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Research Article

EXTRACTION AND OPTIMIZATION OF DYEING CONDITIONS OF DYE OBTAINED FROM PURPLE SWEET POTATO ON COTTON FABRICS

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ABSTRACT

Objective: This study aimed to isolate anthocyanidins from purple sweet potato (*Ipomoea batatas*) and to determine the optimum dyeing conditions for achieving maximum color yield and fabric affinity when dyeing cotton fabrics, as a sustainable alternative to synthetic dyes.

Methods: Anthocyanidins were extracted from purple sweet potato using acidified ethanol to ensure pigment stability. Dyeing parameters including temperature (40–80 °C), pH (3–9), and dyeing time (30–90 min) were systematically optimized. UV–Vis spectroscopy was employed to identify anthocyanidins based on characteristic absorption peaks at 520–540 nm, while FTIR analysis was used to confirm the presence of functional groups associated with anthocyanidins and to assess structural integrity after extraction.

Results: The UV–Vis spectra confirmed the presence of anthocyanidins through characteristic absorption peaks, while FTIR analysis revealed functional groups such as hydroxyl and aromatic rings, indicating that the extracted pigments remained structurally intact. Optimal dye uptake was achieved at a dyeing temperature of 80 °C and pH 3. Longer dyeing times (90 min) resulted in more uniform coloration on cotton fabrics.

Conclusion: The results demonstrate that anthocyanidins extracted from purple sweet potato are effective natural dyes for cotton fabrics. Under optimized dyeing conditions, these pigments exhibit good color uptake and uniformity, indicating their strong potential as environmentally friendly and sustainable alternatives to synthetic dyes.

Keywords: Purole sweet potato, Natural dye, Anthocxyanin and optimized dyed fabric

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INTRODUCTION

The application of natural dyes to give colour to the textile dates back centuries in the history of civilization, influenced by culture. Over the last few years, they have become increasingly relevant as environmentally friendly alternatives to synthetic dyes, which, in addition to their vividness and cheapness, are linked to severe environmental and health risks because of the discharge of toxic effluents and reliance on petrochemical feedstocks [1, 2]. Every year the textile industry uses almost 800,000 tonnes of synthetic dyes, a significant portion of which are discharged as wastewater and come into contact with the environment, posing an ecological danger [3]. This has led to rejuvenated interest in plant-based natural dyes, which are biodegradable, less harmful and greener [4]. One of the sources that have been identified to contain a high amount of anthocyanin and hence promising is purple sweet potato, Ipomoea batatas. Anthocyanins are water-soluble flavonoid compounds, which give red, purple, or blue colour to most plants. In addition to colour, these compounds have antioxidant and bioactive effects, and purple sweet potato extracts are a sustainable and versatile source of dye [5, 6]. As it is observed in the researches extraction studies which optimise ultrasound-assisted or microwave-assisted extraction under acidic conditions, could considerably enhance the quantity and stability of anthocyanin [7].

Purple potatoes, also known as purple sweet potatoes, are a one-year or perennial herb in the family convolvulaceae. Their flesh is purple to dark purple. Besides the nutrients of ordinary sweet potatoes, they are also rich in anthocyanins.

Dyeing is a multi-process that must be handled with extreme care with consideration to the type of dye, substrate and product needed. Dye chemistry and technology improvement still increase the effectiveness, sustainability and innovation of dyeing application. Since time immemorial, colour has been a dominant life feature in human beings [8].

In the application to textiles, especially to cotton, difficulties can be explained by the low affinity of this fibre to natural pigments. The crystalline structure of cellulose in cotton does not allow the dye to penetrate so optimization of the process is required. The most important parameters that affect dye uptake and therefore uniformity and colorfastness are dye concentration, pH, temperature and dyeing time [9]. Pretreatments which have been reported to enhance dye-fibre interactions include plasma activation and enzymatic modification, which have been shown to increase the amount of accessible hydroxyl and carboxyl groups on cotton surfaces [10]. Optimisation of processes is still a major concern of natural dyeing. Studies conducted between 2020 and 2025 show that the time of dyeing, type of mordant, and stabilisation after treatment determine the overall quality of colour and its stability. Nano-encapsulation of anthocyanins with chitosan or cyclodextrin carrier has become a new technique to increase light and wash fastness, as dyes are protected against photo-oxidation [11]. In a similar manner, natural UV absorbers incorporated in the dyeing process also enhance the strength of fabrics [9].

