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Synthesis and characterisation of natural colourant microcapsules from *Clitoria ternatea* flowers

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ABSTRACT

Clitoria ternatea (CT), locally known as *bunga telang*, is traditionally used as a natural food colourant in Malaysia. However, its colour stability is limited due to its high sensitivity to heat. This study investigated the microencapsulation of CT-derived natural colourants using six different polymers, including polymethyl methacrylate (PMMA), carboxymethyl cellulose, sodium alginate, gelatine, acacia gum, and chitosan. The CT flowers were extracted with an alkaline solution (pH 10.5), and encapsulation was performed using *in situ* polymerisation to facilitate microcapsule formation. The structural, morphological, and size characteristics of the microcapsules were analysed using field emission scanning electron microscopy (FESEM). The results revealed that capsule size varied depending on the polymer used. Among the tested polymers, PMMA microcapsules (1.13 ± 0.12 µm) demonstrated superior uniformity, sphericity, and smoother surfaces with fewer cracks compared to other polymers. Microencapsulation efficiency was further evaluated through ultraviolet-visible spectrophotometry, where PMMA microcapsules exhibited the highest absorbance profile, indicating their potential as an efficient polymer for encapsulating CT extracts. Thus, the microencapsulation of CT extracts, particularly with PMMA, is expected to enhance stability and broaden the application of this natural colourant in food, textile, and pharmaceutical industries.

Keywords: *Clitoria ternatea, In-situ polymerisation, Microcapsules*

1. INTRODUCTION

Natural products have a wide range of chemical and biological activities. They have played an important role in the development of medicines, food additives, and cosmetics due to their safety and compatibility with living systems. These products are derived from marine animals, fungi, bacteria, and plants [1]. Over the years, plant extracts, essential oils, and isolated natural compounds in pure form have been utilised for various purposes. Compared to synthetic dyes, natural colourants, which are bioactive components responsible for colour formation, are less stable and more susceptible to oxidation during storage. Moreover, natural colourants that are biocompatible with both plants and animals, such as anthocyanins, carotenoids, and antioxidants, are frequently utilised in the healthcare industry [2]. Consequently, natural colourants are being promoted as alternatives to synthetic dyes, with the aim of protecting the environment and reducing pollution. Many plants contain pigments known as anthocyanins, which have a blue, red, or purple appearance. Natural colourants like anthocyanins are notable for combining vivid colouration with health-promoting properties, such as antioxidant effects. They are most commonly found in fruits, flowers, and tubers. In acidic environments, anthocyanins appear as a red pigment, whereas in alkaline environments, they appear as a blue pigment [3]. Their basic structure consists of a C6–C3–C6 flavylium ion skeleton with hydroxyl and methoxy groups, allowing anthocyanins to interact with metal ions, proteins, and polysaccharides, thereby accounting for their morphological diversity and bioactivity [4]. These qualities make them particularly valuable in industries prioritising safety, sustainability, and aesthetic appeal. Consequently, many healthcare industries extensively use these pigments and other organic colour compounds due to their good antioxidant properties and biocompatibility with both plants and animals [5]. However, factors such as temperature, pH, light, metal ions, and redox agents can readily alter the unstable structure of anthocyanins, eventually resulting in colour changes.

Among anthocyanin-rich plants, *Clitoria ternatea (CT),* locally known as *bunga telang*, has the potential to be utilised as a natural dye. It is an important source of anthocyanins and has recently attracted considerable interest for its high colour intensity and high anthocyanin content, with increasing attention to its potential health benefits [6]. Despite these unique advantages, the industrial application of CT extracts is limited by the inherent instability of anthocyanins, which are highly

sensitive to environmental factors such as light, temperature, and pH [7]. These sensitivities cause degradation that may reduce their efficacy or longevity in various applications. To address this challenge, advanced stabilisation techniques are required to extend the functional lifespan of anthocyanins while maintaining their structural integrity.

