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Evaluating the Stability of Red Dragon Fruit (*Hylocereus polyrhizus*) as Natural Dyes: Impact of Concentration, pH and Storage Duration

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Abstract

This research explores the application of Hylocereus polyrhizus extracts as natural dyes, emphasizing anthocyanin content, stability, and light absorption under varying conditions. The findings indicate that undiluted extracts attain maximum light absorption in the 520-550 nm spectrum, aligning with the anthocyanin pigments that impart the fruit's vivid color. Increased dilution results in diminished absorbance, attributable to reduced anthocyanin levels. The research highlights the importance of pH on pigment stability, with optimal absorption at pH 3-4, while elevated pH leads to decreased absorption due to anthocyanin structural alterations. Notably, a rise in absorbance on Day 15 of a 15-day storage period may indicate pigment stabilization, potentially through copigmentation with phenolic compounds. Nonetheless, a general decline in total anthocyanin content across samples is noted, likely influenced by environmental conditions and extraction inefficiencies. This investigation underscores the potential of red dragon fruit extracts as viable, sustainable dye sources for DSSCs and other applications.

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1. INTRODUCTION

The increasing focus on renewable energy sources has resulted in substantial progress in dye-sensitized solar cells (DSSCs), which serve as a promising and economically viable substitute for conventional silicon-based solar technology. DSSCs are distinguished by their capacity to incorporate natural pigments as sensitizers, thus providing a sustainable and ecologically responsible method for energy conversion [1]. One particularly advantageous source of natural pigments is the red dragon fruit (Hylocereus polyrhizus), which derives its striking hue from the existence of anthocyanins. These natural pigments possess the capability to function as light-harvesting agents in DSSCs, rendering them an appealing alternative to synthetic dyes [2].

Recent research has underscored the promise of extracts from red dragon fruit as potent natural dyes for dye-sensitized solar cells (DSSCs), owing to their substantial anthocyanins content [3], [4]. The pulp and peel of red dragon fruit are rich in these pigments, rendering them feasible candidates for eco-friendly dye production [5]. Nevertheless, the stability and effectiveness of these natural pigments are susceptible to various determinants, including pH levels and storage environments.

Not withstanding the encouraging prospects of natural dyes in dye-sensitized solar cells (DSSCs), a significant void persists in the existing literature concerning the stability of red dragon fruit extracts, particularly from both the pulp and the peel, across varying pH levels and extended storage periods [6]. While prior investigations have largely concentrated on the immediate effectiveness of these dyes, there is a dearth of comprehensive data regarding their long-term stability under diverse environmental conditions [7]. This absence of information impedes the advancement of commercially feasible DSSCs that utilize natural pigments, as stability and longevity are critical for sustained energy production.

Despite the promising potential of red dragon fruit (*Hylocereus polyrhizus*) extracts as natural dyes, particularly for dye-sensitized solar cells (DSSCs), there is limited understanding of the precise mechanisms behind the observed stabilization of anthocyanins over time, as well as the impact of varying environmental conditions on the efficiency of anthocyanin extraction and retention[8]. This research build upon previous studies, which explored the impact of deep eutrentic solvent extraction on the degradation kinetic of anthocyanins under various conditions, highlighting the importance of extraction methods in preserving anthocyanin stability.

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2. MATERIALS AND METHODS

The investigation initiated with the procurement of fresh dragon fruit pulp and peel specimens of varying dimensions. These specimens were subsequently diced into minute fragments, purified, and processed until a homogenous consistency was attained, as illustrated in Figure 1. Following the blending of the material, one percent ethanol and one-tenth hydrochloric acid were amalgamated in a beaker and agitated for ten minutes utilizing a magnetic stirrer. Subsequently, the mixture was enveloped in aluminum foil and allowed to rest for a full twenty-four hours. In order to evaluate the influence of pH, one milliliter of the ethanol extract was combined with three hundred milliliters of citric acid at pH levels of four, five, and six. An ethanol extract solution (1.5% by volume) was assessed in five hundred milliliters of water to ascertain the effects of storage duration. The absorbance of this solution was quantified employing a UV-Vis spectrophotometer across a wavelength range of 300–700 nm. Dragon fruit that had undergone storage for differing durations—specifically, one, eight, and fifteen days—was utilized to evaluate the effect of the storage period. A graphical representation of wavelength and absorbance was constructed using Microsoft Excel subsequent to the statistical analysis of the absorbance data, and it was juxtaposed with the reference anthocyanin spectrum to ascertain the efficacy of the anthocyanin extraction procedure. Furthermore, to elucidate the modifications induced by prolonged storage and variations in pH, the data were systematically organized into tables and line histograms. Provide sufficient detail to allow the work to be reproduced by independent researchers.

