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| RESEARCH ARTICLE

Spectroscopic Characterization and Dye-Fibre Affinity of Plant-Based Textile Dyes on Natural Fibres

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| ABSTRACT

The increasing environmental and health hazards associated with synthetic textile dyes have necessitated intensive research into plant-based alternatives. This study presents a systematic spectroscopic characterization and dye-fibre affinity investigation of fifteen plant-derived textile dyes extracted from leaves, bark of trees, roots, fruit peels, and sheaths from plant materials sourced in Osun and Oyo States, Nigeria. Aqueous extraction was employed, and the extracted dyes were applied to cotton and silk fabrics using three mordants, alum, lemon juice, and cocoa pod ash, through pre-mordanting, simultaneous mordanting, and post-mordanting techniques. Characterization was conducted using Fourier Transform Infrared Spectroscopy (FTIR) and Ultraviolet-Visible (UV-Vis) spectroscopy to identify functional groups and chromophoric systems. FTIR analysis revealed the presence of hydroxyl groups (O-H stretching, 3267–3337 cm^{-1}), C=C stretching (1620–1680 cm^{-1}), and C-O stretching (1000–1055 cm^{-1}) across all samples, consistent with phenolic compounds, tannins, and flavonoids. UV-Vis analysis identified strong absorption bands in the 200-;400 nm range, with extended conjugation in neem bark, cashew bark, and brimstone root. Fastness evaluation showed that cotton consistently outperformed silk in wash, light, and rubbing fastness, with bark-derived dyes demonstrating the highest performance (ratings 4–5). Alum and cocoa pod ash mordants produced superior fastness compared to lemon juice. The findings demonstrate the viability of these plant-derived dyes for sustainable textile applications and contribute scientific evidence to support their adoption in studio practice and cottage textile industries.

| KEYWORDS

Sustainable Tourism, Development, Knowledge Economy, Tourism Governance, Cultural Heritage, Sustainability, Economic Development, International Student Mobility

| ARTICLE INFORMATION

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1. Introduction

The characterization of plant-based textile dyes and their affinity to natural fibres represents a critical frontier in sustainable textile science. Characterization is a fundamental scientific process used to determine the structural, chemical, and functional properties of materials, enabling understanding of their composition, performance, and potential applications. In the context of textile dyes, characterization involves identifying the chemical constituents and functional groups responsible for colour formation and their interactions with textile fibres. Analytical techniques such as Fourier Transform Infrared Spectroscopy (FTIR) and Ultraviolet-Visible (UV-Vis) spectroscopy are widely employed to investigate these properties, enabling the determination of molecular structures and chromophoric systems responsible for colour expression (Muhammadu et al., 2017; Tassew & Zenebesh, 2014). Dye-fibre affinity is another critical concept in textile colouration, referring to the tendency of dye molecules to migrate from a dye bath and adhere to a fibre under specific conditions. This interaction is influenced by several factors, including temperature, pH, dye concentration, and the chemical composition of both the dye and the fibre. A strong affinity between dye and fibre enhances dye uptake, colour uniformity, and fastness properties, which are essential for the durability and aesthetic quality of dyed textiles (Ali et al., 2009; Samanta & Agarwal, 2009).

Mordants play a crucial role in improving dye-fibre interactions. They are typically metallic salts or naturally derived substances that form coordination complexes between dye molecules and textile fibres, thereby enhancing dye fixation and colour fastness. Common mordants include alum, iron salts, and plant-based alternatives such as tannins and ash extracts. The application of mordants not only improves dye uptake but also influences the shade and intensity of the resulting colour, producing a wide range of hues from a single dye source (Shahid & Mohammad, 2013; Yadav et al., 2024). Historically, the use of dyes dates back thousands of years, with evidence of dyed textiles found in ancient civilizations such as Egypt, India, and China. Natural dyes derived from plants, minerals, and insects were the primary sources of colour before the advent of synthetic dyes in the mid-nineteenth century (Cardon, 2007; Melo, 2023). In traditional African societies, particularly among the Yoruba of southwestern Nigeria, natural dyeing practices such as indigo dyeing (Adire) have been integral to cultural expression and textile production (Areo, 2013; Polakoff, 1971).

