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Research Article

Influence of Formulation Parameters on Chitosan-Gum Arabic Microcapsules for *Aloe vera* Oil Delivery

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Abstract

This study focused on the production of *Aloe vera* oil (AEO) microcapsules using chitosan (Ch) and arabic gum (AG) as biopolymers to produce microcapsules. The variation of the components, such as the type of surfactant (Tween 20 or Span 80) and the molecular mass of chitosan, resulted in different characteristics in the final particles. Microcapsules produced with Tween 20 showed larger size and lower uniformity than those produced with Span 80. High molecular mass chitosan resulted in smaller microcapsules. Optical microscopy confirmed the formation of the microcapsules, and the stability of the microcapsules was influenced by particle size and zeta potential, with an inverse relationship between these properties. Fourier Transform Infrared Analysis (FTIR) analyses confirmed the functionalization of the microcapsules in 100% cotton half-mesh fabrics, and scanning electron microscopy (SEM), evidenced the formation of covalent bonds between the microcapsules and the cotton fibers. This bond ensures greater stability and encapsulation efficiency. The controlled release of the encapsulated AEO in the cotton fabric was influenced by the type of crosslinking agent and the molecular mass of chitosan. Microcapsules crosslinked with 1,2,3,4-butanetetracarboxylic acid (BTCA) showed a more consistent release, while those crosslinked with glutaraldehyde provided a slower and more controlled release, ideal for applications that require the gradual release of the active ingredient. This study demonstrated the feasibility of producing AEO microcapsules using chitosan and gum arabic. The properties of the microcapsules can be adjusted by varying the formulation components, allowing the development of controlled release systems with applications in various segments, such as the textile industry.

Keywords: Essential oil; Coacervation; Functionalization; Cellulosic fiber; Crosslink compound

Introduction

Encapsulation is a process that consists of conditioning solid, liquid, and gaseous materials with a polymeric coating forming microcapsules, that is, particles of micrometer size [1]. The structure of the microcapsule consists of a barrier between the core and the wall, preventing chemical and physical reactions, in addition to maintaining the chemical, physical, and biological functions of the encapsulated material [2,3]. Delivery systems for active compounds based on polysaccharide microcapsules can interact with encapsulated bioactive chemical compounds (i.e. through interactions between functional groups), which makes them versatile for a wide variety of syntheses of polymeric microcapsules with hydrophilic and/or hydrophobic functional compounds at their core [4].

Chitosan is a copolymer made of β(1→4)-2-amino-2-deoxy-D-glucopyranose and β(1→4)-2-acetamido-2-deoxy-D-glucopyranose [5]. Sharma and Chakraborty (2024) it is obtained by the deacetylation of chitin in an alkaline medium, which is a polymer extracted from the exoskeleton of crustaceans, insects, and some fungi; it has low chemical reactivity and is insoluble in water and some organic solvents. Furthermore, it is one of the most found biopolymers in nature [6], non-toxic, biodegradable, biocompatible and widely used in antimicrobial and UV protection, anti-odor, and crease-resistant finishes, with others chemical agents [7].

AG has been used for over 5,000 years and is obtained from Acacia species primarily in the arid regions of Africa and Asia, with Sudan as the leading producer. AG is a water-soluble mixture of potassium, magnesium, and calcium salts of polysaccharide acid, functioning as a stabilizer, emulsifier, and bulking agent. Its natural properties meet the rising demand for natural additives, benefiting economically disadvantaged communities. Additionally, Acacia Senegal trees improve soil health and help combat desertification. To increase AG production, it is vital to promote local farming, enhance processing infrastructure, and investigate new applications [8]. Recently, AG microcapsules were prepared by complex coacervation; aiming to preserve the encapsulated chemical components from AEO, increase the chemical stability, and mask the aroma [2].

Being one of the easiest microencapsulation technologies to implement, coacervation can be classified by the number of biopolymers used in the process: in simple coacervation, a single biopolymer is used, while complex coacervation uses two or more types [4,9]; especially the complex coacervation technique involves the interaction between hydrocolloids of opposite charges [2]. Coacervation occurs due to the electrostatic attraction between opposite charges that are deposited around the active agent of choice, which is suspended or emulsified, forming the microcapsule that has a core/shell structure [4,10].

The microcapsule blend containing gum arabic, chitosan, including low and high mass, and some polysaccharides has offered better protection for the AEO [11]. AEO is well known for its natural antioxidant, anti-inflammatory, sunburn relief, immune boost, anti-aging, and multi-natural properties, through scientific developments in analytical, and pharmaceutical applications chemistry [12]. The microencapsulation guarantees the protection of the active principle from AEO, as well as its controlled release of chemical compounds, hence the great interest in its application of AEO in textile materials [2,11].

In the cosmetic industry, plant derivatives gaining much attention since they are an alternative to delivering active ingredients in cosmetics formulations, using a microencapsulation process [12]. One of the oldest medicinal plants ever recorded, AEO has great biological properties and health benefits, to the point that the ancient Chinese and Egyptians used it to treat burns, and wounds and reduce fever; in addition to having the ability to heal skin and other complications [13]. AEO is obtained from the gel, which contains carbohydrates (glucomannan and acemannan), including various mineral salts and complex vitamins, and folic acid [2,12]. However, many factors affect the chemical composition of these compounds, including genetic variation, type or variety of plants, geographical location, and seasonal climate variations, as well as post-harvest drying and storage [9].