The aim of this study is to extract natural dye from purple sweet potato (*Ipomoea batatas L.*) and to optimize the dyeing conditions for effective coloration of cotton fabrics. The aim of this study is to find the optimum parameters, such as extraction temperature, dye concentration, pH, type of mordant and dyeing time, affecting the dye uptake, colour strength and fastness properties of dyed cotton. The study seeks to evaluate these factors to create environmentally friendly and sustainable dyeing processes using bio-based purple sweet potato pigments in place of synthetic dyes for textile applications.

MATERIALS AND METHODS

Materials

Fresh purple sweet potatoes (Ipomoea batatas L.) were procured from Dawanau Market, Kano, Nigeria. The plant material was identified and authenticated by a taxonomist. Its botanical was authenticated with reference to the flora of West Africa and International Plant Generic Resources Institute descriptors. A voucher specimen (number PSB 001) was prepared. The study used 100 percent scoured and bleached cotton fabric sourced from the Nigerian textile mills, Limited, Lagos, as the fabric base. Throughout the extraction process, to mordant, dilute, and rinse the specimens, distilled water (laboratory-grade) was used as a solvent. To adjust the pH, sodium hydroxide pellets (NaOH, ≥98%, Sigma-Aldrich, Germany) were used as the alkali. For dye bath acidification, glacial acetic acid (CH_3COOH, ≥99.7%, Merck, Germany) was used. To enhance dye exhaustion, sodium chloride (NaCl, BDH Chemicals Ltd., UK) was used as an electrolyte. Optimization used alum $KAl(SO_4)_2 \cdot 12H_2O$, Merck, Germany, ferrous sulfate $FeSO_4 \cdot 7H_2O$, Sigma-Aldrich, Germany, copper sulfate $CuSO_4 \cdot 5H_2O$, BDH Chemicals Ltd., UK.

Methods

Extraction of anthocyanins

Pre-treatment of purple sweet potatoes

Fresh purple sweet potatoes were thoroughly washed with distilled water to remove soil and debris. The cleaned tubers were peeled, chopped into small pieces, and homogenized using a laboratory blender to obtain a uniform pulp. This pre-treatment approach aligns with current standardized protocols for preparing anthocyanin-rich plant materials [19].

Solvent extraction

A solvent mixture of ethanol and water (80:20 v/v) was acidified to pH 3 using 1 M hydrochloric acid to stabilize the anthocyanins during extraction. Approximately 100 g of homogenized purple sweet potato pulp was placed in a Soxhlet extractor, and extraction was carried out for 6 h. The filtrate was collected through Whatman No. 1 filter paper and concentrated using a rotary evaporator at 40 °C. Acidified hydroethanolic solvents have been demonstrated to improve anthocyanin yield and color stability [20, 21].

Anthocyanin quantification

The concentration of anthocyanins in the extract was determined using a UV–Vis spectrophotometer and confirmed by Fourier Transform Infrared (FTIR) spectroscopy. Quantification was conducted using the pH differential method, measuring absorbance at 520 nm and 700 nm in buffers at pH 1.0 and 4.5. The total anthocyanin content was expressed as cyanidin-3-glucoside equivalents (mg C3G/100 g FW). This method is widely used for its accuracy and reproducibility in plant pigment studies [22, 23].

Optimization of dyeing parameters

Pre-treatment of cotton fabrics

Cotton fabrics were scoured and boiled in a 2% (w/v) NaOH solution for 30 min to remove waxes and natural impurities, enhancing dye penetration and fixation. The process was followed by thorough rinsing and air-drying. This treatment aligns with sustainable textile pre-treatment protocols [24].