The development of synthetic dyes in 1856 by William Henry Perkin marked a significant shift in textile colouration. Although synthetic dyes offered advantages such as a wide range of colours and ease of application, their extensive use has raised serious environmental and health concerns. Many synthetic dyes are non-biodegradable, toxic, and can cause allergic reactions, carcinogenic effects, and environmental pollution due to the presence of hazardous chemicals and heavy metals in textile effluents (Shahid & Mohammad, 2013; Singh et al., 2016). In response, there has been a renewed global interest in natural dyes as sustainable alternatives. Plant-based dyes are generally biodegradable, eco-friendly, and derived from renewable resources. Additionally, many plant-based dyes possess antimicrobial, antioxidant, and medicinal properties, making them safer for both users and the environment (Repon et al., 2023; Yadav et al., 2024). Despite these advantages, the scientific understanding of natural dyes, particularly their chemical composition, functional groups, and interaction mechanisms with textile fibres, remains limited in the Nigerian context.

This study, therefore, focuses on the spectroscopic characterization and dye-fibre affinity of textile dyes extracted from fifteen selected plant materials indigenous to southwestern Nigeria. Using FTIR and UV-Vis spectroscopy, the study identifies the functional groups present in the extracted dyes and evaluates their interactions with cotton and silk fibres, with a view to generating scientific data to support sustainable textile dyeing practice.

2. Literature Review

2.1 Natural Dyes: Definition, History and Classification

Natural dyes have been in use since ancient times for dyeing of textiles, leather, food, and objects of daily use. Krizova (2015) traced the history of dyeing from 2,600 BC to the nineteenth century, when synthetic dyes displaced natural dyes from industries. She identified plant, animal, and mineral resources as primary sources of natural dyes and noted that the renewed global environmental consciousness has driven a resurgence in natural dye research. As Bushira et al. (2018) explain, dyes obtained from natural materials such as plant leaves, roots, and bark of trees are harmonizing to the human eye, some are anti-allergens, safe for skin contact, and are mostly non-hazardous to human health, unlike synthetic dyes that are carcinogenic, cause various allergic reactions, tumor formation, and are very toxic.

Saxena and Raja (2014) observed that rapid research strides in synthetic chemistry supported by the industrialization of textile production led to the development of synthetic dyes that pushed natural dyes into near extinction. However, they noted that environmental issues associated with the production and application of synthetic dyes have revived consumer interest in natural dyes, which are eco-friendly and may also provide health benefits to the wearer. Kasiri and Safapour (2014) corroborate this by reviewing abundant publications on the extraction, modification, and processes of natural dyes and their applications on textiles, confirming a global revival of interest in natural dye technologies.

2.2 Spectroscopic Characterization of Natural Dyes

The spectroscopic characterization of natural dyes is essential for identifying their chemical composition and understanding their dyeing behaviour. Tassew and Zenebesh (2014) demonstrated that UV-Vis spectroscopic analysis is useful in understanding the UV absorbance criteria of natural dyes, and their characterization through UV-visible spectroscopic and chromatographic analysis enabled the determination of colour fastness properties. Muhammadu, Muhammadu, and Okoro (2017) conducted characterization of ripe cashew fruits using infrared and ultraviolet spectrophotoscopy and found that the results revealed the types of chromophores in the active dye compound, including anthraquinonoid, naphthoquinone, and indigo dyes.

Dhanush et al. (2020) extended spectroscopic analysis to GC-MS for dye characterization from Lantana camara, identifying n-Hexadecanoic acid and 1,2-Benzenedicarboxylic acid among prominent compounds. Oyeleke et al. (2021) similarly employed UV-visible and FTIR spectroscopy on sunflower petal extracts, highlighting factors that determine solubility and the effect of different solvents on dye reactivity. Yadav et al. (2024) emphasize that recent studies have reinforced the importance of integrating spectroscopic techniques in natural dye research to improve scientific understanding and industrial application. The importance of characterization, as these researchers collectively establish, includes the identification of functional groups, explanation of dye-fibre interaction, support of colour prediction, and the enhancement of reproducibility.

