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RESEARCH PAPER

Determination of Phytochemicals, Antioxidant and Pigment Stability of Selected Agro-Wastes for Industrial Application as Food Colorants

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ABSTRACT

Valorization of agro-wastes is an eco-friendly method for the conversion of agricultural wastes into valuable products or energy, aimed at reducing waste, creating economic value, and promoting sustainability. Valorisation of agro-waste for natural colourants was carried out through the acidified-methanol extraction of sugarcane peel, pumpkin peel, onion peel, and sorghum stalks. Extracts were analyzed for phytochemicals, DPPH antioxidant activity (62.5–500 µg mL^{-1}) and pigment stability across pH 2–8, light (6 h) and heat (60°C, 1 h). Sorghum stalk extract contained the highest phenolics and tannins, giving the strongest DPPH scavenging (83% at 500 µg mL^{-1}) and superior light stability (4% loss). Sugarcane peel yielded comparable phenolics/flavonoids (≈ 21 µg g^{-1}) and 80% DPPH activity, yet lost 14% colour under light. Pumpkin peel, rich in flavonoids (22 µg g^{-1}) and in carotenoids, displayed the highest pH-independent absorbance and an unusual photo-intensification, but 20% thermal loss. Onion peel, despite having the highest flavonoids, showed the lowest DPPH activity (62%), indicating that glycoside-linked quercetin is less redox-active. All pigments were most intense at pH 2, declining sharply at neutral/alkaline pH. Sorghum stalk emerges as the most balanced antioxidant-colorant for acidic foods, whereas pumpkin peel suits wider pH formulations. The study confirms these wastes as sustainable, functional sources of natural pigments that may find applications in the food industry.

Keywords: Phytochemical, Antioxidant, Stability, Pigments

INTRODUCTION

The increasing global demand for natural and sustainable colorants has intensified research into the recovery of bioactive pigments from agricultural residues. Agro-wastes, traditionally regarded as disposal challenges, are now recognized as valuable sources of phytochemicals with potential industrial and nutraceutical applications. This growing interest is driven by concerns over the environmental and health risks associated with synthetic colorants, many of which have been linked to toxicity and carcinogenic effects (Ali et al., 2021; Sharma et al., 2020). Consequently, the valorization of agro-wastes aligns with the principles of a circular bioeconomy, emphasizing waste minimization, resource recovery, and environmental sustainability.

Among the various agricultural by-products, sugarcane peel, pumpkin peel, onion peel, and sorghum stalks are promising sources of natural pigments and antioxidant compounds. Onion peels (Allium cepa L.) are particularly rich in flavonoids such as quercetin and its derivatives, known for their potent antioxidant activity and distinct pigmentation properties (Benítez et al., 2011). Sugarcane peels (Saccharum officinarum L.), a largely underutilized residue of sugar production, contain considerable amounts of phenolic acids and flavonoids that contribute to their antioxidant capacity and potential use as natural yellow-brown colorants (Da Silva et al., 2020). Sorghum stalks (*Sorghum bicolor L. Moench*), on the other hand contain significant

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quantities of anthocyanins, tannins, and polyphenols that account for their red to brown hues and strong free radical scavenging abilities (Awika & Rooney, 2004). Likewise, pumpkin (*Cucurbita spp*.) is a versatile crop cultivated globally for its nutritional and medicinal value. The pulp and seeds are commonly used, but peels, often treated as waste, are rich in bioactive compounds like carotenoids and phenolic compounds (El-Beltagi et al., 2022). The exploitation of these plant residues not only adds economic value to waste materials but also mitigates environmental pollution resulting from their improper disposal. Phytochemical characterization plays a fundamental role in identifying classes of bioactive compounds responsible for colour expression and functional properties in plant extracts. Qualitative phytochemical tests provide insight into the presence of flavonoids, phenolics, tannins, alkaloids, and other secondary metabolites that influence biological activity. Complementarily, antioxidant evaluation using the 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging assay provides a rapid and reliable measure of an extract's capacity to neutralize free radicals, thereby reflecting its potential health-promoting and preservative attributes. Therefore, this study aims to extract and characterize food-grade colorants using acidified-methanol extracts obtained from sugarcane peels, pumpkin peels, onion peels, and sorghum stalks. Through the integration of qualitative phytochemical screening, DPPH radical scavenging assay, and pigment stability test, the research seeks to establish the chemical and stability profiles of these agro-waste extracts as potential sources of natural colorants. The findings are expected to support sustainable waste valorization efforts and promote the use of eco-friendly, bioactive pigments in food and related industries.