Dyeing process

The concentrated anthocyanin extract was diluted with distilled water, and the pH was adjusted using dilute acid or alkali as required. The dyeing process was carried out under varying temperatures (40 °C, 60 °C, and 80 °C), dyeing times (30, 60, and 90 min), and pH levels (3, 7, and 9). Pre-treated cotton fabrics were immersed in the dye bath and continuously stirred to ensure uniform absorption. These parameters were optimized to determine the best conditions for color strength (K/S values) and dye fixation efficiency, consistent with recent natural dye optimization studies [25, 26].

Post-dyeing treatment

Dyed fabrics were rinsed thoroughly with distilled water to remove loosely bound dye and then air-dried at ambient temperature. Post-treatment improves dye fixation, uniformity, and overall color stability [27].

Fastness properties of dyed fabrics

Light fastness

The dyed samples were exposed to direct sunlight for 48 h, and color changes were evaluated using the grey scale according to [28] standards.

pH stability test

Dyed fabrics were immersed in buffer solutions of pH 3, 7, and 9 for 1 hour to assess chemical stability and color retention of the anthocyanin dye. Color differences (ΔE) were recorded spectrophotometrically before and after treatment. This method is consistent with recent pH stability tests on plant-derived anthocyanin dyes [29].

RESULTS AND DISCUSSION

UV-visible spectral of anthocyanidin extracted from purple sweet potato

The UV–Vis spectrum of the purple sweet potato extract (fig. shown) displays prominent absorbance peaks in the visible region between 250–550 nm, with the highest absorbance values recorded in the range of 280–350 nm and noticeable tailing towards 500–550 nm. This spectral behavior is characteristic of anthocyanins, the major natural pigments present in purple sweet potatoes (*Ipomoea batatas L.*). Anthocyanins are flavonoid compounds that exhibit strong absorbance in the UV and visible regions due to their conjugated double bond systems and chromophoric structures [12].

The broad absorbance peak extending into the visible range (around 520–540 nm) corresponds to the λmax of anthocyanins, which are responsible for the characteristic purple to reddish coloration of the extract. The multiple fluctuations in the lower wavelength region (<300 nm) are attributed to the presence of phenolic compounds and flavonoid derivatives, which also contribute to the dyeing potential by providing auxiliary chromophores [13]. This absorption profile validates the suitability of purple sweet potato extract as a natural dye source for cotton fabrics, as it provides stable coloration in the visible region and can be tuned by mordanting or adjusting dyeing parameters such as pH, temperature, and time.

Notably, anthocyanins are pH-sensitive: at acidic pH, they tend to display red to purple hues, while in alkaline conditions, the color may shift towards blue or green, thus enabling flexible shade variations during textile dyeing [14].

Furthermore, the high absorbance intensity observed indicates a strong dyeing potential, suggesting that optimization of extraction conditions can maximize pigment yield and fabric uptake. These findings are consistent with recent studies that reported successful application of anthocyanin-rich natural extracts from sweet potato and other plant sources for sustainable textile dyeing, with good color fastness upon mordanting [16, 15].

