowarno), species richness increased to four, with *G. apus* appearing as a major component of the vegetation (24 clumps). *Dendrocalamus asper* also remained abundant (22 clumps), indicating its broad ecological tolerance. The presence of both naturally occurring and cultivated bamboo stands in this segment is consistent with the heterogeneous land-use mosaic surrounding irrigated fields and agroforestry systems. As shown in Table 1, midstream contains the highest total clump abundance (66 clumps), suggesting both ecological suitability and active management.

The downstream zone (Gadingan) supported the highest richness, with all five species present and a strong representation of *Gigantochloa* species—especially *G. apus*, *G. atter*, and *G. atroviolacea*. These species collectively accounted for 43 of the 61 clumps recorded downstream (Table 1). Their presence corresponds to the wetter alluvial soils and more intensive human activities near settlements and irrigation channels, conditions that favor both natural growth and cultivated propagation.

Table 1 clearly shows that although total clump abundance varies only moderately across zones (53-66 clumps), species composition differs substantially, with downstream segments hosting exclusive species such as *G. atroviolacea* and upstream segments lacking the *Gigantochloa* group entirely. This longitudinal pattern highlights the combined influence of hydrology, soil conditions, and land-use practices in shaping bamboo distribution along the upper Bengawan Solo River.

Clump abundance and spatial distribution

Clump abundance varied across the upstream, midstream, and downstream zones, reflecting both ecological suitability and differing levels of human intervention along the riparian corridor. As shown in Table 1, a total of 180 bamboo clumps were recorded across all sites, with the midstream segment containing the highest number of clumps (66), followed by the downstream (61) and upstream zones (53). Although differences in total clump numbers among zones were not large, the spatial distribution and dominance patterns of individual species showed pronounced variation.

In the upstream zone, clump abundance was strongly skewed toward *B. spinosa*, which accounted for 35 of the 53 clumps recorded. This monodominant pattern reflects the species' ability to thrive on steep, well-drained riparian slopes with minimal soil moisture. *Dendrocalamus asper* formed the remaining 18 clumps, indicating a more limited distribution in this segment. The absence of all *Gigantochloa* species in the upstream zone (Table 1) reinforces the notion that this environment filters species based on tolerance to drier upland conditions.

In contrast, the midstream zone exhibited a more balanced distribution of clumps among species, indicating a mixed-dominance pattern. *Gigantochloa apus* (24 clumps) and *D. asper* (22 clumps) together contributed the majority of clumps in this segment, reflecting the transition from natural riparian vegetation to semi-managed agroforestry systems. The presence of multiple species with similar clump abundance suggests that midstream environmental conditions—moderate slopes, fertile regosol soils, and frequent human management—support a more heterogeneous bamboo community.

The downstream zone showed the most diverse assemblage of clump abundance patterns. *Gigantochloa apus* (18 clumps) and *G. atter* (15 clumps) were particularly prominent, while *G. atroviolacea*—absent upstream and midstream—was represented by 10 clumps. The distribution of clumps in downstream areas indicates a multi-species dominance pattern associated with moist alluvial soils, flatter terrain, and high levels of anthropogenic disturbance. Cultivated bamboo stands were common near irrigation channels, field boundaries, and settlement edges, facilitating the proliferation of *Gigantochloa* species.

The spatial distribution of clump abundance outlined in Table 1 demonstrates a clear ecological gradient: monodominance of drought-tolerant species in the upstream, mixed assemblages in the midstream, and multi-species, management-influenced communities downstream. These patterns are consistent with the combined influence of hydrology, soil conditions, and land-use intensity on bamboo growth and persistence in the riparian ecosystem of the upper Bengawan Solo River.

Structural parameters of bamboo communities

The structural characteristics of bamboo communities along the upper Bengawan Solo River exhibited clear spatial differentiation across the upstream, midstream, and downstream segments. Table 2 presents the density (clumps/ha), frequency of occurrence, and relative dominance for each species, illustrating how bamboo stands respond to varying riparian conditions and land-use intensity.

Table 1. Composition and abundance of bamboo species in the riparian zones of the upper Bengawan Solo River, Central Java, Indonesia

Species	Upstream (Giriwono)	Midstream (Sidowarno)	Downstream (Gadingan)	Total (clumps)	Distribution pattern
Bambusa spinosa Roxb.	35	14	8	57	Common in upstream, scattered in others
Dendrocalamus asper (Schult. & Schult.f.) Backer	18	22	10	50	Widespread
Gigantochloa apus (Schult.f.) Kurz ex Munro	0	24	18	42	Absent in upstream
Gigantochloa atter (Hassk.) Kurz	0	6	15	21	Concentrated in the downstream
Gigantochloa atroviolacea Widjaja	0	0	10	10	Restricted to the downstream
Total clumps (individuals)	53	66	61	180	—
Species richness (S)	2	4	5	11	—

Table 2. Density, frequency, and dominance of bamboo species in three riparian zones of the upper Bengawan Solo River, Central Java, Indonesia

Species	Clumps	Density (clumps/ha)	Frequency (%)	Relative dominance	Ecological remarks
Upstream (Giriwono)					
Bambusa spinosa	35	87.5	90	High	Highly clustered; forms pure stands
Dendrocalamus asper	18	45.0	60	Medium	Scattered along moist banks
Gigantochloa apus	0	0	0	—	Absent
Gigantochloa atter	0	0	0	—	Absent
Gigantochloa atroviolacea	0	0	0	—	Absent
Total	53	132.5	150		
Midstream (Sidowarno)					
Bambusa spinosa	14	35.0	50	Low–medium	Patchy; mostly in drier terraces
Dendrocalamus asper	22	55.0	70	High	Robust culms; strongly competitive
Gigantochloa apus	24	60.0	80	High	Most abundant in midstream
Gigantochloa atter	6	15.0	30	Low	Locally cultivated
Gigantochloa atroviolacea	0	0	0	—	Absent
Total	66	165.0	230		
Downstream (Gadingan)					
Bambusa spinosa	8	20.0	40	Low	Minor component
Dendrocalamus asper	10	25.0	50	Medium	Widespread along canals
Gigantochloa apus	18	45.0	70	High	Dominant along moist levees
Gigantochloa atter	15	37.5	60	High	Very common near settlements
Gigantochloa atroviolacea	10	25.0	50	Medium	Restricted to shaded wet patches
Total	61	152.5	270		

In the upstream zone (Giriwono), overall bamboo density reached 132.5 clumps/ha, largely driven by the dominance of *B. spinosa*. This species recorded the highest density (87.5 clumps/ha) and frequency (90%), forming dense, nearly monospecific stands along steep slopes. Its high structural dominance reflects strong adaptation to dry upland riparian environments, where thorny, robust culms help stabilize eroded surfaces. *Dendrocalamus asper* showed moderate density (45 clumps/ha) and frequency (60%), occurring mainly in wetter microhabitats near shaded banks. No *Gigantochloa* species were recorded in this zone (Table 2), indicating strong environmental filtering against moisture-dependent taxa.

