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Biodiversity and stratification of dye plants in urban green spaces at Universitas Syiah Kuala, Banda Aceh, Indonesia

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Abstract. *Iqbar, Novita. 2026. Biodiversity and stratification of dye plants in urban green spaces at Universitas Syiah Kuala, Banda Aceh, Indonesia. Biodiversitas 27 (1): d270115. https://doi.org/10.13057/biodiv/d270115.* Urban green spaces are increasingly recognized for their role in conserving biodiversity and supporting cultural ecosystem services. This study presents the first systematic assessment of dye-producing plant diversity and ecological stratification within a university-based green open space, positioning the campus as a living laboratory for biocultural conservation and sustainable natural dye innovation. Floristic surveys recorded 32 dye-producing plant species from 18 families in the Green Open Space (GOS) of Universitas Syiah Kuala (USK), Indonesia, with Fabaceae and Asteraceae as the dominant families. Species richness, growth forms, pigment classes, and plant parts used for dye extraction were analyzed across canopy, understory, and groundcover strata. Statistical analyses revealed significant differences in species richness and species composition among vegetation strata (ANOVA, $p<0.05$), indicating pronounced vertical structuring of dye-producing plants. Trees dominated the canopy layer, providing long-term sources of pigments and associated ecosystem services. In contrast, understory and groundcover shrubs and herbaceous plants contributed rapidly renewable pigments suitable for small-scale extraction and educational applications. Flavonoids, tannins, and anthocyanins were the most prevalent pigment classes, generating a wide spectrum of natural colors. Compared with other urban ethnobotanical studies in Southeast Asia, dye-plant richness at USK was relatively high, reflecting spatial heterogeneity and the combined presence of native and ornamental species. Overall, this study demonstrates that urban academic landscapes can serve as living laboratories that integrate biodiversity conservation, ethnobotanical knowledge, and sustainable eco-textile education into multifunctional urban green-space management.

Keywords: Natural dyes, pigment stratification, plant diversity, Universitas Syiah Kuala, urban ecology

INTRODUCTION

Natural dyes derived from plants, animals, and minerals represent one of humanity's oldest and most enduring technologies, linking material culture, biodiversity, and craftsmanship across civilizations. Archaeological and historical evidence indicates their use as early as 2600 BCE in Egypt, India, and China, where they served not only decorative purposes but also medicinal, ritual, and symbolic functions (Ibrahim 2020; Gur-Arieh and Madella 2024). In Asia, dyeing traditions such as Indonesian batik, Japanese shibori, and Indian ikat reflect strong cultural connections between natural dyes and textile heritage, with motifs and techniques embodying social meaning and environmental knowledge (Alegbe and Uthman 2024). These traditions demonstrate how natural dyes function as repositories of cultural memory and ecological knowledge accumulated over centuries.

The introduction of synthetic dyes in the mid-nineteenth century, following William Perkin's discovery of mauveine, revolutionized global textile production. Synthetic dyes rapidly gained market dominance due to their affordability, color consistency, and ease of application (Slama et al. 2021; Alegbe and Uthman 2024). However, this industrial shift generated substantial environmental consequences. Modern textile industries rely heavily on petroleum-based dyes, which consume large volumes of water and energy and release toxic residues, including azo compounds and heavy metals, into aquatic ecosystems (Islam et al. 2025). These pollutants degrade water quality and pose serious risks to biodiversity and human health. In contrast, natural dyes are biodegradable, generally non-toxic, and often exhibit multifunctional properties such as antimicrobial, antioxidant, and UV-protective effects, aligning with contemporary demands for sustainable and environmentally responsible textile production (Dey et al. 2025).

Indonesia, one of the world's 17 megadiverse countries, has considerable potential for developing natural dyes. Ethnobotanical knowledge preserved by rural and indigenous communities includes dye-yielding species such as *Curcuma longa* L. (yellow), *Indigofera tinctoria* L. (blue), and *Cudrania javanensis* Trecul (red-orange), which have historically supported traditional textiles, including batik, ulos, and songket (Seran et al. 2024). However, this knowledge base is increasingly threatened by generational transitions, rapid urbanization, and widespread reliance on inexpensive synthetic dyes (Madsen et al. 2022; Mason et al. 2022). Existing documentation of natural dye resources in Indonesia has primarily focused on rural or forested landscapes, while comparable studies in urban ecosystems remain scarce.