2.3 Mordants and Dye-Fibre Interactions

Mordants are fundamental to the fixation of natural dyes on textile fibres. Ali et al. (2014) demonstrated that mordant treatments can significantly influence the colour strength and fastness properties of natural dyes on cotton fabrics. Mohammed (2015) documented that metallic mordants such as ferrous sulphate produce excellent light fastness, while washing and light fastness properties were found to be from good to excellent when henna dye is applied on silk fabric. For a successful commercial use of natural dyes, Miah et al. (2017) argued that appropriate scientific techniques need to be established by scientific studies on dyeing methods, dyeing kinetics, and compatibility of selective natural dyes in order to obtain shades with acceptable colour fastness behaviour and reproducible colour yield (Samanta, Ashis & Priti, 2009).

Opoku-Asare, Korankye, and Adu (2013) examined the efficacy of dyes extracted from some local plants for colouring cotton fabrics and established that mordants control the colours of dyes and make them permanent. Geetha, Sumathy, and Judia (2013) employed pre-mordanting, post-mordanting, and simultaneous mordanting methods in their investigation and concluded that natural dyes could serve as an alternative to synthetic dyes for the dyeing of natural fibre. Krizova (2015) further highlighted that mordants improve dye exhaustion to fibres and achieve a broad spectrum of colour with long shade ranges and better fastness properties.

2.4 Gap in Existing Literature

A review of existing studies reveals that although there is substantial research on plant dye extraction and application, many studies are not specifically focused on textile dyeing in the Nigerian context, and some dye sources are not locally available. Additionally, several studies did not test dyes on fabrics to determine their fibre affinity. There is also limited research on the affinity characterization of plant-based textile dyes using combined FTIR and UV-Vis analysis, particularly from plants indigenous to southwestern Nigeria. This gap in knowledge justifies the current study.

3. Materials and Methods

3.1 Plant Materials and Sample Preparation

Fifteen plant materials were selected from plants indigenous to Osun and Oyo States, Nigeria, categorized into three groups: five leaves (Neem-Azadirachta indica; Hibiscus-Hibiscus sabdariffa; Blood leaf-Justicia carnea; Mango leaf-Mangifera indica; Henna-Lawsonia inermis), five barks (Kapok-Ceiba pentandra; Cashew-Anacardium occidentale; Mango-Mangifera indica; Neem byAzadirachta indica; Guava-Psidium guajava), and five roots/other parts (Turmeric-Curcuma longa; Brimstone root-Morinda lucida; Carrot-Daucus carota; Onion peels-Allium cepa; Sorghum sheaths-[76]Sorghum bicolor). These selections are presented in Table 1.

Table 1: Selected Plant Materials for Dye Extraction

S/N	Plant Name	Botanical Name	Plant Part	Dye Group	Yield Colour
1	Neem	*Azadirachta indica*	Leaves	Leaves	Yellow
2	Hibiscus (Zobo)	*Hibiscus sabdariffa*	Leaves	Leaves	Red/Pink
3	Blood Leaf	*Justicia carnea*	Leaves	Leaves	Yellow/Purple
4	Mango	*Mangifera indica*	Leaves	Leaves	Yellow
5	Henna	*Lawsonia inermis*	Leaves	Leaves	Golden Yellow
6	Kapok Tree	*Ceiba pentandra*	Bark	Bark	Reddish Brown
7	Cashew Tree	*Anacardium occidentale*	Bark	Bark	Brown
8	Mango Tree	*Mangifera indica*	Bark	Bark	Yellow
9	Neem Tree	*Azadirachta indica*	Bark	Bark	Orange/Purple
10	Guava Tree	*Psidium guajava*	Bark	Bark	Grey/Black
11	Turmeric	*Curcuma longa*	Root	Root/Other	Golden Yellow
12	Brimstone Root	*Morinda lucida*	Root	Root/Other	Yellow/Red
13	Carrot	*Daucus carota*	Root	Root/Other	Yellow/Orange
14	Onion Peels	*Allium cepa*	Fruit Peels	Root/Other	Orangish Yellow
15	Sorghum Sheaths	*Sorghum bicolor*	Sheaths	Root/Other	Red/Wine

Source: Author's classification compiled from fieldwork (2023)

All plant materials were thoroughly washed to remove dirt and impurities, air-dried (leaves for approximately 52 hours; bark for 7 days; roots and other parts for 48 hours to 7 days), and ground into fine powder using an electric grinder. The powdered samples were sieved and stored in airtight, labelled containers at room temperature until use. Thirty grams (30 g) of each powdered sample was measured for extraction.