Structural patterns became more heterogeneous in the midstream zone (Sidowarno). Total density increased to 165 clumps/ha, the highest among the three zones. *Gigantochloa apus* and *D. asper* showed very similar structural contributions, with densities of 60 and 55 clumps/ha, respectively, and high frequencies of 80% and 70%. Their co-dominance suggests that midstream riparian strips—characterized by moderate slopes, fertile regosol soils, and semi-managed agroforestry—provide suitable conditions for both naturally regenerating and cultivated bamboo stands. *Bambusa spinosa* exhibited reduced density (35 clumps/ha) and lower dominance, reflecting its preference for drier upland terrains. *Gigantochloa atter*, though less abundant (15 clumps/ha), appeared consistently in cultivation zones near irrigated fields.

In the downstream zone (Gadingan), structural parameters reflected the highest species-level diversity and the strongest influence of human management. Total density reached 152.5 clumps/ha, slightly lower than the midstream but distributed across all five species. *Gigantochloa apus* and *G. atter* showed high density values (45 and 37.5 clumps/ha) and high frequencies (70% and 60%), demonstrating their competitive advantage in moist alluvial soils. *Gigantochloa atroviolacea*—absent in upstream and midstream zones—was structurally significant here, with moderate density (25 clumps/ha) and frequency (50%), indicating its affinity for shaded, wetter riparian microhabitats. *Bambusa spinosa*, in contrast, had minimal structural contribution downstream, consistent with its ecological preference for upland and semi-dry slopes.

Comparisons across zones reveal several clear patterns. First, structural dominance is strongly type-specific: *B. spinosa* dominates uplands; *D. asper* and *G. apus* co-dominate transitional midstream habitats; and *Gigantochloa* species diversify and dominate lowland alluvial zones. Second, total density generally increases from upstream to midstream, reflecting greater management and vegetative propagation in midstream agroforestry areas. Finally, downstream communities exhibit the most balanced structural distribution, driven by high moisture availability, fertile alluvial substrates, and intentional cultivation by local communities.

Taken together, the structural data from Table 2 demonstrate that bamboo community structure along the upper Bengawan Solo River is shaped by a combination of hydrology, topography, substrate conditions, and human influence. These factors jointly determine which species can dominate, coexist, or persist in each riparian segment.

Ecological dominance based on Importance Value Index (IVI)

The ecological dominance of bamboo species along the upper Bengawan Solo River varied substantially across the upstream, midstream, and downstream zones, as reflected by the Importance Value Index (IVI). IVI integrates Relative Density (RD), Relative Frequency (RF), and Relative Dominance (RDo), thereby providing a comprehensive measure of each species' structural and ecological contribution. The Importance Value Index presented in Table 3 clearly illustrate a strong longitudinal shift in dominance patterns along the riparian gradient.

In the upstream zone (Giriwono), *B. spinosa* exhibited the highest IVI (192.0), indicating overwhelming ecological control and forming nearly pure stands on steep riparian slopes. Its dominance is supported by consistently high RD, RF, and RDo values (each 60-66%), confirming that this species is not only the most abundant but also the most spatially and structurally influential in the upstream environment. *Dendrocalamus asper* followed with an IVI of 108.0, functioning as a secondary yet substantial co-dominant species. No *Gigantochloa* species were detected in this zone (Table 3), highlighting strong environmental filtering against taxa that prefer moist or alluvial substrates.

The midstream zone (Sidowarno) displayed a more balanced dominance structure, with *G. apus* attaining the highest IVI (107.6), followed closely by *D. asper* (97.0). These two species jointly structured the midstream bamboo community, reflecting moderately disturbed, fertile riparian strips with frequent agroforestry management. *Bambusa spinosa* held a much lower IVI (64.1), indicating a sharp decline in dominance relative to upstream conditions. *Gigantochloa atter*, while present, exhibited only a minor ecological role (IVI = 31.2), corresponding to its limited cultivation and lower structural impact (Table 3).

In the downstream zone (Gadingan), ecological dominance shifted further toward *Gigantochloa* species. *Gigantochloa apus* maintained the highest dominance (IVI = 84.9), followed by *G. atter* (71.4). Both species exhibited high RD and RDo values, consistent with their preference for moist alluvial soils and their frequent cultivation near irrigation channels. *Dendrocalamus asper* and *G. atroviolacea* shared equal IVI values (51.3), suggesting co-dominance in shaded or saturated riparian microhabitats. *Bambusa spinosa* had the lowest dominance downstream (IVI = 41.0), confirming its declining influence toward the lower river segments (Table 3).

A longitudinal comparison of Table 3 reveals three major ecological patterns. First, upstream zones are characterized by single-species dominance (*B. spinosa*), reflecting environmental filtering imposed by steep slopes, lower moisture, and minimal cultivation. Second, midstream zones display co-dominance, especially between *G. apus* and *D. asper*, reflecting a mixture of natural regeneration and human-supported cultivation. Third, downstream zones exhibit multi-species dominance, with *Gigantochloa* species becoming structurally prominent due to wetter soils, high nutrient availability, and intensive land-use modification.

These findings collectively indicate that ecological dominance in riparian bamboo communities is shaped by a combination of hydrological gradients, edaphic conditions, and human activities. The gradual replacement of *B. spinosa* by *Gigantochloa* species from upstream to down-stream reflects both species-specific habitat affinities and the increasing influence of cultivation in lowland riparian zones. This zonation underscores the dynamic interplay between natural ecological filters and anthropogenic pressures in determining bamboo community structure along the upper Bengawan Solo River.

Table 3. Importance Value Index (IVI) of bamboo species in the riparian zones of the upper Bengawan Solo River, Central Java, Indonesia.

Species	RD	RF	RDo	IVI	Dominance status
Upstream (Giriwono)					
Bambusa spinosa	66.0	60.0	66.0	192.0	Very dominant
Dendrocalamus asper	34.0	40.0	34.0	108.0	Co-dominant
Gigantochloa apus	0	0	0	0	Absent
Gigantochloa atter	0	0	0	0	Absent
Gigantochloa atroviolacea	0	0	0	0	Absent
Midstream (Sidowarno)					
Gigantochloa apus	36.4	34.8	36.4	107.6	Very dominant
Dendrocalamus asper	33.3	30.4	33.3	97.0	Co-dominant
Bambusa spinosa	21.2	21.7	21.2	64.1	Common
Gigantochloa atter	9.1	13.0	9.1	31.2	Subdominant
Gigantochloa atroviolacea	0	0	0	0	Absent
Downstream (Gadingan)					
Gigantochloa apus	29.5	25.9	29.5	84.9	Very dominant
Gigantochloa atter	24.6	22.2	24.6	71.4	Dominant
Dendrocalamus asper	16.4	18.5	16.4	51.3	Co-dominant
Gigantochloa atroviolacea	16.4	18.5	16.4	51.3	Co-dominant
Bambusa spinosa	13.1	14.8	13.1	41.0	Subdominant

Note: IVI: Importance Value Index, RD: Relative Density, RF: Relative Frequency, RDo: Relative Dominance

Bamboo diversity and evenness across the riparian gradient

Bamboo diversity along the upper Bengawan Solo River shows a pronounced longitudinal pattern driven by species richness, relative abundances, and environmental filtering. As presented in Table 4, all diversity indices—Shannon–Wiener (H′), Margalef richness (R), Simpson (1–D), and Evenness (E)—increase gradually from the upstream to downstream segments, indicating a shift from structurally simple to more compositionally balanced bamboo communities.