Correspondingly, microencapsulation offers an effective means to overcome these challenges. Microencapsulation is a technique that protects sensitive compounds, such as anthocyanins, by encapsulating them in a stable carrier material. This process protects the bioactive compounds from adverse environmental factors, improves their stability, and enables controlled release in applications related to food preservation, drug delivery, and textile dyeing [8]. The encapsulation technique can be developed for various purposes using different polymers, which optimise stability, release rate, and compatibility with the medium. Different polymers exhibit distinct physicochemical properties that influence the stability, permeability, and release kinetics of encapsulated anthocyanins. The selection of these polymers was based on their unique interactions, which affect stability and release profiles. They were also selected for their proven safety, scalability, and broad acceptance in food, pharmaceutical, and cosmetic applications. Therefore, this study offers a comparative evaluation of their effectiveness in encapsulating CT extracts and provides insights into their potential for industrial-scale use. The hydrophobic and rigid characteristics of polymethyl methacrylate (PMMA) ensure good barrier properties against moisture and oxidation [9]. Carboxymethyl cellulose (CMC) is a polymeric material that forms a viscous solution in an aqueous medium due to its high solubility in water [10]. Meanwhile, the biodegradable gel-forming polymer sodium alginate allows slow and controlled diffusion of anthocyanins [11]. Gelatine is a protein-based polymer that interacts with anthocyanins through hydrogen bonding, which enhances adhesion and stability [12]. Acacia gum, a natural polysaccharide, protects anthocyanins with a smooth protective coating while maintaining the solubility of *C. ternatea* [13]. Additionally, chitosan is a cationic biopolymer that exhibits strong electrostatic interactions with anthocyanins, enhancing encapsulation efficiency and antimicrobial properties [14].

Despite the growing interest in natural colourants, the instability of anthocyanins from CT under environmental stress limits their industrial application. Microencapsulation is a promising method to improve their stability; however, few comparative studies have been conducted using different encapsulating polymers. Therefore, this study aims to synthesise and characterise microcapsules of CT extracts using six different polymers: PMMA, CMC, sodium alginate, gelatine, acacia gum, and chitosan through *in situ* polymerisation. It is hypothesised that the choice of polymer will greatly affect the morphology, stability, and release behaviour of the microcapsules. This will help identify the most suitable candidates for potential applications in the food, pharmaceutical, and textile industries.

2. MATERIALS AND METHODS

Dried CT flowers were supplied by PWJ Herbs, Selangor, Malaysia. The primary encapsulating agent, MMA, along with the polymerisation initiator, azobisisobutyronitrile (AIBN), were supplied by Sigma-Aldrich (USA). Other chemicals used, including liquid paraffin, polyethylene glycol sorbitan monooleate (TWEEN® 80), sorbitol monooleate (Span® 80), and sodium hydroxide (NaOH), were obtained from Chemiz (M) Sdn. Bhd. (Shah Alam, Malaysia). The polymer encapsulating materials, such as CMC, sodium alginate, acacia gum, chitosan, and gelatine, were also purchased from the same company. All chemicals used were of analytical grade. Alkaline solutions were prepared using distilled water and NaOH to achieve the required pH values.

2.1. Extraction of CT Dye

Five grams of dried CT flower was soaked in 50 mL of alkaline solution with a pH of 10.5 in a refrigerator at 8°C (SC-D3-1830TCH Sakato, Malaysia) for 24 h. The alkaline solution was prepared by adjusting 5% NaOH to achieve the desired pH. The pH of the solution and extracts was measured using a handheld pH meter (Hanna Instruments, UK). The solutions were then filtered, and the pH of the extracts was measured. After that, the extracts were stored in a refrigerator (SC-D3-1830TCH Sakato, Malaysia) at 4°C and used within 48 h.

2.2. Synthesis of CT Microcapsules using *In Situ* Polymerisation

The synthesis of the microcapsules was carried out using *in situ* polymerisation involving two phases: aqueous and oil phases. For the aqueous phase, 1% TWEEN® 80 was mixed with 33.7 mL of extract. For the oil phase, PMMA was mixed with 8% AIBN dissolved in liquid paraffin and 1% Span® 80 in a 91:8:1 (v/v/v) ratio to create the oil phase. The aqueous and oil phases were then mixed in a 3:1 ratio and homogenised using an Ultra-Turrax homogeniser (T-25 Ultra-Turrax, Ika Malaysia) at 15,000 rpm for 5 min to create an aqueous-in-oil emulsion. Subsequently, the emulsion was incubated for 4 h at 70°C in an oven (SOV140B, Thermo-Line, Australia). Following the reaction, microcapsules were obtained by filtering the emulsion using Whatman filter paper No. 1. The resulting microcapsules were allowed to dry at 4°C in a refrigerator. The steps were repeated for other polymers, replacing PMMA with CMC, sodium alginate, gelatine, acacia gum, and chitosan, respectively [15]. The microcapsules were placed in a 60 mm × 15 mm glass petri dish, centred on a white A4 sheet, and images were taken with a smartphone camera (iPhone 13, USA) at a 90° vertical (top-down) angle under constant ambient laboratory lighting.