The present paper aims to analyze the potential use of high and low chitosan to design new textile substrates with microcapsules and the challenges of the molecular types of chitosan-based textiles products research developed, including the different possibilities using a binder for obtaining AEO-microcapsules release profiles from cotton fabrics. The paper provides data on the interest in using this AEO chemical compound to functionalize the textile and details the main applications of chitosan-based textile processing by pad dry cure method.

Materials and Methods

Supply of raw materials

Arabic gum (ACS® Científica, Brazil), chitosan of low (20–300 cP, deacetylation ≥ 75%), and high molecular mass (800–2000 cP, deacetylation ≥ 75%), Span® 80 and Tween® 20 were purchased from Sigma-Aldrich®. *Aloe vera* oil (AEO) was obtained from a cold-pressure extraction system. Chloridric acid, acetic acid, tannic acid, and other laboratory materials were used as received unless noted otherwise.

Preparation of microcapsules

The methodology proposed by Valle JAB, et al. [14] was used for the preparation of microcapsules suitable for enrichment. The microcapsules were synthesized using AG, Ch, and AEO as bioactive core, with four samples AG/Ch AEO-encapsulated, and two without encapsulation AG-Ch, for standard comparison among them. Initially, two aqueous solutions were prepared, one of AG at 1% (w/w) and the other of Ch at 2% (w/w) in a water bath at 40 °C, where chitosan was dissolved in a 10% v/v acetic acid solution. In the next step, *Aloe vera* oil was incorporated into the oil-in-water (O/W) solution using Span® 80 or Tween® 20 in a ratio of 2% (w/w). This mixture was homogenized with an Ultra Turrax® homogenizer at 3000 rpm for one minute. For the synthesis of microcapsules, it was supplemented with 50% distilled water. The temperature of the AEO emulsion with chitosan was adjusted to 40 °C, and the pH was reduced to 3.5 with the addition of an aqueous solution of hydrochloric acid (0.2 M), completing with 16% (v/v) distilled water. The arabic gum solution was then incorporated into the chitosan emulsion, together with 8% (v/v) distilled water. The AEO and AG/Ch emulsion was mechanically stirred at 8000 rpm for 1 minute and then slowly cooled in water to a temperature of 5 °C with constant stirring (400 rpm) for 3 hours. After 5 minutes of reaction, tannic acid (10% v/v) was added dropwise to crosslink the microcapsules. Then, the microcapsules were poured into plastic containers and stored in the refrigerator until the impregnation process in the fabric. Figure 1 shows the scheme used in this study.

Table 1 shows the variation of AG/Ch microcapsules and surfactants used in this study.

Table 1: Samples of microcapsules with variations of Ch molecular mass and surfactants.

Sample	Wall 1	Wall 2	EO	Surfactant	Abbreviation
Test 1	Ch-HW	AG	AEO	Tween® 20	T1
Test 2	Ch-LW	AG	AEO	Tween® 20	T2
Test 3	Ch HW	AG	AEO	Span® 80	T3
Test 4	Ch-LW	AG	AEO	Span® 80	T4

Where HW is a Ch-high molecular mass and LW is a Ch-low molecular mass.

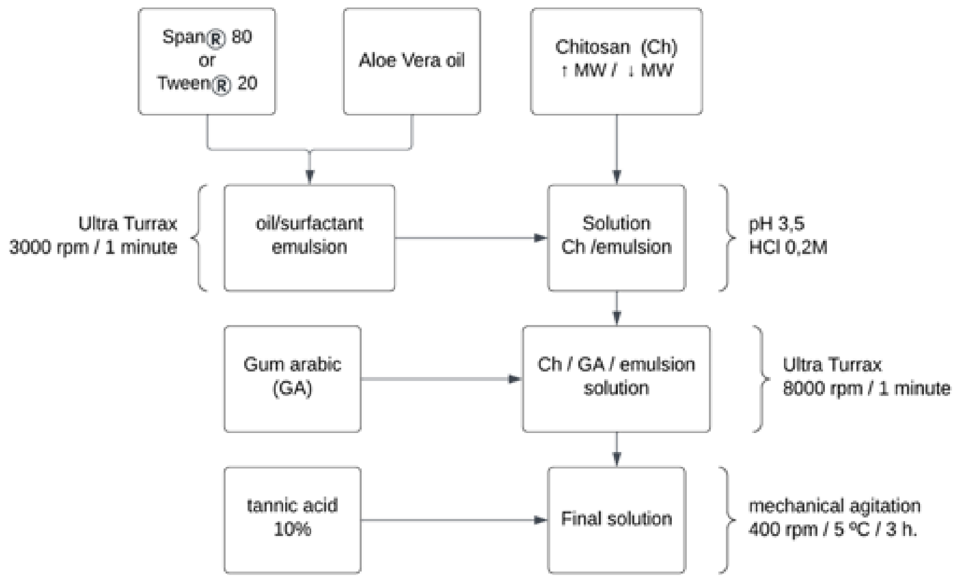

Figure 1: Scheme for obtention of the *Aloe vera* microcapsules.