METHODOLOGY

Chemicals and Reagents

All chemicals used were of analytical grade and were products of BDH Chemicals Ltd, Poole.

Sample Collection and Preparation

The selected agro-wastes were collected from Kure market, Minna, then chopped into smaller pieces and air-dried under shade for several days. Once dried, the peels/stalks were ground into fine powder using a high-power blender. The powdered samples were stored in an airtight amber bottle at room temperature in a cool, dark cabinet until extraction.

Extraction of colorant from agro waste

Cold maceration was carried out as described by Kavan et al. (2025). A 99 % methanol solution was used as the extraction solvent, conc. HCl was added in drops gradually while stirring until the pH reached 2.0, measured using a calibrated pH meter. 700 ml of the acidified methanol was added to 300 ml of distilled water. 100 g of the powdered agro waste was added to the extraction solvent and shaken vigorously, and then covered with aluminium foil to prevent evaporation and allowed to stand for 24 h. The solution was filtered using a muslin cloth, and the filtrate was concentrated in a water bath. The extraction yield was calculated using the formula:

$$\text{Extraction Yield (\%)} = \frac{\text{Final weight of sample}}{\text{Initial weight of sample}} \times 100$$

Phytochemical Screening

Phytochemical screening for all three extracts was carried out according to Usman et al. (2020).

Initial Characterization

Initial characterization of the extracts was carried out as described by Jing et al. (2024). The crude extract was visually examined for color properties (hue, clarity, brightness). The pH was measured to confirm the maintenance of acidic conditions required for pigment stability. Observations such as shifts in hue or pH were recorded as early indicators of extraction efficiency

Spectrophotometric Color Intensity

Spectrophotometry was carried out as described by Sirajunisa et al. (2024). A diluted aliquot of the extract was scanned over a wavelength of 400–700 nm using the UV-Vis spectrophotometer. The wavelength of maximum absorbance (λ max) was measured and used for the following absorbance readings. The absorbance value was used as direct indicator of color intensity, with higher absorbance showing higher pigment presence or concentration.

pH-Dependent Color Stability

pH-dependent color stability test was carried out as described by Mahmoud et al. (2007). Aliquots of the samples (10 ml) were placed in separate test tubes and adjusted to different pH of 2, 4, 6, and 8 using dilute HCl solutions. After adjustment, the samples were analyzed and their absorbance were measured at the specific wavelength.

Light and Heat Stability

Light and heat color stability tests were carried out as described by Mahmoud et al. (2007). For the light stability check, 10 ml of the aliquots of extract were placed in transparent glass containers and exposed directly to sunlight for about six hours, while control samples were kept in amber vials in a dark cabinet.

For heat stability check, separate aliquots were placed inside a water bath maintained at 60 °C for exactly 60 minutes. After treatment, all samples were allowed to cool, and each absorbance was measured and compared to the controls.

DPPH (2,2-Diphenyl-1-Picrylhydrazyl) Radical Scavenging Assay

The antioxidant activity of the plant extract was estimated using the DPPH radical scavenging assay as described by Gulcin et al. (2023). The experiment was performed in triplicate. The percentage antioxidant activity was calculated using the formula below:

$$\% \text{ Inhibition} = \frac{\text{Ablank} - \text{Asample}}{\text{Ablank}} X100$$

Statistical Analysis of Data

All analyses were conducted in triplicate values and are presented in mean ± standard error of mean. $P < 0.05$ was considered significant.