2.3. Morphological Characterisation

Field emission scanning electron microscopy (FESEM, Smur4800, Hitachi, Japan) was employed to investigate the structural and morphological characteristics of the microcapsules. An auto fine coater (JFC-1600, Jeol,

Malaysia) was used to apply a thin layer of gold onto the microcapsules. The coating process was carried out for 10 min at 50 mA under vacuum. After coating, the microcapsules were drop-cast onto the conductive tape, and the surface morphology of the CT-polymer microcapsules was examined. High-magnification images (5,000× and 10,000×) of the microcapsules were captured to assess the size, shape, and effect of the microcapsules.

2.4. Light Absorption Profiling

The encapsulation efficiency of the microcapsules produced was analysed by examining their light absorption profile. Prior to analysis, the CT-polymer microcapsules were dissolved in distilled water at a concentration of 6.86 mg/mL and vortexed (JuanJuan, China) for 5 min, followed by centrifugation using a Sigma 1-14 mini centrifuge (Santorius, USA) at 8,000 × g for 30 s. The supernatant was subsequently analysed at wavelengths ranging from 400 to 700 nm using an ultraviolet-visible (UV-vis) spectrophotometer (UV-1280, Shimadzu, Japan). For each sample, three separate aliquots were prepared and measured.

2.5. Ternatin Index

The Ternatin index (TI) was calculated as the ratio of absorbance at 617 nm to that at 573 nm, as shown in Equation (1), measured using a UV-vis spectrophotometer (UV-1280, Shimadzu, Japan).

$$\text{Ternatin Index (TI)} = \frac{A_{617}}{A_{573}} \quad (1)$$

2.6. Statistical Analysis

All data are presented as mean ± standard deviation. Each experiment was conducted in triplicate, and the data were analysed using one-way analysis of variance, followed by Tukey's honest significant difference test at a significance level of $p < 0.05$ using Minitab (Version 17, Minitab LLC, 2010).

3. RESULTS AND DISCUSSION

3.1. Visual Observation of CT-Polymer Microcapsules

Figure 1 illustrates the differences in visual appearance of the microcapsules produced using various polymers. The microcapsules exhibited a range of conditions, from dry, powdery forms to gel-like structures, and showed variations in colour intensity, indicating polymer-dependent differences in morphology and encapsulation behaviour. The PMMA microcapsules (Figure 1(a)) exhibited a compact and granular structure, indicating uniform particle distribution and reduced aggregation. The CMC microcapsules (Figure 1(b)) have a gel-like texture and are dark with an opaque appearance. A less-defined structure was shown by the irregular and diffuse edges. Additionally, the microcapsules appeared to have an uneven distribution of contents, as evidenced by the darker spots within. In contrast, the surface of sodium alginate microcapsules (Figure 1(c)) is irregular and features darker clusters. These microcapsules displayed a gel-like texture and a semi-transparent appearance. The edges were slightly irregular, and the interior showed a mix of lighter and darker regions, indicating a non-uniform distribution of the contents. Furthermore, the microcapsules prepared with gelatine (Figure 1(d)) were observed to be uniform in appearance, light blue, and have a comparatively smooth structure. They have a translucent blue colouration with a relatively uniform distribution of the encapsulated material. However, they exhibited a gel-like appearance with a semi-transparent texture. There was little variation in colour throughout the structure, while the edges were comparatively well-defined. Meanwhile, the acacia gum microcapsules (Figure 1(e)) appeared less uniform, with darker and irregular areas suggesting uneven encapsulation or partial agglomeration of the core substances. Their bluish colouring and noticeable dark patches indicate that the enclosed material is not evenly distributed. Compared to other microcapsules, the edges seemed diffused and slightly rough, giving the particles a less defined outline based on visual observation. Similar to PMMA, chitosan microcapsules (Figure 1(f)) also formed powdery microcapsules with a slightly dark blue colour. The surface appeared rough and compact, suggesting a dry and rigid structure compared to the other polymers.