The upstream zone (Giriwono) exhibits the lowest diversity (H′ = 0.653; R = 0.252), reflecting its two-species community strongly dominated by *B. spinosa* (Table 4). Although evenness appears high (E = 0.942), this largely reflects the proportional balance between only two species rather than true ecological heterogeneity, consistent with strong dominance by *B. spinosa* in upstream plots, where one species contributes disproportionately to basal area. The low Simpson value (1–D = 0.449) further indicates that community structure is heavily influenced by a single dominant species. These patterns align with the environmental characteristics of the upstream segment—steeper slopes, drier soils, and broader natural riparian buffers—which collectively restrict the establishment of species that depend on higher moisture or more disturbed microhabitats.

In contrast, the midstream site (Sidowarno) presents moderate richness and diversity (R = 0.716; H′ = 1.288; 1–D = 0.740). The co-occurrence of *D. asper*, *G. apus*, and several minor taxa produces a more heterogeneous assemblage. Evenness remains relatively high (E = 0.929), suggesting that species abundances are not strongly skewed toward a single dominant species. The intermediate values recorded here reflect the transitional landscape—rice fields, mixed agroforestry, and semi-managed riparian vegetation—that facilitates coexistence between naturally occurring and cultivated bamboo species.

The downstream zone (Gadingan) has the highest species richness (S = 5) and diversity (H′ = 1.515; R = 0.973; 1–D = 0.790). Evenness is likewise high (E = 0.942), indicating that no single species overwhelmingly dominates the community. The fertile alluvial soils, shallow slopes, and intensive land use contribute to greater environmental heterogeneity, while human-directed planting enhances the establishment of *Gigantochloa* species such as *G. apus* and *G. atter*.

The simultaneous increase of H′, R, and 1–D values toward the downstream zone reflects a pronounced ecological gradient, beginning with low-diversity communities in the upstream where strong natural filtering limits species establishment, transitioning into the midstream where mixed natural–managed assemblages emerge under moderate environmental heterogeneity and human influence, and culminating in the downstream area where intensified management interventions and more favorable site conditions support highly diverse, structurally complex plant communities.

This pattern suggests that intermediate disturbance and human management can elevate bamboo diversity, whereas the upstream region retains a more specialized assemblage adapted to harsher geomorphological conditions. The combined indices from Table 4 thus highlight the complementary roles of environmental gradients and land-use intensity in shaping the riparian bamboo diversity of the upper Bengawan Solo River.

Environmental characteristics of the riparian zones

Environmental conditions varied markedly along the upstream–midstream–downstream gradient of the upper Bengawan Solo River, as summarized in Table 5. These variations shaped the structure, composition, and ecological performance of bamboo communities across the three zones. In the upstream area (Giriwono), steeper slopes (12-25%), moderately moist soils, and cooler microclimates (24-27°C air temperature) produced a physiographic setting that favored drought-tolerant species such as *B. spinosa*. Soil pH was slightly acidic (6.1-6.4), and canopy openness ranged from moderate to closed, reflecting the presence of remnant forest patches and agroforestry vegetation.

The midstream zone (Sidowarno) presented more moderate environmental conditions, with gentle slopes (5–12%), intermediate soil moisture, and a slightly wider pH range (6.3–6.7). This zone also exhibited moderate canopy openness (40–70%), which, combined with extensive agroforestry and irrigated agriculture, created structurally heterogeneous riparian habitats. The predominance of alluvial-volcanic soils and moderate disturbance favored the co-dominance of *D. asper* and *G. apus*.

Table 4. Diversity indices of bamboo communities across three riparian zones of the upper Bengawan Solo River, Central Java, Indonesia

Zone	Species richness (S)	Total clumps (N)	Margalef richness (R)	Shannon–Wiener (H′)	Simpson (1–D)	Evenness (E)
Upstream (Giriwono)	2	53	0.252	0.653	0.449	0.942
Midstream (Sidowarno)	4	66	0.716	1.288	0.740	0.929
Downstream (Gadingan)	5	61	0.973	1.515	0.790	0.942

Table 5. Environmental characteristics of the three riparian zones of the upper Bengawan Solo River, Central Java, Indonesia

Environmental variable	Zone		
	Upstream (Giriwono)	Midstream (Sidowarno)	Downstream (Gadingan)
Elevation (m asl)	135	95	85
Slope gradient (%)	12-25 (moderate–steep)	5-12 (gentle–moderate)	0-5 (flat)
Soil moisture class	Moderately moist–wet	Moderately moist	Dry–moderately moist
Soil pH (field measurement)	6.1-6.4	6.3-6.7	6.5-6.9
Soil temperature (°C)	25-27	26-28	27-29
Air temperature (°C)	24-27	25-29	27-31
Relative humidity (%)	70-82	67-78	65-75
Canopy openness	Moderate–closed (40-70%, >70%)	Moderate (40-70%)	Open–moderate (<40%, 40-70%)
Distance to river channel (m)	5-20	3-15	2-10
Dominant land use	Dryland farming, forest edges	Rice fields, agroforestry	Rice fields, settlements
Riparian buffer width (approx.)	10-30 m	5-15 m	3-10 m

Table 6. Summary of Pearson correlation trends between environmental variables and ecological indices

Environmental variable	Correlation with H′ (Diversity)	Correlation with IVI (Dominance)
Soil pH	Weak positive	Weak–moderate positive
Soil moisture	Moderate positive	Weak positive
Soil temperature	Weak negative	Weak negative
Canopy openness	Moderate positive	Very weak / non-significant
Slope gradient	Moderate positive	Weak negative
Distance to river	Weak negative	Non-significant
Air temperature	Weak–moderate negative	Weak negative

Note: IVI: Importance Value Index

In contrast, the downstream zone (Gadingan) was characterized by flat terrain (0-5%), drier soil conditions, and higher temperatures (up to 31°C). Soil pH tended toward the neutral range (6.5-6.9), and canopy openness was predominantly open to moderate, reflecting intensive agriculture and human settlement. Riparian buffer widths were narrow (3-10 m), and distances to the river were shortest (2-10 m), indicating strong hydrological influence but also substantial anthropogenic modification. These conditions supported the highest bamboo richness and structural diversity, particularly for *G. apus*, *G. atter*, and *G. atroviolacea*, which tolerate or benefit from more disturbed, sun-exposed environments. The environmental contrasts among the zones—especially slope, canopy openness, soil moisture, and pH—provided strong ecological filters that contributed to the distinct zonation patterns observed in bamboo communities along the river.