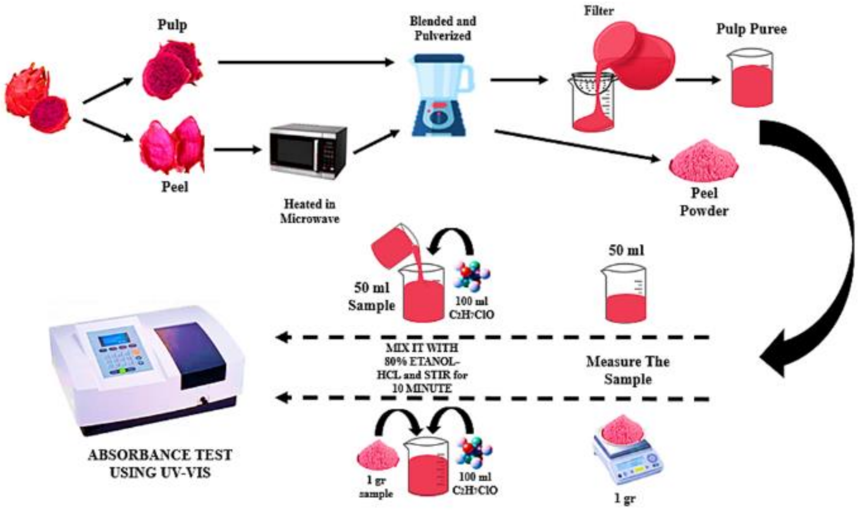


Figure 1. The process of extracting anthocyanin from pulp and dragon fruit peel

3. RESULT AND DISCUSSION

Effect of Concentration

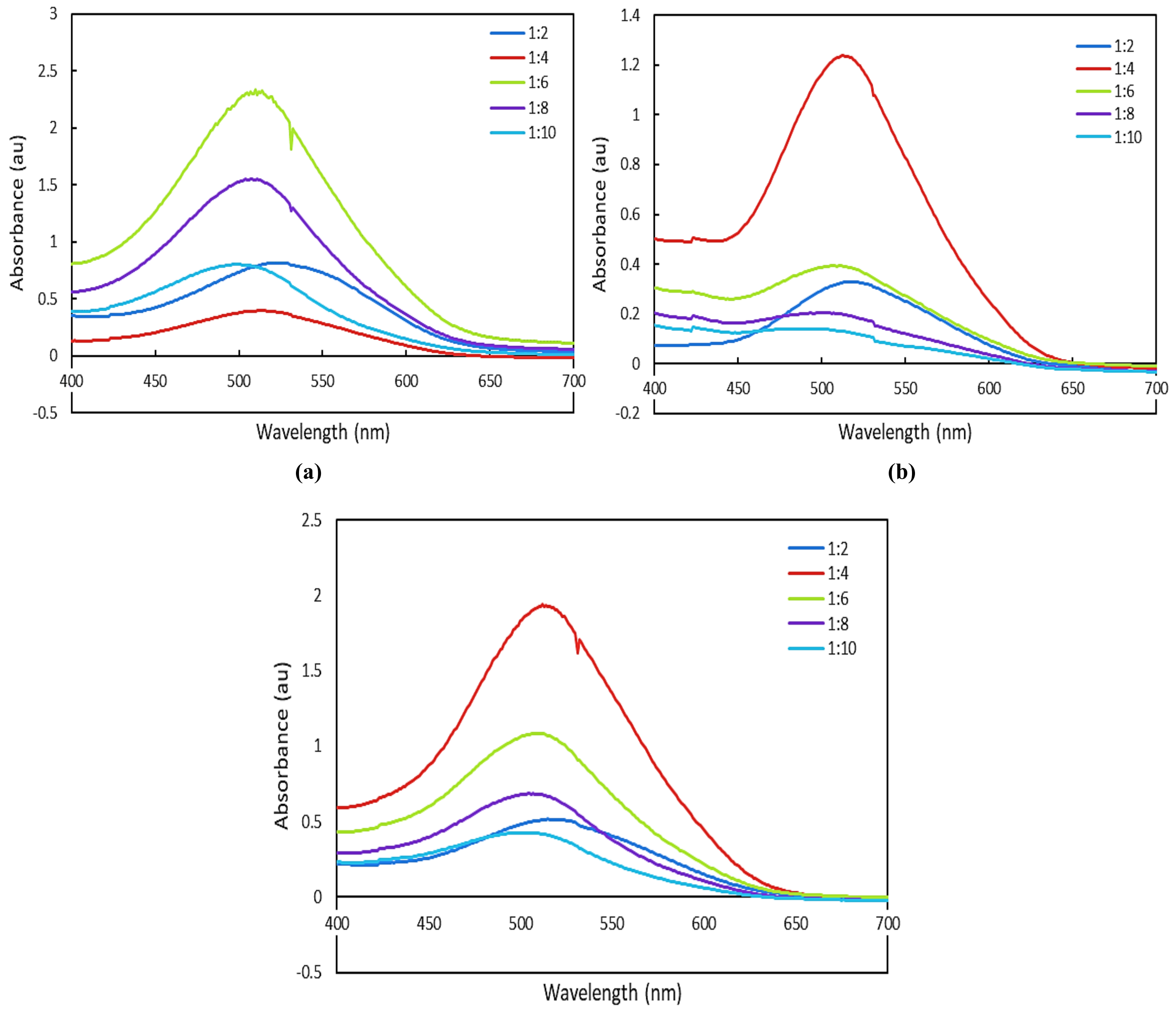
Figure 2 illustrates the absorbance spectra of distinct extracts from red dragon fruit (*Hylocereus polyrhizus*), specifically those derived from the pulp, peel, and a combination of both, evaluated across a range of light wavelengths. Each graph represents the absorbance at various dilution ratios (1:2, 1:4, 1:6, 1:8, 1:10), with the most significant peaks observed in the undiluted samples. Each extract attains its peak absorbance within the 520-550 nm range, which aligns with the light-absorbing characteristics inherent to anthocyanins, the pigments that confer the dragon fruit's rich red-violet hue. As the degree of dilution escalates, the absorbance diminishes, a phenomenon frequently observed as the concentration of anthocyanins declines, thereby lessening the ability to efficiently absorb light. The graphs further elucidate certain distinctions between the pulp and peel extracts, with the pulp extract exhibiting a wider peak and the peel extract manifesting a more discrete peak, implying potential differences in anthocyanin composition or concentration.