3.2 Dye Extraction

An aqueous extraction process was employed to extract textile dyes from all 15 samples. This method was selected because it is cost-effective, environmentally friendly, and straightforward. As Salauddin et al. (2021) note, aqueous extraction is conventional, simple, and suitable for the extraction of plant components that can be distilled with steam without changing the molecular structure. Thirty grams of each powdered sample was placed in a 500 ml beaker filled with 500 ml of distilled water and heated in a water bath at 80°C for one hour. The resulting solutions were filtered through muslin cloth, collected in labelled plastic bottles, and stored for dyeing and characterization.

3.3 Fabric Preparation and Mordanting

Cotton and silk fabrics were purchased, thoroughly washed to remove industrial starch, and cut into 10 cm × 10 cm pieces. Three mordants were employed in this study: alum (aluminium potassium sulphate), lemon juice (citric acid), and cocoa pod ash (alkaline mordant). Three mordanting techniques were applied: pre-mordanting (fabric treated with mordant before dyeing), simultaneous mordanting (mordant and dye applied together), and post-mordanting (dye applied first, followed by mordant treatment). Each fabric piece was soaked in dye baths for 12 hours, after which it was rinsed with distilled water and air-dried at room temperature. Opoku-Asare et al. (2013) corroborate the necessity of such mordanting protocols for improving colour fastness in natural dyeing systems.

3.4 Characterization Techniques

Two analytical instruments were employed for the characterization of the extracted dyes. UV-Vis spectroscopy was conducted using a UV/Vis spectrophotometer at the Central University Research Laboratory (CURL), Bowen University, Iwo, Nigeria. The instrument measured light intensity after passage through the sample (I) in comparison to the initial intensity (I_0) across the 200–800 nm spectral range. FTIR analysis was carried out using an FTIR Spectrometer based on the Michelson Interferometer principle, which identifies chemical bonds in molecules by producing an infrared absorption spectrum. The technique was used to identify functional groups and phytocompounds present in each of the fifteen extracts.

3.5 Fastness Property Evaluation

Fastness properties were evaluated at Federal University, Akure, using a standard grey scale rating from 1 (poor) to 5 (excellent) for wash fastness, light fastness, and rubbing fastness (both dry and wet conditions) on cotton and silk fabrics dyed with each of the 15 extracts under the three mordant systems.

4. Results and Discussion

4.1 UV-Vis Spectroscopic Analysis

The UV-Vis absorption spectra of all fifteen dye extracts were recorded in the 200–800 nm range. The results reveal distinct absorption profiles corresponding to different chromophoric systems, which determine the colour and dyeing potential of each extract. Selected results of the most analytically significant samples are discussed below, with summary data presented in Table 2.

Neem leaves (Sample A) showed the most prominent peak at 227.5 nm (3.753 AU), followed by significant peaks at 229.5 nm (3.115 AU) and 299 nm (3.394 AU). These intense absorptions are characteristic of $\pi \rightarrow \pi^*$ and $n \rightarrow \pi^*$ electronic transitions, commonly associated with conjugated double bonds and aromatic systems. Moderate absorbance values were also observed at 328 nm (1.658 AU) and 385 nm (1.148 AU), suggesting the presence of extended conjugation or substituted aromatic groups. The declining absorbance beyond 400 nm indicates limited visible-range pigmentation, consistent with the faintly yellow colour observed.

Hibiscus (Sample B) showed its maximum absorption at 308 nm (3.777 AU), with additional strong peaks at 324 nm (3.519 AU) and 297.5 nm (3.187 AU). These absorptions are characteristic of aromatic rings and extended conjugated systems, while moderate absorptions extending into the 338–373 nm range suggest the presence of flavonoids and related phytochemicals. The pH-sensitive behaviour of hibiscus, producing acidic-condition red shades and alkaline-condition blue-purple shades, is consistent with anthocyanin chromophoric structures, as reported by Bechtold and Mussak (2009).