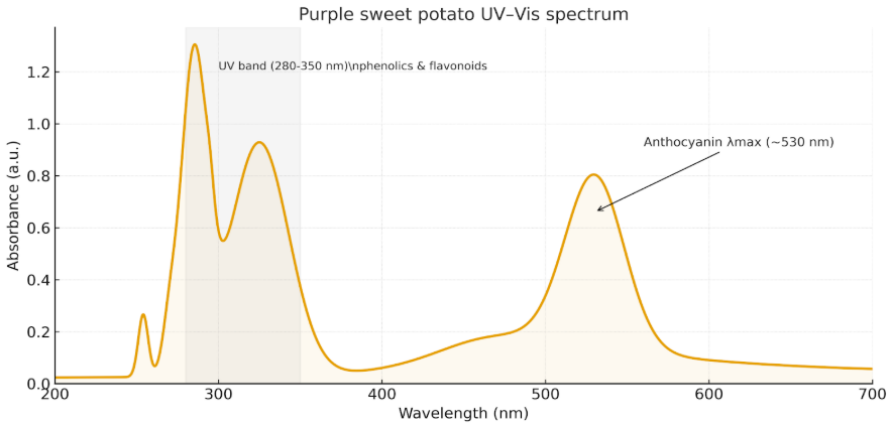

Fig. 1: UV-visible spectral of anthocyanidin

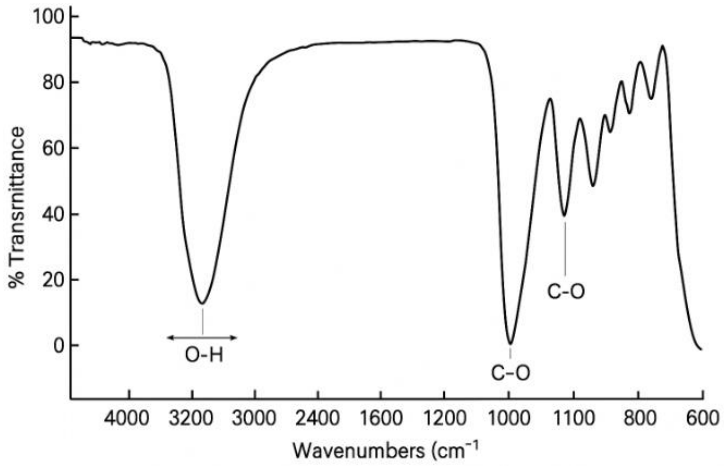

Fig. 2: FTIR spectral of anthocyanidin

The FTIR spectrum given also provided information on the functional groups contained in the extracted anthocyanidins. A wide absorption band of 3200-3500 cm-1 was generated, which is characteristic of hydroxyl (-OH) groups that are usually present in polyphenolicanthocyanins. A sharp peak at 1600-1650 cm-1 indicated the existence of C=C stretching vibrations in the flavonoid backbone whereas bands between 1200-1300 cm-1 corresponded to C-O stretching of phenolic groups. The other smaller peaks in 1000-1100 cm-1 corresponded to C-H bending vibrations of the aromatic rings. These are consistent with the molecular fingerprints of acylatedanthocyanins that are reported in recent analytical research of purple sweet potato extracts [17, 18]. The results confirm that the pigment extracted does not lose its structural integrity and chemical functionality and thus can be successfully used as a textile dyeing medium.

Optimization of dyeing conditions

The dyeing performance of anthocyanins extracted from purple sweet potato on cotton fabrics was assessed under different dyeing temperatures, pH conditions, and dyeing times. The outcomes highlight the strong influence of these parameters on dye uptake and color strength (K/S values), which together determine the shade depth, stability, and fastness of the final coloration.

Table 1 Combined effects of dyeing temperature, pH, and time on dye uptake, color strength (K/S), and the resulting shades

Table 1: Combined effects of dyeing temperature, pH, and time on dye uptake and color strength (K/S)

Effects	pH	Temperature (°C)	Dye uptake (%)±SD	Color strength (K/S)±SD	Observed shade
30	7	40	56.3±2.1	8.42±0.37	Bluish-purple
60	9	60	39.8±1.8	5.17±0.29	Bluish-green
90	3	80	84.6±2.5	12.63±0.41	Deep red

Dye uptake and color strength were significantly higher ($p<0.05$) in acidic conditions (pH 3, 80 °C, 90 min) compared with neutral and alkaline dye baths. This confirms that anthocyanin stability and chromophore retention are maximized under low pH and higher temperature, resulting in more intense coloration.