Urban green spaces (UGS), including parks, gardens, and university campuses, are now widely recognized as critical components of urban biodiversity. They provide ecosystem services such as carbon sequestration, microclimate regulation, and pollinator habitat, while also offering educational and recreational benefits (Kabisch et al. 2016). Importantly, UGS can serve as platforms for applied ethnobotanical research, linking biodiversity conservation with cultural heritage and sustainability initiatives. International studies highlight urban landscapes as "living laboratories" that facilitate interdisciplinary collaboration among botany, design, and sustainability sciences (Lupp et al. 2021). Despite these insights, systematic inventories of dye-producing plants in Indonesian urban environments, particularly within university campuses, remain largely absent.

The Universitas Syiah Kuala (USK) campus in Banda Aceh, Indonesia, represents a complex urban ecological mosaic encompassing approximately 1,200 ha, including ornamental gardens, roadside corridors, and semi-natural vegetated areas (Puspa et al. 2022). Despite this environmental heterogeneity, no prior research has systematically documented the presence of dye-producing plant species in these landscapes. This lack of baseline data constrains opportunities to integrate campus biodiversity into education, eco-craft training, and cultural revitalization efforts, especially amid growing global emphasis on sustainable design and green innovation.

This study provides the first systematic inventory and ecological stratification analysis of dye-producing plants within the green open spaces of an Indonesian university campus. By integrating floristic diversity, vertical vegetation structure, and pigment-functional attributes, the research demonstrates that urban academic landscapes can serve as living laboratories for conserving biocultural diversity while supporting sustainable natural dye innovation. Addressing gaps in urban ethnobotany, the study focuses on the green open spaces of Universitas Syiah Kuala with three specific objectives: (i) to document the taxonomic diversity and family-level composition of dye-yielding plant species, (ii) to analyze their ecological stratification across canopy, understory, and groundcover layers, and (iii) to evaluate their potential contributions to biodiversity conservation, cultural heritage preservation, and sustainability-oriented innovation in urban academic environments. Through these objectives, the study highlights the strategic role of universities as active custodians of biocultural resources and as catalysts for biodiversity-based sustainable textile development in Indonesia and other tropical regions experiencing rapid urbanization.

MATERIALS AND METHODS

Study area

The study was conducted in the green open space (GOS) of USK, Banda Aceh, Indonesia (5°34′ N, 95°21′ E) (Figure 1). The 1,200-ha campus includes ornamental gardens, roadside corridors, and semi-natural vegetated plots that host diverse microhabitats supporting a wide variety of flora (Puspa et al. 2022). Field surveys used a stratified walk-through method across 15 subplots (each measuring 20 × 20 m). Plant species were recorded if they were documented as sources of natural dye or recognised locally as dye-yielding. Taxonomic and ecological traits were recorded, and unidentified species were preserved at the Herbarium Universitas Syiah Kuala (HUSK). Species richness, family representation, and environmental stratification were analysed quantitatively to characterise dye-plant diversity across different habitat types.