Neem bark (Sample I) presented the most intense absorption of all samples, with a major band at 293 nm (4.000 AU). The shoulders observed between 362–375 nm and weaker peaks extending to 518 nm suggest that the sample has partial light absorption in the visible range, imparting noticeable coloration and pointing to the presence of polyene chains or highly conjugated aromatic systems. Brimstone root (Sample L) exhibited a highly conjugated chromophoric system with a broad and intense band between 305–361 nm (3.71–3.894 AU), with extension into the visible region at 421–472 nm and faintly at 644–798 nm, indicating the capacity to impart noticeable color in the yellow-brown range. Cashew bark (Sample G) showed a pronounced band at 344 nm (3.706 AU), suggesting extended conjugation with chromophores substituted with auxochromes such as -OH, $-OCH_3$, or $-NH_2$, which shift absorption into longer wavelengths.

Table 2: Summary of UV-Vis Spectroscopic Characteristics of Selected Dye Extracts

S/N	Sample	Major λmax (nm)	Max Absorbance (AU)	Inferred Chromophores
1.	Neem Leaves	227.5, 299	3.753	Polyphenols, flavonoids
2.	Hibiscus	308, 324	3.777	Anthocyanins, flavonoids
3.	Blood Leaf	300.5, 334, 312	3.865	Polyphenols, alkaloids
4.	Mango Leaves	240.5, 292	3.709	Tannins, polyphenols
5.	Henna Leaves	203, 228, 241	2.611	Lawsone, polyphenols
6.	Cashew Bark	247, 344	3.883	Tannins with auxochromes
7.	Neem Bark	293, 316	4.000	Highly conjugated aromatic systems
8.	Guava Bark	307, 352	2.440	Moderate conjugation, tannins
9.	Brimstone Root	305–342, 361	3.894	Highly conjugated, visible range
10.	Onion Peels	271.5, 371	2.299	Quercetin, flavonoids
11.	Sorghum Sheaths	200, 292, 326	2.975	3-deoxyanthocyanidins

Source: Author's spectroscopic analysis at CURL, Bowen University (2024)

4.2 FTIR Spectroscopic Analysis

FTIR analysis of all fifteen dye extracts revealed distinct functional group profiles that explain their dyeing potential and chemical composition. Table 3 presents a summary of the most significant functional groups identified across the fifteen samples.

A broad absorption band in the 3267–3337 cm^{-1} region was consistently observed across nearly all samples (A, C, E, G, H, J, K, L, N), corresponding to O-H stretching vibrations indicative of hydroxyl groups in phenolics, tannins, and flavonoids. These polyphenolic compounds are well-known chromophores responsible for yellow-to-brown colouration in natural dyes and also function as mordanting agents on cellulose fibres (Samanta & Agarwal, 2009). The recurrence of the C=C stretching band in the 1620–1680 cm^{-1} region across 12 of the 15 samples confirms the presence of alkenyl and aromatic systems, which are essential chromophoric features in natural dye chemistry. The C-O stretching band at 1000–1055 cm^{-1} was identified in samples A, C, D, E, G, K, J, reflecting glycosidic linkages, alcohols, and polysaccharide-associated structures that may enhance dye solubility and bioavailability.

Neem bark (Sample I) was characterized by distinctive imine (C=N) stretching at 1638.2 cm^{-1} and aromatic C=C-C at 1459.3 cm^{-1}, consistent with alkaloid and nitrogenous phytochemical content. Mango bark (Sample H) showed an unusual diversity of functional groups including –OCN stretching (cyanate/thiol at 2016.5 cm^{-1}), C=C acetylenic stretching (1627.0 cm^{-1}), Si-O-Si stretching (1075.3 cm^{-1}), and P-O-C stretching (1000.8 cm^{-1}), suggesting a rich and chemically diverse composition. Brimstone root (Sample L) yielded unique absorption bands at 2105.9 and 2037.0 cm^{-1} assigned to –NCS stretching characteristic of isothiocyanates, and a C-S stretching band at 669.1 cm^{-1} confirming disulfide compounds—a composition consistent with the plant's reported use as a dye yielding a yellow-to-red colorant (Burkill, 1985; Adetuyi et al., 2005).

