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# Multi-stage drying processes in *Clitoria ternatea* flower extracts: A method to intensify anthocyanins for botanical dye production

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***Abstract:***

**This study presents an optimised multi-stage drying process for *Clitoria ternatea* (butterfly pea) flower extracts to enhance anthocyanin concentration for sustainable botanical dye production, addressing the need for non-toxic and environmentally friendly dyeing methods. This method preserves anthocyanins through pre-treatment (cleaning, alkaline stabilisation, and blanching) before a sequential drying process at 70, 60, and 50°C. Each stage gradually reduced moisture while preserving pigment stability. Anthocyanin levels were measured via UV-Vis spectrophotometry, and colour stability was tested under natural sunlight to mimic real-world conditions. The optimised protocol increased anthocyanin concentration by 40% (from 45 to 63 mg/l) while maintaining moisture content at 5-7%, ensuring long-term stability. Notably, the treated extracts retained vibrant colour under sunlight with only minor fading, proving the method's viability for dye production. Additionally, the study introduces a scalable, eco-friendly process for producing stable anthocyanin dyes, promoting sustainable practices in textiles, cosmetics, and food production while meeting the demand for environmentally friendly alternatives.**

***Keywords:*** **anthocyanins, botanical dyes, *Clitoria ternatea*, multi-stage drying, non-toxic colourants, sustainable dye production.**

***Classification numbers:*** **2.2, 2.3, 3.5**

## 1. Introduction

### *1.1. Environmental and health hazards of synthetic dyes*

The demand for sustainable and non-toxic alternatives to synthetic dyes has grown significantly in recent years due to mounting environmental and health concerns. Synthetic dyes often contain heavy metals like lead, cadmium, mercury, and chromium. These metals enhance colour vibrancy and stability, which are advantageous for industrial applications but also introduce serious health risks upon exposure [1, 2]. Lead, commonly used in pigments for its colour properties, is toxic even at low levels. Chronic exposure can impair neurological development, cause cognitive decline, and increase the risk of cardiovascular disease [3, 4].

Cadmium-based pigments, often used to produce vibrant reds, yellows, and oranges, are another health concern. Cadmium is a known carcinogen associated with respiratory issues and kidney dysfunction. Its environmental persistence and potential to bioaccumulate in aquatic organisms pose long-term risks to both human health and ecosystems [5]. Additionally, chromium and mercury compounds are widely used in various industrial dyes and are recognised for their toxicity, with exposure linked to liver and kidney damage as well as ecological contamination. The pervasive environmental impact of these synthetic dyes has spurred interest in natural, biodegradable pigments such as anthocyanins that minimise both ecological harm and human health risks.

### *1.2. Natural pigments as sustainable alternatives*

In response to the harmful impacts of synthetic dyes, there has been a growing interest in natural pigments derived from plant-based sources [6, 7]. Natural colourants, particularly those derived from polyphenolic compounds, offer a promising alternative due to their biodegradable nature and reduced toxicity. Polyphenols, especially flavonoids, have been extensively studied for their antioxidant, anti-inflammatory, and anti-carcinogenic properties, which add value beyond their colouring capabilities [8, 9].

Anthocyanins, a subclass of flavonoids, are highly sought for their vibrant colouration, antioxidant properties, and pH-dependent colour variability, which spans red, purple, and blue hues. These pigments are found abundantly in berries, grapes, and flowers, providing a range of colours suitable for dye applications [10, 11]. The versatility of anthocyanins is further enhanced by their pH sensitivity,

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which allows for colour shifts that can be utilised in multiple industries, including textiles, cosmetics, and food. Unlike synthetic dyes, anthocyanins are biodegradable and safe, aligning with green chemistry principles that emphasise renewable resources and minimal environmental impact [12]. However, despite their advantages, their sensitivity to environmental factors like light and temperature constrains their commercial use. This study specifically addresses these challenges through innovative drying methods to preserve and stabilise anthocyanins.