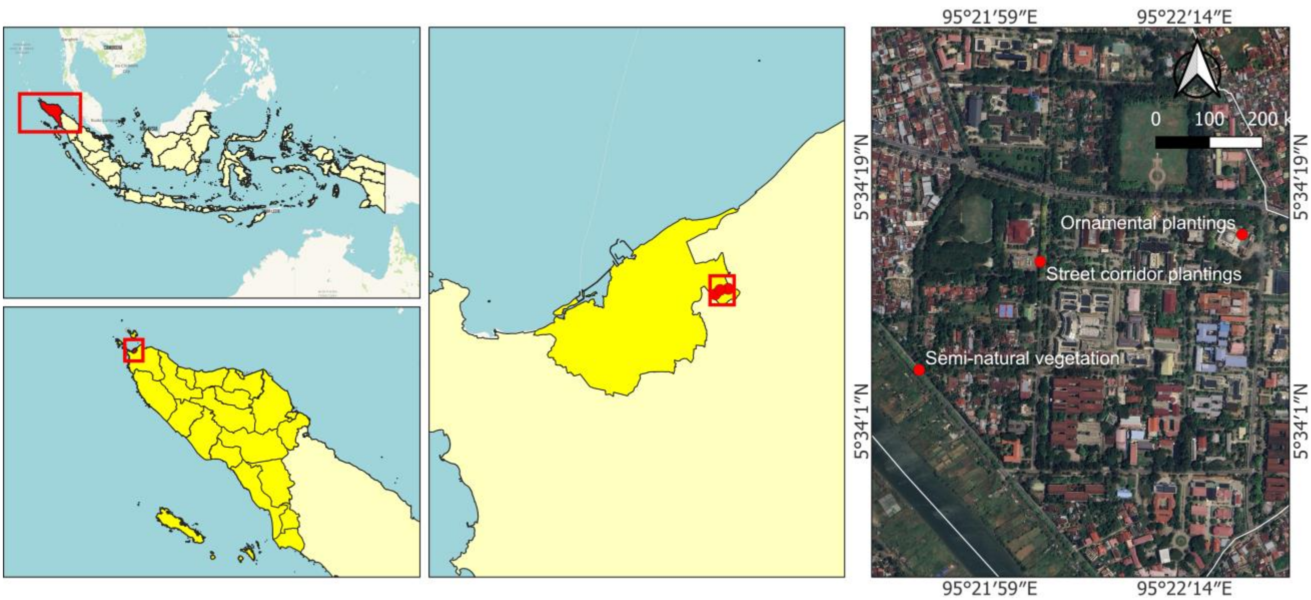

Figure 1. Map of the sampling locations within the GOS of USK, Banda Aceh, Aceh, Indonesia (5°34′ N, 95°21′ E). The map displays three vegetation categories: Ornamental plantings (5°34′15″ N, 95°22′18″ E), semi-natural vegetation (5°34′05″ N, 95°21′54″ E), and street corridor plantings (5°34′13″ N, 95°22′03″ E)

Sampling design

Field surveys were conducted from April to June 2025, coinciding with the post-monsoon growing season when most dye-producing plants' vegetative and reproductive parts were well developed, enabling accurate identification and pigment assessment. A stratified walk-through method was used to ensure comprehensive coverage of all major habitat types within the Universitas Syiah Kuala GOS, including the canopy (tree-covered areas), understory (shrubs and climbers), and groundcover (herbaceous plants). In each habitat, five 20 × 20 m subplots were randomly established, collectively representing 15 sampling units spanning shaded, semi-shaded, and open sites. This setup ensured uniform sampling intensity and comparability across vegetation layers. All vascular plants displaying visible pigmentation or recognised for dye potential were systematically recorded, ensuring the inclusion of both native and cultivated species.

Selection criteria

Three main criteria guided plant inclusion, balancing ethnobotanical relevance with scientific validation. First, species previously cited in regional or Southeast Asian references as sources of natural dye were prioritised, based on sources such as Puspa et al. (2022) and Seran et al. (2024). Second, recognition by local informants (campus gardeners, landscape maintenance personnel, and artisans linked to USK's textile design programme) was considered as empirical evidence of dye use or potential. Third, plants displaying visibly pigmented tissues (leaves, bark, flowers, fruits, or roots) were cross-verified using ethnobotanical and phytochemical databases (e.g., Dr. Duke's Phytochemical Database). For trees, only individuals with a diameter at breast height (DBH) of ≥10 cm were recorded (Ekoungoulou et al. 2017; Bhebhe et al. 2025), while all shrubs, herbs, and climbers were included regardless of size, as smaller forms often contain concentrated pigments in their reproductive organs or young shoots.

Data collection and analysis

Data recorded for each species included taxonomic identity (family, genus, species, and voucher number), growth form (tree, shrub, herb, or climber), plant parts used for dye extraction, and the dominant pigment class (anthocyanins, flavonoids, tannins, curcuminoids, indigoids, carotenoids, or anthraquinones). Voucher specimens were processed in accordance with standard herbarium procedures and deposited at the Herbarium Universitas Syiah Kuala (HUSK).

Data analysis focused on taxonomic distribution (species and family richness), ecological stratification (canopy, understory, and groundcover), and functional attributes (pigment classes and plant parts utilised). Species richness (S), family representation (%), and proportional abundance by growth form were calculated for each vegetation stratum. Differences in species and family richness, and in proportional abundance among strata, were tested using one-way analysis of variance (ANOVA) at $\alpha = 0.05$. When significant differences were detected, Tukey's HSD test was applied for post hoc comparisons. Where data did not meet parametric assumptions, Kruskal-Wallis tests were used as non-parametric alternatives. These statistical procedures provided a robust quantitative basis for comparing diversity patterns among vegetation strata and with external datasets.