Relationships between environmental variables and bamboo diversity

The influence of environmental gradients on bamboo diversity and ecological dominance was evaluated using Pearson correlation analysis, with the main trends summarized in Table 6. Diversity (H′) showed positive correlations with soil moisture and canopy openness, indicating that bamboo communities became more diverse in areas with higher moisture availability and greater light penetration. This trend aligns with the higher species richness and evenness recorded in the downstream zone, where open canopies and moderately moist alluvial soils favored the coexistence of multiple *Gigantochloa* species.

Soil pH exhibited a weak positive correlation with H′, suggesting that slightly more neutral soils, as found downstream, may support broader species establishment. Slope gradient showed a moderate positive correlation with H′ at the overall dataset level, but this relationship is likely influenced by midstream variation, since the steepest upstream slopes still maintained low diversity due to environmental filtering. As a result, the positive slope–diversity trend weakened toward the downstream zone, where terrain becomes flatter and topographic constraints are minimal.

Negative correlations were observed for soil temperature and air temperature, implying that hotter conditions reduced overall diversity. This is consistent with the physiological limitations of some bamboo taxa in dry, exposed microhabitats, although managed planting downstream partially compensated for these thermal constraints.

In terms of ecological dominance (IVI), correlations were generally weaker than those for diversity. IVI had a weak to moderate positive correlation with soil pH, indicating that some dominant species, particularly *D. asper* and *G. apus*, performed better in neutral to slightly acidic soils. Canopy openness showed little to no correlation with IVI, suggesting that dominance patterns were influenced more by clump expansion and management than by light availability.

Distance to the river exhibited weak or non-significant correlations with both H′ and IVI, reflecting the ability of bamboo to thrive in both near-bank and slightly elevated positions, depending on species-specific adaptations. These relationships highlight that moisture, canopy structure, and pH are the key drivers of bamboo diversity, whereas dominance patterns are more strongly shaped by species traits and management practices.

Utilization potential of bamboo species

The five bamboo species recorded along the upper Bengawan Solo River exhibited diverse and culturally significant utilization patterns, as detailed in Table 7. Across all sites, bamboo uses spanned construction, handicrafts, agriculture and forestry applications, food, medicinal use, cultural activities, and landscaping. However, the degree of multifunctionality varied across species.

Dendrocalamus asper demonstrated the broadest utility (seven categories) and represents the most valuable species for local communities. Its large, thick-walled culms are essential for heavy construction, bridges, and farm structures, while its edible shoots (*rebung*) are widely consumed. The species' high IVI in the midstream and downstream zones reflects both ecological success and strong socio-economic demand. Its leaves and culm sheaths are also used in fodder and traditional medicine, integrating the species into numerous livelihood activities.

Gigantochloa atter and *G. atroviolacea* both support six categories of use but differ functionally. *Gigantochloa atter* is highly valued for furniture, utensils, and craftwork due to its flexibility and moderate culm thickness, and its edible shoots provide an additional resource. *Gigantochloa atroviolacea*, recognized by its distinctive dark culms, plays an important role in cultural expression and ornamentation. Although its shoots are edible, they are not widely consumed. Its aesthetic and symbolic functions contribute to its sustained planting in downstream settlements. *Gigantochloa apus*, widely cultivated along midstream and downstream riparian strips, is indispensable for weaving, scaffolding, and erosion-control structures due to its straight, durable culms. Its high IVI corresponds with its exceptional practical value, making it a cornerstone species in village construction and irrigation maintenance. *Bambusa spinosa*, while less economically versatile, remains ecologically and culturally significant. Its thorny culms form natural barriers used for fencing, erosion control on steep banks, and ceremonial structures in traditional events. The species' strong dominance upstream reflects its ecological suitability to harsh slopes rather than its economic flexibility.

The relationship between IVI and utilization patterns demonstrates that species with high ecological dominance tend to provide broad socio-economic benefits, but species with unique morphological or cultural attributes may receive special attention from local communities despite lower abundance. This interplay between ecological performance and human preference underscores the integrated ecological–cultural role of bamboo in riparian landscapes of Central Java.

Discussion

Environmental filtering and longitudinal zonation of bamboo communities

The longitudinal variation in bamboo species composition along the upper Bengawan Solo River reflects a strong environmental filtering process shaped by topographic gradients, hydrological regimes, and edaphic heterogeneity. Species richness increased from the upstream (S = 2) to the downstream segment (S = 5) (Table 1), a pattern consistent with theoretical and empirical studies showing that riparian vegetation becomes more diverse under lower elevation, gentler slopes, and more stable moisture regimes (Sharma and Chongtham 2015; Nath et al. 2020; Chen et al. 2022). Steep slopes (12-25%), lower soil moisture, and cooler microclimate in the upstream zone (Table 5) restricted colonization to drought-tolerant taxa, most notably *B. spinosa*, whose mechanical rigidity, thorny culms, and deep-rooting rhizomes confer strong resistance to desiccation and slope instability. These traits position *B. spinosa* as an upland ecological specialist, illustrating a classic case of environmental filtering where only taxa with specific stress-tolerant traits can persist under harsh abiotic conditions—a pattern observed in tropical riparian bamboo systems across India, Nepal, and Indonesia (Sofiah et al. 2018; Larinmuana et al. 2025).

In contrast, the midstream zone represents a transitional environment with moderate slopes (5-12%), higher soil moisture, and mixed agroforestry influence (Table 5), enabling the coexistence of *D. asper* and *G. apus*. The increase in species richness (S = 4) and a more balanced abundance distribution (Table 1) indicate weakened environmental filtering and stronger niche complementarity. *Dendrocalamus asper* tolerates periodic disturbance and varied moisture regimes, whereas *G. apus* thrives in semi-managed habitats with intermediate canopy openness. Their co-occurrence supports the intermediate disturbance model, where moderate anthropogenic and hydrological disturbance promotes coexistence of tolerant and disturbance-dependent taxa (Connell 1978; Chazdon 2014). Recent studies have shown similar mixed-dominance configurations in agro-riparian bamboo assemblages in Vietnam and Laos (Chen et al. 2022).

Downstream sites exhibited the highest species richness (S = 5) and diversity (H′ = 1.515) (Table 4), driven by the presence of *G. atter* and *G. atroviolacea*, which prefer moist alluvial soils with high nutrient content. These species benefited from shallow slopes (0–5%), near-neutral soil pH (6.5-6.9), and frequent human cultivation (Table 5). The combination of favorable edaphic conditions and anthropogenic management created a heterogeneous mosaic that supports both natural regeneration and cultivation-driven expansion. This downstream pattern aligns with broader regional studies showing that bamboo diversity peaks in lowland floodplain environments with strong hydrological stability and human-assisted propagation (Kleinhenz and Midmore 2001; Nath et al. 2020).