The primary factor contributing to the noted modifications (Figure 2) in the absorption spectra is predominantly ascribed to the dilution of the extracts, which leads to a reduction in anthocyanin concentration and a subsequent decline in their ability to absorb light. In addition to dilution, variables such as pH sensitivity and the potential degradation of pigments over time may further influence the absorption characteristics[9]. Anthocyanins are well-documented for their peak absorption within the visible spectrum and demonstrate a high sensitivity to pH variations, which can result in alterations in the wavelength or intensity of the absorption peaks. This phenomenon corresponds with the observation that anthocyanin absorption decreases with dilution and is subject to modulation by environmental factors[10].

Effect of pH

Figure 3 presents the absorbance spectra for dragon fruit extracts (pulp, skin, and a combination) under various pH levels, such as unbuffered samples and those at pH 3, 4, 5, and 6. Throughout all three charts, the absorbance peaks are predominantly located around the 520-550 nm range, which corresponds to anthocyanin absorption. In the unbuffered situation, the absorbance remains consistently lower, indicating that pH control may contribute to anthocyanin instability. At pH 3 and pH 4, the extracts display elevated absorbance peaks, particularly in the pulp and peel extracts, suggesting that anthocyanins are more stable and absorb light more effectively in these slightly acidic environments. As the pH rises to 5 and 6, the absorbance decreases, which may be due to structural changes in the anthocyanins as they lose color and become less proficient at absorbing light.

The observed shifts (Figure 3) can be attributed to the pH-sensitivity of anthocyanins, which alter their molecular structures based on the pH of their surroundings. At lower pH values, anthocyanins take on their red-hued flavylium cation form, leading to enhanced light absorption due to heightened absorbance. Conversely, as the pH progresses towards neutrality, anthocyanins change into less vibrant quinoidal bases or chalcones, thereby decreasing their capacity to absorb light[11]. This behavior is consistent with studies that anthocyanins exhibit maximum stability in acidic conditions (pH 1-4) and anthocyanins degrade in alkaline conditions, consequently lowering their light absorption [12].