RESULTS AND DISCUSSION

Floristic composition

This study documents the diversity and composition of dye-producing plants on an urban university campus, highlighting the previously underexplored ethnobotanical value of urban green spaces. The findings emphasise the previously overlooked role of urban green spaces as reservoirs of natural dye resources and as platforms for biodiversity-based education and sustainable textile innovation. The floristic survey of the Green Open Space (GOS) at Universitas Syiah Kuala (USK) recorded 32 dye-producing plant species across 18 botanical families (Table 1).

This level of taxonomic richness reflects substantial plant diversity within an urban academic landscape and highlights the capacity of campus green spaces to support multifunctional biodiversity. The family Fabaceae contributed the highest number of species (7), followed by Asteraceae (4), Arecaceae (3), and Myrtaceae (2), while the remaining families were each represented by a single species. Such a distribution indicates moderate family dominance, with legumes and composites forming the taxonomic backbone of the dye-producing flora.

The prominence of Fabaceae and Asteraceae is consistent with broader ethnobotanical and phytochemical studies across tropical regions, where these families are repeatedly reported as significant sources of natural pigments, medicinal compounds, and bioactive secondary metabolites (Borgo et al. 2024; Saensouk et al. 2025). Fabaceous taxa such as *Indigofera tinctoria* and *Clitoria ternatea* are globally recognised for their indigoid and anthocyanin pigments. At the same time, members of Asteraceae often yield flavonoid and anthocyanin-based dyes with additional medicinal value.

Analysis of growth forms revealed a strong structural bias towards woody vegetation. Trees accounted for 21 species (65.6%), followed by shrubs (6 species; 18.8%) and herbs (5 species; 15.6%). A one-way ANOVA showed significant differences in proportional abundance among growth forms ($p<0.05$), confirming the dominance of arboreal taxa within the campus vegetation structure. This pattern aligns with findings from other urban biodiversity studies, which emphasise that mature trees frequently dominate species composition in long-established green spaces due to their longevity, spatial dominance, and multifunctional roles (Kirk et al. 2021; Mejía et al. 2024).

From a functional perspective, pigment classes were dominated by flavonoids, tannins, and anthocyanins, producing a broad chromatic spectrum ranging from yellow and brown to red, purple, and blue. The primary plant parts used for pigment extraction included leaves, bark, fruits, and heartwood, reflecting substantial functional diversity within the recorded flora. Such diversity is ecologically advantageous, as it reduces pressure on any single plant organ and allows flexible, context-dependent harvesting strategies. Overall, the floristic profile reveals a biocultural mosaic, where pigment diversity and traditional heritage combine to form a living record of natural dye potential within an urban environment.

Ecological stratification

Species distribution within the USK Green Open Space showed clear vertical differentiation across canopy, understory, and groundcover strata. The canopy layer was dominated by long-lived tree species such as *Terminalia catappa*, *Mangifera indica*, and *Acacia auriculiformis*, which supplied pigments primarily from bark, heartwood, and mature leaves while providing key ecosystem services, including carbon sequestration, shade provision, and microclimate regulation-functions widely attributed to mature urban trees in tropical environments (Lenk et al. 2024).

The understory stratum comprised shrubs and small trees, notably *Morinda citrifolia* and *Jatropha curcas*, which contributed pigments from fruits, roots, and secondary tissues, with seasonally variable availability. Such intermediate strata are known to enhance functional connectivity between canopy and groundcover layers while supporting ethnobotanically valuable species with flexible harvesting regimes (Zhao et al. 2022). In contrast, the groundcover layer was dominated by herbaceous species such as *Indigofera tinctoria* and *Curcuma longa*, characterized by rapid growth and high concentrations of secondary metabolites, traits commonly associated with short-cycle pigment production and experimental dye applications (Kusumastuti et al. 2023; Saensouk et al. 2025). The variation in plant growth forms observed in this study (Figure 2) reflects adaptive strategies to local environmental conditions at Universitas Syiah Kuala's GOS.