The zonation pattern along the Bengawan Solo River demonstrates a coupled natural–anthropogenic gradient. In the upstream, abiotic filters—steep slopes, lower moisture, and narrower niche space—determine community assembly. In the midstream, ecological tolerance and moderate disturbance shape mixed assemblages. Downstream, environmental heterogeneity and cultural management jointly promote the proliferation of species with higher moisture requirements and socio-economic value. This interaction between topographic constraints, hydrological regimes, and land-use practices reinforces the view that riparian bamboo communities in tropical landscapes form a socio-ecological continuum driven by both environmental determinism and human selection.

Spatial variation in community structure and dominance along the riparian gradient

Spatial variation in bamboo community structure along the upper Bengawan Solo River reflects the combined influence of topographic constraints, hydrological gradients, and species-specific functional strategies. Patterns of structural dominance, as indicated by density, frequency, and IVI values (Tables 2 and 3), show a clear longitudinal shift from monodominant upland stands to multi-species assemblages in downstream floodplains. In the upstream zone, *B. spinosa* exhibits overwhelming dominance (IVI = 192), forming dense monospecific stands on steep slopes with moderately moist but rapidly draining soils. Its thick-walled culms, thorny morphology, and deep rhizome system align with traits associated with upland stabilizer species in tropical riparian systems, where mechanical resistance to drought and geomorphological disturbance confers strong competitive advantage (Sharma and Chongtham 2015; Larinmuana et al. 2025). The structural simplicity of this zone, expressed through low richness (S = 2) and high frequency of a single taxon, exemplifies a community filtered predominantly by abiotic pressures.

In the midstream segment, community structure becomes more heterogeneous. *Gigantochloa apus* and *D. asper* attain comparable IVI values (107.6 and 97.0, respectively), producing a co-dominance configuration characteristic of transitional riparian habitats where environmental filtering weakens and niche overlap increases. This structural complexity is supported by moderate slopes, higher soil moisture, and semi-managed agroforestry systems that allow for both natural regeneration and human-mediated propagation. Similar mid-gradient dominance sharing among bamboo species has been documented in managed riparian corridors of Thailand, Laos, and southern China, where intermediate disturbance and greater canopy heterogeneity facilitate competitive coexistence (Chen et al. 2022). The presence of multiple structurally significant species in Sidowarno suggests that competitive hierarchies shift in response to changes in hydrological stability and land-use intensity.

The downstream zone presents the most compositionally and structurally diverse bamboo assemblage, driven by favorable alluvial soils, open canopies, and intensive human cultivation. Here, *G. apus* retains high dominance (IVI = 84.9), but its influence is balanced by substantial contributions from *G. atter* (IVI = 71.4) and *G. atroviolacea* (IVI = 51.3). These species possess traits associated with floodplain specialists, including rapid culm production, tolerance to periodic inundation, and strong vegetative propagation. The reduction in dominance of *B. spinosa* downstream (IVI = 41.0) marks a clear ecological transition from environmentally filtered upland specialists to human-supported lowland assemblages.

The gradual shift from single-species dominance upstream to multi-species co-dominance downstream illustrates a structural continuum governed by both environmental severity and socio-ecological facilitation. As hydrological regimes stabilize, soil fertility increases, and human management intensifies, dominance hierarchies weaken and structural heterogeneity rises. This pattern aligns with broader ecological theory suggesting that community structure in riparian vegetation is jointly regulated by abiotic filtering at higher elevations and competitive–facilitative dynamics in lowland, human-modified environments (Chazdon 2014; Breton et al. 2023). The structural transitions observed in the Bengawan Solo system therefore reflect the interplay of natural gradients and anthropogenic influence, producing a mosaic of bamboo communities that vary predictably in dominance, composition, and ecological function along the river corridor.

Diversity indices and their ecological significance

Patterns of alpha diversity along the upper Bengawan Solo River indicate that riparian bamboo communities are structured by a combination of environmental filtering, species functional traits, and cumulative land-use intensity. Diversity indices (H′, R, 1–D, E) in Table 4 reveal a consistent increase from upstream to downstream, reflecting a shift from environmentally constrained, low-richness assemblages toward more compositionally balanced and functionally diverse communities in lowland riparian zones. This gradient aligns with global evidence that riparian vegetation diversity correlates strongly with hydrological stability, soil moisture, and topographic moderation (Tabacchi et al. 2000; Capon et al. 2013).

The upstream zone, with only two species, displays low Shannon diversity (H′ = 0.653) and low Simpson diversity (1–D = 0.449), confirming that community structure is strongly dominated by *B. spinosa*. Although evenness is numerically high (E = 0.942), this pattern reflects proportional balance between only two species rather than genuine ecological heterogeneity. The dominance of *B. spinosa* underscores the role of environmental filtering on steep, erosion-prone upland slopes, where drought-tolerant and mechanically robust taxa outcompete moisture-dependent bamboo species. Similar patterns of low-diversity, morphologically uniform bamboo stands have been reported in upland river margins of Southeast Asia, as well as Java and Sumatra where steep terrain and shallow soils limit colonization by competitively weaker taxa (Valentin et al. 2008; Sofiah et al. 2018; Fitmawati et al. 2021).

Table 7. Documented and potential utilization categories of bamboo species in the riparian zones of the upper Bengawan Solo River, Central Java, Indonesia

Species	Potential utilization							Total categories	Notable remarks
	Construction	Handicraft	Agriculture / Forestry	Food	Medicine	Culture	Landscape		
Bambusa spinosa	✓	✓	✓	–	–	✓	✓	5	Thorny culms useful for fencing, erosion control, and ceremonial arches; forms natural protective barriers in dry zones.
Dendrocalamus asper	✓	✓	✓	✓	✓	✓	✓	7	Most multifunctional species; culms used for buildings and bridges; tender shoots (*rebung*) widely consumed; leaves used for fodder and traditional medicine.
Gigantochloa apus	✓	✓	✓	–	–	✓	✓	5	Highly valued for weaving, scaffolding, and stabilizing irrigation canal banks; commonly cultivated around settlements.
Gigantochloa atter	✓	✓	✓	✓	–	✓	✓	6	Flexible culms preferred for furniture, utensils, and craftwork; young shoots edible and occasionally marketed; often planted near agricultural areas.
Gigantochloa atroviolacea	✓	✓	–	✓	✓	✓	✓	6	Distinct dark culms favored for furniture and ornamentation; young shoots edible but not commonly consumed; valued for cultural and landscaping uses in downstream areas.

In midstream habitats, diversity metrics increase substantially (H′ = 1.288; R = 0.716; 1–D = 0.740), reflecting a transition from environmentally constrained dominance toward more equitable species contributions. The coexistence of *D. asper* and *G. apus*, supported by intermediate soil moisture and agroforestry practices, produces a structurally heterogeneous community with reduced dominance and greater niche overlap. These conditions mirror mid-gradient riparian zones elsewhere in Southeast Asia, where moderate disturbance and enhanced canopy heterogeneity promote species coexistence and functional redundancy (Chen et al. 2022). The relatively high evenness (E = 0.929) further suggests that species abundances are not strongly skewed toward a single taxon, reinforcing the role of midstream riparian corridors as biodiversity transition zones.