Table 3: Summary of FTIR Functional Groups in Selected Dye Extracts

S/N	Sample	Key Frequency (cm^{-1})	Functional Group	Phytocompounds Identified
1.	Neem Leaves	3267, 1636, 1459, 1013, 663	O-H, C=O, CH_2, C-O, C-H	Phenolics, tannins, aliphatics, aromatics
2.	Hibiscus	3302, 2197, 1638	O-H, C≡C, C=C	Hydroxyl, alkyne, alkenyl compounds
3.	Blood Leaf	3337, 1638, 1008, 669	O-H, C=C, CH_3, C=C (alkyne)	Hydroxyl, alkenyl, methylene, alkyne
4.	Mango Leaves	3334, 2918, 2849, 1638, 669	N-H, C-H, C=C, C-H bend	Imino, methylene, alkenyl, aromatic
5.	Henna Leaves	3337, 1638, 1321, 1032	O-H, C=C, O-H/C-N, C-N	Hydroxyl, alkenyl, primary amine
6.	Cashew Bark	3337, 1625, 1315, 1030, 657	O-H, C=C, C=N, CH, C-H	Phenolics, alkenyl, amine, methylene, alkyne
7.	Mango Bark	3268, 2927, 2016, 1627, 1509	O-H, C-H, -OCN, C=C, aromatic	Hydroxyl, methylene, cyanate, acetylenic, aromatic
8.	Neem Bark	3337, 1638, 1422, 1459, 1023	O-H, C=N, CO_3^{2-}, C=C, C-C	Amide, imine, inorganic, aromatic, organohalogen
9.	Guava Bark	3304, 2098, 1638, 1034	O-H, -NCS, C=C, CH	Hydroxyl, isothiocyanate, alkenyl, methylene
1	Turmeric	3324, 1636, 1013	O-H, C=C, C-O	Phenols, flavonoids, glycosides, carbohydrates
1	Brimstone Root	3322, 2105, 2037, 1838, 669	O-H, -NCS, C-H, C-S	Polyphenols, isothiocyanates, anhydrides, disulfides
1	Sorghum Sheaths	3333, 2086, 1636, 728	N-H, -NCS, C=C, C-H	Imino/amine, isothiocyanate, alkenyl, methylene

Source: Author's FTIR analysis at CURL, Bowen University (2024)

4.3 Fastness Properties and Dye-Fibre Affinity

The evaluation of fastness properties of the fifteen dye extracts on cotton and silk fabrics under three mordant systems provides direct evidence of dye-fibre affinity. Table 4 presents a summary of the fastness ratings obtained.

The results clearly show that cotton fabrics consistently exhibited higher fastness ratings than silk for all dye extracts and mordant systems studied. This is because cotton's cellulose structure, rich in hydroxyl groups, allows for stronger hydrogen bonding and interaction with dye molecules, unlike silk, which is a protein fibre with more complex and less reactive functional groups (Broadbent, 2001; Samanta & Agarwal, 2009). Cotton's affinity for natural dyes, particularly those containing polyphenolic and tannin-based compounds, is well established in the literature (Shahid & Mohammad, 2013).

Alum and cocoa pod ash mordants consistently produced superior fastness properties compared to lemon juice, confirming the efficacy of metallic and alkaline mordants in enhancing dye fixation. This finding is consistent with Miah et al. (2017), who reported good colour fastness properties with alum as a pre-mordant on silk fabric. Dyes extracted from bark of trees (neem, mango, guava, cashew, kapok) showed the highest overall performance (ratings predominantly 4–5 on cotton), attributed to their high tannin content which facilitates stronger dye-fibre binding. In contrast, carotenoid-based dyes (carrot) and anthocyanin-based dyes (hibiscus) exhibited lower light fastness due to photodegradation of their chromophoric systems, as also documented by Shahid et al. (2013).

