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Forest Biomass as a Source of Natural Dyes: Extraction, Applications and Value Addition

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INTRODUCTION

Natural dyes are colour-producing substances obtained from renewable biological resources and have attracted renewed interest as alternatives to conventional synthetic colourants. Forest resources represent an important but comparatively underutilized source of natural dyes, particularly through bark, wood, leaves, cones, sawdust and other residues generated during forest management and wood processing.

The utilization of these materials provides an opportunity to convert low-value forest biomass into value-added products while reducing dependence on conventional colourants (Santos *et al*., 2022). The colour-producing potential of forest biomass is largely associated with secondary metabolites such as tannins, flavonoids, anthocyanins, quinones and other phenolic compounds.

These compounds are responsible for a broad range of colours and may also provide additional functional properties, including antibacterial activity, ultraviolet (UV) protection and antioxidant activity (Gao *et al*., 2024). Their interaction with textile fibres can be enhanced through mordanting, which influences colour intensity, shade development and fastness properties. the practical applicability of forest-derived dyes depends on several factors, including dye yield, extraction efficiency, colour reproducibility, fastness, mordant selection, *etc*. Although many studies have demonstrated successful dyeing of natural and regenerated fibres, challenges remain regarding standardization, scalability, economic competitiveness and consistent colour performance (Mahltig, 2024).

Forest Biomass as a Source of Natural Dyes

Forest ecosystems provide a diverse range of biomass that can serve as sources of natural colourants. Traditionally, dye-producing materials have been obtained from bark, heartwood, leaves, fruits and other plant parts, but increasing attention is now being given to residues and by-products generated during forestry and wood-processing operations. Sawdust, wood chips, cones, bark residues, pruning materials and processing liquors can therefore be considered potential feedstocks for natural dye production (Pizzicato *et al*., 2023). The importance of these materials lies particularly in their potential for waste valorization. Instead of depending exclusively on purpose-grown dye plants or harvesting biomass specifically for colour extraction, residues from existing forest and wood-processing activities can be utilized. This approach can reduce competition with agricultural resources and provide additional value to biomass streams that otherwise have relatively low economic value (Barreto *et al*., 2025). Different forest-derived materials contain different concentrations and combinations of colour-producing compounds. Bark, for example, is often rich in tannins and other phenolic compounds, whereas wood and heartwood may contain flavonoids, quinones and related extractives. Leaves and cones can also contain phenolic compounds and other pigments capable of producing useful shades. Consequently, the colour obtained from a particular biomass depends not only on the plant species but also on the plant part, chemical composition, extraction conditions and subsequent dyeing process (Gao *et al*., 2024).

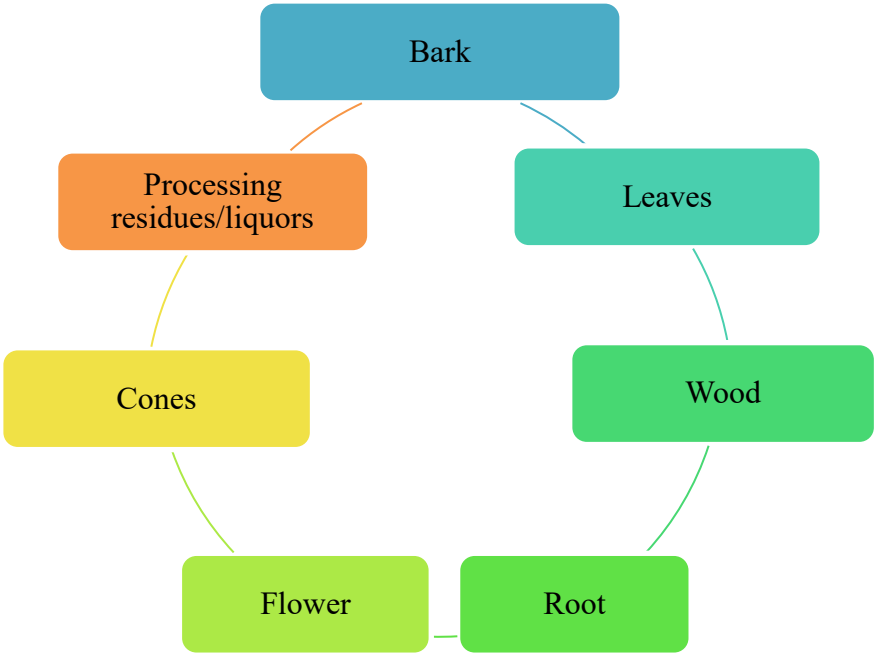

Figure 1: Sources of forest-based dyes

Chemistry Behind Forest-Derived Natural Dyes

The colour-producing ability of forest biomass is primarily associated with its extractive compounds, particularly polyphenolic secondary metabolites. Among the major groups, tannins, flavonoids, anthocyanins, quinones and phenolic compounds play important roles in determining the colour and dyeing behaviour of forest-derived materials.