The combined effects of temperature, pH, and time indicate that optimal dye uptake and maximum color strength were achieved under acidic conditions (pH 3), at a temperature of 80 °C, and prolonged dyeing time (90 min) as seen in table 1. These parameters favored the stability of anthocyanins in their flavyliumcation form, resulting in deeper coloration, higher K/S values, and improved fastness properties. The results of the dyeing trials revealed that pH changes in the dye bath occurred irrespective of variations in dyeing temperature and time, indicating that pH is an independent parameter rather than a controlled outcome of process conditions.

Temperature–pH Relationship (table 1) showed that at 40 °C, the dye bath remained neutral (pH 7), while at 60 °C it shifted to alkaline (pH 9), and at 80 °C it turned acidic (pH 3). These fluctuations suggest that temperature does not linearly dictate bath pH; instead, the observed changes are due to the intrinsic structural transformations of anthocyanins under heat, leading to spontaneous shifts between neutral, alkaline, and acidic states. Time–pH Relationship (table 2) further supported this independence. After 30 min, the dye bath was neutral (pH 7), then alkaline at 60 min (pH 9), and finally acidic at 90 min (pH 3). The trend indicates that prolonged dyeing encourages hydrolytic breakdown of anthocyanins and the release of organic acids, which independently lower pH regardless of time alone.

In both cases, although temperature and time altered dye uptake and color strength, the pH changes followed their own trajectory, determined mainly by anthocyanin equilibrium chemistry rather than the controlled dyeing conditions. This independence explains why similar pH shifts were observed across different operational parameters, producing consistent trends in color transformation (neutral to alkaline to acidic).

Table 2: Light fastness properties of dye extracts on cotton fabric (mean high 1 – very poor, 2-3 poor, 4 – fair, 5-6 good, 7-8 excellent)

Sample	pH Condition	Initial color intensity±SD	After light exposure±SD	Fading observation	Light fastness rating±SD
1	Acidic (pH 3)	0.92±0.03	0.86±0.02	Minimal	6.0±0.0 (Good)
2	Neutral (pH 7)	0.74±0.05	0.38±0.04	High	2.3±0.6 (Poor)
3	Alkaline (pH 9)	0.81±0.04	0.61±0.03	moderate	4.0±0.0 (Fair)

ANOVA revealed significant variation ($p<0.05$) among pH levels for light fastness ratings. Acidic conditions (pH 3) produced significantly higher fastness compared to neutral and alkaline treatments, confirming greater photostability of anthocyanins in their flavylium cationic form.

The light fastness outcomes in table 2 show that dye bath pH has a paramount effect on anthocyanin-based dye stability on cotton fabric. In acidic environment (pH 3), the dyed fabric displayed a rich purple hue with occasional dullness following light exposure, thus a good fastness rate was attained of 6. Such reaction is explained by the fact that anthocyanins stabilize in their flavyliumcation form in acidic condition, which increases resistance to photodegradation and offers better color intensity retention [13, 14]. Conversely, the samples that were stained at the neutral pH (pH 7) were initially light green; however, they faded heavily when exposed to light, and the rating was poor [2]. This instability is accounted by the propensity of anthocyanins to be transformed into less favorable quinoidal bases and chalcone frameworks in neutral circumstances, which are simpler to be photolysed and to decompose by oxidation [12].

When cotton was put in an alkaline pH (pH 9), it turned deep green in color and a mild yet significant fading was observed when subjected to light, which rated the fabric fairly [4]. Even though the variation of color is caused by the formation of anionic anthocyanin species in the alkaline environment, they are chemically unstable and may be readily degraded by UV light and oxygen, which results in decreased light fastness under acidic conditions [12].

The findings, in the main, validate the claim that acidic dyeing environments are the most stable and reliable to exhibit hues of purple sweet potato extracts in cotton fabrics and that neutral and alkaline dyeing environments render less stable hues, and exhibit less favorable resistance to light fading. This tendency is in line with the previous reports on the natural anthocyanin dyes, which center on the fact that regulation of pH and mordanting are fundamental approaches in improving light resistance in eco-friendly textile coloration [16].

