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Original Research Paper

A COMPREHENSIVE STUDY ON THE EFFICACY OF IXORA COCCINEA FLOWER AND PTEROCARPUS MARSUPIUM BARK EXTRACTS AS NATURAL COLOURANTS IN THE DEVELOPMENT OF SAFE AND STABLE PHARMACEUTICAL DOSAGE FORMS

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ABSTRACT

Background: Synthetic dyes are widely used in pharmaceutical formulations often raise safety concerns due to allergenicity, toxicity, and carcinogenicity. The need for eco-friendly and therapeutic alternatives has directed focus toward natural colourants. The study aimed to evaluate the efficacy of *I. coccinea* flowers and *P. marsupium* bark extracts by assessing their extractability, stability, phytochemical composition, antioxidant potential, safety, and formulation compatibility.

Methodology: Plant materials were collected and extracts were characterized using UV-Vis, FTIR, and DSC analyses. Stability was tested across varying pH (1–14) and temperatures (25–90°C). Antioxidant activity was evaluated by DPPH assay, and acute toxicity was assessed in Wistar rats following OECD 425 guidelines. Extracts were incorporated into model tablet and suspension formulations for compatibility testing.

Results: Hydroalcoholic extracts yielded the deepest hues, with *P. marsupium* showing superior pH (3–10) and thermal stability, while *I. coccinea* was optimal at acidic to neutral pH. Both extracts were rich in flavonoids, tannins, and phenolics, with quercetin and anthocyanins identified as key pigments. DPPH assay confirmed dose-dependent radical scavenging, higher in *P. marsupium*. Toxicity studies confirmed safety up to 2000 mg/kg and 1500 mg/kg, respectively. Formulation studies indicated good stability and no drug-extract incompatibility.

Discussion: The findings highlight the dual role of these extracts as natural pigments and bioactive agents. *P. marsupium* is more suited for thermally processed dosage forms, whereas *I. coccinea* fits low-temperature aqueous formulations.

Conclusion: *Ixora coccinea* and *Pterocarpus marsupium* extracts demonstrate significant potential as safe, stable, and multifunctional natural colourants for pharmaceuticals, supporting their integration into sustainable formulation strategies.

Keywords: Ixora coccinea, Pterocarpus marsupium, natural colourants, pharmaceutical formulations, antioxidant activity

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INTRODUCTION

According to the United States Food and Drug Administration, a colour additive is any substance that imparts colour to drugs, food, cosmetics, or the human body, and may be synthetic or derived from natural sources [1]. The pharmaceutical industry has long used synthetic dyes for their availability, stability, and cost-effectiveness [2]. However, the risk of adverse effects like allergic reactions, toxicity and carcinogenicity has led to growing interest in safer, eco- friendly, and therapeutic colour alternatives.

Natural dyes from plants, microbes, and minerals offer eco-friendly and bioactive properties, including flavonoids and tannins, providing vibrant hues [3]. Ixora coccinea and Pterocarpus marsupium, known for medicinal uses, show promise as pharmaceutical colorants [4,5]. Rising consumer demand for sustainable products has boosted the natural dye market, projected to grow over 8% annually through 2030, with Asia-Pacific leading due to rich biodiversity and herbal traditions. [6]

Natural dyes derived from plants, animals, and minerals provide a promising solution. They are typically biodegradable, non-toxic, and often offer additional pharmacological benefits. The increasing consumer preference for clean-label products and regulatory encouragement for sustainable sourcing have driven extensive research into natural colorants for pharmaceutical and nutraceutical applications [7-9].

Among the botanical candidates, Ixora coccinea (Rubiaceae) and Pterocarpus marsupium (Fabaceae) stand out. Traditionally used in Ayurvedic and ethnomedicine for their antimicrobial, anti-inflammatory, antioxidant, and antidiabetic properties, these plants are rich in bioactive compounds such as anthocyanins, flavonoids, and stilbenoids [10-12].

This manuscript presents an in-depth scientific evaluation of these plant-based dyes, analyzing their extraction, stability, phytochemical profiles, and compatibility with pharmaceutical bases And Furthermore.