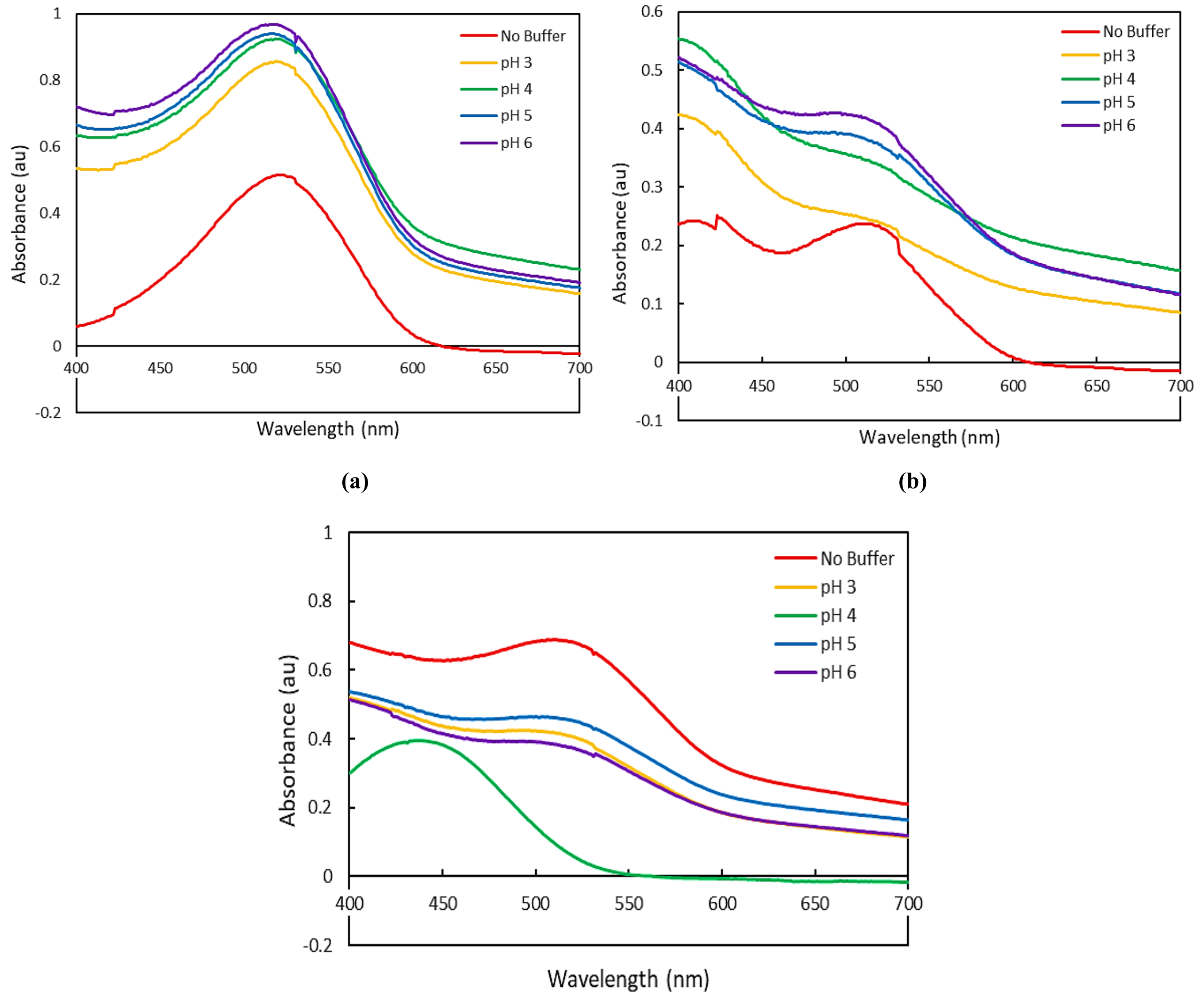
(a) (b) (c)

Figure 2. Sample absorbance spectrum from various concentration of (a) dragon fruit pulp extract, (b) dragon fruit peel extract, (c) dragon fruit peel mix with pulp extract

Effect of Storage Duration

The illustration at Figure 2 showcases the absorbance spectra of red dragon fruit pulp (A), peel (B), and their combined extracts (C) over a 15-day span, with measurements taken on Days 1, 8, and 15. In all cases, the primary absorbance peaks appear around 520-550 nm, indicating the presence of anthocyanins, primarily in the pulp and peel extracts. Over this period, a significant enhancement in absorbance is observed, with the maximum peaks appearing on Day 15 across the entire spectrum. This pattern suggests that the pigment concentration in the extracts might be either maintaining or increasing steadily, with the peel extract exhibiting a more expansive and pronounced peak in the 520-600 nm range, suggesting potential interactions with other pigments such as betalains or flavonoids. Additionally, the combined peel and pulp extract demonstrates a substantial rise in absorbance, most notably from Day 1 to Day 8, implying that the integration of both fruit components may contribute to enhanced pigment stabilization.

The shifts in absorbance could be linked to a gradual release of pigments from the dragon fruit's cellular structure, coupled with the potential enhancement of anthocyanins' stability over time. Anthocyanins, known to deteriorate under specific environmental circumstances, can display enhanced absorbance when paired with other polyphenols or stabilizing agents [13]. This boost in absorbance is a result of copigmentation, a process where anthocyanins interact with other phenolic compounds, resulting in improved color stability and heightened light absorption [14]. These results suggest that the augmented absorbance observed in dragon fruit extracts might be attributed to these stabilization mechanisms, enabling the pigments to absorb light more efficiently over an extended period.