The powdery morphology of the PMMA microcapsules suggests that PMMA forms a solid encapsulating matrix with limited moisture retention, resulting in dry and stable microcapsules. This behaviour can be attributed to the rigid structure of PMMA, which facilitates the formation of stable particulate powders. This indicates effective encapsulation with distinct limits. During *in situ* polymerisation, the smooth surface indicates homogeneity in particle production. Polymethyl methacrylate is ideal for sensitive bioactives such as anthocyanins due to its hydrophobic properties and polymerisation process, which may offer enhanced protection against environmental factors like light and moisture [16]. Conversely, chitosan, a naturally occurring polysaccharide, also forms powdery

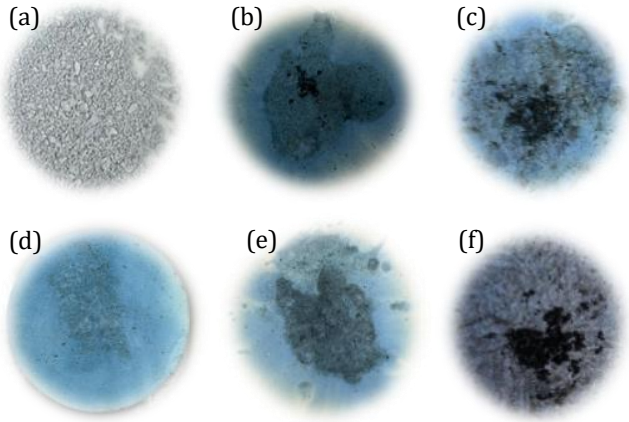

Figure 1. CT microcapsules produced using different polymers: (a) PMMA, (b) CMC, (c) sodium alginate, (d) gelatine, (e) acacia gum, and (f) chitosan

microcapsules. Its interaction with the CT extract may have caused a rough and granular texture, likely due to the limited solubility of chitosan under neutral conditions and strong hydrogen bonding. Chitosan microcapsules exhibit a denser core with a darker, textured appearance, probably resulting from strong interactions between the polymer and the core material. Derived from chitin, chitosan is a cationic polymer that is highly effective for encapsulating anionic substances like anthocyanins [17]. This characteristic makes it possible to encapsulate these substances efficiently, leading to the formation of dense microcapsules with high encapsulation efficiency [1]. However, due to its pH-dependent solubility, chitosan is susceptible to acidic conditions, which may cause instability or partial dissolution. This pH sensitivity can affect the release profile and overall stability of the encapsulated compounds, making it an important consideration in the design of chitosan-based delivery systems [1].

Meanwhile, CMC microcapsules have a denser core with a slightly diffused or smeared appearance. The darker areas most likely show an uneven distribution of the dye or bioactive substances. Carboxymethyl cellulose is a hydrophilic polymer that interacts well with water and possesses strong polar emulsification due to its hydroxymethyl group, making it suitable for proportionally encapsulating polar compounds, including anthocyanins derived from CT extract [18]. Consequently, CMC can also enhance anthocyanin stability and bioavailability; previous studies have shown that the use of CMC in emulsions improved both encapsulation efficiency and protection of anthocyanins from degradation. The relatively uneven distribution may reflect difficulties in organising a consistent polymeric matrix around particles during encapsulation, including factors such as the viscosity of the CMC solution, the encapsulation method employed, and the interactions between the polymer and anthocyanins. This suggests that the substances being encapsulated may have aggregated or partially leaked. In contrast, the irregular and gel-like shapes of sodium alginate microcapsules arise from their hydrophilic nature, which enables gel formation in the presence of divalent cations such as calcium [19]. Sodium alginate is quite effective at encapsulating water-soluble compounds [20]. This characteristic makes it appropriate for various applications, including food preservation and drug delivery. Based on visual observations, PMMA and chitosan appear to be the best polymers for encapsulating the CT extract.

3.2. Morphological Characteristics of CT-Polymer Microcapsules

Figure 2 presents the surface characteristics of microcapsules prepared with different polymers at 10,000× magnification using FESEM, highlighting their distinct morphological features. The PMMA microcapsules (Figure 2(a)) appeared spherical and uniform in shape, indicating a smooth surface morphology with minimal irregularities, hence showing a well-formed structure. The arrangement of the microcapsules suggests a closely packed or aggregated pattern, with distinct boundaries visible between individual microcapsules. The images also showed no large pores or defects on the surface, revealing compactness and consistent encapsulation. In contrast, although chitosan microcapsules exhibited a powdery form when conducting FESEM, the images for chitosan microcapsules (Figure 2(f)) revealed a rough and uneven surface with noticeable folds and creases. These folds and creases compact the formations into irregularly textured shapes, with no visible uniformity in shape. The surface displays pronounced protrusions and indentations, indicating a rugged and dense morphology.

