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Case Report

Biopolymers-based microencapsulation technology for sustainable textiles development: A short review

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ABSTRACT

Microencapsulation methods in product development may result in innovative products with improved stability, functionality, and active chemical release (s). Microcapsules may be made out of biopolymers instead of synthetic polymers because of their biodegradability, lower production costs, and greater accessibility. The potential of biopolymers-based microencapsulation technology in sustainable textiles is substantial despite this field only getting started. This short review explores the role of biopolymers such as chitosan, gelatin, alginate, and cellulose in microencapsulation-mediated sustainable textile technology. The long-term effects of using microencapsulation made from biopolymers are also discussed, with an eye toward sustainability.

1. Introduction

Microencapsulation is the process of isolating active substances (in a liquid, solid, or gaseous state) to produce micrometrically sized, spherical products in which a membrane protects the active material or core from the outside environment [1,2]. The microencapsulation process results in a solid partition between the interior and outside components. It shields fragile components from the environment, including humidity, pH, and oxidation. Shearing, solubilization, heating, pH, or enzyme activity are only some of the methods that might cause the release of microparticle material at regulated rates. In light of this, microencapsulation technology has been singled out as a viable method to extend the useful life of textiles [3,4].

Microencapsulation is a research field with significant untapped potential for further advancement. This is particularly evident in the area of environmentally friendly formulations, which can be determined by the active ingredient selection for the coating, the polymeric membrane structures, textile finishing methods for fixing the particles, and the functionalization medium [5,6]. According to the observations made by Gordon Nelson [7], the ultimate goals for the majority of textile applications that make use of a microencapsulation formulation are for the formulation to be readily applied, for it not to change the qualities of the fabric, and for it to have adequate durability to the garment so that it may ease the process of maintaining the textiles. Microencapsulation protects the core and the surrounding environment from potential chemical reactions. Microencapsulation has several advantages, one of which is the ability to adjust the rate at which the active ingredient in the core is released [8]. Applying new chemicals like scents, colors, insect repellents, antimicrobials, or phase change materials may be made possible via microencapsulation, which presents a number of significant potentials for the enhancement of the textile sector [9,10]. Since then, there has been a vigorous study on getting items that may satisfy even

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the most demanding client requests. This research has resulted in numerous commercial products, and many more are now in the research and development stage. As a direct consequence, items that just a few decades ago were regarded as being in the realm of science fiction may today be found in almost every market. The most demonstrative examples are textiles with long-lasting perfumes, shirts with thermo-changeable colors, military uniforms with microencapsulated insecticides, thermoregulation car seats, ski coats and gloves, etc. [11,12]. The design of the process, on the other hand, has to ensure that product standards are satisfied while also complying with limits regarding cost and the environment.

As public interest in and understanding the value of safe, environmentally friendly materials and methods grows, so do researchers' and producers' interest in green chemistry techniques. While there are some microcapsules manufactured of phenol-formaldehyde, melamine-formaldehyde, or urea-formaldehyde resins, the vast majority of those on the market are designed for use in textiles. While these polymers are useful because of their thermal stability and adaptability, they pose a significant risk to human and environmental health due to their potential to be manipulated to achieve specific release profiles. The carcinogenic and poisonous properties of formaldehyde are a major factor, as well as the fact that thermosetting polymers are not recyclable [13,14]. Therefore, it is crucial to find alternatives to these polymeric systems that are both safe for the environment and do not pose any health risks to humans. Natural and naturally derived polymers are being seen as viable replacements for synthetic polymers for several reasons, including their low environmental impact, high availability, and lack of potential health risks to humans [15]. Because of their versatility and availability, biopolymers, including chitosan, gelatin alginate, and cellulose, have drawn interest for use in various ecological and medicinal contexts. Large surface area, high efficiency, bioactivity, nontoxicity, elasticity, antimicrobial activity, and ease of synthesis are the remarkable features of these biopolymers [16,17]. The selectivity and reactivity of biopolymers much surpass those of man-made polymers. Microencapsulation based on biopolymers may be affixed to textiles without altering the materials' inherent qualities like softness or breathability, allowing them to retain their structural integrity. Since then, biopolymers have been the most popular option for preparing sustainable microencapsulation toward multifunctional fabrics.

Microencapsulation based on biopolymers has been the subject of various research on functional textiles in recent years. However, there has not been a unified strategy in the published efforts on creating functional textiles based on biopolymers' microencapsulation. This article aims to synthesize information from the literature on the principles of combination, manufacturing techniques, and emerging trends for making biopolymers microencapsulated functional textiles. To the authors' knowledge, this is the first review to focus on microencapsulation based on biopolymers and their potential use in the textile industry.

2. Microencapsulation on textiles materials

Several chemical techniques, including interfacial polymerization, *in situ* polymerization, sol-gel, coacervation, and phase separation, are used in microencapsulation procedures. Microcapsules range from a few microns to a few millimeters [18]. Depending on their shape, microcapsules may be divided into three distinct categories: Monocore, Polycore, and Matrix (Fig. 1) [19].