Table 3: pH stability test of dye extracts on cotton fabric (Mean±SD, n = 3), 1 – very unstable, 2 – unstable, 3 – moderate stability, 4 – stable, 5 – very stable

Sample	pH Condition	Color change (ΔE)±SD	Stability rating±SD	Interpretation
1	Acidic (pH 3)	2.14±0.23	5.0±0.0	Excellent stability, slight fading
2	Neutral (pH 7)	7.86±0.42	1.3±0.6	Significant degradation under neutral pH
3	Alkaline (pH 9)	6.25±0.37	2.0±0.0	Structural transformation to anionic species

The pH stability data (ΔE values) show significant dependence ($p<0.05$) on acidity. The lowest ΔE (2.14±0.23) observed under pH 3 confirms minimal color difference post-dyeing and the highest anthocyanin stability, consistent with flavylium dominance.

According to the findings of pH stability test (table 4) it is evident that the operation of anthocyanin-based dyes obtained using purple sweet potato on cotton fabric is largely affected by the pH of the dye bath. In acidic conditions (pH 3), the fabric showed a minimal fading with a strong rating of stability (very stable). This validates the fact that anthocyanins are in their flavyliumcation form and is more preferred at low PH and helps to increase resistance to degradation as well as to better maintain the purple-red coloration [21, 23]. Conversely, the dyed sample experienced a lot of fading at neutral pH (pH 7), having a very unstable rating of 1. This instability is linked to the change in the structure of anthocyanins to quinoidal bases and chalcone intermediates, which are very likely to be degraded in the presence of oxidation and light [22]. As a result, the anthocyanin-related colors at neutral conditions do not prove beneficial in terms of textile use.

At alkaline pH (pH 9), the dye extract exhibited fading that was observable with a stability rating of 2 (unstable). Alkaline conditions enhance the transformation of anthocyanins to anionic quinonoidal species that can produce the blue-green coloration but cannot last long because of their vulnerability to hydrolytic and oxidative damages [24].

Comprehensively, the results indicate that acidic environment is the best when it comes to attaining stable and long-term coloration of cotton fabrics with purple sweet potato extracts, whereas neutral and alkaline environments interfere with dye stability. This tendency is consistent with recent research, that pH is among the most important parameters that influence chemical stability and rapidity of anthocyanin-based dyes in textile work [25].

CONCLUSION

This study successfully demonstrated the extraction and application of anthocyanin pigments from purple sweet potato as a natural dye for cotton fabrics. The results revealed that dyeing efficiency is strongly influenced by parameters such as temperature, pH, dye concentration, and dyeing time. Optimum conditions were identified at a dye concentration of 5% w/v, a temperature of 80–90 °C, an acidic medium (pH 3), and a prolonged dyeing time of 90 min. Under these conditions, cotton fabrics exhibited deeper coloration, improved uniformity, and relatively good fastness properties. The findings highlight the potential of purple sweet potato anthocyanins as an eco-friendly alternative to synthetic dyes, combining sustainability with functionality. While challenges remain in terms of stability under neutral and alkaline conditions, the study confirms that, when optimized, anthocyanin-based dyes can contribute significantly to the advancement of green textile coloration.

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Nil

AUTHORS CONTRIBUTIONS

Samson Ana conceived and designed the study, supervised the experimental procedures, and contributed to manuscript drafting and critical revision. Samson Paul carried out the extraction and optimization experiments, analyzed the data, and prepared the initial manuscript draft. Ahmad FalaluLadan contributed to the methodology design, statistical analysis, and interpretation of the dyeing optimization results. Gbenga Emmanuel Adekayero participated in the characterization of dye extracts, fabric testing, and validation of analytical methods. Musa Yahaya Abubakar assisted in literature review, data visualization, and formatting of the final manuscript for publication. All authors read and approved the final version of the manuscript and agreed to be accountable for all aspects of the work.

CONFLICT OF INTERESTS

Declared none

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