RESULTS AND DISCUSSION

Table 1. DPPH Radical Scavenging Activity of Sugar Cane Peel Extract

Concentration (mg/L)	Percentage of Scavenging	
	Extract	Ascorbic Acid
500	79.86±0.20^{b}	95.95±0.12^{a}
250	71.08±0.18^{d}	87.02±0.11^{c}
125	60.03±0.05^{f}	71.10±0.16^{e}
62.5	47.96±0.08^{h}	62.00±0.08^{g}

The presented values represent the mean ± standard error of mean (SEM) from triplicate measurements. Significant values within the same column is indicated by different letters as superscripts and are considered significant at p <0.05

The sugarcane extract demonstrated concentration-dependent antioxidant activity with a reasonably high DPPH scavenging percentage, though lower than ascorbic acid.

Table 2. DPPH Radical Scavenging Activity of Sorghum Stalk Extract

Concentration (µg/mL)	Percentage of Scavenging	
	Extract	Ascorbic Acid
500	83.42±0.04^{a}	92.85±0.01^{b}
250	71.08±0.07^{c}	81.74±0.08^{d}
125	59.33±0.05^{e}	70.26±0.06^{f}
62.5	46.27±0.06^{h}	55.43±0.05^{g}

The presented values represent the mean ± standard error of mean (SEM) from triplicate measurements. Significant values within the same column is indicated by different letters as superscripts and are considered significant at p <0.05

The DPPH assay evaluates the antioxidant capacity of plant extracts by measuring their ability to donate electrons or hydrogen to

neutralize DPPH free radicals. The sorghum stalk extract shows a clear dose-dependent increase in radical scavenging ability, showing the strongest activity at 500 µg/mL (83.42%), moderate activity at 250–125 µg/mL, and the lowest activity at 62.5 µg/mL (46.27%).

Table 3. DPPH Radical Scavenging Activity of Onion Peel Extract

Concentration (µg/mL)	Percentage of Scavenging	
	Extract	Ascorbic Acid
500	62.02±0.06[a]	96.07±0.09[b]
250	51.94±0.07[c]	86.14±0.15[d]
125	41.03±0.26[e]	63.05±0.07[f]
62.5	29.98±0.12[h]	50.99±0.10[g]

The presented values represent the mean ± standard error of mean (SEM) from triplicate measurements. Significant values within the same row is indicated by different letters as superscripts and are considered significant at p <0.05.

Onion peel extract demonstrated a clear dose-dependent antioxidant effect: highest scavenging at 500 µg/mL (62.02%), moderate activity at 250–125 µg/mL and lowest at 62.5 µg/mL (29.98%).

Table 4. DPPH Radical Scavenging Activity of Pumpkin Peel Extract

Concentration (mg/L)	Percentage of Scavenging	
	Extract	Ascorbic Acid
500	75.98±0.20[a]	95.99±0.09[a]
250	63.96±11.95[b]	86.01±0.11[b]
125	51.00±0.18[c]	62.98±0.04[c]
62.5	36.96±0.08[d]	50.91±0.09[g]

The presented values represent the mean ± standard error of mean (SEM) from triplicate measurements. Significant values within the same row is indicated by different letters as superscripts and are considered significant at p <0.05.

The pumpkin peel extract (PPE) shows a clear increase in radical scavenging activity as concentration increased; the strongest activity at 500 mg/L (75.98%), moderate activity at 250–125 mg/L and the lowest activity at 62.5 mg/L (36.96%).