Statistical analyses revealed significant differences in species richness among vegetation strata (one-way ANOVA, $p<0.05$). Tukey's HSD test indicated that both understory and groundcover strata differed significantly from the canopy layer, reflecting pronounced vertical heterogeneity. Where parametric assumptions were not met, Kruskal-Wallis tests confirmed similar patterns. These results align with established ecological theory that plant communities are vertically organized according to growth form, resource acquisition strategies, and functional roles rather than randomly distributed (Kirk et al. 2021). Zero ("0") values reported in phenological and pigment-availability tables represent confirmed absence of harvestable structures during the sampling period rather than missing data, ensuring accurate interpretation of seasonal pigment dynamics and avoiding analytical bias (Frisk et al. 2022).

Table 1. Dye-producing plant species recorded at the GOS of USK

Scientific name	Local name	Family	Growth form	Pigment class	Dominant color
Acacia auriculiformis A.Cunn. ex Benth.	*Akasia*	Fabaceae	T	Tannins	Dark brown
Annona muricata L.	*Sirsak*	Annonaceae	T	Flavonoids	Green-brown
Areca catechu L.	*Pinang*	Arecaceae	T	Tannins	Brown-red
Artocarpus heterophyllus Lam.	*Nangka*	Moraceae	T	Flavonoids	Yellow
Bougainvillea spectabilis Willd.	*Bunga kertas*	Nyctaginaceae	S	Anthocyanins	Magenta-purple
Chloris barbata Sw.	*Rumput goyang*	Poaceae	H	Flavonoids	Yellow
Clitoria ternatea L.	*Bunga telang*	Fabaceae	S	Anthocyanins	Blue-purple
Cocos nucifera L.	*Kelapa*	Arecaceae	T	Tannins	Brown
Curcuma longa L.	*Kunyit*	Zingiberaceae	H	Curcuminoids	Yellow
Eclipta prostrata (L.) L.	*Urang-aring*	Asteraceae	H	Anthocyanins	Black-green
Elaeis guineensis Jacq.	*Kelapa sawit*	Arecaceae	T	Carotenoids	Red-orange
Emilia sonchifolia (L.) DC. ex Wight	*Tempuh wiyang*	Asteraceae	H	Flavonoids	Yellow-orange
Hibiscus × rosa-sinensis L.	*Kembang sepatu*	Malvaceae	S	Flavonoids	Red-orange
Indigofera tinctoria L.	*Tarum (indigo)*	Fabaceae	S	Indigoids	Blue
Ixora paludosa (Blume) Kurz	*Asoka*	Rubiaceae	S	Flavonoids	Red-orange
Jatropha curcas L.	*Jarak pagar*	Euphorbiaceae	S	Anthraquinones	Red-brown
Leucaena leucocephala (Lam.) de Wit	*Petai cina*	Fabaceae	T/S	Tannins	Brown
Mangifera indica L.	*Mangga*	Anacardiaceae	T	Flavonoids	Yellow-orange
Manilkara zapota (L.) P.Royen	*Sawo manila*	Sapotaceae	T	Tannins	Brown-red
Mimosa pudica L.	*Putri malu*	Fabaceae	H	Flavonoids	Yellow-green
Morinda citrifolia L.	*Mengkudu*	Rubiaceae	T	Anthraquinones	Red
Muntingia calabura L.	*Cer/kersen*	Muntingiaceae	T	Anthocyanins	Red-purple
Pluchea indica (L.) Less.	*Beluntas*	Asteraceae	H	Tannins	Brown-green
Psidium guajava L.	*Jambu klutuk*	Myrtaceae	T	Flavonoids	Yellow-brown
Pterocarpus indicus Willd.	*Angsana/narra*	Fabaceae	T	Flavonoids	Yellow-brown
Punica granatum L.	*Delima*	Lythraceae	S	Anthocyanins, Tannins	Red-brown
Swietenia mahagoni (L.) Jacq.	*Mahoni*	Meliaceae	T	Tannins	Brown-red
Syzygium cumini (L.) Skeels	*Jamblang*	Myrtaceae	T	Anthocyanins	Purple-black
Tamarindus indica L.	*Asam jawa*	Fabaceae	T	Tannins	Brown-yellow
Tectona grandis L.f.	*Jati*	Lamiceae	T	Tannins	Brown
Terminalia catappa L.	*Ketapang*	Combretaceae	T	Tannins	Brown-black
Tridax procumbens L.	*Tridax*	Asteraceae	H	Flavonoids	Yellow-brown