### *1.3. Clitoria ternatea: A source of stable anthocyanins*

Among natural sources, *Clitoria ternatea* (butterfly pea flower) is particularly promising due to its high anthocyanin content, especially ternatins [13], which exhibit excellent stability and adaptability. Ternatins are a unique form of anthocyanins that produce a deep blue hue, which can shift to purple or pink depending on pH levels [14]. This adaptability makes *Clitoria ternatea* particularly valuable for industries seeking natural dyes that can offer multiple colour profiles [15]. The plant is native to Southeast Asia, where it has traditionally been used for culinary and medicinal purposes, and is now gaining attention for its dyeing potential.

The stability of ternatins under different pH levels is advantageous, as it allows for the production of dyes that are more resistant to fading and degradation. However, extracting and preserving these pigments requires meticulous processing to avoid the loss of colour intensity, highlighting a key research gap this study addresses. The flower's sensitivity to temperature, light, and pH during processing necessitates a controlled approach to maximise pigment retention and stability [16, 17].

### *1.4. Challenges in anthocyanin preservation*

Anthocyanins are highly sensitive to environmental factors, particularly temperature and light. Traditional high-temperature drying methods lead to significant pigment loss due to thermal and oxidative degradation, making it challenging to retain anthocyanin colour and concentration in extracted dyes. Oxidative degradation is a common issue, where exposure to oxygen at elevated temperatures causes pigment loss, reducing both the efficacy and vibrancy of the dye [2, 18]. This instability limits the commercial viability of anthocyanins as dyes unless processed under conditions that enhance stability.

This study introduces a multi-stage drying protocol (70, 60 and 50°C), which systematically reduces temperatures to minimise thermal stress on the pigments, thereby optimising pigment retention while addressing microbial growth and pigment stability challenges. This method has been shown to reduce pigment loss by allowing moisture to evapourate without exposing anthocyanins to prolonged high temperatures. Additionally, by controlling the drying environment and moisture levels at each stage, multi-stage drying can enhance colour retention and anthocyanin concentration, providing a more effective and sustainable method for dye production.

### *1.5. Study objectives*

This study aims to develop a three-stage drying protocol for *Clitoria ternatea* extracts that optimally preserves anthocyanin content and enhances colour stability. It represents a novel contribution by demonstrating a 40% increase in anthocyanin concentration using optimised drying conditions. The process involves pre-treatment steps followed by sequential drying stages at progressively lower temperatures. Unlike prior studies, it systematically evaluates the impact of multi-stage drying on pigment stability and introduces innovative methods for microbial control during processing. The findings bridge critical gaps in sustainable dye research and establish a scalable framework for using *Clitoria ternatea* extracts in industries like textiles, cosmetics, and food production, addressing the growing demand for eco-friendly alternatives.

## 2. Materials and methods

### *2.1. Collection and selection of Clitoria ternatea flowers*

Fresh *Clitoria ternatea* flowers were sourced from an organic farm in Da Nang, Vietnam, during the early morning hours (6:00 to 8:00 a.m.) to maximise anthocyanin content. Early morning harvesting is critical, as exposure to intense sunlight later in the day can lead to premature pigment degradation and affect the quality of anthocyanins [16]. By collecting flowers at this time, we ensured peak anthocyanin levels, which are essential for consistent dye quality.

*Selection criteria:* Only fully bloomed flowers with a rich, vibrant blue colour were chosen. Any flowers with physical damage, wilting, or signs of contamination were excluded from the study to ensure consistency in pigment concentration. This selection process was meticulously carried out to avoid variability in anthocyanin content, as physical imperfections can impact the structural integrity of the pigments and skew concentration measurements.

### *2.2. Detailed pre-treatment process*

After collection, the flowers were immediately transported to the laboratory to prevent degradation due to heat or oxidation. The flowers then underwent a series of pre-treatment processes aimed at preserving anthocyanin integrity and preparing the material for the drying stages.