Impregnation method

The final solution was made considering the mass of the fabric sample, which represented 5% of the final volume of the solution, the microcapsule samples represented 10% of the final solution, the crosslinkers (BTCA, citric acid, and glutaraldehyde) were added at a rate of 3%, and monobasic sodium phosphate was also added at a rate of 3%. Pretreated 100% cotton knitted fabrics (10 cm x 70 cm) (type PT donated by Werken Química Brasil SA) were immersed in the impregnation solution for 10 minutes. Using laboratory Foulard equipment (Mathis) at 3 bar pressure and a speed of 2 m/min, the excess solution was removed, and the sample returned to the impregnation bath, repeating the procedure described. The impregnation resulted in a high moisture absorption capacity with a pick-up of ≥ 90% after both cycles. The distribution of microcapsules in the fabrics was visually evaluated and drying was performed at 80 °C for 30 minutes in an oven. The fabric samples were stored in a desiccator until characterization.

Characterization Methods

Microcapsule size and zeta potential

The impact of surfactants and chitosan (Ch) molecular mass on microcapsule particle size and zeta (ζ) potential was assessed using a MALVERN® Zetasizer Nanosizer and MPT-2 Autotitrator model DP1 (UK). Dynamic light scattering with a 633 nm He-Ne laser, adhering to ISO 22412:2017, was employed. Each measurement was performed in triplicate, and the average values were recorded.

Morphology characterization

Microcapsule morphology and cotton functionalized with microcapsules were examined using scanning electron microscopy (SEM) with a JEOL® JSM-6390LV. SEM images were acquired at magnifications of 1000x, 2000x, and 4000x. Samples were prepared by direct fixation onto carbon tape and gold coating. Microcapsules were also observed by optical microscopy (OM) with a BioFocus® microscope.

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Fourier transformed infrared analysis

Infrared spectra of cotton fabrics were obtained using a PerkinElmer® Spectrum Two™ spectrometer by Attenuated Total Reflection (ATR) mode in the spectral range of 4000-550 cm^{-1}.

Release profiles experiments

The release behavior of AEO oil of the microcapsule-treated fabrics was determined following the methodology that was previously studied with modifications (VALLE; VALLE; DA COSTA; MAESTÁ et al., 2024). After the chemical functionalization with microcapsules, the fabrics (2 cm × 2 cm) were placed with 20 mL of deionized water and maintained in a thermostable bath at 37 °C ± 0.5 °C for approximately 50 min. Aliquots of 0.7 mL were extracted from each solution and mixed with absolute ethanol (0.3 mL), and for each sample, the same volume was introduced and the final dilution was considered. The cumulative release and their absorbance were determined by UV-Vis spectroscopy at 340 nm, obtained from the absorbance standard curve (y=0.012 x – 0. 0044, r^2=0.9918).

Statistical analysis

Statistical analysis was performed for particle sizes and zeta potential results, using STATGRAPHICS® software to verify the correlation between particle size and the Ch molar mass. All of them follow the assumptions of simple analysis of variance (ANOVA) regression, being normality, linearity, and independence of all groups. Whenever the null hypothesis was rejected.

Results and Discussion

Optical microscopy

Optical microscopy was performed on the post-production suspensions to confirm microcapsule formation. The resulting micrographs are shown in Figures 2a-2d.

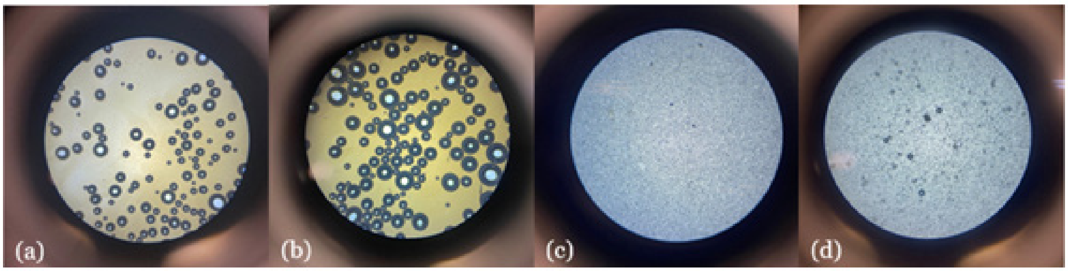

Figure 2: Optical microscopy of microcapsules with *Aloe vera* oil (a) T1, (b) T2, (c) T3 e (d) T4 (magnification 40x).

The images revealed the influence of both the surfactant type and the molecular mass of chitosan on the size of the microcapsules. Formulations containing Tween® 20 exhibited larger average diameters compared to those with Span® 80. In samples T3 and T4, formulated with Span® 80, the microcapsule wall was not observed. Furthermore, the use of high molecular mass chitosan contributed to an apparent reduction in particle size, supporting the findings reported by Badke, et al. [2]. The micrographs display spherical microcapsules with well-defined interfaces, showing the expected characteristics under acidic conditions, as described by Espinosa-Andrews, et al. [15].

