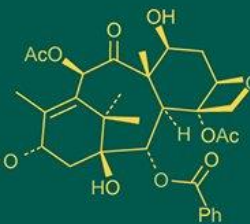
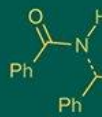


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Stink bean processing by-products as natural dyes for eco-friendly textiles: A review

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Abstract

The rising demand for sustainable textile production has enhanced the interest in natural dyes obtained from agricultural by-products. In today's time, the tremendous use of artificial dyes will lead to enormous amounts of waste and highly toxic substances, posing a great risk to our health and environment. Therefore, there is a need for research to find out a viable natural dye, like Stink beans (*Parkia speciosa*) pod peels. Recent studies have demonstrated that these by-products contain valuable pigments, including polyphenols, chlorophyll derivatives and beta lutein-like compounds that can be utilised as natural colourants for textile productions. This review examines the potential of stink bean pod peels as a sustainable dye source for eco-friendly textiles. The paper discusses the benefits of Stink bean (*Parkia speciosa*), phytochemical composition of stink bean by-products, colour fastness properties, ultraviolet (UV) protective performance, and environmental benefits.

Keywords: *Parkia speciosa*, stink bean pod, natural dyes, textile colouration, agricultural waste valorisation, sustainable textiles, eco-friendly dyeing

Introduction

In the textile industry, sustainability is the ability to reduce the environmental pollution during the whole journey of producing textile material, which includes raw material, production, transportation and waste effluent management. Due to the high usage of water, the textile industry has been known worldwide as the biggest polluter of the environment. Presently, the need for sustainability has become the most important thing in the textile industry (Rahaman *et al.*, 2024) ^[10].

Since ancient human history, colour has served as a means of symbolism, facilitating visual communication, and expressing ideas contributing to the cultural evolution of societies. Colour was used in many prehistoric environments is believed to be interconnected to the artistic and cognitive growth of individuals, and more closely related to our emotions, personal traits, seasonal cycles, passions and cultural celebrations (Soundarya *et al.*, 2021; Ardila *et al.*, 2021) ^[8, 9].

Natural dyes are chemical substances that are obtained from natural sources. Traditionally, the majority of these colour sources originated from plants. From different parts of the plants, natural dyes can be extracted, including leaves, barks, stems, flowers, peels, husks and shells. Natural dyes are known for producing soothing, unique, and rich shades and hues as compared to the synthetic dyes (Ragab *et al.*, 2022) ^[7].

Plant-based dyes that come from natural substances like plants, insects, and minerals have been in existence for many years now, and are being embraced again due to their non-toxicity and sustainability. Recent research has emphasised the valorisation of agricultural and food-processing wastes as alternative dye sources, aligning with circular economy principles and waste minimisation strategies. Agricultural residues are particularly attractive because they provide low-cost raw materials while simultaneously addressing waste-disposal challenges.

Studies have reported that extracts obtained from stink bean pods can successfully dye silk and other textile substrates, producing shades ranging from yellowish-brown to dark brown while offering acceptable colour fastness and ultraviolet protection. These findings suggest that stink bean processing waste may serve as a sustainable source of natural dyes,

contributing to both waste valorisation and environmentally friendly textile production. This review aims to synthesise current knowledge regarding the utilisation of stink bean by-products as natural dyes and assess their potential for future industrial applications.

Stink bean (*Parkia speciosa*)

Parkia speciosa is a perennial tree that can grow up to 15-40 m in height. It produces long, flat pods containing bright green seeds arranged in a row. The seeds are commonly consumed raw, roasted, fried, or incorporated into traditional dishes. The plant thrives in humid tropical climates and is often cultivated in agroforestry systems.

Parkia speciosa, or otherwise called stink bean, petai, sator, and bitter bean, is an edible plant from the tropical region that belongs to the Fabaceae family. This plant originates from Southeast Asia and grows in several countries, including Malaysia, Indonesia, Thailand, and some parts of India, particularly the northeastern region. The plant is valued for its edible seeds, distinctive aroma, nutritional properties, and medicinal potential (Verheij *et al.*, 1992)^[6].

The experiment by Fatin *et al.* (2020) involved the use of *Parkia speciosa* peel (SBP) as a material to remove the dye called procion red mx-5B (PR) using adsorption. This batch experiment was conducted to analyze the effect of different experimental conditions by varying dose, adsorption time, and initial concentration. Functional groups responsible for dye removal were analyzed by Fourier Transform Infrared Spectroscopy (FTIR). Isotherms were analyzed using Langmuir, Freundlich, and Temkin models. This important finding revealed that the stink bean peel can be considered as a biosorbent for organic pollutants, especially textile effluents.