On the other hand, the surface structure of CMC microcapsules (Figure 2(b)) exhibited flattened, irregular morphological features, with noticeable areas of smooth regions interspersed with rough patches. Cracks or lines were present in some areas, indicating possible surface tension effects or deformation. Furthermore, the morphology displayed dense and slightly depressed areas, suggesting that the encapsulation process was non-homogeneous. In contrast, the images of sodium alginate microcapsules, as presented in Figure 2(c), showed a highly porous surface morphology with interconnected networks of voids. The structure was irregular, featuring a rough texture and well-defined ridges. The dominant structure was porous, containing small cavities and openings across the surface, thereby giving it a spongy appearance. These surface irregularities suggest a less compact encapsulation, with visible gaps and crevices.

Apart from that, the surface morphology of gelatine microcapsules (Figure 2(d)) showed minimal surface irregularities, with a more uniform texture compared to other polymers. However, no circular shapes appeared in the images. The microcapsules displayed a slightly wavy or layered structure, with a few scattered depressions or indentations visible in certain areas. Additionally, images of acacia gum microcapsules (Figure 2(e)) revealed rough and uneven surface morphologies. Visible ridges, folds, and irregular patterns give a rugged appearance. These microcapsules are relatively non-compact, with some regions appearing porous or loosely packed.

The spherical and uniform shape of the PMMA microcapsules indicates cross-linking or stable polymerisation during encapsulation. For controlled-release applications, a spherical shape usually offers the best surface area-to-volume ratio, as it reduces the rate at which encapsulated substances diffuse [21]. The smooth surface suggests the absence of major surface defects, minimal interaction with ambient moisture during fabrication, and effective polymer curing [22]. In contrast, chitosan microcapsules showed rough and porous structures, implying rapid solvent evaporation that results in uneven polymer layers. Possible causes of this unevenness include rapid solvent evaporation during processing, such as solvent casting or spray drying [23]. Insufficient polymer chain relaxation or redistribution during drying also occurs. Certain areas of the images revealed fractured or irregular layers, indicative of weak polymer chain cross-linking or insufficient contact with the encapsulated substance [24]. Furthermore, chitosan is

prone to shrinkage during dehydration, which may increase the likelihood of an uneven and rough surface.

The flattened or uneven microstructures observed in CMC microcapsules suggest potential issues or special features in the encapsulation process. It is possible that the structure partially collapsed during drying, indicating inadequate cross-linking or reduced mechanical strength of the polymer. Flattening may also result from the loss of internal moisture or air pockets in the matrix [25]. Furthermore, the morphology of the CMC microcapsules exhibits an irregular surface. These surface irregularities, which could arise from pH sensitivity or insufficient mixing, indicate uneven polymerisation or interactions between the polymer and the encapsulated molecule. In contrast, sodium alginate microcapsules display dense networks with considerable porosity, potentially attributable to strong cross-linking or drying artifacts. Sodium alginate is a hydrophilic polymer that effectively encapsulates active compounds by forming a gel matrix when cross-linked with calcium ions [26]. The strong interactions between alginate chains and the encapsulated compounds, particularly in aqueous conditions, may account for the rough and porous structure observed in some microcapsules. These porous networks offer advantages for certain delivery applications, such as in