In the optical micrographs of the larger microcapsules (Figures 2a and 2b), the presence of two distinct layers formed by the polymers used is visible, confirming the complex coacervation process employed in this study.

To find out the size and zeta potential of the microcapsules the dynamic light scattering method was conducted and the results are shown in Table 2.

Table 2: Size distribution and zeta potential properties of AG/Ch microcapsules group.

Samples	Particle size (μm)	Zeta Potential (mV)
T1	0.273 ± 0.014[d]	14.57 ± 0.64[a]
T2	3.058 ± 0.213[a]	0.439 ± 0.05[d]
T3	1.458 ± 0.086[b]	4.62 ± 1.25[c]
T4	0.863 ± 0.006[c]	6.55 ± 1.48[b]

Note the letters following the standard deviation indicate significant differences.

The samples with the largest particle sizes were those combining low molecular mass chitosan with Tween® 20 (T2) and high molecular mass chitosan with Span® 80 (T3); these also exhibited the lowest zeta potential values. In contrast, the samples combining high molecular mass chitosan with Tween® 20 (T1) and low molecular mass chitosan with Span® 80 (T4) showed smaller particle sizes and higher surface charges. After conducting the statistical analyses, it can be observed that the samples are different from each other, reinforcing the idea that the use of chitosan with different molecular weights, as well as different surfactants, produces distinct microcapsules among themselves.

The deprotonation of carboxylic groups in arabic gum (AG) results in the formation of an anionic polyelectrolyte, which interacts with positively charged species, such as acidic chitosan solution, as described by Badke, et al. [2]. The variation in zeta potential values may be related to the degree of interaction between arabic gum and chitosan; the more positive the zeta potential, the greater the number of protonated amino groups from chitosan available on the particle surface.

It is noteworthy that the zeta potential values observed for sample T1 are close to those reported by Tavares L, et al. [16] for garlic extract microcapsules, which used the same wall materials as in this study. Although zeta potential values higher than +30 mV or lower than −30 mV are generally associated with stable colloidal systems due to electrostatic repulsion [17]. Other factors—such as the presence of adsorbed polymers on the particle surface and hydrophobic interactions—may also contribute to dispersion stability.

Selecting an appropriate pH for the complex coacervation process is crucial, as the surface charge of biopolymers varies significantly with pH [2]. The microcapsules obtained in this study exhibited slightly positive zeta potential values, making them promising candidates for application on anionic textile substrates due to potential electrostatic interactions between the particles and the substrate.

Scanning Electron Microscopy

To observe the morphology and surface of the microcapsules, scanning electron micrographs were used. In Figure 3a-3d, the microcapsules can be observed in the 1000x magnifications.

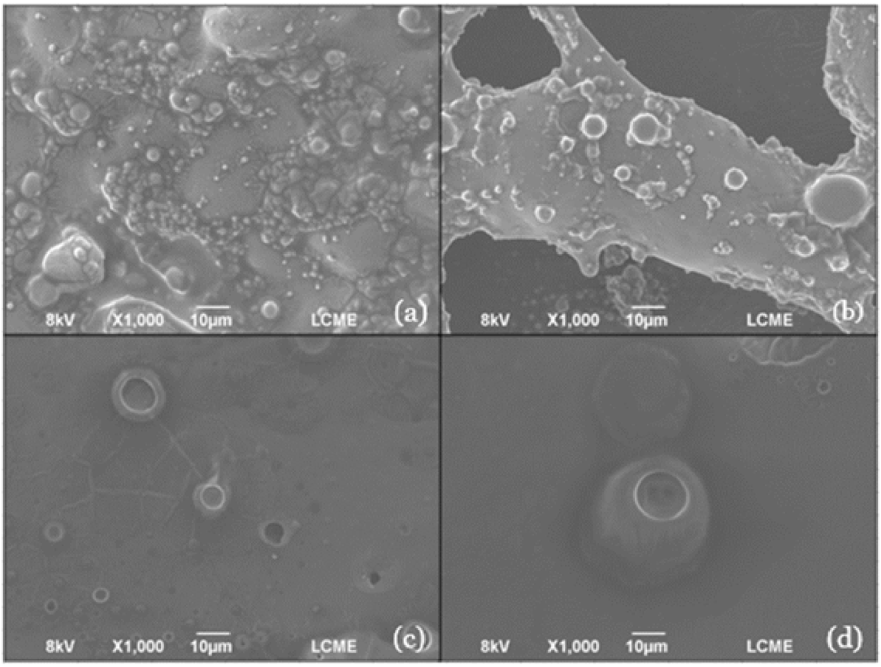

Figure 3: SEM of microcapsules with AEO (a) T1, (b) T2, (c) T3 e (d) T4.

The microcapsules predominantly exhibit a spherical morphology, smooth surface, and a polydisperse size distribution. A greater number of particles was observed in samples T1 and T2, which were produced using the surfactant Tween® 20; residual material from the microcapsule fabrication process is also noticeable by the shapeless material. In contrast, images of samples T3 and T4, prepared with Span® 80, show a smaller number of particles, a trend also observed in optical microscopy.