Table 4: Summary Fastness Properties of Selected Dye Extracts on Cotton and Silk (Alum Mordant)

Dye Source	Wash Cotton	Wash Silk	Light Cotton	Light Silk	Dry Rub Cotton	Dry Rub Silk	Wet Rub Cotton	Wet Rub Silk
Neem Leaves	4	3	3	2–3	4	3	3	2
Neem Bark	5	4	4	3	5	4	4	3
Mango Leaves	4	3	3	2–3	4	3	3	2
Mango Bark	5	4	4–5	3–4	5	4	4	3
Hibiscus	4	3	3	2–3	4	3	3	2
Henna Leaves	5	4	4	3	5	4	4	3
Kapok Bark	5	4	4	3	5	4	4	3
Cashew Bark	5	4	4	3	5	4	4	3
Guava Bark	5	4	4	3	5	4	4	3
Turmeric	4	3	2–3	2	4	3	3	2
Brimstone Root	4	3	3	2–3	4	3	3	2
Carrot	3–4	2–3	2	1–2	3	2	2	1–2
Onion Peels	4–5	4	3–4	3	4	4	3	3
Sorghum Sheaths	5	4	4	3	5	4	4	3

Rating Scale: 1 = Poor | 2 = Fair | 3 = Good | 4 = Very Good | 5 = Excellent. Source: Author's fastness evaluation at Federal University, Akure (2024/2025)

4.4 Colour Development and Mordant Influence

The visual assessment of colour shades obtained from the fifteen plant sources under varying mordanting conditions demonstrated that both mordant type and mordanting technique significantly influence the aesthetic outcome on cotton and silk fabrics (Table 5). Pre-mordanting generally produced the most consistent and vibrant shades, as the mordant binds to fabric fibres before dye application, creating a reactive surface for dye uptake. This is consistent with observations by Geetha, Sumathy, and Judia (2013) who reported that pre-mordanting yields better colour uniformity.

Alum mordant enhanced brightness and stability across most dye sources, particularly for yellow and golden shades obtained from neem leaves, mango leaves, and turmeric. Cocoa pod ash, being alkaline, generally shifted shades toward brownish, olive, or muted tones, for example, blood leaves produced light blue to bluish-brown, and sorghum sheaths shifted to yellow-brown to burgundy. This pH-induced colour modification aligns with the known behaviour of pH-sensitive anthocyanin and flavonoid chromophores (Bechtold & Mussak, 2009). Lemon juice, as an acidic mordant, tended to brighten and soften hues, particularly enhancing red pigments in hibiscus and yellow tones in brimstone root extract.

Silk consistently exhibited paler or lighter shades compared to cotton across most dye systems, confirming its lower dye affinity for polyphenolic natural dyes. The exception was observed with protein-reactive dyes such as hibiscus (alum pre-mordanting), where silk's protein fibres interacted more effectively with the metallic mordant, yielding brighter pink-red hues. Bark-derived dyes demonstrated consistently deeper and more uniform colouration on cotton, attributed to the high tannin content of bark extracts, which has a high affinity for cellulose fibres through hydrogen bonding and van der Waals forces (Shahid & Mohammad, 2013).

Table 5: Selected Colour Shades Obtained from Plant Dyes under Different Mordanting Conditions

Plant Source	Mordant	Technique	Cotton Shade	Silk Shade	Key Observation
Hibiscus	Lemon	Pre	Bright Pink/Red	Bright Pink/Red	Acid enhances anthocyanins
Hibiscus	Cocoa Ash	Post	Light Green	Dark Green	Alkaline shift in pH-sensitive pigments
Sorghum Sheaths	Alum	Post	Red Pink	Pale Red Pink	Stable 3-deoxyanthocyanidins
Blood Leaves	Cocoa Ash	Pre	Light Blue	Bluish Brown	Alkaline shift from pinkish-red
Guava Bark	Alum	Pre	Light Brown	Deep Brown	High tannin content
Onion Peels	Alum	Pre	Deep Golden Orange	Yellowish Green	Quercetin complexation with Al
Turmeric	Cocoa Ash	Pre	Yellow-Orange	Deep Yellow	Curcumin stable in mild alkali

Source: Author's visual assessment and classification (2024/2025)

5. General Discussion

The results of this study demonstrate the viability of selected Nigerian plant materials as sources of textile dyes with measurable spectroscopic profiles and quantifiable fibre affinity. The FTIR data collectively confirm that the chromophoric systems responsible for colouration in these plant extracts belong predominantly to three chemical classes: polyphenolic compounds (tannins, flavonoids), alkaloid-related structures, and isothiocyanate-bearing compounds. The consistent presence of O-H stretching vibrations (3200–3400 cm^{-1}) across all bark samples is particularly significant, as tannin-rich dyes are well-documented for their strong affinity to cellulose fibres, forming stable hydrogen bonds with hydroxyl groups in cotton (Samanta & Agarwal, 2009; Broadbent, 2001). This explains the superior fastness ratings (4–5) consistently observed for bark-derived dyes on cotton fabrics.