Suchanuch Wonghirundecha (2014)^[15] conducted the study to find out the total phenolic content, antioxidant and antimicrobial activities of *Parkia speciosa* Hassk extracts. It was seen that the extraction yield, total phenolic and total flavonoid contents of Sataw-Dan pod extract were higher than the Sataw-Khao pod extract. As far as the antioxidant activity is concerned, both stink bean pod extracts exhibited strong antioxidant activity through the radical scavenging method of DPPH and ABTS and metal ion chelating method. Moreover, both extracts exhibited antimicrobial activity against the food-borne pathogenic and spoilage bacteria. So, stink bean pod extracts could be efficiently used as a natural preservative.

Parkia speciosa, which is called stink bean, grows its long fruits which are composed of bean pods with bright green seeds. Usually, seeds are extracted from the peel before being used and they are usually used in the pharmaceutical industries for their restorative effects like anticancer effect. But the peel of the fruit is considered as waste material and has usually not been given attention about being recycled or reutilized (Ghasemzadeh, *et al.*, 2018)^[14].

Begum and Ahmaruzzaman (2021)^[16] investigated the biosynthesis of zinc oxide (ZnO) nanoclusters from *Parkia speciosa* pod extract in an environment-friendly process called hydrothermal process. It is evident from the research that the biomolecules present in the plant extract function as natural reducing and capping agents, thereby avoiding the use of chemicals in the synthesis of nanoparticles. The ZnO nanoclusters prepared in this study were thoroughly analysed using various methods, which confirmed that the synthesised nanoclusters are highly pure, crystalline, and

nanosized. These nanoclusters have shown highly effective photocatalytic activity in degrading naphthol green B dye up to 99% under the irradiation of UV light in a short time span and even in repeated reuse cycles. The study's strengths include its sustainable synthesis approach, detailed material characterisation, and practical environmental application.

In their comprehensive review, Singha *et al.* (2021)^[2] examine the potential of the relatively unknown tree bean *Parkia roxburghii* in improving food security, nutrition, and sustainable development in Northeast India and other Southeast Asian nations. This article presents a complete discussion of the botanical details, geographical locations, nutritional benefits, medicinal uses, and ecological importance of the plant species. The authors emphasise the highest content of protein, carbohydrates, vitamins, minerals, and antioxidants contained in the pods and seeds, which make the plant a promising alternative food source. Furthermore, it was explained how *P. roxburghii* can be used in agroforestry, soil fertility enhancement, carbon sequestration, and revenue creation in rural areas.

A review by Chhikara *et al.* (2018)^[5] covered the bioactive components, food uses, and medicinal properties of *Parkia speciosa*. The experiment gave information regarding the nutrition content of the seed and pod, which had high amounts of protein, vitamins, minerals, fibers, and biologically active compounds such as flavonoids, phenolics, alkaloids, and terpenoids. The health effects of *Parkia speciosa* include antioxidant, antidiabetic, antihypertensive, antimicrobial, and anticancer activities. Moreover, this paper considered the role of stink bean in developing functional foods and the significance of this underutilised crop in the context of its great commercial and medicinal potential. It is useful as it encompasses the nutritional, pharmacological, and food science aspects; nevertheless, it indicates that there is a need for more clinical trials to confirm many health effects.

Foo (2013)^[17] investigated the nutritional attributes, medicinal value, and other uses of *Parkia speciosa* as an underutilised tropical plant. The author describes *Parkia speciosa* as an abundant source of proteins, essential amino acids, vitamins, minerals, and phytochemicals. He presents evidence regarding the antioxidant, antimutagenic, antimicrobial, anti-angiogenesis, hypoglycemia, and anti-inflammatory effects of stink beans obtained through experiments. He highlights the use of *Parkia speciosa* in the development of food products, pharmaceutical medicines, and environmental engineering, such as the use of stink beans as natural adsorbents.

Phytochemical Compounds of Stink bean (*Parkia speciosa*)

The Commercial processing unit and consumption generate significant amounts of waste, including Pod husks, Peels, Seed coats and Fibrous residues. These by-products can constitute more than half of the fruit biomass and are often discarded. However, they contain valuable phytochemicals such as polyphenols, tannins, chlorophyll derivatives, and natural pigments.

The study conducted by Ahmad *et al.* (2022)^[1] investigated the phytochemical composition and pharmacological significance of *Parkia speciosa* with regard to its use in diabetic vasculopathy and cardiovascular disease management. According to the paper, *Parkia speciosa* possesses a wide range of phenolic components, such as

gallic acid, catechin, quercetin, ellagic acid, and epicatechin, responsible for the antioxidant and anti-inflammatory effects of the plant. The review highlights the ability of *Parkia speciosa* to exhibit hypoglycemic, hypolipidemic, antihypertensive, and vasoprotective effects, suggesting that the plant may possess anti-oxidant and anti-inflammatory properties.