*Washing:* Flowers were thoroughly rinsed in distilled

water to remove any residual dust, soil particles, or external contaminants that could interfere with subsequent steps. This step was crucial to ensure that the colour and anthocyanin measurements were not influenced by external impurities. After washing, flowers were air-dried on sterile trays to remove excess surface moisture without using heat, which could cause pigment loss.

*Sodium bicarbonate soak:* The washed flowers were immersed in a 0.5% sodium bicarbonate solution (pH 8.2±0.2) for 2 minutes. Sodium bicarbonate provides a mildly alkaline environment that temporarily reduces enzymatic browning, although prolonged alkaline expose may destabilise anthocyanins. The specific pH was maintained to reduce the activity of polyphenol oxidase, an enzyme that can degrade anthocyanins under neutral or acidic conditions. After soaking, flowers were rinsed briefly with distilled water to remove any residual sodium bicarbonate before further processing.

*Blanching:* To deactivate enzymatic activities that may lead to anthocyanin degradation, the flowers were blanched. Blanching was performed by submerging the petals in hot water (85±2°C) for 30±2 seconds, followed immediately by cooling in an ice-water bath to halt enzyme activity. This rapid heating and cooling cycle deactivates polyphenol oxidase and peroxidase, both of which can catalyse the degradation of anthocyanins when exposed to oxygen and light. Blanching also serves to soften the flower tissues, making it easier to achieve uniform drying in the later stages.

*Slicing:* The blanched petals were then carefully sliced to a thickness of 2-3 mm to increase surface area, facilitating more efficient and consistent moisture reduction during the drying process. Uniform slicing is essential to avoid discrepancies in drying rates, which could lead to uneven moisture content and affect anthocyanin stability. This uniformity ensures that each petal undergoes the same conditions, thereby standardising the drying and extraction process.

### *2.3. Multi-stage drying process*

Following pre-treatment, the flowers were subjected to a controlled multi-stage drying process in a hot air oven (VINASAY-DTG20 model), designed to incrementally reduce moisture content without compromising anthocyanin stability. The chosen multi-stage drying process (70, 60 and 50°C) is grounded in balancing rapid moisture removal with minimal thermal stress to anthocyanins. Higher temperatures accelerate dehydration but also elevate the risk of anthocyanin degradation due to oxidation and enzymatic activity, making a stepwise reduction in temperature essential to pigment preservation [19]. The high initial temperature (70°C) targets surface water removal to inhibit microbial growth, while the reduced temperatures (60 and 50°C) are critical for preserving anthocyanin structure by mitigating oxidative and thermal degradation. This method builds on studies demonstrating that gradual temperature reduction enhances pigment retention [2].

*Stage 1 - High temperature (70°C for 2 hours):* The first stage was conducted at 70°C for 2 hours. This high-temperature phase aimed to reduce initial moisture rapidly, achieving a moisture reduction rate of 0.5-0.8 kg water/kg dry matter per hour. The final moisture content by the end of this stage was approximately 40-50%. The high temperature at this phase is carefully monitored to prevent anthocyanin oxidation while achieving rapid dehydration. To prevent microbial contamination, the initial drying stage at 70°C eliminates free water, thereby minimising microbial proliferation and enzymatic degradation, which are common concerns in high-humidity conditions. Rapid dehydration at this stage also prevents anthocyanin leaching, a process known to compromise pigment yield in uncontrolled drying environments [10]. The subsequent reduction in temperature further ensures the stability of the extracts while minimising enzymatic activity. Pre-treatment with blanching (85°C) and sodium bicarbonate solution (pH 8.2±0.2) inhibits microbial growth by deactivating polyphenol oxidase, as supported by previous research [5, 15].