STUDY OBJECTIVES

This study aims to evaluate Ixora coccinea flower and Pterocarpus marsupium bark extracts as natural dyes for pharmaceutical use by examining their extractability, stability, composition, and compatibility. Objectives include solvent-based extraction, testing under different pH and temperatures, phytochemical profiling, analysis using UV-Vis, FTIR and DSC, antioxidant activity via DPPH assay, toxicity following OECD 423 and integration into model formulations.

MATERIALS AND METHODS

Collection and Authentication of Plant Material

Fresh Ixora coccinea flowers and Pterocarpus marsupium bark were collected from the botanical garden of Royal College of Pharmacy and Health Sciences, Berhampur, Odisha. The plant specimens were authenticated by a certified taxonomist and assigned voucher specimens for institutional records. The collected materials were washed, shade-dried, and ground to a fine powder using a mechanical grinder. The powders were stored in airtight containers at room temperature (25°C) away from light and moisture.

Extraction Procedures

Three methods were employed for extraction. In the aqueous method, 25 g of dried plant powder was boiled in 250 mL of distilled water for 2 hours, and the resulting decoction was filtered through Whatman No. 1 filter paper. For alcoholic extraction, 25 g of the powder was soaked in 250 mL of 70% ethanol for 72 hours with intermittent shaking, followed by filtration and concentration under reduced pressure using a rotary evaporator. The hydroalcoholic method used a 40:60 ethanol-water mixture under similar conditions, yielding deeply pigmented viscous residues. All extracts were dried using a lyophiliser and stored at 4°C until further analysis.

Dried and powdered plant materials of Ixora coccinea (whole plant and flowers) and Pterocarpus marsupium (bark) were subjected to successive Soxhlet extraction using petroleum ether and ethanol, each for 72 hours. The extracts were concentrated using a rotary vacuum evaporator and dried with a freeze dryer. Additional aqueous, alcoholic, and hydroalcoholic extracts were prepared using distilled water, ethanol, and a 40:60 ethanol- water mixture, respectively.

Physicochemical and Stability Studies

To determine the thermal and pH stability of the dyes, 5 mL aliquots of each extract were subjected to various temperatures (25°C, 50°C, and 90°C) and pH conditions (pH 1-14 using standard buffer solutions). Colour changes were observed visually and measured spectrophotometrically using UV-Vis analysis. These tests were done in triplicate to ensure reproducibility.

Phytochemical Screening

Standard qualitative methods were used to detect major phytochemical groups in the extracts. Alkaloids were identified using Mayer's and Wagner's reagents, while flavonoids were detected through the Shinoda test. The presence of tannins and phenolic compounds was confirmed using the ferric chloride test. Glycosides were evaluated with the Keller-Killiani test, and saponins were identified using the froth formation method.

INSTRUMENTAL CHARACTERIZATION

1. UV-VIS spectral method of analysis:

This study employed UV-Visible (UV-Vis) spectrophotometry to investigate the absorbance characteristics and pigment content of Pterocarpus marsupium and Ixora coccinea extracts. The method was based on the principle that molecules absorb ultraviolet and visible light at specific wavelengths, leading to electronic transitions between molecular orbitals.

Absorbance is directly proportional to the analyte concentration, as described by the Beer- Lambert Law: A = εcl.

A double-beam UV-Visible spectrophotometer equipped with quartz cuvettes (1 cm path length) was used for all measurements. Methanol and distilled water were used in a 40:60 v/v ratio as the solvent system. Analytical grade reagents, volumetric flasks, micropipettes, and pipette tips were used for sample preparation. The instrument was calibrated and blanked using the solvent before each measurement session.

Accurately weighed 10 mg each of Pterocarpus marsupium and Ixora coccinea dried extract was transferred to a calibrated 10 mL volumetric flask. The samples were dissolved in a 40:60 methanol-water co-solvent system to prepare a primary stock solution of 100 µg/mL. From this stock, various working solutions were prepared by serial dilution to achieve concentrations of 15, 25, 35, 45, and 55 ppm for each extract.

The UV-Visible spectrophotometer was turned on and allowed to stabilize according to the manufacturer's instructions. A blank measurement was first taken using the methanol-water solvent system to calibrate the instrument. Each prepared sample was then placed into a clean quartz cuvette, and the absorbance spectrum was recorded over the range of 200–400 nm.

For each concentration, the λmax (wavelength of maximum absorbance) was determined, and absorbance values were recorded at characteristic peaks, particularly around 280 nm. All measurements were performed in triplicate to ensure consistency.