Downstream stands exhibit the highest richness and diversity (S = 5; H′ = 1.515; 1–D = 0.790), indicating a community that benefits from stable hydrology, fertile alluvial soils, and intensive human management. High evenness (E = 0.942) demonstrates that no species monopolizes community structure, a pattern typical of riparian bamboo assemblages cultivated for multiple socio-economic purposes. The presence of *G. atter* and *G. atroviolacea*, both floodplain-adapted species, reflects the combination of natural alluvial conditions and selective propagation by local communities. Such downstream enhancement of bamboo diversity parallels findings from the Mekong Basin and South China, where lowland riparian systems support the highest bamboo complexity due to favorable geomorphology and sustained resource management (Kamoto and Juntopas 2007; Xu et al. 2020; Breton et al. 2023; Yang et al. 2025).

Taken together, the longitudinal increase in diversity indices demonstrates a predictable ecological transition: environmentally constrained, specialist-dominated systems upstream give way to mixed natural–managed assemblages midstream, culminating in highly diverse, multifunctional communities downstream. These patterns support contemporary meta-analyses showing that riparian vegetation diversity is best explained by combined effects of hydrological reliability, soil fertility, and human facilitation (Capon et al. 2013). The Bengawan Solo case thus illustrates how bamboo communities function not merely as passive recipients of environmental gradients but as dynamic socio-ecological systems shaped by both biophysical processes and long-term human management.

Functional roles of dominant bamboo species in riparian stability and local livelihoods

The dominance patterns of *B. spinosa*, *D. asper*, and *Gigantochloa* species along the Bengawan Solo riparian gradient reveal distinct functional roles that integrate ecological processes with socio-economic practices. These species represent complementary ecological strategies—ranging from mechanical stabilization in upper catchments to multifunctional provisioning services in mid- and downstream systems. This functional differentiation aligns with broader evidence that bamboo taxa act as both ecological engineers and livelihood-supporting resources in tropical riparian landscapes (Kumar et al. 2023; Camargo-Caicedo et al. 2025).

In the upstream zone, *B. spinosa* functions primarily as a structural stabilizer. Its dense, thorny clumps and deep rhizome systems confer strong resistance to erosion and surface runoff, particularly on steep slopes. These traits are consistent with findings in Himalayan upland watersheds, where clump-forming bamboo species significantly reduce soil loss and reinforce riverbank integrity under high-gradient conditions (Panmei et al. 2025; Singh et al. 2025). Although its socio-economic value is limited compared with downstream species, *B. spinosa* provides essential regulating services that underpin hydrological stability and sediment control, indicating its role as a foundational ecological species within the upper riparian corridor.

In the midstream zone, *D. asper* occupies a dual ecological–economic niche. Ecologically, its tall culms and extensive rhizome networks enhance riverbank buffering capacity, moderate flood impacts, and generate microhabitats for understory vegetation and soil fauna. Socio-economically, *D. asper* is one of Southeast Asia's most valuable bamboo resources, widely utilized for construction, furniture, scaffolding, and edible shoots. Its high growth rate and tolerance of moderate disturbance allow communities to integrate this species into agroforestry and mixed-cropping systems without compromising ecological function. Such multifunctionality reflects broader patterns observed in managed riparian bamboo systems in Thailand, Vietnam, and Yunnan, where *D. asper* contributes substantially to both ecological resilience and rural income diversification (Chen et al. 2022).

Downstream communities dominated by *G. apus*, *G. atter*, and *G. atroviolacea* display the highest degree of functional multifunctionality. These species collectively support diverse provisioning services—ranging from craft materials and ornamental culms to edible shoots—while also maintaining ecological contributions such as soil binding, canopy stratification, and hydrological buffering. Their presence in alluvial zones parallels global observations that lowland riparian habitats support bamboo species with the most extensive socio-economic value due to fertile soils, stable hydrology, and historical cultivation. Notably, *G. atroviolacea* adds cultural and aesthetic value through its dark culms, reinforcing the role of bamboo in traditional art, architecture, and ritual practices.

The functional interactions among these species demonstrate a gradient-based socio-ecological system in which ecological performance and human use co-evolve. Upstream stabilizer species, midstream dual-function taxa, and downstream multifunctional species collectively form a riparian mosaic that supports watershed protection, resource production, and cultural heritage. This integration is consistent with emerging socio-ecological resilience frameworks emphasizing that vegetation with high functional diversity enhances long-term system adaptability and livelihood security under climate variability (Capon et al. 2013; Folke et al. 2016).

The functional roles of dominant bamboo species along the Bengawan Solo River reflect both species-specific ecological traits and culturally embedded management practices. Understanding these complementary functions is essential for designing riparian restoration and bamboo-based landscape management strategies that balance environmental stability with sustainable resource use.

Cultural and economic dimensions of bamboo utilization

Bamboo utilization along the Bengawan Solo riparian corridor reflects an integrated socio-ecological system in which species availability, cultural traditions, and rural economies are mutually reinforcing. The spatial variation in dominant taxa—*B. spinosa* upstream, *D. asper* midstream, and *Gigantochloa* spp. downstream—corresponds directly with differentiated cultural practices and livelihood strategies, demonstrating that bamboo functions not only as a biological resource but also as a cultural infrastructure. Such patterns are consistent with recent studies indicating that bamboo-rich communities in tropical Asia maintain long-term socio-ecological resilience through culturally embedded resource use (Ihsan et al. 2024; Dutta et al. 2025).

In midstream and downstream communities, bamboo plays a central economic role through multipurpose utilization. *Dendrocalamus asper* supports rural construction, scaffolding, and craft industries, while also supplying edible shoots essential to local diets and small-scale markets. The microeconomic importance of this species aligns with broader assessments of bamboo-based livelihoods across Indonesia, China, and India, where diversified bamboo enterprises substantially contribute to household income and reduce dependence on timber resources (Hogarth and Belcher 2013; Acharya et al. 2014). *Gigantochloa atter* and *G. atroviolacea* further strengthen downstream economies by providing high-quality culms for furniture, weaving, and ornamental products. Their mechanical strength and aesthetic characteristics support craft traditions that increasingly feed into eco-cultural tourism and niche markets.

Culturally, bamboo remains embedded in Javanese ritual identity, architectural symbolism, and collective environmental stewardship. Downstream species such as *G. atroviolacea* are widely used in ceremonial structures, traditional instruments, and symbolic markers of communal events. These cultural functions enhance species persistence by maintaining local demand and intergenerational knowledge transfer—mechanisms recognized in recent ethnobiological studies as critical for biocultural conservation (Ihsan et al. 2024; York 2025). The persistence of bamboo in cultural domains underscores its role as a biocultural keystone, reinforcing the social value necessary for long-term habitat maintenance.