(a) (b)

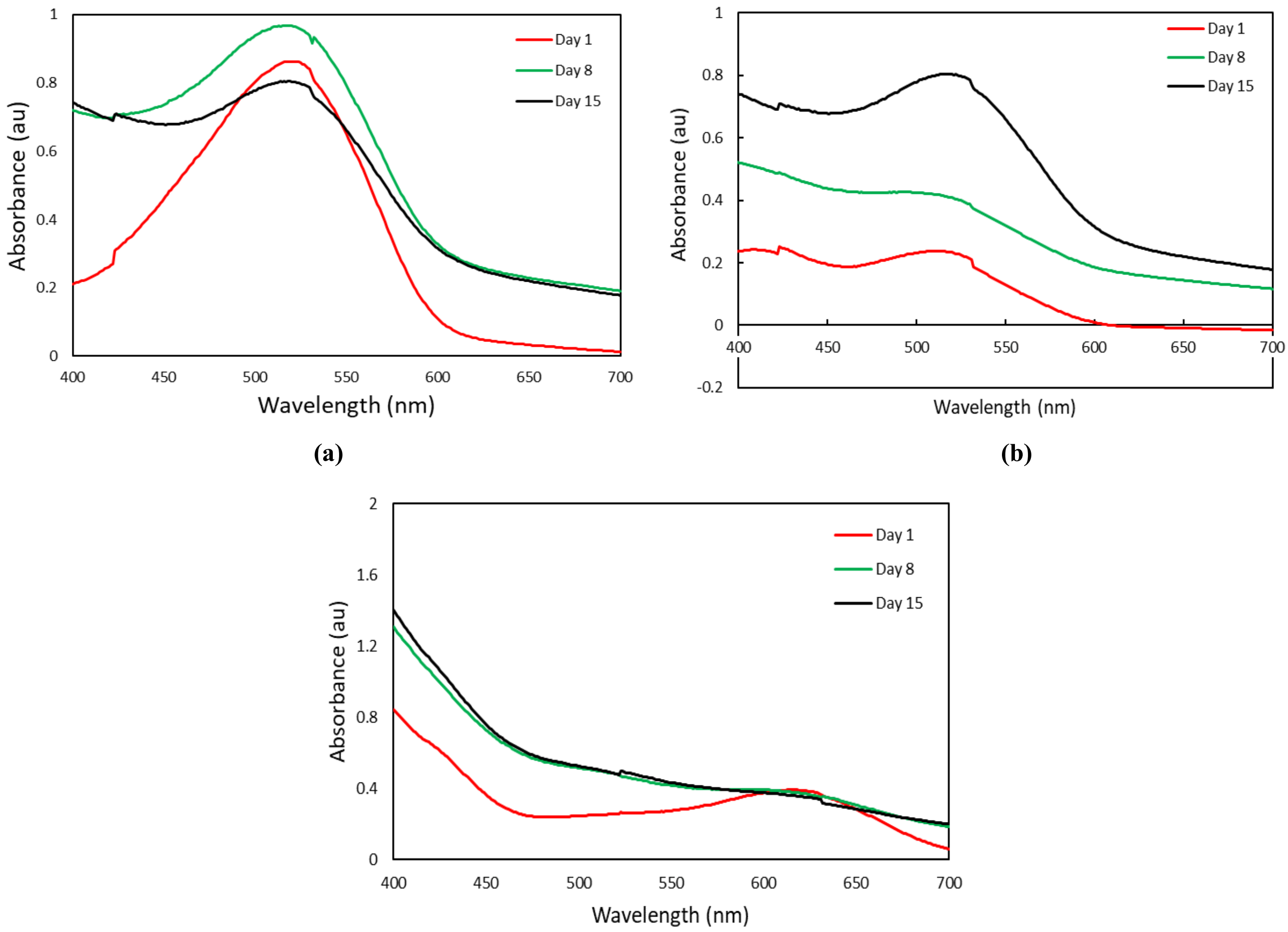
(c)

Figure 3. Sample absorbance spectrum from various pH of (a) dragon fruit pulp extract, (b) dragon fruit peel extract, (c) dragon fruit peel mix with pulp extract.

Total Anthocyanin

Figure 5 presents the total anthocyanin content (mg/L) in four separate dragon fruit extract samples, each weighing between 10.118 g and 10.708 g. The anthocyanin concentration begins at 81.825 mg/L for a 10.237 g sample, but it gradually decreases to 61.786 mg/L in the 10.708 g sample. The slight variations in the sample weights do not significantly impact the overall trend, which shows a clear decrease in anthocyanin content. This decline suggests that factors outside of the sample weight, such as pigment degradation, variations in extraction efficiency, or alterations in environmental conditions during the extraction process, may have affected the anthocyanin levels.