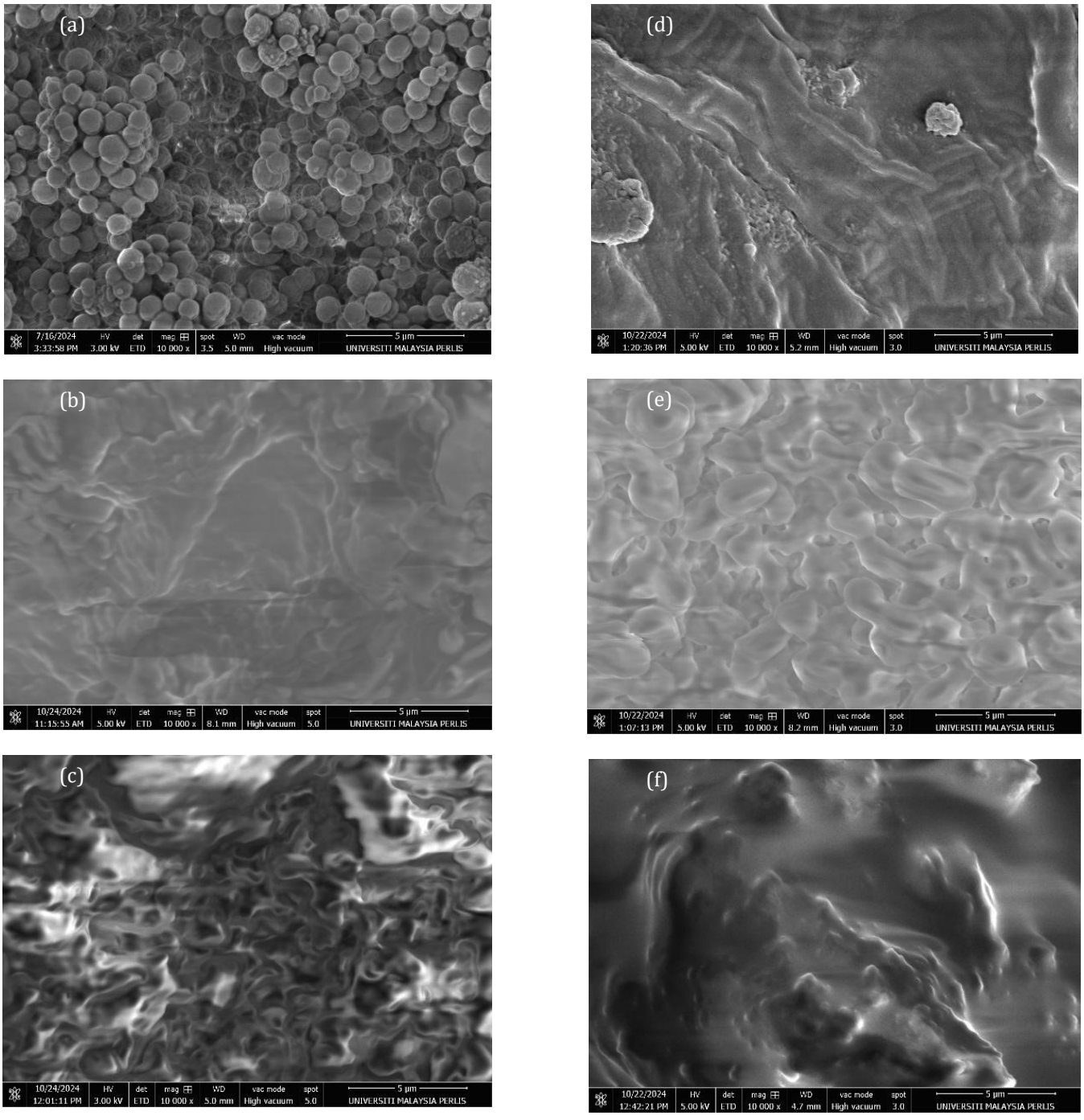

Figure 2. FESEM images of CT-polymer microcapsules prepared using different polymers of CT extracts: (a) PMMA, (b) CMC, (c) sodium alginate, (d) gelatine, (e) acacia gum, and (f) chitosan

food or pharmaceuticals, as they can accelerate water release but may lose stability under harsh or acidic conditions [27].

Conversely, the gelatine microcapsules, as shown in Figure 2(d), exhibited wavy, layered structures. The image indicates a shrinkage or folding phenomenon, probably due to drying, in which the polymer matrix collapses as the water or solvent evaporates. This effect is common in hydrophilic polymers. Such folding can influence encapsulation efficiency and release behaviour, making these structures suitable for applications requiring semi-porous films for controlled release [28]. Environmental factors such as humidity, pH, and temperature during dehydration may also affect the morphology. In contrast, the acacia gum microcapsules were observed to consist of dense, intertwined polymer networks, indicating strong cross-linking interactions. This structure enhances encapsulation efficiency by providing robust coverage of active compounds. The dense matrix is useful for pharmaceutical and food delivery systems, as it preserves bioactive compounds and ensures sustained release under regulated conditions [29].

The different morphologies of the gelatine and acacia gum microcapsules reflect the influence of polymer properties on the encapsulation process. While the wavy and layered structures observed in gelatine suggest a tendency to shrink during drying, the dense and intertwined network seen in acacia gum microcapsules indicates strong cross-linking interactions [30]. These structural differences not only affect the visual morphology of the microcapsules but also influence their size, as shown in Table 1**,** where acacia gum produced the largest microcapsules and gelatine formed the smallest ones. This underlines the unique structural and physical properties of polymers that determine the dimensions of the resulting microcapsules and their potential applications.