Therefore, it is speculated that the spatial conformation of this surfactant plays a role in microcapsule formation. The lipophilic portion of the Span® 80 molecule is more elongated, which may favor the formation of emulsions in which the oil phase is continuous. Conversely, Tween® 20 contains a larger and more flexible hydrophilic segment, composed of twenty repeating polyethylene glycol units, which can facilitate the formation of oil-in-water emulsions, as in this study.

Following the functionalization of the cotton fabric, the images show that the AEO microcapsules retained their spherical morphology, although they became more porous, both in the citric acid microcapsules (Figure 4a) and in those with BTCA (Figure 4b), supporting the findings of Sousa, et al. [9]. Furthermore, a difference in sample density was observed after the foulard process, with samples T1 and T3 exhibiting higher density compared to T2 and T4 (Figures 4a1, 4a3, 4b1, and 4b3).

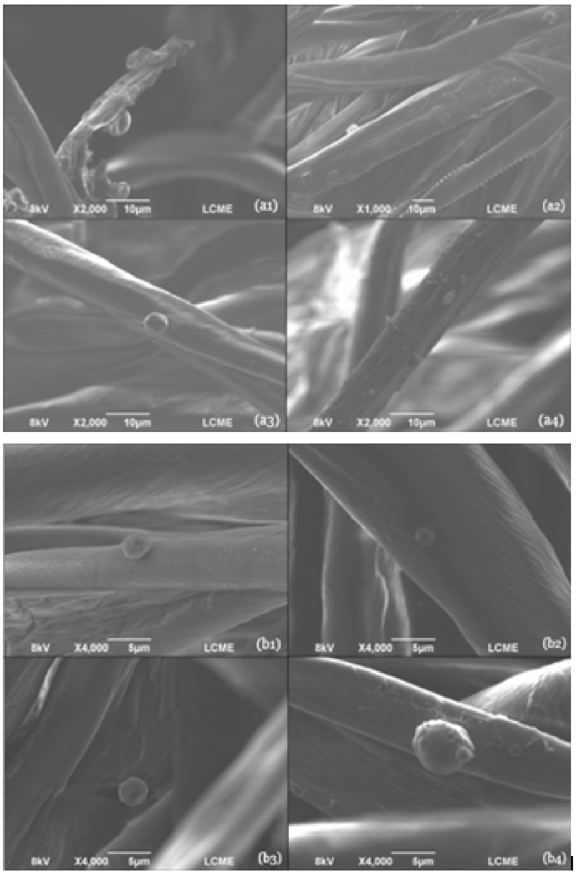

Figure 4: SEM of microcapsules with AEO in cotton fabrics (a1-a4) citric acid and (b1-b4) BTCA.

The application of microcapsules to textiles requires specific characteristics, including uniform size distribution, high loading capacity, encapsulation efficiency, and resistance to finishing processes and chemical treatments. Previous studies [18] have shown that the crosslinking reaction does not significantly affect particle size when microcapsules are applied to cotton fabrics. These capsules are fixed both on the surface and within the fibers through esterification reactions. Furthermore, Yang, et al. [19] demonstrated the effectiveness of citric acid as a crosslinking agent for cotton fabrics.

In an earlier study, Badulescu, et al. [20] observed the formation of ester bonds between microcapsules and cotton fabrics, mediated by BTCA and a catalyst, even at room temperature. FTIR analysis revealed a low-intensity band at 1743 cm^{-1}, characteristic of ester groups, after the thermofixation process. This suggests that the applied temperature was sufficient to promote the esterification reaction between the microcapsules and the hydroxyl groups of cotton cellulose without causing capsule rupture and release of the encapsulated essential oil.

The encapsulation method employed proved effective in enhancing the controlled release of AEO from microcapsules incorporated into cotton fabrics. Capsule fixation was achieved through thermal treatment using crosslinking agents that promote adhesion to cotton fibers. Previous research [21] has shown that the deposition of polycarboxylic acids can result in increased fabric surface roughness. On the other hand, Yang, et al. [22] studied the incorporation of vanillin into chitosan microcapsules using citric acid as a binder and sodium hypophosphite as a catalyst. In that study, crosslinking conditions were optimized by employing lower temperatures and reduced catalyst amounts, contributing to a more chemically sustainable process.

Fourier Transform Infrared Analysis (FTIR)

After the foulard process, swelling was observed on the surface of the fabrics, indicating the deposition of microcapsules. FTIR analysis supports this observation by revealing characteristic bands of the carboxylic acids used as functionalizing agents, confirming the incorporation of the microcapsules into the cotton fabric.

Figure 5 presents the FTIR spectra of cotton treated with microcapsules crosslinked using citric acid, BTCA, and glutaraldehyde, enabling the identification of new bands or shifts in characteristic ones, which may indicate interactions between the system components.