At the same time, bamboo utilization pathways contribute to ecological sustainability by promoting renewable, fast-growing materials in rural production systems. The integration of *D. asper* and *Gigantochloa* spp. into agroforestry and mixed-riparian land uses reduces harvesting pressure on natural forests, aligning with global recommendations for nature-based livelihoods that balance productivity with biodiversity conservation (FAO 2020). However, sustainability challenges persist, particularly downstream, where increased market demand and limited management guidelines risk overharvesting of shoots and culms. These pressures mirror concerns in other parts of tropical Asia, where intensification without ecological safeguards has led to stand degradation and reduced regeneration capacity (Teejuntuk et al. 2003; Fitmawati et al. 2021).

The cultural and economic significance of bamboo in the Bengawan Solo region reflects a reciprocal relationship between species functionality and human use. Bamboo provides materials, food, ritual value, and income, while cultural norms and community management practices sustain species availability across generations. This co-dependence demonstrates that riparian bamboo ecosystems function as biocultural landscapes, in which ecological processes and social systems are tightly coupled. Strengthening this integration through community-based harvesting guidelines, livelihood diversification, and value-added bamboo industries can enhance both cultural continuity and ecological resilience in the region.

Riparian bamboo as a model for sustainable ecosystem management

The longitudinal patterns observed in this study position riparian bamboo stands as a practical model for ecosystem-based management in tropical river basins. Species such as *B. spinosa*, *D. asper*, and *Gigantochloa* spp. simultaneously stabilize riverbanks, regulate microclimate, and supply renewable biomass, aligning closely with the principles of nature-based solutions and ecosystem-based adaptation in fluvial landscapes (Chazdon 2014; FAO 2020). The strong dominance of *B. spinosa* on steep upstream slopes, combined with the structurally diverse and multifunctional *D. asper–Gigantochloa* assemblages in midstream and downstream segments, demonstrates how different bamboo taxa can be strategically aligned with segment-specific management objectives, from erosion control to livelihood support.

From a biophysical perspective, the high clump density, extensive rhizome networks, and persistent canopy cover recorded in all three zones indicate a strong capacity of bamboo to reduce surface runoff, stabilize alluvial and colluvial deposits, and buffer hydrological extremes. These traits correspond with reported reductions in soil loss and improved bank stability in bamboo-dominated riparian systems elsewhere in Asia (Sofiah et al. 2018; Nath et al. 2020). In the Bengawan Solo context, upstream stands dominated by *B. spinosa* function as protection belts that reinforce slope stability in the catchment, whereas mid- and downstream stands composed of *D. asper* and *Gigantochloa* spp. operate as hybrid protection–production systems that maintain bank integrity while supplying poles, shoots, and craft materials.

Socio-ecologically, the strong overlap between species with high ecological importance (high IVI) and high utilization value—particularly *D. asper*, *G. apus*, and *G. atter*—creates favorable conditions for community-based management. Local dependence on bamboo for construction, crafts, and food creates incentives for maintaining vegetative cover along riverbanks, effectively aligning household-level economic interests with riparian conservation goals. Such coupling of ecological function and livelihood value is a key feature of resilient social–ecological systems and underpins many successful community forestry and agroforestry schemes in tropical regions (Folke et al. 2016; FAO 2020). In this way, the Bengawan Solo riparian bamboo system illustrates how management interventions can leverage existing cultural practices rather than imposing entirely new land-use regimes.

At the same time, the results highlight several risks and constraints that must be addressed if bamboo is to be used as a model for sustainable riparian management. Downstream areas with narrow buffers, high temperatures, and intensive cultivation (Table 5) are particularly vulnerable to over-harvesting of shoots and culms, simplification of stand structure, and replacement of mixed bamboo groves by single fast-growing taxa. Such trends could reduce diversity (H′) and evenness, weaken bank protection, and increase susceptibility to pests and climate extremes, as documented in simplified bamboo plantations in other tropical regions (Pertiwi et al. 2021; Irawan et al. 2025). The moderate correlations between environmental variables, diversity, and dominance (Table 6) also indicate that bamboo-based management cannot rely solely on planting; it must integrate slope, hydrology, and microclimate constraints into spatial planning.

Taken together, the Bengawan Solo case suggests a zonation-based management framework: upstream segments prioritized as protection corridors dominated by structurally robust stabilizers such as *B. spinosa*; midstream zones managed as mixed protection–production belts where *D. asper* and *G. apus* are retained in multi-species groves; and downstream zones maintained as multifunctional production landscapes where *Gigantochloa* spp. are managed under explicit guidelines for buffer width, harvesting intensity, and species mixture. Such a framework is consistent with contemporary river-basin and green-infrastructure planning that emphasize continuous vegetated corridors, diversified species portfolios, and community participation as core elements of sustainable management (Capon et al. 2013; Chazdon 2014). In this sense, riparian bamboo stands along the upper Bengawan Solo River offer not only a locally grounded solution but also a transferable model for integrating ecological engineering, rural livelihoods, and climate-resilient river management in tropical landscapes.

Comparative insights and broader implications

The spatial patterns observed in the upper Bengawan Solo River align closely with riparian bamboo dynamics reported across tropical Asia and other warm-humid regions, indicating a degree of ecological convergence driven by hydrological gradients, soil conditions, and human land-use histories. In many Southeast Asian river systems—including those in northern Thailand, the Mekong Basin, and southern China—species richness increases toward lowland floodplains, where hydrological stability, finer-textured alluvial soils, and moderate disturbance create conditions favorable for mixed bamboo assemblages (Sharma and Chongtham 2015; Chen et al. 2022). The transition documented here—from monodominant *B. spinosa* on steep upstream slopes to species-rich *Gigantochloa* groves downstream—mirrors these regional patterns, suggesting that topographically driven environmental filtering and human-mediated cultivation operate as consistent structuring forces in tropical riparian bamboo ecosystems.

The dominance of *B. spinosa* in upper catchments, despite its low contribution to downstream diversity, highlights a common biogeographical phenomenon in bamboo systems: steep gradients exert strong abiotic filtering, limiting species capable of tolerating nutrient-poor soils, high drainage, and mechanical stress. Similar monodominant stands have been reported in the uplands of northeastern India, Thailand and Sumatra, where a few ecologically hardened taxa persist under erosive slope conditions (Teejuntuk et al. 2003; Fitmawati et al. 2021). In contrast, the diversified stands in the Bengawan Solo lowlands reflect patterns observed in managed floodplain and agro-riparian zones in Thailand and Vietnam, where *Dendrocalamus* and *Gigantochloa* species thrive under moderate disturbance and high nutrient availability.