Note: T: tree, S: shrub, H: herb, C: climber. Color hues indicate primary dye outcome under standard aqueous extraction

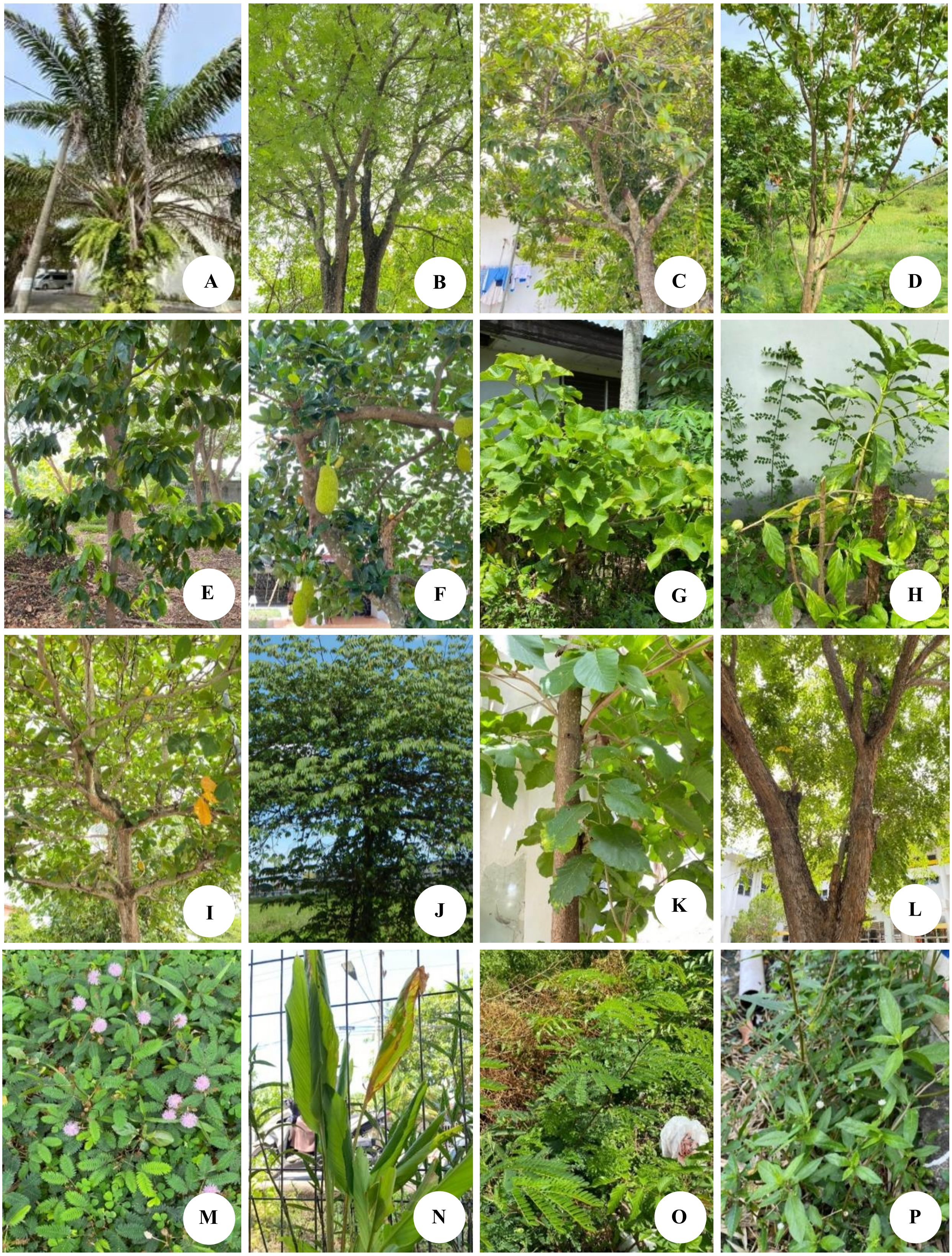

Figure 2. Representative morphological forms of dye-producing plants at Universitas Syiah Kuala's GOS. A. *Elaeis guineensis*, B. *Tamarindus indica*, C. *Manilkara zapota*, D. *Psidium guajava*, E. *Annona muricata*, F. *Artocarpus heterophyllus*, G. *Jatropha curcas*, H. *Morinda citrifolia*, I. *Terminalia catappa*, J. *Muntingia calabura*, K. *Tectona grandis*, L. *Pterocarpus indicus*, M. *Mimosa pudica*, N. *Curcuma longa*, O. *Leucaena leucocephala*, P. *Eclipta prostrata*. Images illustrate diagnostic vegetative and reproductive features relevant to pigment extraction