Table 1: Major classes of forest-based dyes

Compound class	Representative compounds	Major forest sources	Colour potential
Condensed tannins	Catechin, epicatechin	Pine and spruce bark	Brown, beige
Hydrolysable tannins	Gallotannins, tannic acid	Oak and eucalyptus bark	Brown
Flavonoids	Quercetin, isoquercetin, naringenin	Bark and wood-derived materials	Yellow, orange, reddish shades
Anthocyanins	Anthocyanin pigments	Pigment-rich leaves and other plant materials	Red, purple and related shades
Quinones	Alizarin-related compounds	Dye-rich wood/root materials	Red, red-orange
Phenolic compounds	Phenolic acids and related compounds	Bark, wood and leaves	Yellow to reddish/brown shades

(Source: Krotova and Boev, 2022; Santos *et al*., 2022; Gao *et al*., 2024)

Extraction and Characterization of Forest-based Dyes

Extraction is a critical step in recovering colour-producing compounds from forest biomass, as the extraction method influences dye yield, chemical composition and the resulting colour characteristics. Aqueous, solvent, alkaline, enzymatic, ultrasound-assisted, microwave-assisted and pressurized extraction methods have been investigated for different forest-derived materials. Among these, ultrasound and microwave-assisted techniques offer potential for improving recovery efficiency and reducing extraction time. The selection of extraction conditions should consider the biomass type, solvent, temperature, extraction time and nature of the target compounds. Characterization of the resulting extracts is essential for understanding their chemical composition and dyeing potential. UV–Visible spectroscopy and FTIR spectroscopy are commonly used as initial characterization tools, while HPLC, LC–MS/MS, NMR, TLC, Raman spectroscopy and GC–MS can provide more detailed information on individual compounds and chemical profiles (Pizzicato et al., 2023; Gao *et al*., 2024).

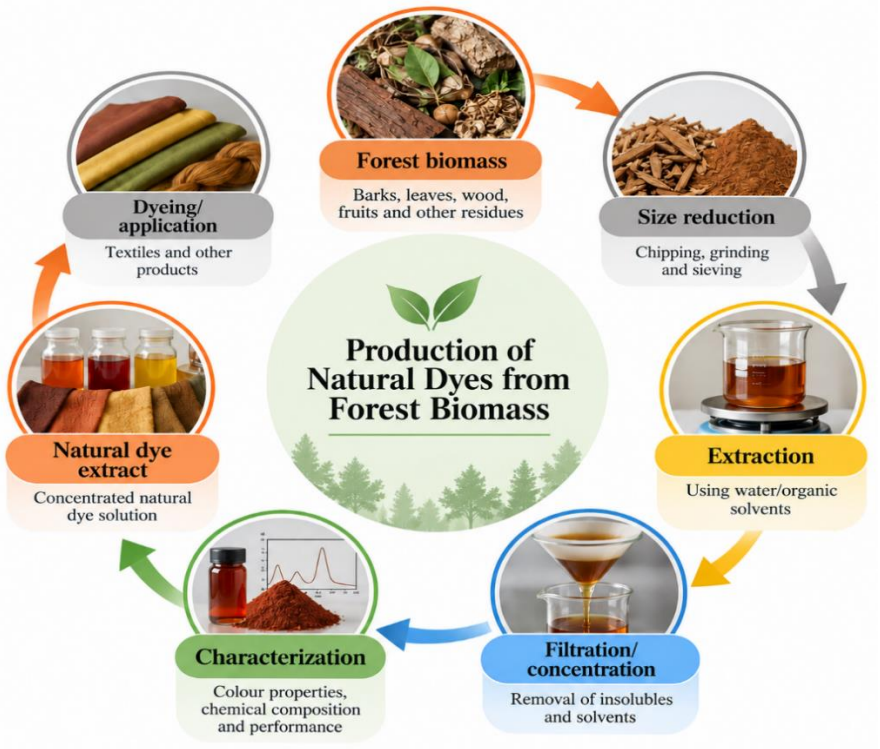

Figure 2: Conversion of forest biomass into natural dye products

Applications and Value Addition

Forest-derived natural dyes have applications extending beyond conventional textile dyeing. Colourants obtained from bark, wood residues, sawdust, cones, leaves and other forest biomass can be used for dyeing cotton, wool, silk, viscose, jute and other textile materials. In addition to colour, many polyphenol-rich extracts may impart functional properties such as UV protection, antibacterial and antioxidant activity, creating opportunities for the development of multifunctional textiles (Pizzicato *et al*., 2023). The use of forest-processing residues as dye sources is particularly significant because it allows a low-value biomass stream to be converted into a useful and potentially higher-value product. The potential of these colourants also extends to paper and packaging, wood staining and finishing, and biocosmetic applications. Wood residues have been investigated as sources of natural colourants for paper-based products, while wood-derived extracts can be used in finishing systems where colour may be accompanied by properties such as UV and mildew resistance. Forest-derived colourants may also find applications in cosmetic formulations, providing opportunities for diversification beyond the textile sector (Pizzicato *et al*., 2023). At the community level, the processing of locally available forest residues into natural dyes could support small-scale enterprises and craft-based activities, while contributing to circular utilization of forest biomass (Barreto *et al*., 2025).

Figure 3: Value added products from forest-based dyes

CONCLUSION

Forest biomass represents a promising source of natural colourants and offers an opportunity to convert low-value forest residues and wood-processing by-products into value-added products. Bark, sawdust, wood residues, cones, leaves and other biomass contain diverse colour-producing compounds, particularly tannins, flavonoids and other phenolic constituents, which can be recovered through suitable extraction approaches. Their applications extend beyond textile dyeing to

areas such as paper and packaging, wood finishing and biocosmetics, with some dyeing systems also providing additional functional properties. The utilization of forest biomass for natural dyes can therefore contribute to better resource efficiency, product diversification and circular bioeconomy approaches. Nevertheless, challenges related to extraction yield, colour reproducibility, fastness, sustainable biomass sourcing, wastewater management and large-scale economic feasibility need continued attention. Future efforts should focus on efficient and environmentally compatible extraction, safer mordanting approaches, standardized processing and greater utilization of forest-processing residues. With such improvements, forest biomass can serve as a valuable feedstock for developing sustainable natural colourants and diversified forest-product applications.

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