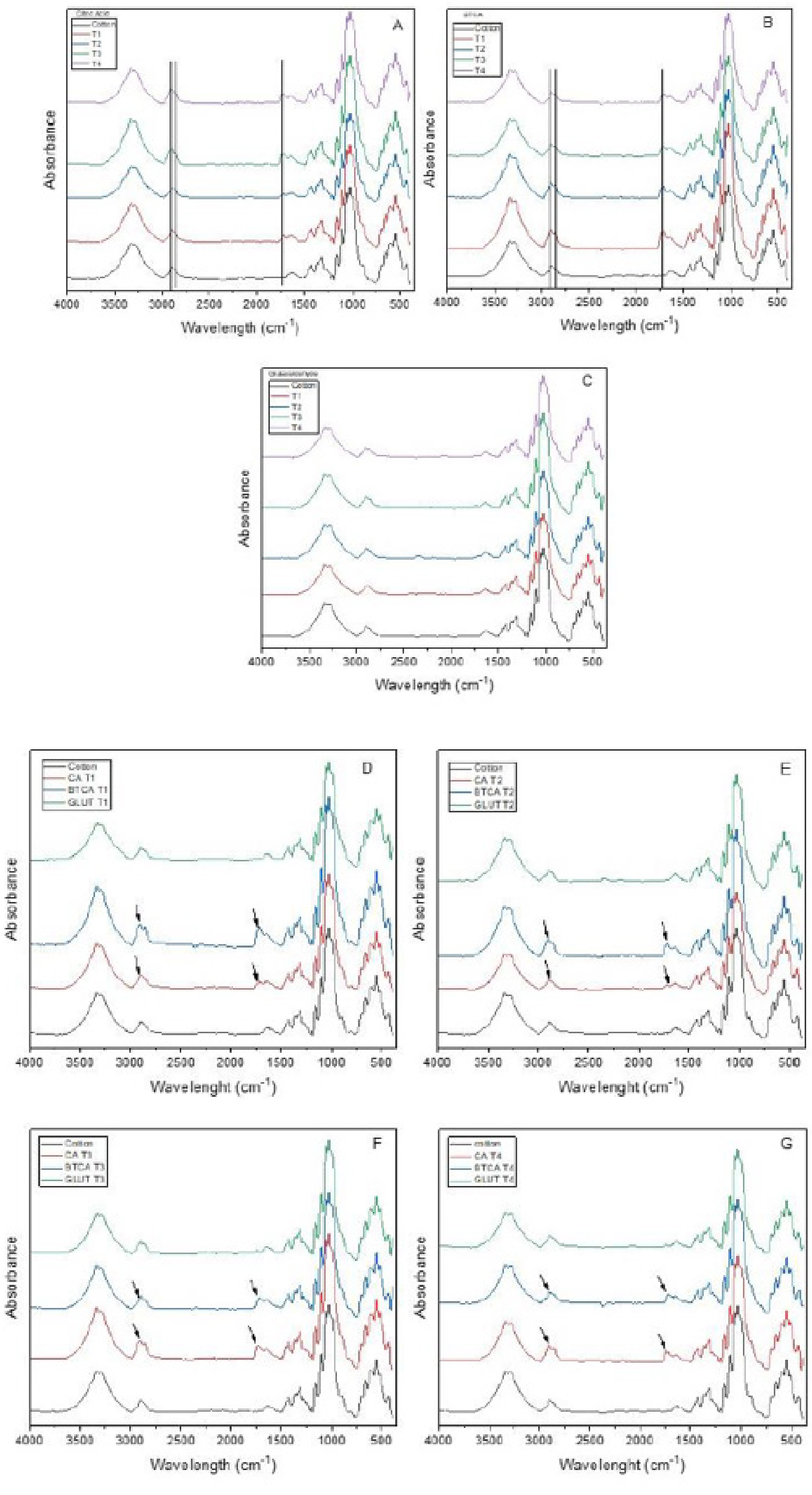

Figure 5: FTIR spectra of functionalized cotton fabrics.

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In Figure 5a, related to citric acid as the crosslinking agent, a pronounced band is observed at 1741 cm^{-1} for samples T3 and T4, and at 1721 cm^{-1} for T1, corresponding to the C=O stretching vibration of carboxylic acid groups. The band observed at 2897 cm^{-1} in pure cotton was shifted to 2910 cm^{-1} in T3 and T4, with the appearance of a new band at 2856 cm^{-1}, associated with the C-H stretching of methylene groups.

In Figure 5b, related to BTCA, the band at 2900 cm^{-1} shifted to 2910 cm^{-1} in all samples. A new band at 2856 cm^{-1} was also observed in T1 and T2, similarly attributed to C-H stretching, as seen with citric acid. Additionally, all samples in this group exhibited a new band at 1721 cm^{-1}, corresponding to the C=O vibration of the carboxylic group.

In contrast, Figure 5c, corresponding to glutaraldehyde treatment, shows no significant shifts or emergence of bands characteristic of this molecule in the treated fabrics [11,20].

Figures 5d through 5g show grouped spectra according to the nanoparticle formulation (T1 to T4). For all samples, a distinct C=O band around 1720 cm^{-1} and a band near 2860 cm^{-1}, related to C-H stretching, are observed—especially in those crosslinked with BTCA. In samples treated with citric acid, the same bands are present but with lower intensity. It is further confirmed that glutaraldehyde-treated samples exhibit no spectral differences compared to pure cotton.