Calibration curves were constructed by plotting absorbance values at 280 nm against their respective concentrations. These curves were used to identify and quantify characteristic compounds such as quercetin (in Pterocarpus marsupium) and anthocyanins (in Ixora coccinea) based on their known absorbance behavior and reference data from the Indian Pharmacopoeia.

2. INFRA-RED analysis:

The extracts were subjected to multiple instrumental analyses to characterize their chemical and thermal properties. Infrared (IR) spectroscopy was employed to identify the functional groups and phytochemical components present in the ethanol extracts of Pterocarpus marsupium bark and Ixora coccinea flowers. The analysis was conducted using a Shimadzu IR spectrophotometer.

Solid samples were finely powdered, homogenized, and pressed into KBr pellets for transmission mode analysis. Spectra were recorded in the range of 4000 to 400 cm^{-1} at room temperature. Background correction was performed before sample scanning using pure KBr as a reference. The observed absorption peaks were analyzed to determine the presence of characteristic functional groups based on standard IR correlation charts.

3. DSC Analysis:

Differential Scanning Calorimetry (DSC) was employed to determine the thermal behaviour and stability of Pterocarpus marsupium (IK) and Ixora coccinea (IC) extracts.

Approximately 2.9 mg of dried Pterocarpus marsupium extract and 2.8 mg of Ixora coccinea extract were accurately weighed and placed in aluminum sample pans. A matching empty aluminum pan was used as a reference. The analysis was conducted using a calibrated DSC instrument, scanning from 40°C to 280°C at a heating rate of 40°C/min under a nitrogen atmosphere. Thermal transitions including melting, crystallization, and exothermic events were recorded. Onset, peak, and end temperatures, as well as enthalpy changes (ΔH), were documented to evaluate the thermal stability and phase transitions of the samples.

Acute Oral Toxicity Study

The acute oral toxicity study was carried out following OECD guideline 425 in the Pharmacology Laboratory of R.C.P.H.S., after obtaining approval from the Institutional Ethics Committee.

Female Wistar rats (n = 6 per group) were used, as they are more sensitive to chemical toxicity than males. All animals were maintained under standard laboratory conditions with access to food and water ad libitum. The test substances (IC and IK extracts) were of known purity and suspended in distilled water as a vehicle. A range of doses (100, 500, 1000, 1500, and 2000 mg/kg) was selected based on preliminary screening, and each dose was administered once orally by gavage. Control animals received distilled water (10 mL/kg).

Following dosing, the animals were observed for signs of toxicity, changes in behaviour, and mortality over a 14-day period. Body weights were recorded weekly. At the end of the study, all animals were subjected to necropsy for gross pathological examination.

Antioxidant Assay (DPPH Radical Scavenging Activity)

The antioxidant activity of the Ixora coccinea flower extracts was evaluated using the DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay, a widely recognized method for assessing free radical scavenging potential [13].

A 0.1 mM DPPH solution was freshly prepared in methanol and protected from light during the assay. Stock solutions of plant extracts were prepared in methanol and serially diluted to obtain test concentrations of 50, 100, 150, 200, and 250 µg/mL. Each reaction mixture contained 2 mL of DPPH solution and 2 mL of test extract solution. A control solution consisted of DPPH with methanol but without any sample, while ascorbic acid served as the reference antioxidant standard. All mixtures were incubated in the dark at room temperature for 30 minutes. The decrease in

absorbance was measured at 517 nm using a UV-Vis spectrophotometer.

Formulation Compatibility Study

Both extracts were incorporated into model tablet coatings and suspension formulations. Physical attributes such as colour intensity, homogeneity, sedimentation rate, and taste masking were evaluated. Drug-extract compatibility was preliminarily assessed using HPLC and visual assessment.

RESULTS

Extraction Yield and Observational Analysis

Extraction yields varied across the three solvents. Aqueous extracts of Ixora coccinea yielded 11.2% w/w, whereas alcoholic and hydroalcoholic extractions yielded 13.6% and 15.4% respectively. Similarly, Pterocarpus marsupium bark extracts showed yields of 9.8%, 12.3%, and 14.1% for aqueous, alcoholic, and hydroalcoholic solvents, respectively. The hydroalcoholic extracts provided the deepest hues, suggesting efficient extraction of chromophoric phytoconstituents.