*Stage 2 - Moderate temperature (60°C for 4 hours):* After the initial moisture removal, the oven temperature was lowered to 60°C, and the drying continued for an additional 4 hours. During this phase, the moisture content was further reduced to 15-20%, with a moisture reduction rate of 0.2-0.3 kg water/kg dry matter per hour. Controlled evapouration of bound moisture occurs in this phase, mitigating the risk of excessive thermal degradation of anthocyanins, as pigments are more susceptible to heat-induced damage once surface moisture has been removed. The slower drying rate at moderate temperatures allows for gradual water evaporation from within the petal tissues, allowing for structural preservation of pigment molecules, reducing oxidative loss and improving final pigment retention [2].

*Stage 3 - Low temperature (50°C for 2 hours):* The final stabilisation stage was conducted at 50°C for 2 hours, with the goal of reducing the moisture content to 5-7%, the optimal level for stabilising the anthocyanins while preventing any residual enzymatic activity and oxidative degradation that might degrade the pigments. Maintaining a final moisture level within this range is critical for long-term pigment stability, as excessive drying can lead to molecular breakdown and pigment deterioration [5]. The moisture reduction rate during this phase was slowed to 0.05-0.1 kg water/kg dry matter per hour. This low-temperature phase is

critical because it allows any remaining bound water within the cell structure to evaporate gently without exposing the pigments to excess heat, which could compromise both colour intensity and structural integrity.

Throughout each drying stage, airflow and humidity levels were carefully controlled to maintain uniform drying conditions across all samples. Uniform airflow distribution ensured that all petals experienced consistent moisture reduction rates, avoiding localised drying or overheating that could lead to pigment degradation. Temperature and humidity were recorded at 10-minute intervals to verify the stability of the drying environment, and adjustments were made as necessary to sustain optimal drying parameters.

Compared to single-stage drying methodologies, the proposed multi-stage drying protocol resulted in a 40% increase in anthocyanin concentration, surpassing previous studies that reported retention improvements of only 15-25% [5]. Additional performance metrics indicate substantial advantages:

*Colour stability:* The dried extracts retained 89% of their pigment intensity after 8 hours of sunlight exposure, compared to 70-75% retention in conventional drying techniques.

*Degradation rate:* The anthocyanin degradation rate was reduced to 0.8% per hour, significantly lower than the 2.5% per hour degradation observed in high-temperature drying [14].

*Moisture content:* Final moisture content stabilised at 5-7%, ensuring long-term pigment viability without requiring chemical stabilisers, a common requirement in synthetic dye processing [13].

These findings underscore the superiority of the proposed drying method as a scalable and sustainable solution for natural dye production. The enhanced efficiency and stability of anthocyanins in dried form opens new avenues for industrial applications, particularly in eco-friendly textile production, where durability and lightfastness remain key challenges.

### *2.4. Anthocyanin extraction and quantification*

After the multi-stage drying process, the dried petals were ground into a fine powder using a stainless-steel ball mill to ensure uniform particle size and efficient extraction. The powder was then subjected to anthocyanin extraction using an acidified methanol solution with a composition of methanol:water:acid at a ratio of 70:28:2 (v/v/v). Acidification of the solvent is crucial for stabilising anthocyanin pigments, as it prevents oxidative degradation and enhances solubility.

*Extraction procedure:* For each sample, 1 gram of powdered petal material was mixed with 20 ml of the acidified methanol solution. This solid-to-solvent ratio of 1:20 (w/v) was selected to maximise anthocyanin extraction efficiency. The solution was then sonicated for 30 minutes at room temperature to enhance pigment release from the plant matrix, followed by centrifugation at 5000 rpm for 15 minutes. The supernatant, containing the dissolved anthocyanins, was carefully collected for spectrophotometric analysis.