The decrease in anthocyanin concentration (Figure 5) may be attributed to several plausible reasons, including the deterioration of anthocyanins during the extraction process, which can be instigated by unwelcome conditions such as exposure to heat, light, or pH fluctuations [15]. Anthocyanins are vulnerable to environmental changes, and any alterations in the extraction procedure, such as inconsistent homogenization or disparities in solvent penetration, could decrease their stability and concentration. Research from various sources, indicates that anthocyanins deteriorate rapidly under conditions like high temperature, neutral or alkaline pH, and sunlight exposure [16]. This deterioration process likely contributes to the observed decrease in anthocyanin concentration across the various sample weights.



(c)

Figure 4. Sample absorbance spectrum from various storage duration of (a) dragon fruit pulp extract, (b) dragon fruit peel extract, (c) dragon fruit peel mix with pulp extract.

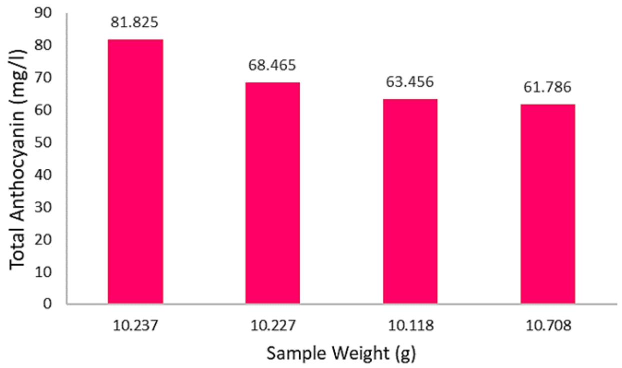


Figure 5. Anthocyanin content in the unit mg/g for dragon fruit in various weight

From Figure 5, we can see some interpretations as follows:

1. **Relationship Between Sample Weight and Anthocyanin Content:**
   The figure shows that as the sample weight increases, the total anthocyanin content decreases. This trend is consistent across the different sample weights presented. This inverse relationship suggests that smaller samples of dragon fruit may have a higher concentration of anthocyanins on a per-gram basis. This could imply that the anthocyanin content is not uniformly distributed within the fruit, potentially due to differences in the cellular structure, pigment concentration in different parts of the fruit, or variations in the efficiency of the extraction process at different sample sizes[17].

2. **Anthocyanin Content Variation:**
   The total anthocyanin content varies significantly among the samples, ranging from 61.786 mg/L to 81.825 mg/L. This variation could be attributed to several factors, including the ripeness of the fruit, environmental conditions during growth, or differences in the efficiency of the extraction process[18]. It is also possible that other phenolic compounds present in the samples could interact with anthocyanins, either stabilizing or degrading them, leading to the observed differences.

3. **Implications for Practical Applications:**
   The data indicates that there is a non-linear relationship between the weight of the dragon fruit sample and the extracted anthocyanin content. For practical applications, such as using dragon fruit extracts as natural dyes or in DSSCs, it may be more efficient to use smaller, more concentrated samples to maximize anthocyanin yield[19]. This insight can guide the optimization of extraction protocols to ensure the highest possible anthocyanin content, which is crucial for the efficacy of the extract in various applications.

4. **Potential Limitation in Data Interpretation:**
   The weights of the samples are very close to each other (ranging from 10.118 g to 10.708 g), which might limit the generalization of the observed trend. A broader range of sample weights could

provide a clearer understanding of how weight influences anthocyanin content[20]. The method of extraction and its efficiency are not detailed in the figure, which could affect the anthocyanin content measured. Variability in the extraction process might lead to inconsistencies in the data, primarily if not standardized across samples.

Figure 5 suggest a potential optimization strategy for maximizing anthocyanin yield from dragon fruit by adjusting sample sizes. However further research with a wider range of weights and controlled extraction methods is necessary to understand relationship between sample weight and anthocyanin content fully[21]. This would enable more precise application in food science, cosmetic, renewable energy fields.

Table 1. showcases various plant sources of anthocyanins, their concentration amounts, applications, and related scientific referencing