Colour observations revealed that aqueous decoction of the Ixora coccinea whole plant produced a brick red residue that dissolved into an orange solution, while decoction of the flowers alone resulted in a distinct dark pink colour. Ethanol and hydroalcoholic extracts of the whole plant yielded green residues, whereas hydroalcoholic extraction of the flowers produced a black residue. Notably, the hydroalcoholic extract of Pterocarpus marsupium bark initially exhibited a jamun-berry colour, which oxidized into a light brick red, indicating strong potential as a natural dye.

Stability Evaluation

The extracts were subjected to a comprehensive analysis of stability under pH and temperature variation. Ixora coccinea extracts demonstrated colour stability between pH 2-6, with marked degradation and browning observed at alkaline pH > 9. Conversely, P. marsupium exhibited broad pH resilience, retaining its coloration across pH 3-10. Thermal exposure revealed that I. coccinea pigments degraded visibly beyond 50°C, while P. marsupium remained thermally stable up to 90°C, making it a superior candidate for heat- processed dosage forms.

Phytochemical Findings

Both plant extracts were rich in bioactive constituents. Phytochemical screening indicated the presence of flavonoids, tannins, phenolics, glycosides, and minor amounts of alkaloids and saponins. Notably, P. marsupium contained strong ferric chloride reactivity, indicating dense polyphenolic content, supported by its known composition of pterostilbene and epicatechin.

Spectral and Thermal Characterization UV-VIS Analysis

Three major absorbance peaks were observed in all concentrations of Pterocarpus marsupium, notably at 281 nm, 322 nm, and a strong band around 207–234 nm. The absorption maximum at 280 ± 2 nm is indicative of quercetin or pterostilbene, which is consistent with the Indian Pharmacopoeia standards. Absorption peaks were observed at 280 nm and 221–234 nm for Ixora coccinea, with the 280 nm peak attributed to anthocyanins, as confirmed by IP standards.

An another dataset illustrates pigment absorption shifts in various extraction and mordanting conditions. Anthocyanins, betalains, chlorophylls, carotenoids, and phycobiliproteins (phycocyanin and phycoerythrin) were identified across aqueous and methanol extracts with different mordants such as alum, copper sulfate, ferrous sulfate, and stannous chloride.

IR Analysis

The IR spectra of Pterocarpus marsupium and Ixora coccinea extracts confirmed the presence of key phytochemical groups. In P. marsupium, peaks at 3597 and 2845 cm^{-1} indicated alcohols, while 1714 and 1608 cm^{-1} confirmed carboxylic acids and ketones. Bands at 1444, 1230, and 1149 cm^{-1} suggested saponins and amides; 1377 and 1464 cm^{-1} reflected terpenoids.

For I. coccinea, O–H and N–H stretching appeared at 3734 and 2536 cm^{-1}. Peaks from 1750– 1680 and 1618–1386 cm^{-1} confirmed acids, ketones, and aromatics. Saponins appeared at 1150–1250 cm^{-1} and carbohydrates at 1000–1300 cm^{-1}. These findings confirm the presence of alcohols, acids, ketones, saponins, flavonoids, and terpenoids in both extracts.

DSC Analysis

The Differential Scanning Calorimetry (DSC) analysis of Pterocarpus marsupium revealed a well-defined endothermic thermal event. The thermal transition began at an onset temperature of 169.09°C and reached a peak at 189.75°C, with the event concluding at 212.41°C. This transition is indicative of the melting of amorphous regions in the extract. The enthalpy change (ΔH) associated with this event was calculated to be 60.0220 J/g, and the total area under the peak was 174.064 mJ, with a corresponding peak height of 4.0250 mW. These values reflect moderate thermal stability and a relatively tightly packed molecular arrangement in the extract.

DSC profile of Ixora coccinea showed a thermal transition starting at an onset temperature of 128.95°C, with a peak at 134.86°C, and ending at 151.67°C. This event corresponds to the melting or decomposition of less thermally stable components. The enthalpy change recorded was 84.5168 J/g, which is higher than that of Pterocarpus marsupium, indicating a more energy-intensive phase transition. The area under the peak was 236.647 mJ, and the peak height was 8.8183 mW, suggesting a sharper and more rapid thermal event, possibly due to the volatilization of moisture or lighter phytoconstituents.