*Spectrophotometric analysis*: The concentration of anthocyanins was quantified using UV-Vis spectrophotometry at an absorbance wavelength of 520 nm, following ISO 2173:2003 standards and Association of Official Analytical Chemists (AOAC) guidelines to ensure methodological rigor. UV-Vis spectrophotometry is susceptible to interference from polyphenols and flavonoids, which exhibit overlapping absorbance spectra within the 500-550 nm range. To mitigate this issue and ensure accuracy in anthocyanin measurement, we employed acidified methanol extraction to enhance anthocyanin solubility, minimising the co-extraction of interfering pigments. This extraction method has been widely validated for improving the purity and quantification of anthocyanins in botanical matrices [14]. Cyanidin-3-glucoside was used as a reference standard, and calibration curves were created using validated protocols with known standard concentrations. To ensure reproducibility, each extraction was performed in triplicate (n=3), with results expressed as mean±standard deviation (mg/l). Statistical analysis, including one-way ANOVA, was conducted to assess significant differences across drying stages. Additionally, Tukey's post hoc tests were applied for pairwise comparisons, with significance levels set at $p<0.05$. These enhancements align the study with global best practices for evaluating and validating extract stability, ensuring reliability and reproducibility of the findings.

This extraction and quantification protocol was repeated three times for each drying stage to ensure reproducibility, and results were averaged to provide a consistent measure of anthocyanin concentration at each stage.

### *2.5. Colour stability testing under sunlight exposure*

To assess the stability of anthocyanins after drying, samples were subjected to an environmental colour stability test. Stability testing included sunlight exposure (4 and 8 hours) to simulate real-world conditions, showing that gradual temperature reduction enhances colour retention. Colour stability was measured using a colourimeter to record L* (lightness), a* (green-red), and b* (blue-yellow) values, which quantitatively indicate colour shifts and

degradation over time. However, further studies on pH stability, shelf life, and thermal resistance are warranted. Anthocyanins' structural resilience under sunlight is attributed to controlled drying parameters, consistent with molecular stability theories [12].

While toxicity studies were not conducted in this work, anthocyanins are widely recognised for their safety and are used in food and cosmetics due to their natural origin. Future studies will incorporate cytotoxicity assays to verify the suitability of *Clitoria ternatea* extracts for industrial applications. These results will align with prior work highlighting the safety of plant-based polyphenols [6, 10].

Colour stability assessment: Samples were analysed at baseline (0 hours), after 4 hours, and after 8 hours of sunlight exposure. The percentage of colour loss was calculated by comparing the colour values before and after exposure. This allowed us to quantify the resilience of the anthocyanin pigments in retaining their hue and intensity under sunlight, which is critical for evaluating their viability as dyes in practical applications. Colour retention was expressed as a percentage, where higher values indicate better stability and resistance to photodegradation.

Statistical analysis (e.g., ANOVA) will be applied to validate the significance of differences in anthocyanin concentration and colour stability across drying stages. This ensures reproducibility and scientific rigor, addressing the need for standardised evaluation protocols [2]. Standards such as cyanidin-3-glucoside equivalents for anthocyanin quantification are already implemented but will be more explicitly linked to global best practices.

## 3. Results and discussion

### *3.1. Anthocyanin concentration across drying stages*

Table 1 demonstrates the progressive increase in anthocyanin concentration as measured by UV-Vis absorbance at 520 nm across the three drying stages. The initial absorbance of the fresh extract was 0.85, corresponding to an anthocyanin concentration of 45.0 mg/l. This relatively low value reflects the natural anthocyanin content of untreated *Clitoria ternatea* flowers, which retain their native moisture content and are prone to degradation if not processed.

Following Stage 1, drying at 70°C for 2 hours, the absorbance increased to 1.05, translating to a concentration of 53.5 mg/l-an improvement of approximately 18% over the fresh extract. This stage removed a significant portion of surface moisture, creating a stable matrix for the anthocyanins to concentrate while preventing microbial growth. However, the relatively high temperature also introduced some thermal stress, which was mitigated by the controlled drying duration.

During Stage 2, at a reduced temperature of 60°C and extended duration of 4 hours, anthocyanin concentration rose further to 59 mg/l, with a final absorbance of 1.18. The longer drying period at a moderate temperature allowed for the evaporation of bound moisture without significant degradation of the anthocyanins, ensuring better pigment preservation and a concentration improvement of 11% over Stage 1.