Plan Name	*Anthocyanin Content*	Application of Anthocyanin	References
Citrus Sinesis	20 – 50 mg/100 g	Beverages with functional properties and natural hues in cosmetic products	(Hillebrand et al., 2004)
Fragaria x ananassa	30 – 60 mg/100 g	Nutritional supplements, food dyes, cosmetic skincare items	(Chaves et al., 2017)
Hylocereus polyrizhus	90 – 190 mg/L	Solar cells powered by natural food dyes (Natural Food Dye-Sensitized Solar Cells, NFD-SSC)	(Sundawan et al., 2022)
Malus domestica	10 – 30 mg/100 g	Nutritional boosters, organic hue providers, additional nutritional sources, organic food dyes, Dietary enhancements, all-natural coloring agents for food	(Chen et al., 2021)
Prunus cerasus	100 – 250 mg/100 g	Medications against excess weight, functional ingredients for food enrichment	(Damar & Ekşi, 2012)
Ribes nigrum	200 – 400 mg/100 g	Inflammation-reducing substances, antioxidant compounds, and hues obtained from natural resources for food coloring.	(Slimestad & Solheim, 2002)
Rubus ideaus	200 – 400 mg/100 g	Inflammation-reducing substances, plant-based pigments, cosmetic constituents	(Bowen-Forbes et al., 2010)
Sambucus nigra	700 – 1.500 mg/100 g	Boosters for the immune system, antiviral substances, and all-natural dyes derived from food.	(Inami et al., 1996)
Vaccinium Coeymbosum	250 – 500 mg/100 g	Antioxidant-laden supplements, serving as natural food pigments, enhance cardiovascular health.	(Wagh et al., 2024)
Vitis vinifera	300 – 700 mg/L	Wine tint preservation, antioxidant compounds, dietary supplements with therapeutic properties	(Núñez et al., 2004)

Table 1 showcases various plant sources of anthocyanins, their concentration amounts, applications, and related scientific referencing. The Citrus sinensis (offering 20-50 mg/100 g) is utilized in functional beverages and cosmetics, as per Hillebrand et al., 2004. The Fragaria × ananassa (boasting 30-60 mg/100 g of anthocyanins) is incorporated into nutritional supplements and skincare products, as stipulated by Chaves et al., 2017. The Hylocereus polyrhizus (providing 30-300 mg/L) contributes to powering natural food dye-sensitized solar cells, as Sundawan et al., 2022 revealed. The Malus domestica (containing 10-30 mg/100 g) is employed in food coloring and nutritional enhancement, according to Chen et al., 2021. The Prunus cerasus (offering 100-250 mg/100 g) aids in weight management and functional food ingredients, as reported by Damar & Ekşi, 2012. The Ribes nigrum and Rubus idaeus (both delivering 200-400 mg/100 g) provide anti-inflammatory agents and natural colorants, as cited by Slimestad & Solheim, 2002 and Bowen-Forbes et al., 2010. The Sambucus nigra (offering 1,200-1,500 mg/100 g) supports immune function and functions as an antiviral, as demonstrated by Inami et al., 1996. Vaccinium corymbosum (providing 250-500 mg/100 g) serves as an antioxidant-rich food pigment, as anticipated by Wagh et al., 2024, while Vitis vinifera (delivering 300-700 mg/L) preserves wine color and has therapeutic potential.

For a more detailed comparison of each content Table 1 includes limitations as follows:

1. **Citrus Sinensis (Orange)**
   Anthocyanin Content: 20–50 mg/100 g
   Application: Used in beverages for functional properties and as natural hues in cosmetic products.
   Explanation: Citrus Sinensis is utilized primarily for its moderate anthocyanin content, which provides a natural coloring agent for beverages and cosmetic products[22]. The anthocyanins contribute to the vibrant color and also offer some health benefits due to their antioxidant properties.
   Limitation: The relatively low anthocyanin content may require large quantities of raw material to achieve the desired pigmentation, which might not be cost-effective. Additionally, the specific type of anthocyanin in Citrus Sinensis may not be as stable or effective in all formulations, limiting its utility in certain products[23].

2. **Fragaria x ananassa (Strawberry)**
   Anthocyanin Content: 30–60 mg/100 g
   Application: Used in nutritional supplements, food dyes, and cosmetic skincare items.
   Explanation: Strawberries are valued for their moderate anthocyanin content, making them a popular choice for natural food dyes and in cosmetic products that benefit from their antioxidant properties[24].
   Limitation: The anthocyanin content in strawberries can be quite variable, depending on the ripeness and growing conditions[25]. Additionally, the stability of strawberry anthocyanins might be lower, leading to color fading over time in processed products.

3. **Hylocereus polyrhizus (Red Dragon Fruit)**
   Anthocyanin Content: 90–190 mg/L

Application: Applied in dye-sensitized solar cells (Natural Food Dye-Sensitized Solar Cells, NFD-SSC).
Explanation: Red dragon fruit is noted for its use in solar cells due to its relatively high anthocyanin content, which is effective in absorbing light in specific wavelengths, making it suitable for energy applications[26].
Limitation: The anthocyanin content is presented in mg/L, which might vary depending on the concentration of the fruit extract used[27]. The efficiency of the dye in solar cells might also be impacted by the stability of the anthocyanins under prolonged exposure to light and varying temperatures.