Table 1: Differential Scanning Calorimetry (DSC) Parameters of *Pterocarpus marsupium* (IK) and *Ixora coccinea* (IC) Extracts

Parameter	Pterocarpus marsupium (IK)	Ixora coccinea (IC)
Sample Weight (mg)	2.900	2.800
Onset Temperature (°C)	169.09	128.95
Peak Temperature (°C)	189.75	134.86
Endset Temperature (°C)	212.41	151.67
Enthalpy Change ΔH (J/g)	60.0220	84.5168
Area Under Peak (mJ)	174.064	236.647
Peak Height (mW)	4.0250	8.8183

Acute Oral Toxicity Evaluation

The acute oral toxicity study of Ixora coccinea (IC) and Pterocarpus marsupium (IK) was conducted according to OECD Guideline 425. No mortality or signs of toxicity were observed in any of the treated groups, including at the highest dose of 2000 mg/kg for the IK extract. Similarly, the IC extract was well tolerated up to 1500 mg/kg, with no evidence of adverse behavioral, physical, or neurological effects. Weekly monitoring showed no significant changes in body weight or external appearance, and all animals remained active and healthy throughout the 14-day observation period. Gross necropsy did not reveal any abnormalities in major organs.

Antioxidant Capacity (DPPH Assay)

The DPPH assay results revealed a dose-dependent increase in radical scavenging activity for both extracts. At the highest tested concentration (250 µg/mL), IK exhibited 59.88% inhibition while IC showed 52.02% inhibition. Ascorbic acid demonstrated the highest inhibition across all concentrations, reaching 81.18% at 250 µg/mL. The IC50 values followed the order: Ascorbic acid < IK < IC, indicating stronger antioxidant potential in the standard and Pterocarpus marsupium compared to Ixora coccinea.

Table 2: IC50 Values for DPPH Scavenging of Extracts vs. Standard

Concentration (µg/mL)	Ascorbic Acid (%)	IK Extract (%)	IC Extract (%)
50	35.26	11.27	12.93
100	53.15	28.44	26.16
150	64.01	37.75	34.95
200	73.42	51.50	43.85
250	81.18	59.88	52.02

Formulation Compatibility and Visual Uniformity

Both extracts were successfully integrated into placebo tablet coating and suspension prototypes. No precipitation or sedimentation was observed for 30 days under ambient conditions. HPLC analysis confirmed no chemical interaction between model APIs and dye extracts, indicating their compatibility.

DISCUSSION

The findings of this study underscore the tremendous potential of Ixora coccinea and Pterocarpus marsupium extracts as natural colorants suitable for pharmaceutical applications. Their distinct pigmentation, derived from anthocyanins and polyphenolic compounds, contributes not only to aesthetic enhancement but also to therapeutic benefit. This dual utility aligns with the current industry trends promoting clean-label, multifunctional excipients.

Stability assessments revealed that P. marsupium extract holds superior resilience against thermal degradation and pH variation, making it more adaptable to diverse pharmaceutical processes, including granulation, drying, and coating. In contrast, I. coccinea extracts may be better suited for aqueous syrups, suspensions, and other low-temperature formulations.

The UV-Vis analysis of Pterocarpus marsupium and Ixora coccinea revealed prominent absorption peaks around 280 nm, indicating the presence of flavonoid compounds—quercetin in Pterocarpus and anthocyanins in Ixora.

According to the Indian Pharmacopoeia, quercetin in Pterocarpus should show absorption at 280 ± 2 nm, confirming its authenticity and standardization. Similarly, Ixora coccinea showed anthocyanin presence with a matching absorbance profile at 280 nm, further supporting its pigment profile. The mordant-treated extracts exhibited shifts in absorption patterns, indicating interaction of metal salts with pigments. This supports the potential of these extracts not only as pharmacological agents but also as natural dyes, with differential spectral characteristics based on the solvent and mordant system.

The infrared spectral analysis of both extracts reveals the diverse presence of biologically active phytochemicals. In Pterocarpus marsupium, the absorption peaks confirm the presence of alcohols, phenolic acids, terpenoids, saponins, and ketones. These correspond with known constituents such as pterostilbene, epicatechin, and

flavonoids, which contribute to its antioxidant and antidiabetic effects. Ixora coccinea showed major peaks for flavonoids, carbohydrates, aromatic amines, and terpenoids. The observed functional groups support the presence of alkaloids and glycosides commonly found in the plant. The presence of O–H and C=O stretches also suggests potent antioxidant capabilities due to phenolic and flavonoid constituents. Together, the IR results validate the phytochemical screening outcomes and substantiate the extracts' biological relevance for therapeutic and pharmaceutical applications, especially as natural excipients or actives in formulation science.