From Table 1, acacia gum produced microcapsules with the largest size (1.85 ± 0.43 µm), whereas gelatine formed the smallest microcapsules (0.78 ± 0.36 µm). Acacia gum has a highly branched structure, and its capacity to form larger matrices contributed to the production of the largest microcapsules. This structural characteristic improves the ability of acacia gum to efficiently encapsulate a variety of compounds by enabling the formation of larger matrices [18]. The reduced size of gelatine microcapsules may be attributed to a more compact matrix formed by this polymer and its distinct encapsulation properties. Compared to other polymers, PMMA microcapsules exhibited relatively small sizes (1.13 ± 0.12 µm), likely due to the synthetic nature of PMMA, which allows precise control over polymerisation conditions. Owing to their compact design, PMMA microcapsules offer stability and protection against environmental factors such as temperature and UV exposure, making them advantageous for applications requiring precise and sustained release [31]. Based on the observation, the PMMA microcapsules are ideal for applications requiring smaller, more uniform particles. Smaller microcapsules generally release active compounds faster due to a higher surface area-to-volume ratio. Other polymers producing larger microcapsules are more suitable for applications favouring larger particles; however, there may be trade-offs regarding uniformity and stability.

Table 1. Size of CT-polymer microcapsules

Polymer	Size (µm)
PMMA	1.13 ± 0.12^{bc}
CMC	1.03 ± 0.23^{bc}
Sodium Alginate	1.36 ± 0.31^{b}
Gelatine	0.78 ± 0.36^{c}
Acacia Gum	1.85 ± 0.43^{a}
Chitosan	0.79 ± 0.15^{c}

Data represent means $\pm$ standard deviation (N = 5). Values followed by different letters within each column are significantly different ($p < 0.05$), as determined using Tukey's honest significant difference test.

Although FESEM images suggested that sodium alginate microcapsules appeared more porous and less compact than those of CMC microcapsules, the particle data in Table 1 showed that sodium alginate had a larger average size distribution (1.36 ± 0.31 µm). This apparent inconsistency is because FESEM captures the surface structure at a specific spot, whereas particle size measurements represent an average size for the entire sample. Porosity and compaction influence surface texture but do not necessarily correlate directly with mean particle size. Factors such as polymer cross-linking density, degree of swelling, and aggregation tendencies in aqueous environments can also play a role [32]. Therefore, sodium alginate particles may appear more porous in structure but still exhibit larger overall dimensions compared to CMC-based particles.

Furthermore, the standard deviation of the microcapsule size reflects the variation among the samples, with acacia gum showing the highest variability (0.43 µm), indicating a wider range of particle sizes.

3.3. Light Absorption Profile of CT-Polymer Microcapsules

The light absorption profile was employed to evaluate the encapsulation efficiency of CT–polymer microcapsules. The distinct absorption characteristics reflect the stabilisation and behaviour of anthocyanins within the microcapsules, thereby providing insights into the interactions between CT extracts and the various polymers used. All extracts showed similar profiles, consisting of two λ_{peak} with one $\lambda_{shoulder}$, representing all the coloured species of anthocyanin: red $\mathbf{AH^+}$, purple **A**, and blue $\mathbf{A^-}$. It was observed that the absorbance intensity was higher and the peaks were smoother for all the microcapsules. For PMMA microcapsules, the absorbance at the 617 nm peak was the highest, measuring 2.278, compared to the other polymers. The absorbance values for microcapsules from CMC, sodium alginate, gelatine, acacia gum, and chitosan were 1.957, 1.993, 1.603, 1.596, and 1.114, respectively. The light intensity for PMMA microcapsules was also higher than that of the other polymers. The colour intensity of the

PMMA microcapsules appeared bluer compared to the red colour, which was characterised by a lower intensity observed in the chitosan microcapsules. Despite this, PMMA microcapsules exhibited significant absorption peaks, suggesting a higher encapsulation efficiency and a higher concentration of the encapsulated dye.

The observations highlight the distinct optical properties of microcapsules formed with different polymers, each exhibiting unique absorption characteristics. The stability and interaction of anthocyanins with PMMA are reflected in the peak representing its maximum absorbance, while other polymers, such as chitosan, gelatine, and sodium alginate, display their own characteristic spectral profiles. The absorption intensity suggests that the polymer matrix may have altered the durability of the dye or the encapsulation efficiency [33]. It was determined that the dye was encapsulated within the microcapsules, resulting in a decrease in the absorbance range. The hydrophobic properties of PMMA form a protective matrix around the encapsulated anthocyanins, protecting them from oxidation and pH changes [16]. The wide peak indicates minimal aggregation or degradation, thereby preserving structural integrity and optical qualities.