A notable distinction of the Javanese case lies in the degree of socio-ecological integration. Unlike some regions where bamboo is primarily cultivated for commercial timber substitutes or industrial shoot production, downstream communities in Central Java maintain bamboo not only for material use but also for cultural, ritual, and household functions. This biocultural embeddedness enhances long-term conservation because species valued for identity, ceremony, and heritage tend to be retained even when market demand fluctuates (Ihsan et al. 2024). Consequently, the persistence of *G. atroviolacea* in shaded, wet downstream pockets is not solely an ecological phenomenon but is reinforced by aesthetic and cultural preference—an example of how human selection maintains species that might otherwise be outcompeted in intensively managed landscapes.

The broader implications extend beyond local riparian management. The multifunctional and socially integrated nature of bamboo positions it as a key resource in climate adaptation strategies, green infrastructure development, and ecosystem-based disaster risk reduction. Given its high growth rate, strong carbon sequestration capacity, and ability to rapidly stabilize disturbed banks, bamboo is increasingly recognized as a viable component of river restoration and climate-resilient land-use planning (Capon et al. 2013; Yen et al. 2018). The Bengawan Solo system exemplifies these potentials, showing that bamboo-based buffers can be both ecologically effective and socially acceptable—an essential combination for long-term sustainability.

Furthermore, the observed balance between natural regeneration upstream and human-supported diversification downstream illustrates a hybrid model of riparian vegetation that can be advantageous under accelerating environmental change. While purely natural forests may struggle to regenerate under rising human pressure and climate extremes, and purely cultivated systems often lack resilience, bamboo-based hybrid systems retain both ecological robustness and management flexibility. Such systems align with global frameworks promoting ecosystem-based adaptation, biocultural conservation, and nature-positive development under the Convention on Biological Diversity's Post-2020 agenda.

Comparative evidence reinforces that bamboo-rich riparian ecosystems operate as socio-ecological mosaics shaped simultaneously by physical gradients and long-standing human–environment relationships. The Bengawan Solo case contributes to global understanding by illustrating how ecological resilience and cultural continuity can be co-maintained in multifunctional landscapes—a principle increasingly central to sustainable river-basin management in the tropics.

Synthesis and conceptual framework

The ecological and socio-cultural patterns observed along the upper Bengawan Solo River form an integrated socio-ecological system in which bamboo diversity, structural dominance, and human utilization co-evolve across the riparian gradient. The upstream–midstream–downstream continuum demonstrates that bamboo ecosystems are shaped not by isolated factors but by the interplay among environmental filtering, hydrological dynamics, species functional traits, and local management practices. This synthesis highlights that the observed zonation is not merely a biophysical outcome but a reflection of dynamic reciprocal interactions between ecological processes and human decisions.

At the ecological level, the longitudinal gradient from *B. spinosa* monodominance upstream to mixed *Gigantochloa–Dendrocalamus* assemblages downstream illustrates how environmental filters—topography, soil moisture, hydrological stability, and microclimate—act as primary determinants of species distributions. Steep slopes and well-drained soils promote the persistence of structurally robust, drought-tolerant taxa, while alluvial floodplains accommodate more diverse bamboo stands due to higher nutrient availability, moderated water tables, and lower mechanical stress. These patterns match broader ecological principles in riparian ecosystems, where increasing environmental benignity downstream supports higher richness and functional redundancy (Sharma and Chongtham 2015; Chen et al. 2022). The strong upstream dominance of *B. spinosa* also exemplifies the role of foundation species whose rhizome networks stabilize geomorphologically vulnerable landscapes.

From a functional perspective, bamboo species along this gradient occupy distinct ecological and socio-economic niches. *Dendrocalamus asper* and *G. apus* exemplify multifunctional taxa capable of providing both ecological services (e.g., erosion control, microhabitat formation, flood buffering) and socio-economic benefits (construction materials, edible shoots, handicraft resources). This dual functionality increases the resilience of mid- and downstream communities, reflecting a pattern consistent with ecosystem-service diversification reported in managed bamboo systems across Southeast Asia (Dutta et al. 2025; Li et al. 2025). Conversely, species such as *B. spinosa* contribute disproportionately to ecological stability despite limited direct economic use, showing how protective specialists reinforce upstream watershed integrity even in low-diversity contexts.

Human dependence emerges as a third central dimension in shaping riparian bamboo systems. Local communities actively maintain, propagate, and harvest bamboo based on cultural values, utility needs, and traditional ecological knowledge. Species with high cultural resonance—such as *G. atroviolacea* used for ritual and artisanal purposes—persist downstream even when they are not the most ecologically dominant. This alignment between cultural preference and ecological management mirrors biocultural conservation models documented in tropical agro-riparian landscapes, where traditional practices enhance long-term species retention and landscape heterogeneity (Heartsill-Scalley and Aide 2003; Ihsan et al. 2024). Human management thus modifies natural ecological trajectories, facilitating coexistence between naturally regenerating and intentionally cultivated bamboo stands.

Integrating these three dimensions—ecological dominance, functional multifunctionality, and human dependence—results in a conceptual triangular framework (sensu Weinberger et al. 2015; Lohbeck et al. 2016) that captures the interdependencies shaping bamboo-based riparian landscapes. Ecological dominance ensures structural stability and environmental buffering; multifunctionality supports both ecological processes and livelihood needs; and human dependence provides cultural continuity and management incentives. The interaction of these dimensions produces socio-ecological feedback loops that maintain resilient and multifunctional riparian ecosystems over time.

This synthesis suggests that bamboo-rich riparian systems offer a scalable model for nature-based solutions in tropical river basins. By aligning ecological suitability with community management, such systems can enhance watershed protection, mitigate climate-related disturbances, and sustain rural economies. Future research should quantify ecosystem-service flows (e.g., carbon storage, soil stabilization rates, flood attenuation), evaluate socio-economic trade-offs among species, and explore participatory governance structures that integrate scientific ecological knowledge with traditional management practices. Strengthening these interdisciplinary linkages will help operationalize bamboo-based strategies in broader landscape restoration and climate adaptation frameworks, positioning riparian bamboo ecosystems as key assets in achieving sustainable and resilient tropical river-basin management.

In conclusion, this study shows that bamboo diversity and ecological structure along the upper Bengawan Solo River are jointly shaped by environmental gradients and human management. Species composition shifts from *B. spinosa* dominance in the steep, drier upstream zone to mixed *Dendrocalamus* and *Gigantochloa* assemblages in the more fertile and intensively managed mid- and downstream segments. These longitudinal patterns reflect the roles of slope, soil moisture, hydrological stability, and land-use intensity in filtering species and shaping community structure. Bamboo stands provide essential ecosystem functions—such as erosion control, bank stabilization, and habitat support—while multifunctional species contribute significantly to local livelihoods through construction materials, food, and cultural uses. Thus, riparian bamboo systems represent effective nature-based solutions for sustainable watershed management. Future studies incorporating multi-seasonal monitoring, molecular identification, and detailed soil–hydrological analyses will strengthen ecological interpretation and support long-term socio-ecological planning in tropical riparian landscapes.

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