Table 5. Quantity of Phytochemicals in Sorghum stalk, Sugar cane, Onion, and Pumpkin peel Extract

	Concentration (µg/g)			
Extract Constituents	Sugar cane	Sorghum stalk	Onion peel	Pumpkin
Flavonoids	21.40±0.02[a]	14.08±0.01[b]	22.33±0.01[a]	21.82±0.01[a]
Phenols	20.63±0.02[a]	21.17±0.05[a]	13.21±0.01[c]	20.26±0.02[b]
Alkaloids	11.05±0.01[b]	6.84±0.03[d]	12.88±0.01[c]	14.33±0.02[d]
Saponins	10.50±0.02[b]	5.94±0.01[d]	6.82±0.01[d]	15.13±0.02[c]
Terpenoids	10.14±0.02[b]	12.82±0.01[b]	14.02±0.01[b]	6.37±0.01[e]
Reducing Sugar	9.82±0.02[b]	12.31±0.01[b]	6.09±0.00[e]	3.19±0.07[f]
Tannins	7.22±0.02[c]	10.80±0.03[c]	5.26±0.01[f]	0.00±0.00[h]
Steroids	6.86±0.02[c]	0.00±0.00[e]	5.05±0.03[f]	0.00±0.00[h]
Glycosides	0.00±0.00[d]	0.00±0.00[e]	6.21±0.00[e]	0.00±0.00[h]
C/Glycosides	0.00±0.00[d]	0.00±0.00[e]	0.00±0.00[g]	4.22±0.02[b]
Carbohydrates	0.00±0.00[d]	13.51±0.01[b]	14.71±0.01[b]	0.00±0.00[h]

The presented values represent the mean ± standard error of mean (SEM) from triplicate measurements. Significant values within the same column is indicated by different letters as superscripts and are considered significant at p <0.05

The phytochemical profile of the sugarcane peel extract revealed the presence of several important bioactive compounds in varying concentrations. Flavonoids are the most abundant, followed by phenolic compounds, with moderate levels of alkaloids, saponins, terpenoids, and reducing sugars, while tannins and steroids are present in lower quantity. Quantitatively, sorghum stalk extract showed that phenols are the most abundant compounds in the extract (21.17 ± 0.05 µg/g). Flavonoids formed the second major group (14.08 ± 0.01

µg/g), while present in lower concentrations were alkaloids and saponins. Onion peel showed distinct dominance of flavonoids and other polyphenolic compounds. Dominant Phytochemicals found in the extract were flavonoids (22.33 ± 0.01 µg/g). The dominant phytochemicals found in pumpkin peel extract were flavonoids (21.82 µg/g), phenols (20.26 µg/g), while free Reducing Sugar (3.19 µg/g) was moderately present.

Table 6. Color Absorbance at Different pH Measured at 540nm of Sorghum stalk, Sugar cane, Onion, and Pumpkin peel Extracts

	Absorbance (nm)			
pH	**Sugar cane**	**Sorghum**	**Onion**	**Pumpkin**
2.0	0.82±0.02[a]	0.81±0.02[a]	0.82±0.01[a]	0.85±0.01[a]
4.0	0.60±0.02[b]	0.69±0.02[b]	0.62±0.01[b]	0.70±0.01[b]
6.0	0.25±0.01[c]	0.40±0.01[c]	0.35±0.01[c]	0.60±0.01[c]
8.0	0.08±0.02[d]	0.21±0.01[d]	0.15±0.00[d]	0.40±0.01[d]

The presented values represent the mean ± standard error of mean (SEM) from triplicate measurements. Significant values within the same column are indicated by different letters as superscripts and are considered significant at $p < 0.05$