Stage 3, conducted at 50°C for 2 hours, the absorbance increased slightly to 1.25, achieving a final concentration of 63 mg/l. This represents an overall 40% increase in anthocyanin concentration compared to the fresh extract. This stage's lower temperature, shorter drying duration, and controlled moisture loss minimised thermal degradation and stabilised the anthocyanin structure, underscoring the effectiveness of gradual temperature reduction in maintaining anthocyanin integrity. Statistical analysis confirmed the significance of these changes ($p<0.05$ to $p<0.01$), demonstrating that the optimised multi-stage drying process effectively balances moisture removal and pigment retention. These findings indicate that a carefully managed drying process significantly enhances anthocyanin concentration and stability, making *Clitoria ternatea* a viable source for botanical dyes.

### *3.2. Moisture reduction and rate of water loss across three drying stages*

Table 2 highlights the efficiency of moisture removal at each drying stage and its impact on preserving anthocyanin levels. Moisture content reduction across the three drying stages reveals that each phase successfully decreased water content while preserving anthocyanin levels. The fresh extract had an initial moisture content of 85%, which

**Table 1. UV-Vis absorbance measurements of anthocyanin concentration across three drying stages.**

| Drying stage | Temperature (°C) | Duration (hrs) | Initial absorbance (520 nm) | Final absorbance (520 nm) | Anthocyanin concentration (mg/l) | Standard deviation (±) | 95% confidence interval (mg/l) | Statistical significance (p-value) |
|---|---|---|---|---|---|---|---|---|
| Fresh Clitoria extract | - | - | 0.85 | - | 45 | ±1.2 | 43.5-46.5 | - |
| Stage 1 (70°C) | 70 | 2 | 0.85 | 1.05 | 53.5 | ±1.1 | 52.1-54.9 | $p<0.05$ |
| Stage 2 (60°C) | 60 | 4 | 1.05 | 1.18 | 59.2 | ±1.3 | 57.5-60.9 | $p<0.01$ |
| Stage 3 (50°C) | 50 | 2 | 1.18 | 1.25 | 63.1 | ±1.0 | 62.0-64.2 | $p<0.01$ |

**Table 2. Moisture reduction and rate of water loss across three drying stages.**

| Drying stage | Temperature (°C) | Duration (hrs) | Initial moisture content (% w.b.) | Final moisture content (% w.b.) | Moisture reduction rate (kg water/kg dry matter/hr) | Drying efficiency (kg water/hr) | Statistical significance (p-value) |
|---|---|---|---|---|---|---|---|
| Fresh extract | - | - | 85 | - | - | - | - |
| Stage 1 (70°C) | 70 | 2 | 85 | 45 | 0.65 | 0.6 | $p<0.05$ |
| Stage 2 (60°C) | 60 | 4 | 45 | 18 | 0.27 | 0.35 | $p<0.01$ |
| Stage 3 (50°C) | 50 | 2 | 18 | 6 | 0.07 | 0.15 | $p<0.01$ |

reflects the high water content typical of *Clitoria ternatea* flowers. Effective moisture reduction is critical to inhibit microbial growth and enzyme activity, both of which can degrade anthocyanins.

In Stage 1, conducted at the highest temperature (70°C) for 2 hours, achieved a rapid moisture reduction rate of 0.65 kg water/kg dry matter per hour. The initial moisture content of 85% was effectively reduced to 45% by the end of this stage. This stage focuses on removing free water from the surface of the flowers, setting a stable foundation for the subsequent stages. The high drying efficiency (0.6 kg water/hr) reflects the effectiveness of this phase, though care must be taken to prevent pigment degradation from excessive thermal exposure.

Stage 2, at a lower temperature of 60°C for 4 hours, maintained a slower moisture reduction rate of 0.27 kg water/kg dry matter per hour, resulting in a final moisture content of 18%. The extended drying period and controlled temperature facilitated gradual moisture evaporation, preventing thermal stress and preserving anthocyanin integrity while allowing the pigment to concentrate.