The phytochemical constituents of *Parkia speciosa* and its application potential as an herbal drug were studied by Ahmad *et al.* (2019) [4]. Flavonoids, tannins, phenolic acids, terpenoids, and alkaloids were among the biologically active components of the plant whose antioxidant, antimicrobial, anti-inflammatory, and anticancer properties were considered in the study. The research also included the description of traditional uses of *P. speciosa* in medicine and the prospects of the development of pharmaceuticals and nutraceuticals from it. Isolation of active substances and further clinical studies are needed to use it therapeutically.

Functional Properties of Stink Bean (*Parkia speciosa*) Pod Dye

Among its emerging applications, stink bean pod waste has gained attention as a sustainable natural dye source. The phenolic and tannin-rich extracts can produce yellowish-brown to dark brown shades on natural fibres such as silk and cotton. These dyes also provide additional benefits, including ultraviolet (UV) protection and antioxidant functionality, making them attractive for eco-friendly textile production.

The functional performance of natural dyes is an important consideration for their application in sustainable textile production. Stink bean (*Parkia speciosa*) pod extract has demonstrated promising functional properties, particularly in terms of ultraviolet (UV) protection and color fastness. According to Masae *et al.* (2017) [11], silk fabrics dyed with stink bean pod extract exhibited "fair to good fastness to washing and crocking" and "fair to good" water and perspiration fastness ratings. Nonetheless, light fastness was described as "very poor to poor" except those textiles treated with iron chloride, whose resistance to fading had increased. The authors further observed that "silk fabrics mordanted with iron chloride and dyed with stink bean usually showed good UV-protection levels," indicating that the dye can impart functional UV-shielding properties to textiles. This was explained on the basis that the extract from the pods had polyphenols, chlorophyll pigment, and betalains in its composition, which absorb ultraviolet radiation and reduce UV transmission through the fabric.

Sunarsono *et al.* (2026) synthesized biodegradable films from polyvinyl alcohol (PVA) with *Parkia speciosa* (stink bean) pod extract incorporation to improve their mechanical and UV protection capacity for sustainable food packaging. In this study, it was found that pod extract of *Parkia speciosa*, which contained high levels of phenols, increased UV shielding efficiency without decreasing transparency. 1 wt% of extract increased the tensile strength and toughness of PVA film significantly because of the hydrogen bond interaction between the extract and the polymer matrix, as revealed by FTIR, XRD, and FESEM analysis results. The synthesized composite films had moderate antibacterial effect on *Staphylococcus aureus* and good thermal stability, which made them suitable for active food packaging. The main strength of this study is that it is eco-friendly as an agricultural waste product was used as the natural additive

to synthesize biodegradable films with enhanced properties. However, no identification of phytochemical compounds responsible for UV blocking and antibacterial activity was done, and performance was assessed only in laboratory conditions. In summary, this study demonstrates the possibility of using *Parkia speciosa* pod extract as a green natural UV barrier for biodegradable films for food packaging.

Recent studies have further confirmed the applicability of stink bean pod dyes in sustainable textile systems. Viseshpan *et al.* (2025) [12] reported that cotton waste fabrics dyed with *P. speciosa* pod extract maintained good colourfastness performance after needle-felting treatment. The study found that colour fastness to water, laundering, perspiration, rubbing, and dry cleaning showed no significant deterioration after processing.

Dhanalaxmi (2025) [3] assessed the effectiveness of Yongchaak (*Parkia speciosa*) pod extract as a natural dye for cotton fabrics through wash and light fastness properties of the dyed fabric. The study showed that cotton fabrics that were pretreated and mordanted had superior colour fastness compared to those that were scoured and non-mordanted. Cotton fabric, which was bleached before dyeing, had excellent wash and light fastness (4-5). This study proves that appropriate fabric pre-treatment and mordanting improve the dyeing efficiency of *Parkia speciosa* pods. Thus, this plant can be used as a replacement for artificial dyes owing to its environmental friendliness. Nonetheless, this research only considers wash and light fastness properties and fails to consider other characteristics of the dye, such as rub fastness, ultraviolet protection, color strength, and phytochemical composition.

Conclusion

The increasing issues regarding the environment that are faced by artificial dyes have raised the need to find sustainable substitutes in the textile industry. Natural dyes have re-emerged as promising eco-friendly colourants due to their renewable origin, biodegradability, low toxicity, and compatibility with sustainable manufacturing practices. Especially, the use of agro-food industrial by-products for dye production is in accordance with the concept of a circular economy since they convert waste materials into useful products.

The multifunctional nature of stink bean pod dyes provides additional value beyond colouration. The presence of antioxidant-rich phenolic compounds not only contributes to UV absorption but may also enhance the protective properties of dyed textiles. Consequently, stink bean processing by-products represent a promising source of eco-friendly functional dyes capable of producing aesthetically appealing shades while simultaneously providing UV protection and acceptable fastness characteristics.

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