The absorbance values of the sugarcane peel extract at different pH levels show a strong dependence of pigment stability and intensity on acidity. With maximum absorbance at pH 2.0, which gradually decreases toward pH 4.0. At pH 6.0, absorbance drops to 0.25, which is less than half of the value at pH 4.0 and at pH 8.0, absorbance is only 0.08. The absorbance of the sorghum stalk extract at 540 nm shows a strong dependence on the acidity or alkalinity of the medium. The extract showed strong color expression at acidic pH (pH 2.0–4.0), a sharp decline at near-neutral pH (pH 6.0) and alkaline pH (pH 8.0). pH stability results showed how the pigment intensity and structural stability of onion peel extract change across acidic, neutral, and alkaline conditions. Onion peel extract showed its maximum absorbance at pH 2.0 (0.82), absorbance declined to 0.62 at pH 4.0, a sharp absorbance drop from 0.62 to 0.35 at pH 6.0 and a further drop to 0.15 at pH 8.0, nearly 20% of the intensity observed at pH 2.0. The strongest color expression for pumpkin peel was seen at pH 2.0 (highly acidic condition), which was followed by a gradual decline in absorbance from pH 4 to pH 6 and a significant decline at pH 8.0 (alkaline condition).

Table 7. Results of Light Stability Test on Sorghum stalk, Sugar cane, Onion, and Pumpkin peel Extract at pH 2.0 Measured at 540 nm

	Absorbance (nm)			
Condition	**Sugar cane**	**Sorghum**	**Onion**	**Pumpkin**
Control	0.81±0.02[a]	0.81±0.02[a]	0.82±0.01[a]	0.49±0.18[a]
Treated Sample	0.70±0.02[b]	0.78±0.01[b]	0.75±0.01[b]	0.75±0.02[a]

The presented values represent the mean ± standard error of mean (SEM) from triplicate measurements. Significant values within the same column are indicated by different letters as superscripts and are considered significant at $p < 0.05$.

The light stability test evaluates how exposure to light affects the pigment intensity of the extract. The absorbance of the light-treated sample (0.70) is lower than the control (0.81), indicating ~14% reduction upon exposure to light after a period of 24 hours. Sorghum stalk extract showed ~4% decrease in absorbance after 24 hours light treatment at pH 2. The absorbance for onion peel decreased from 0.82 to 0.75, this represents an 8.5 % drop in intensity. Interestingly, there was an absorbance increase observed in pumpkin peel (0.49 to 0.75) after 24 hours of sunlight exposure. This is different

from typical photodegradation results, where pigments lose color under light.

Table 8. Results of Heat Stability on Sorghum stalk, Sugar cane, Onion, and Pumpkin peel Extract

	Absorbance (nm)			
Condition	**Sugar cane**	**Sorghum**	**Onion**	**Pumpkin**
Control	0.82±0.02[a]	0.58±0.03[a]	0.82±0.01[a]	0.81±0.11[a]
Treated Sample	0.60±0.02[b]	0.42±0.02[b]	0.68±0.02[b]	0.65±0.21[b]

The presented values represent the mean ± standard error of mean (SEM) from triplicate measurements. Significant values within the same column are indicated by different letters as superscripts and are considered significant at $p < 0.05$

The heat stability test evaluates how thermal exposure affects the pigment intensity of the extract. The heated sugarcane peel sample showed an absorbance decrease from 0.82 to 0.60, indicating ~27 % degradation after 1 hour at 60 °C. Sorghum stalk following heating at 60 °C for 1 hour, a ~28 % decrease in absorbance was observed. Following heating, the absorbance of onion peel declined from 0.82 to 0.68, representing a loss of ~17% of its color after heating at 60 °C for 1 hour. Pumpkin peel showed absorbance decrease from 0.81 to 0.65, indicating ~20% loss of color intensity at 60 °C for 1 hour.

Phytochemical Composition

From the results, the relatively high phenol and flavonoid levels in sugar cane extract (SCE), sorghum stalk extract (SSE), and Pumpkin extract (PE) suggest these extracts are rich in compounds with potential antioxidant properties. The particularly high tannin content in SSE may confer an advantage in radical scavenging capacity, given that tannins often exhibit stronger antioxidant activity than simple phenolics or flavonoids, due to multiple aromatic rings and hydroxyl groups. Literature supports a strong correlation between condensed tannins in sorghum and antioxidant activity (Nagy et al., 2021).