4. **Malus domestica (Apple)**
Anthocyanin Content: 10–30 mg/100 g
Application: Used in nutritional boosters, organic hue providers, and as natural coloring agents in food.
Explanation: Apples have a lower anthocyanin content[28], making them less potent as a coloring agent but useful in organic and health-focused products due to their additional nutritional benefits.
Limitation: The low anthocyanin content means that apples are not the most efficient source for pigmentation[29]. The type of anthocyanins present in apples may also be less vibrant compared to other sources, limiting their application in products where strong coloration is required.

5. **Prunus cerasus (Sour Cherry)**
Anthocyanin Content: 100–250 mg/100 g
Application: Used in medications for weight management and as functional ingredients for food enrichment.
Explanation: Sour cherries are rich in anthocyanins[30], making them effective in health-oriented products, particularly for their antioxidant and anti-inflammatory properties.
Limitation: The anthocyanin content can vary significantly with different cultivars and environmental factors. The bioavailability of anthocyanins from sour cherries in therapeutic applications might also vary, potentially reducing their efficacy[31].

6. **Ribes nigrum (Blackcurrant)**
Anthocyanin Content: 200–400 mg/100 g
Application: Used as inflammation-reducing substances, antioxidant compounds, and natural food coloring.
Explanation: Blackcurrants are a potent source of anthocyanins, widely used for their health benefits and strong pigmentation in food products[11].
Limitation: While blackcurrants have a high anthocyanin content, their intense flavor and acidity may limit their use in some food products[32]. Additionally, the stability of the anthocyanins in blackcurrants can be affected by processing methods, leading to potential color degradation.

7. **Rubus idaeus (Raspberry)**
Anthocyanin Content: 200–400 mg/100 g
Application: Used in inflammation-reducing substances, plant-based pigments, and cosmetic constituents.
Explanation: Raspberries are valued for their high anthocyanin content, making them effective as natural colorants in both food and cosmetics, as well as for their anti-inflammatory properties[33].
Limitation: The anthocyanin content in raspberries can be inconsistent due to factors like ripeness and harvest time. Additionally, raspberry anthocyanins are prone to degradation under heat and light, which can limit their stability in processed products[34].

8. **Sambucus nigra (Elderberry)**
Anthocyanin Content: 700–1,500 mg/100 g
Application: Used as immune system boosters, antiviral substances, and all-natural dyes derived from food.
Explanation: Elderberries are extremely rich in anthocyanins, making them one of the most potent natural sources for health supplements and natural dyes with strong pigmentation[35].
Limitation: Despite their high anthocyanin content, elderberries may have a strong, bitter taste, limiting their use in certain food products. The high content also raises concerns about potential overconsumption of anthocyanins, which may lead to adverse effects if not properly regulated[36].

9. **Vaccinium corymbosum (Blueberry)**
Anthocyanin Content: 250–500 mg/100 g
Application: Used in antioxidant-laden supplements, serving as natural food pigments, and enhancing cardiovascular health.
Explanation: Blueberries are well-known for their high anthocyanin content, widely used in health supplements and as natural food colorants[37].
Limitation: The anthocyanin content in blueberries can be affected by storage and processing conditions, leading to potential loss of both color and nutritional benefits. Additionally, the high demand for blueberries can drive up costs, making them less accessible for large-scale applications[38].

10. **Vitis vinifera (Grapes)**
Anthocyanin Content: 300–700 mg/L
Application: Used in wine tint preservation, antioxidant compounds, and dietary supplements with therapeutic properties.
Explanation: Grapes, particularly in wine production, are valued for their anthocyanin content, which contributes to the color and antioxidant properties of wines[39].
Limitation: The anthocyanin content in grapes can vary depending on the grape variety, climate, and winemaking processes[40]. The potential degradation of anthocyanins during fermentation and aging can also affect the final anthocyanin content in the wine, influencing both color and health benefits.

4. CONCLUSION

The research delves into an in-depth examination of the anthocyanin concentration and stability in extracts derived from red dragon fruit (Hylocereus polyrhizus), taking into account variables such as dilution, pH levels, storage duration, and extraction efficiency. The light absorption patterns across varying dilution proportions demonstrate that the highest anthocyanin absorption occurs in the undiluted samples, predominantly within the 520-550 nm spectrum, suggesting the pigments' optimal ability to absorb light. However, as dilution increases, the absorption decreases, aligning with a reduction in anthocyanin concentration. The pH examination underscores the pigments' sensitivity, with the most stability observed at pH 3-4, where the absorbance peaks are most pronounced. Conversely, higher pH levels result in reduced absorption due to structural alterations in the anthocyanins. Over a 15-day storage period, a notable increase in absorption was detected, particularly on Day 15, implying that the pigment concentration either maintains its stability or increases progressively over time, possibly due to copigmentation with other phenolic compounds. Nevertheless, despite these stabilizing factors, a progressive decline in the total anthocyanin content was observed in some samples.

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