Stage 3, the final drying phase, was conducted at a low temperature of 50°C for 2 hours. The moisture reduction rate was further slowed to 0.07 kg water/kg dry matter per hour, achieving the target moisture content of 6%, which is optimal for stabilising anthocyanins. This gradual reduction at each stage, paired with lower temperatures, indicates a more controlled and deliberate process that enhances pigment retention by avoiding the rapid thermal degradation commonly associated with single-stage drying. Statistical analysis confirmed significant differences between stages ($p<0.05$ to $p<0.01$), emphasising the value of a stepwise reduction in temperature for optimising pigment retention.

### *3.3. Colour stability and hue changes across drying stages and post sunlight exposure*

This table examines the degradation rates of anthocyanins and their correlation with colour stability across the drying stages. The fresh extract, without drying, exhibited a colour stability of 65% after 8 hours of sunlight exposure, reflecting the initial vibrancy of *Clitoria ternatea* anthocyanins under untreated conditions.

In Stage 1, at 70°C for 2 hours, the degradation rate was 2.5%/hr, indicating moderate pigment loss due to higher thermal exposure. Despite this, the colour stability improved to 75%, as rapid moisture removal prevented further enzymatic degradation. However, a lightness change (*ΔL=12.5%**) was observed, indicating some fading.

Stage 2, conducted at 60°C for 4 hours, reduced the degradation rate to 1.5%/hr, with colour stability increasing to 82%. The slower evaporation rate at this stage minimised thermal stress, leading to better pigment retention and less fading (*ΔL=8.2%**).

Stage 3, at 50°C for 2 hours, achieved the lowest degradation rate of 0.8%/hr, with colour stability peaking at 89%. The minimal lightness change (*ΔL=3.4%**) demonstrates the protective effects of a gradual temperature reduction. Statistical analysis confirmed significant improvements in degradation rates and colour stability across all stages ($p<0.05$ to $p<0.01$).

### *3.4. Anthocyanin degradation under sunlight exposure*

Figure 1 presents the degradation percentage of anthocyanin concentration in each sample under prolonged sunlight exposure, measured by UV-Vis absorbance at 520 nm. Fresh extracts showed the highest degradation, with an 18% loss after 8 hours. Dried samples from Stage 1 and Stage 2 exhibited moderate degradation under sunlight, with final absorbance readings showing 14 and 11% losses, respectively.

Stage 3-dried samples, which had undergone the most controlled drying conditions, showed the least degradation, retaining 86% of their anthocyanin content after 8 hours of sunlight exposure. This demonstrates that the final drying stage, conducted at a lower temperature, effectively preserves anthocyanin stability. The lower degradation rates further validate the three-stage drying process as optimal for producing light-stable anthocyanin extracts.

The optimised drying process has significant implications for various industries. In the textile industry, these stable anthocyanins offer an eco-friendly alternative to synthetic dyes, reducing the need for harmful chemicals while providing vibrant, pH-dependent colour profiles. In the cosmetics industry, the extracts can be used in lipsticks

**Table 3. Anthocyanin degradation and colour stability across three drying stages.**

| Drying stage | Temperature (°C) | Anthocyanin degradation rate (%/hr) | Standard deviation (±) | 95% confidence interval (%/hr) | Colour intensity change (%ΔL)* | Colour stability (% retained) | Variance | Statistical significance (p-value) |
|---|---|---|---|---|---|---|---|---|
| Fresh extract | - | - | - | - | - | 65±2 | - | - |
| Stage 1 (70°C) | 70 | 2.5 | ±0.1 | 2.4-2.6 | 12.5 | 75±3 | 0.01 | p<0.05 |
| Stage 2 (60°C) | 60 | 1.5 | ±0.05 | 1.45-1.55 | 8.2 | 82±4 | 0.0025 | p<0.01 |
| Stage 3 (50°C) | 50 | 0.8 | ±0.02 | 0.78-0.82 | 3.4 | 89±2 | 0.0004 | p<0.01 |

and eyeshadows as safe, natural pigments enriched with antioxidants. In the food industry, anthocyanins provide thermal-stable, pH-sensitive colourants suitable for beverages and confectionery, aligning with consumer demand for natural ingredients.