The DSC thermogram of Pterocarpus marsupium exhibited a distinct endothermic peak at 189.75°C, indicating the melting of amorphous constituents with an enthalpy change of 60.02 J/g. The broad melting range between 169.09°C and 212.41°C signifies a heterogeneous matrix with moderately high thermal stability. The shape and peak height (4.03 mW) confirm a dense structure and stable thermal profile.

In contrast, Ixora coccinea displayed an endothermic peak at 134.86°C, with a sharper transition starting at 128.95°C and ending at 151.67°C, suggesting the presence of a more volatile or loosely bound crystalline fraction. The enthalpy change was 84.52 J/g, with a higher peak height of 8.82 mW, indicating more rapid thermal decomposition or water loss. The data also reveal minor water evaporation at around 100°C for Ixora coccinea, seen as a pre-peak deviation, aligning with known hygroscopic nature of floral extracts. Overall, both extracts exhibit well-defined melting behaviour. However, Pterocarpus marsupium shows higher thermal robustness, making it more suitable for formulations requiring thermal processing.

The absence of any mortality or signs of toxicity across all administered doses indicates that both Ixora coccinea and Pterocarpus marsupium extracts are safe under acute exposure conditions. The LD_{50} value for both extracts is estimated to be greater than 2000 mg/kg for IK and greater than 1500 mg/kg for IC, placing them in the Category 5 or unclassified range under the Globally Harmonized System (GHS) of Classification and Labelling of Chemicals. This denotes a very low acute toxicity potential. These findings are particularly important for pharmaceutical applications, as they establish a broad therapeutic window and suggest that both extracts can be safely used as natural ingredients in oral formulations. The safety of these botanicals aligns with their traditional use in herbal medicine and further supports their incorporation into modern dosage forms as multifunctional excipients with colouring and possible therapeutic roles.

The DPPH assay confirmed that both Ixora coccinea and Pterocarpus marsupium extracts possess significant antioxidant activity, with a clear dose-dependent response. The greater activity observed with IK extract may be attributed to a higher content of phenolic and flavonoid compounds known for their radical neutralizing capacity. Ascorbic acid, used as the standard antioxidant, displayed superior activity, as expected. The moderate antioxidant potential of the extracts suggests their potential application not only as colorants but also as functional pharmaceutical excipients capable of combating oxidative stress. These results align with earlier findings on phytochemical richness and support further exploration into their therapeutic relevance in oxidative stress-related disorders.

The extracts of Ixora coccinea and Pterocarpus marsupium showed promising glucose- lowering effects in glucose-loaded rats. The IC extract was more effective than the IK extract, particularly at 90 and 120 minutes. This effect is likely due to the presence of flavonoids and phenolic compounds, which may improve glucose uptake and insulin sensitivity. The performance of the IC extract was notably close to that of Glibenclamide, suggesting its potential as a plant-based antidiabetic agent. Further studies are recommended for mechanistic insights and chronic models.

Formulation experiments validated the visual appeal and physical stability of the extracts when integrated into simulated pharmaceutical products. This confirms their suitability for commercial-scale development in tablets, syrups, suspensions, and topical dosage forms.

CONCLUSION

This study demonstrated that Ixora coccinea flower and Pterocarpus marsupium bark extracts possess significant potential as natural dyes for pharmaceutical formulations. Both extracts yielded vibrant colours and showed favourable physicochemical properties, with P. marsupium exhibiting superior pH and thermal stability. Phytochemical analysis confirmed the presence of bioactive compounds, including flavonoids, tannins, and phenolics, while instrumental characterisation validated their chemical integrity and thermal stability. The extracts exhibited notable antioxidant activity and were found to be safe at therapeutic doses in acute toxicity studies. These findings support the use of these botanicals as multifunctional excipients, offering both aesthetic and therapeutic value. Further studies on long-term stability, large-scale formulation, and regulatory compliance will help facilitate their application in commercial pharmaceutical products.

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