The crosslinking mechanism between the microcapsules and the cotton fabric involves the formation of ester bonds between the carboxylic acid groups of the crosslinking agents and the hydroxyl groups present in both the fabric and the microcapsules [11]. Previous studies also describe the esterification reaction mechanism involving carboxylic acids (-COOH), cotton hydroxyl groups (-OH), and cyclodextrins (–OH) [23]. The intense absorption band observed around 1700 cm^{-1} is characteristic of the carbonyl (C=O) stretching of carboxylic acids and indicates the presence of unreacted carboxylic groups from BTCA [20].

The formation of intermediate anhydrides, as proposed by Badanayak, et al. [21], is plausible due to the presence of multiple carboxylic groups in the BTCA and citric acid crosslinkers, which can influence the overall efficiency of the crosslinking process.

FTIR analysis confirms the successful surface functionalization of the cotton fabrics with polysaccharide-based microcapsules. The presence of characteristic bands in the spectra indicates the formation of crosslinks between the functional groups of the crosslinkers—particularly BTCA and citric acid—and the components of the microcapsules and fabric, confirming the effectiveness of the treatment.

Release profiles experiments

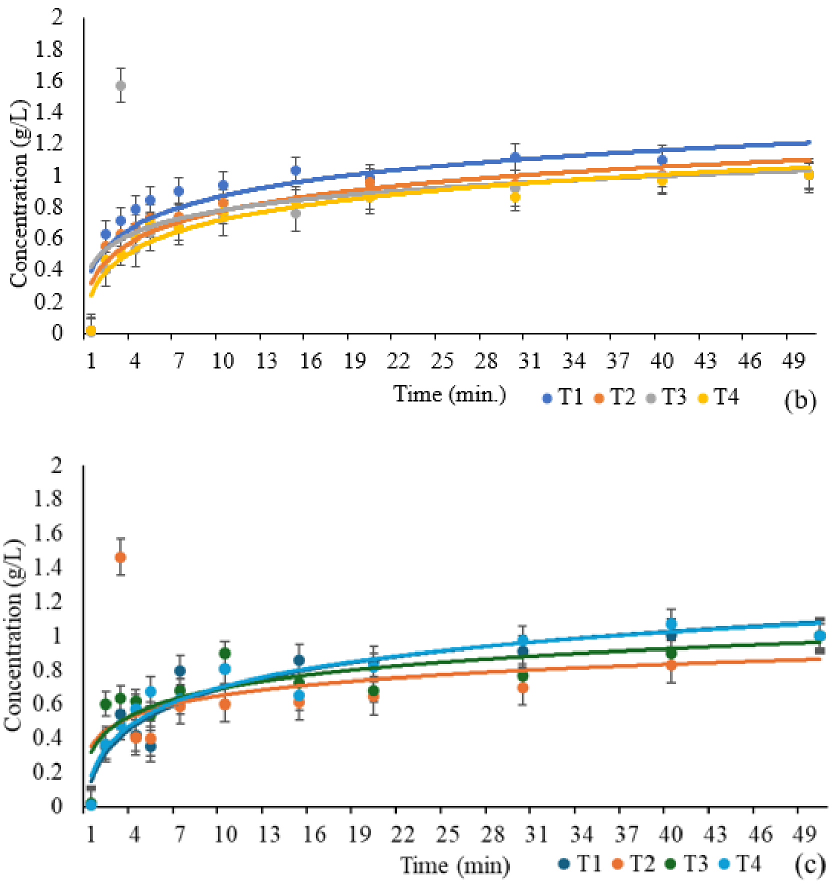
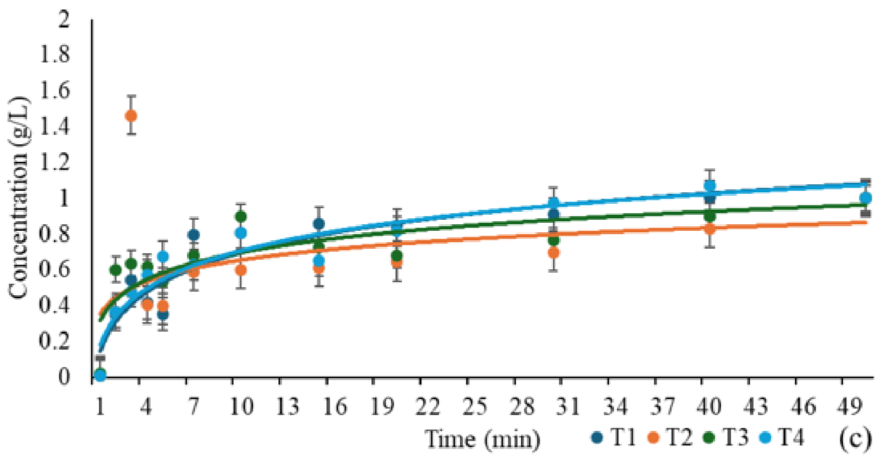


Figure 6: Release profiles of microcapsules in cotton fabrics crosslinked with (a) BTCA, (b) citric acid, and (c) glutaraldehyde.