Onion peel extract (OPE)'s high flavonoid level, likely including flavonoids such as quercetin and its glycosides (common in onion peel) suggests potent bioactivity, though flavonoid and glycosides may behave differently than aglycones in functional assays; their solubility, reactivity, and stability may differ. A study by Velisdeh et al. (2024), however, suggests that optimizing quercetin extraction from onion peel, often by specialized methods, tends to maximize yield. The absence of tannins in PE may reduce some antioxidant potency compared to SSE, but its content of flavonoids, phenols, alkaloids and possibly carotenoids (common in pumpkin) may still confer a broad bioactivity profile.

Antioxidant Activity: DPPH Radical Scavenging

The DPPH (2,2-diphenyl-1-picrylhydrazyl) assay is widely used to evaluate the ability of extracts to donate an electron or hydrogen to neutralize free radicals, a measure of in-vitro antioxidant (radical scavenging) capacity. A higher percentage of DPPH scavenging indicates stronger radical quenching ability, which may translate to antioxidative potential in biological or food systems, though in-vivo relevance requires further assays (Suhag et al., 2025).

SSE exhibited the highest DPPH scavenging. This aligns well with its high phenolic and tannin content; tannins are especially effective radical scavengers because of their multiple hydroxyl groups and conjugated aromatic systems. A study by Zhang et al., (2025) on sorghum has however shown a positive correlation between total tannins (or proanthocyanidins) and DPPH/ORAC (oxygen radical absorbance capacity) antioxidant capacities. SCE closely follows SSE, which supports its high phenolic/flavonoid content, though its lower tannin value compared to SSE may slightly reduce potency. The moderate scavenging suggests sugar cane extract is a viable antioxidant source as also reported by Wu et al. (2024).

PE demonstrated moderate antioxidant activity. Its phenolic and flavonoid content provides antioxidant capacity, but the lack of tannins may

limit maximal activity. OPE shows the lowest DPPH activity, despite having the highest flavonoid content. The flavonoids in OPE may be mostly, which often have lower radical-scavenging activity compared to aglycones because the sugar moiety sterically hinders access of the hydroxyl groups to radicals. Supporting this is the research of Joković et al. (2024), which studied onion peel as a potential antioxidant and antimicrobial agent.

From the above results, SSE and SCE appear most promising for applications where strong free-radical scavenging is desired. PE remains valuable but may need lipophilic-solvent extraction (or a different assay) to reveal full antioxidant potential. OPE could be optimized: converting glycosides to aglycones may appreciably enhance antioxidant performance. This is especially relevant if the goal is to harness maximum radical-scavenging capacity; otherwise, OPE may be more useful in other bioactivities.

It is important to note that DPPH only measures one type of antioxidant mechanism (radical scavenging in vitro) and may not predict in vivo behavior or efficacy in complex food/flesh matrices.

pH-Dependent Colour Stability

The pH-dependent colour stability test assesses how pigment-bearing extracts behave under varying pH conditions. This parameter is important for potential application of extracts as natural colorants because colour (hue, intensity) and stability to pH changes affect acceptability, shelf-life, and formulation viability. All extracts show maximum absorbance at highly acidic pH (2.0) and a progressive decrease as pH approaches neutrality and alkalinity. This is typical for many natural pigments whose chromophore structure and conjugation are pH-sensitive. At low pH, the chromophore may be in protonated form that favors light absorption; at higher pH, deprotonation or structural changes reduce absorbance (Villota et al., 2025).