The UV-Vis spectroscopic profiles further corroborate these findings. The broad, intense absorption of neem bark at 293 nm (4.000 AU), the highest absorbance recorded in the study, combined with its extension into the visible region at 362–518 nm, explains its capacity to impart visible colouration and its strong fastness properties. Brimstone root, with its highly conjugated chromophoric system extending to 798 nm, represents the broadest spectral profile in the study and suggests the presence of highly conjugated polyene-like structures consistent with the anthraquinone-related pigments reported by Muhammadu et al. (2017) in similar plant species.

The differential affinity observed between cotton and silk is attributable to fundamental structural differences between the two fibres. Cotton, a cellulose-based fibre with abundant free hydroxyl groups, provides numerous sites for hydrogen bonding with polyphenolic and tannin-containing dyes. Silk, as a protein fibre composed of amino acids with both positive and negative charge groups, interacts differently with natural dye molecules, generally requiring metal mordants to form coordination complexes that bridge the dye and fibre (Gulrajani, 2001). The observation that silk produced brighter results with some dyes under alum pre-mordanting (e.g., hibiscus, henna) is consistent with this mechanism, alum chelates with dye molecules to form coloured complexes that bond effectively to silk's amino acid groups (Miah et al., 2017).

The influence of mordant type on colour development and affinity is a key finding of this study. Alum, as a metallic mordant, forms stable coordination complexes with polyphenolic dye molecules, enhancing both colour depth and fastness. Cocoa pod ash, as an alkaline mordant, shifts the pH of the dye bath and thus the ionisation state of pH-sensitive chromophores such as anthocyanins (hibiscus) and betacyanins (blood leaves), leading to colour modifications from red to green or blue. This is consistent with the documented pH-dependent behaviour of anthocyanin pigments (Bechtold & Mussak, 2009; Cisse et al., 2012). The lower performance of lemon juice as a mordant, particularly for light fastness, may be attributed to its high acidity disrupting the stability of certain chromophoric complexes on the fibre surface.

The findings of this study support the position that plant-based dyes, when combined with appropriate mordanting protocols, can achieve fastness ratings suitable for practical textile applications, especially on cotton. The bark-derived dyes in particular demonstrated consistently excellent fastness properties that rival or match those reported for synthetic mordant dyes in cottage industry contexts (Krizova, 2015; Yadav et al., 2024). These results have important implications for the promotion of eco-friendly, locally sourced textile dyes in the Nigerian cottage industry and for the revival of indigenous dyeing practices that are at risk of obsolescence (Areo, 2013).

6. Conclusion

This study has presented a systematic spectroscopic characterization and dye-fibre affinity evaluation of fifteen plant-derived textile dyes sourced from southwestern Nigeria. Through FTIR analysis, the predominant functional groups across all samples were identified as hydroxyl groups (O-H stretching), C=C alkenyl systems, and C-O stretching vibrations, consistent with polyphenolic, flavonoid, and alkaloid-type chromophoric compounds. UV-Vis spectroscopy confirmed strong absorption profiles predominantly in the 200–400 nm range, with neem bark, cashew bark, brimstone root, and blood leaf displaying the most extended conjugation and highest absorbance values, thereby demonstrating their superior dye potential.

Cotton fabrics consistently showed higher fastness ratings than silk across all dye sources and mordant systems. Bark-derived dyes demonstrated the highest fastness performance due to their high tannin content and strong affinity for cellulose fibres. Alum and cocoa pod ash mordants produced superior colour stability compared to lemon juice, with pre-mordanting emerging as the most effective application technique for colour uniformity and depth.

The findings provide scientific evidence supporting the commercial and practical viability of these Nigerian plant-based dyes for sustainable textile applications. The study contributes to the body of knowledge on natural dye characterization and encourages the integration of indigenous plant resources into modern textile science and the cottage industry. Future work should explore advanced chromatographic characterization (HPLC, GC-MS) and investigate the mechanisms of dye-fibre bonding at the molecular level using computational chemistry tools, as well as the scalability of these dye systems for commercial textile production.

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