To further quantify and interpret the light absorption properties of the CT-polymer microcapsules, the calculation of the TI values provides more information about the balance and dominance of spectral absorption, especially between the wavelengths of 617 and 573 nm, as shown in Table 2. These calculated TI values offer a clearer understanding of the relative dominance of light absorption at 617 nm compared to 573 nm for the CT-polymer microcapsules. Among the polymers, CMC exhibited a high TI value (1.213 ± 0.504), indicating stronger absorption in the blue spectrum at 617 nm, which highlights its suitability for applications where blue spectral absorption is desired. Meanwhile, chitosan recorded the lowest TI value (0.930 ± 0.243), suggesting weaker dominance of absorption at 617 nm relative to 573 nm, and may be advantageous in scenarios where more balanced or red spectral characteristics are desired. On the other hand, PMMA and gelatine demonstrated relatively balanced TI values and could therefore find application in contexts where simultaneous red and blue spectral absorption is required. These results emphasise the distinctive optical properties of each polymer, their value, and possible targeted applications.

Although PMMA microcapsules exhibited the highest absorbance intensity at both λ_{max} values (573 and 617 nm) and demonstrated a strong absorption profile across the visible spectrum, the TI was not the highest among the polymers tested. Instead, CMC and sodium alginate microcapsules recorded higher TI values despite their lower overall absorbance. This discrepancy suggests that, while PMMA enhances light absorption and encapsulation uniformity, the quantification of ternatin content (as reflected by the TI) is influenced not only by absorbance intensity but also by polymer-pigment interactions and encapsulation efficiency. Therefore, a high absorption profile does not directly translate into a higher TI,

Table 2. Absorbance and TI values for CT-polymer microcapsules

Polymer	λ_{max} (nm)		Ternatin Index (TI)
	573	617	
PMMA	2.131	2.25	1.057 ± 0.650^{bc}
CMC	1.617	1.961	1.213 ± 0.504^{a}
Sodium Alginate	1.685	2.001	1.188 ± 0.468^{a}
Gelatine	1.465	1.644	1.123 ± 0.458^{ab}
Acacia Gum	1.393	1.589	1.141 ± 0.391^{ab}
Chitosan	1.176	1.094	0.930 ± 0.243^{c}

Data represent means $\pm$ standard deviation (N = 3). Values followed by different letters within each column are significantly different ($p < 0.05$), as determined using Tukey's honest significant difference test.

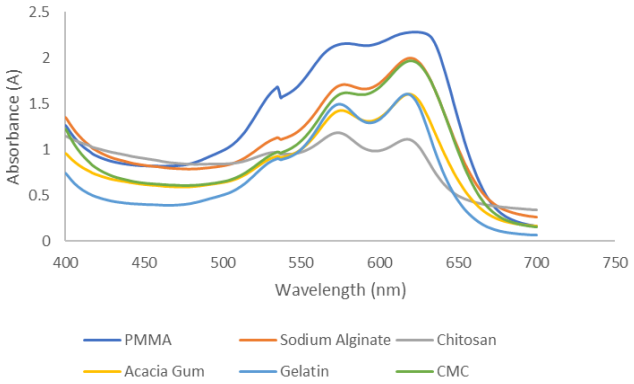

Figure 3. Light absorption profile of CT-polymer microcapsules

indicating that the structural compatibility between CT pigments and the polymer matrix plays a crucial role in determining the actual retention of ternatin within the microcapsules.

4. CONCLUSION

In conclusion, the study was successfully conducted, demonstrating microencapsulation using six different polymers: PMMA, CMC, sodium alginate, gelatine, acacia gum, and chitosan. *In situ* polymerisation improved the stability of anthocyanins against environmental factors such as light, pH, and temperature. Among the tested polymers, PMMA-based microcapsules exhibited superior encapsulation efficiency and stability, making them particularly suitable for long-term preservation and industrial applications. Morphological and light absorption analyses provided valuable insights into the protective capabilities of each polymer matrix, emphasising how polymer properties influence encapsulation performance. In general, the results indicate that these microcapsules hold significant potential for industrial applications, including as natural colourants in food, pharmaceuticals, and textiles. Future research could focus on scaling up the encapsulation process and evaluating the long-term stability of these microcapsules under real-world conditions.

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