PE stands out as the most pH-stable sample. It showed the highest absorbance at all pH values, suggesting that its pigments are relatively resilient to pH changes, making PE a better candidate as a natural colorant across diverse pH conditions. This is in agreement with the study of Sher et al., (2025). SSE showed better pH-stability than SCE and OPE, especially between pH 2.0 and 4.0, suggesting its pigments are moderately stable under mildly acidic conditions. The high phenolic/tannin content of SSE may contribute not only to antioxidant capacity but also to pigment stability under acidic conditions, possibly via complexation or multiple hydrogen bonding that stabilizes chromophores. This is in agreement with the study of Kour et al. (2025). PE's better stability may derive from non-anthocyanin pigments that resist pH-induced structural changes. OPE, despite its flavonoid richness, shows less stable pigment behaviour, possibly because its main flavonoids lose conjugation or structural integrity at higher pH, or because the glycoside moiety makes chromophores more sensitive to pH shifts.

For food/beverage applications, PE appears most suitable as a natural colorant where pH may vary, followed by SSE for acidic products. SCE and OPE may be limited to strongly acidic formulations such as syrups and jams or require stabilization to maintain colour. The pH-dependent decrease in absorbance at neutral to alkaline pH suggests limited suitability in pH-neutral/alkaline food systems unless further stabilization strategies are employed.

Light and Heat Stability

Natural pigments and phenolic compounds may degrade under light exposure or heating critical for real-world applications (storage, processing, packaging). SSE showed the best light stability, with minimal absorbance loss under light. This is consistent with tannin-based chromophores, which are often more photostable than anthocyanins or simple flavonoids, because their multiple aromatic rings and polymeric structure can resist photodegradation (Thakur & Kumar, 2024). This aligns with the studies of Tian et al. (2025) noting condensed tannins confer robust antioxidant and stability properties in sorghum extracts. SCE and OPE show moderate light-induced pigment loss, indicating some photolability, likely due to simpler phenolics or flavonoids whose conjugated systems degrade or isomerize under light. PE however shows an

unusual increase in absorbance after light exposure.

Heat treatment (60 °C, 1 h) caused absorbance losses in all extracts, as expected: thermal energy can degrade conjugated chromophores, cause polymerization, or induce loss of hydroxyl groups Wang et al. (2025). Among the extracts, SSE had the largest drop (≈ 28%), showing that despite good light stability, thermal stability is limited, tannins may degrade under heat or undergo structural rearrangements. SCE and OPE lost ~22–25% absorbance, moderate degradation, while PE lost ~20%, slightly less relative to others, possibly due to a mixture of pigments (lipophilic + hydrophilic) with varying thermal tolerance. This is in corroboration with the studies of Negi (2025) that examined the sustainable applications of natural dyes and pigments.

The light and heat stability of SSE reinforce its potential as a natural antioxidant/colorant in real-world applications where exposure to light and moderate heat occurs. Its high tannin/phenolic content likely contributes to resilience. PE's odd light response suggests more complex pigment chemistry, but the thermal degradation warns that processing or storage under heat may reduce pigment efficacy, encapsulation or formulation with stabilizers may be needed.

CONCLUSION

The four extracts show distinct "profiles," making each more or less suitable depending on the intended application. SSE emerged as the most balanced and robust extract, highest radical scavenging, good pigment stability under light and moderate heat, and reasonable pH-stability in acidic to mildly acidic conditions. Its high tannin and phenolic content underlie these properties. For applications such as functional antioxidant additives, traditional beverages, or acidic food products requiring natural color and antioxidant protection, SSE is the top candidate. SCE also showed strong antioxidant activity and fair stability, though less pigment resilience. Sugar cane extract could be useful as a complementary antioxidant additive or ingredient when color/pigment function is secondary. PE offered a different profile, decent antioxidant activity, good pH-stability, but mixed stability under light/heat depending on pigment chemistry. If further characterized, PE could serve as a dual-purpose functional ingredient as antioxidant and natural pigment especially in acidic or slightly acidic food formulations. OPE, on the other hand, though rich in flavonoids, exhibited the lowest DPPH activity and moderate stability, suggesting that it is a less optimal candidate for antioxidant or colorant applications compared to SSE, SCE, or PE. However, given its rich flavonoid content, it may have other valuable bioactivities.

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