Comparative richness and ethnobotanical context

The dye-plant richness recorded at the Universitas Syiah Kuala (USK) Green Open Space exceeds that reported in most urban ethnobotanical inventories across Southeast Asia, which typically document fewer than 25 dye-producing species. Studies from Vietnam and Thailand commonly report lower richness, often attributed to limited sampling coverage, short survey durations, and the dominance of ornamental vegetation that favors aesthetic uniformity over functional diversity (Averyanov et al. 2022; Gepts 2023). In contrast, the higher richness observed at USK reflects a heterogeneous planting structure that integrates native, multipurpose, and culturally relevant species.

Within Indonesia, ethnobotanical studies related to batik and natural dye resources have traditionally emphasized a narrow group of economically and culturally essential taxa, particularly *I. tinctoria*, *C. longa*, and *M. citrifolia* (Kusumastuti et al. 2023). Although these species remain central to artisanal dyeing due to their reliable pigment profiles, such a focus may underestimate the diversity of potential dye resources present in managed urban landscapes. The USK inventory reveals a broader taxonomic spectrum, including underutilized species such as *T. catappa* L. and *A. catechu*, which possess documented pigment potential but are rarely incorporated into contemporary dye production.

The coexistence of widely used and overlooked dye plants within a single campus highlights the role of university green spaces as ethnobotanical reservoirs that support both cultural continuity and innovation. Urban green spaces managed for ecological and functional diversity can sustain ethnobotanical knowledge systems while expanding opportunities for education, experimentation, and creative application (Biella et al. 2025). Overall, the comparative richness observed at USK demonstrates that well-managed urban campuses can contribute significantly to the conservation and diversification of natural dye resources in rapidly urbanizing regions.

Ecological implication

The diversity of dye-producing plants recorded in the Universitas Syiah Kuala (USK) campus Green Open Space (GOS) provides ecosystem services that extend well beyond ethnobotanical value. Dominant canopy trees such as *T. catappa*, *M. indica*, and *S. mahagoni* play a critical role in microclimate regulation by reducing surface temperatures, moderating incoming solar radiation, and enhancing evapotranspiration. These functions are essential for mitigating urban heat island effects, particularly in tropical cities where thermal stress is intensified by dense built environments (Yang and La Roche 2025).

Woody-dominated vegetation strata also contribute substantially to urban resilience through carbon sequestration and long-term biomass storage. Large trees function as stable carbon sinks, offsetting a portion of urban greenhouse gas emissions while supporting nutrient cycling and soil stabilization (Ariluoma et al. 2021). Structurally complex green spaces characterized by high taxonomic and functional diversity are increasingly recognized as more resilient to environmental disturbances and climatic variability than ornamental-dominated landscapes (Mason et al. 2022). The coexistence of trees, shrubs, and herbaceous species at USK enhances functional redundancy, ensuring continuity of ecosystem processes under seasonal and environmental stress.

Vertical stratification of dye-producing plants further supports sustainable resource utilisation by distributing pigment sources across growth forms. While canopy trees provide long-term, seasonally stable pigment resources, understory and groundcover species such as *I. tinctoria* and *C. longa* supply rapidly renewable biomass suitable for frequent harvesting and experimental dye applications. Similar layered systems have been identified as effective strategies for balancing biodiversity conservation and ethnobotanical use (Flórez et al. 2024; Li et al. 2025).

Importantly, these findings emphasize the role of university campuses as living laboratories for sustainable natural dye production and cultural conservation. Academic green spaces integrate semi-natural vegetation, experimental plantings, and long-term management continuity, enabling interdisciplinary research, education, and innovation. By conserving both widely recognized and underutilized dye species, university landscapes function as reservoirs of biocultural diversity and actively contribute to the revitalization of plant-based cultural practices in rapidly urbanizing regions (Lupp et al. 2021; Gepts 2023; Biella et al. 2025).