The oil release test in water was performed from the fabrics functionalized with the microcapsules, aiming to observe the effects that BTCA, citric acid, glutaraldehyde, and microparticle characteristics have on the oil release behavior. Figure 6 shows the AEO oil release graphs with each crosslinking agent: (a) BTCA, (b) citric acid, and (c) glutaraldehyde.

Upon analyzing the AEO release profile from the samples impregnated with BTCA, it is observed that samples T1, T2, and T4 exhibit very similar release curves, suggesting comparable release rates. However, sample T3 stands out with a significantly higher release curve, indicating either a greater amount of oil released or a faster release rate. It is worth noting that, after approximately 50 minutes, oil concentrations in all samples tend to stabilize, indicating that equilibrium has been reached.

Regarding the citric acid–impregnated samples, shown in graph (b), a more homogeneous release profile is observed compared to graph (a). The release curves are closely aligned, suggesting consistent behavior across the samples. Nevertheless, by the end of the 50 minutes, sample T1 exhibited the highest amount of released oil. This variation indicates that, in addition to the type of crosslinking agent, other factors such as the molecular mass of chitosan or surfactant–polymer interactions may influence the release kinetics.

Although FTIR spectra did not confirm crosslinking with glutaraldehyde, the experimental procedure was identical to the others. In graph (c), samples T1 and T4 on one hand, and T2 and T3 on the other, present similar release profiles. Initially, T2 and T3 show a faster release of AEO; however, over time, T1 and T4 surpass the others in the total amount of oil released. This dynamic indicates that microencapsulation of AEO not only protects and stabilizes the active agent but also allows for modulation of the release kinetics, enabling the development of customized release profiles depending on the intended application.

According to Puertas, et al. [21] and Lengyel, et al. [16], the core-shell composition of the microcapsules plays a crucial role in the selectivity and efficiency of their application in cotton fabrics, especially when using polysaccharide-based microcapsules. These structures, ranging in size from 1 to 1000 µm, can feature various internal architectures—such as matrix or reservoir systems—offering broad potential for controlled release applications.

The significant differences in release profiles between the graphs suggest that the efficiency of microcapsule impregnation into the fabric directly influenced the AEO release kinetics. The BTCA-impregnated samples exhibited more uniform behavior, with T3 showing a slower release—desirable for applications requiring sustained and controlled delivery. The introduction of crosslinkers onto the fabric surface increased the availability of hydroxyl groups, enhancing water adsorption [21].

Additionally, the molecular mass of chitosan had a notable effect on AEO release kinetics. Microcapsules formulated with low molecular mass chitosan exhibited faster release of the essential oil, whereas those with high molecular mass chitosan demonstrated a more gradual release behavior.

Conclusions

Microcapsules with a core-shell structure were successfully synthesized using arabic gum (AG) and chitosan (Ch) to encapsulate AEO oil. While chitosan's inherent properties make it suitable for encapsulation, its molecular mass significantly influences microcapsule size and thermal behavior.

The choice of surfactants, Tween® 20 or Span® 80, also played a crucial role in determining final characteristics, such as particle size and zeta potential. Tween® 20 yielded larger, less uniform microcapsules compared to Span® 80. High molecular mass chitosan resulted in smaller microcapsules. Functionalization of cotton fabric enhanced microcapsule morphology and adhesion. An inverse correlation between zeta potential and particle size highlighted their combined impact on stability.

Crosslinking improved both stability and encapsulation efficiency. Thermal gravimetric analysis (TGA) demonstrated that chitosan molecular mass and surfactant type affected thermal stability. Release kinetics were influenced by both the crosslinking agent and chitosan molecular mass. BTCA provided consistent release, while glutaraldehyde resulted in slower release. Low molecular mass chitosan facilitated faster AEO release. FTIR analysis confirmed successful functionalization onto cotton fabric, indicating covalent bond formation between microcapsules and fibers.

These findings underscore the importance of carefully selecting biopolymers, surfactants, and crosslinking agents, as well as controlling chitosan molecular mass, to optimize microcapsule properties and tailor AEO release. The developed microcapsules show significant promise for high-performance textile applications, enabling controlled active agent release and enhancing fabric properties.

Author Contributions

Rodrigo Hobold Weber: Methodology, Investigation, Validation, Writing – original draft, Data curation, Supervision. Dione Pereira de Castro: Methodology, Investigation, Data curation, Writing – original draft, Larissa Klen Aragão: Methodology, Investigation, Data Curation, Writing – original draft, Mariele Paludetto Sanches: Methodology, Investigation, Data Curation, Writing – original draft. Leonardo Gondim de Andrade e Silva: Thermal Analysis, Data curation, Supervision. Manuel José Lis Arias: Writing – original draft, Validation, Supervision, Data curation, Investigation. Rita de Cássia Siqueira Curto Valle: Writing – review & editing, Conceptualization, Supervision, Project administration.

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Conflict of Interest

Authors declare no conflict of interest.

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