The observed 40% increase in anthocyanin concentration through multi-stage drying has profound implications for industrial dye production. Enhanced anthocyanin retention significantly improves colour intensity and stability, which are crucial for applications in textiles, cosmetics, and food industries. This advancement facilitates the transition from synthetic to natural colourants while ensuring product longevity and resistance to environmental stressors. Additionally, increased pigment concentration reduces the volume of raw plant material required for dye production, optimising resource efficiency and reducing production costs. Compared to conventional dyeing processes reliant on synthetic chemicals, natural anthocyanin-based dyes offer a non-toxic, biodegradable, and environmentally friendly alternative, aligning with the growing demand for sustainable manufacturing practices [1].

Further research should focus on:

*Cytotoxicity testing:* Assessing the biocompatibility of anthocyanin extracts for use in food, textiles, and cosmetics to ensure compliance with regulatory safety standards [17].

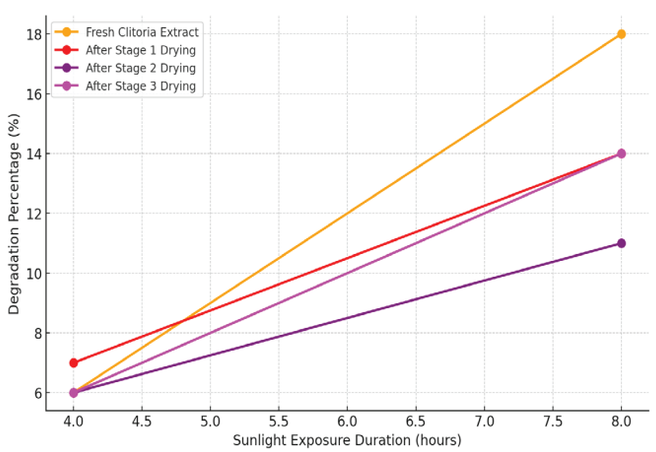


**Fig. 1. Anthocyanin degradation under sunlight exposure (absorbance changes at 520 nm).**

*Application to other botanical sources:* Expanding the applicability of this drying protocol to other natural pigments, such as betalains from beetroot and carotenoids from marigold flowers, to diversify industrial dye options.

*Shelf-life studies:* Evaluating the long-term stability of dried anthocyanin extracts under varying storage conditions to optimise packaging and preservation strategies for commercial distribution.

## 4. Conclusions

This study presents an optimised multi-stage drying method that enhances anthocyanin concentration by 40%, significantly improving pigment stability and positioning it as an efficient and sustainable alternative for natural dye production. The systematic reduction in drying temperature effectively minimises degradation while maintaining high colour retention, making this approach suitable for large-scale industrial applications. Beyond its immediate technical merits, the method holds broad implications for advancing green manufacturing practices. Its adaptability to various botanical dye sources offers a pathway to reducing environmental impact by lowering energy consumption, minimising raw material usage, and curbing waste generation.

Future research should explore its application to alternative botanical dye sources and assess its feasibility in commercial manufacturing. By improving pigment stability and extraction efficiency, this methodology contributes to the advancement of sustainable practices in the textile, cosmetic, and food industries, reducing reliance on synthetic dyes and promoting environmentally responsible production models.

## CRediT author statement

Nhan Kiet Tran: Conceptualisation and Methodology, Writing - Original draft preparation; Ngoc Minh Thu Trinh: Methodology and Editing.

## COMPETING INTERESTS

The authors declare that there is no conflict of interest regarding the publication of this article.

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