Conservation priorities and sustainable utilisation

The predominance of leaf-based pigments among the recorded dye-producing taxa offers a significant conservation advantage, as leaf harvesting is widely recognised as a non-destructive practice that can be conducted without compromising plant survival or long-term productivity. Unlike bark, wood, or root extraction, which may irreversibly damage vascular tissues and reproductive capacity, leaf harvesting allows repeated pigment collection while maintaining physiological integrity and growth potential. This characteristic is particularly relevant in urban environments, where plant populations are spatially limited and subject to multiple ecological stressors.

Promoting leaf-focused extraction strategies should therefore be prioritized as a core principle of sustainable natural dye utilization. When combined with harvest rotation schemes, selective pruning, and seasonal timing that respects phenological cycles, leaf harvesting can significantly reduce pressure on woody tissues and reproductive organs. Such approaches not only support plant health but also enhance pigment quality by aligning extraction with periods of optimal secondary metabolite production. Recent ethnobotanical studies emphasize that sustainable harvesting protocols rooted in plant physiology and traditional knowledge are essential for maintaining pigment yield and species persistence (Breman et al. 2021).

Beyond harvesting practices, active conservation measures are necessary to safeguard culturally and ecologically essential dye plants within urban landscapes. The establishment of on-campus nurseries can facilitate the propagation of both commonly used and underutilized dye species, ensuring a continuous supply of planting material while reducing dependence on wild populations. Nursery-based propagation also provides opportunities for experimental trials, species selection, and educational engagement. Complementing this, ex situ seed banking of priority taxa is a critical long-term strategy for preserving genetic diversity, particularly for species vulnerable to landscape modification or climatic variability.

Routine population monitoring should be integrated into campus landscape management to detect changes in species abundance, health, and regeneration status over time. Monitoring data can inform adaptive management decisions, enabling timely interventions such as replanting or harvesting restrictions when population declines are observed. Such adaptive approaches are increasingly recommended within ethnobotanical conservation frameworks that aim to balance sustainable use with species persistence and ecosystem integrity (Jago et al. 2024; Dang et al. 2025).

Importantly, conservation strategies will be most effective when implemented through collaborative partnerships between university horticultural units, researchers, and local artisan communities. By integrating scientific assessment with traditional ecological knowledge, these collaborations can generate context-specific guidelines for sustainable pigment harvesting, propagation, and utilization. In this way, urban green spaces can function not only as reservoirs of biodiversity but also as dynamic platforms for conservation-oriented innovation and knowledge exchange.

Novelty and applied innovation

This study positions the USK campus GOS as an experiential learning environment for sustainable natural dye research, where biodiversity conservation, traditional knowledge, and design innovation converge within a single urban setting. By integrating floristic inventory data with applied potential, the study demonstrates how academic green spaces can support eco-textile education, experimental dye production, and cultural heritage revitalization.

The framework presented here is transferable to other Indonesian universities and urban planners seeking to embed sustainability, creativity, and biodiversity conservation into green-space management strategies. In this way, campus landscapes can evolve from passive green infrastructure into active nodes of biocultural innovation.

In conclusion, this study demonstrates that the Green Open Space (GOS) of Universitas Syiah Kuala (USK) supports a high diversity of dye-producing plants, representing the first systematically documented dye-plant assemblage within an Indonesian university campus. The dominance of Fabaceae and Asteraceae, together with the prevalence of woody growth forms, underscores the ecological importance of mature vegetation in sustaining pigment diversity and associated ecosystem services. Significant differences in species richness and composition among canopy, understory, and groundcover strata confirm that dye-producing plants are vertically structured, with each vegetation layer contributing distinct pigment sources and functional roles. This stratification enhances ecological resilience and functional complementarity by integrating long-term pigment provision from trees with rapidly renewable resources from shrubs and herbaceous species. Beyond floristic documentation, this study provides novel empirical evidence that university campuses can function as campus-based research systems in which biodiversity conservation, traditional dye knowledge, and applied innovation intersect. Integrating ecological analysis with ethnobotanical relevance demonstrates that urban green spaces can actively support sustainable natural dye development, eco-textile education, and cultural heritage revitalization. Overall, the findings offer a transferable framework for urban biodiversity planning, emphasizing that structurally diverse and culturally significant plant assemblages can simultaneously promote conservation, education, and creative industries, strengthening the role of urban campuses as active contributors to biocultural sustainability rather than passive green infrastructure elements.

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