The application of microcapsules to textiles may be accomplished by stamping processes, exhaustion dyeing, impregnation, padding, coating, or spraying. This application uses microencapsulated liquids in the solid powdered form to easily deposit them onto the textile fibers. In addition, microcapsules can be directly absorbed into the fiber, without causing any changes to its feel or color [20,21]. A binder is necessary for all of these different processes. For example, it might be starch, acrylic, polyurethane, or silicone. It is responsible for securing the capsules onto the cloth to remain in place even after the fabric has been washed and worn. The padding technique relies on squeeze rolls, sometimes known as "mangle rolls," to remove the surplus solution from the cloth after it has been transferred to a bath containing micro or nanocapsules [22]. Because the fabric is submerged in a solution containing micro- and nanocapsules, the substance may diffuse into the fabric similarly to padding but without using squeeze rolls. Using the printing technique, a printing paste may be prepared by combining microcapsules and nanocapsules with a binder. The micro and nanocapsules are printed onto the fabric's surface after the fabric is passed through a rotary screen attached to a rotary roll containing a printing paste. In addition, the coating is created by heating microcapsules and nanocapsules deposited on the cloth's surface [23]. Applying microcapsules or nanocapsules to the fabric's surface in an enclosed space using a spray nozzle is another kind of technological procedure. It is necessary to stabilize the goods, traditionally accomplished by heating them at a high temperature. (130–170 °C). The rapid evaporation and swelling contribute to the capsules' walls being ruptured, allowing the contents to escape and reducing the capsules' stability [24]. Curing by microwaves or ultraviolet light (UV) is an alternative to traditional heating. Microwaves with short wavelengths cause molecules to vibrate and polarize, which results in the production of heat and the stabilization of micro- and nanocapsules on the surface of the fabric [25]. UV curing involves subjecting the fabric to ultraviolet radiation for a short period to polymerize the resin component in the form of a continuous film and stabilize the capsules on the fabric's surface [26]. This process has many benefits,

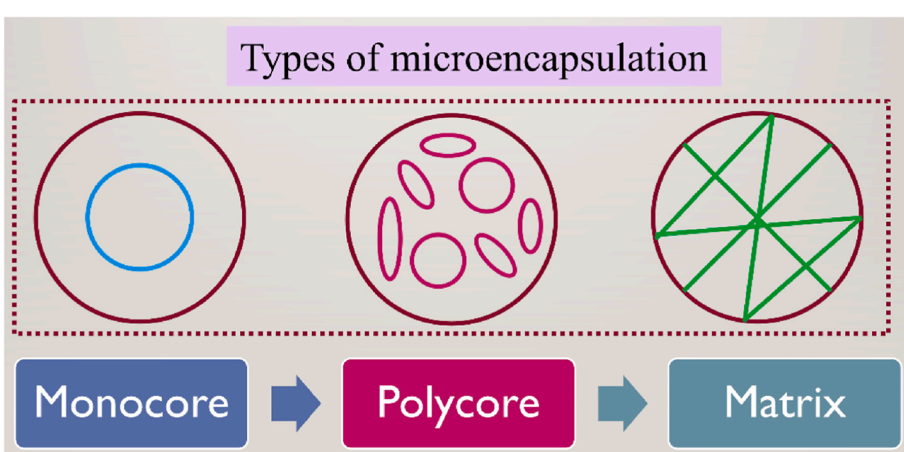


Fig. 1. Different types of microencapsulation.

including a high production rate, a short and low-temperature procedure, significant energy savings, and reduced environmental impact. This prevents shattering the capsules and causing the core material to evaporate, enhancing the product's longevity. The durability of the completed fabric treated UV was almost 50 washes better than that of the fabric cured with thermal curing (25 washes) [27]. The characteristics of the core material determine the choice of a specific approach, the encapsulant, as well as the many features and morphologies that are secured in the capsules. The type of the core and shell chemicals, as well as the solvent necessary to either dissolve or precipitate them, are the primary factors influencing the decision of which procedure to use.

Silk, cotton, synthetic fiber, etc. may all have microcapsules applied to them in order to create a wide variety of functional textiles for use in sports, medicine, fragrance, E-textiles, antimicrobials, thermochromes, UV protection, dyes, phase change materials, and beyond [28]. (Fig. 2). For instance, using mini-emulsion polymerization, Liu et al. [29] synthesized methylmethacrylate-styrene nanocapsules containing cologne essential oil and applied them to cotton fabric by immersion. Because 6.8% of the cologne was still detectable after 15 washes, the treated cloth had a homogenous covering of fragrant nanocapsules on the fabric surface without significant agglomeration, indicating high washing endurance. Saraswathi et al. [30] used a commercial binder, pH 5.5–6, and 120 °C for 2 minutes to cure neem, tulsi, and turmeric microcapsules that they applied to cotton and silk textiles using the simple diffusion technique. Poly(ethyleneglycol)-poly(e-caprolactone)-poly(ethyleneglycol) is a thermo-sensitive hydrogel composite that Gong et al. [31] loaded with curcumin to create a solid dispersion. Hydrogel produced for use as a wound dressing showed good tissue adhesiveness and sustained release of curcumin over a long period. Microencapsulated phase change materials have several applications due to their ability to be used to fabricate active smart textiles that can detect and respond to circumstances or stimulation, appealing to a large and varied consumer base. They may be permanently woven into the fibre to create thermoregulated fibres, embedded in a coating compound at the end of the production line, or blended into a foam before lamination to create a layer. It may be sewn into a wide variety of garments, including outerwear, undergarments, UV protection, gloves, military uniforms, and civilian clothing; it can also be used to make beds, seating, and footwear. (car seats, wheelchair, furniture covering, etc.).

Overall, it can be shown in Table 1 several surface modification methods are available in the literature, but the microencapsulation method has been identified as a versatile route for developing functional textiles by means of application areas.

3. Application of sustainable microencapsulation in textiles

Textiles may be modified in terms of functionality by using microencapsulated materials ranging from natural to synthetic. Consumers in the present day are becoming more interested in and demanding the functionalization of textiles via the use of sustainable natural materials. To meet the criteria of environmentally friendly chemical finishing of textiles, biopolymers in microcapsule form may be used (Table 2).

3.1. Chitosan-based microencapsulated textiles

Chitosan is an emerging biopolymer that has been extensively used for textile-based encapsulation due to its biocompatibility, bacterial resistance, cheapness, availability, lower toxicity effects, etc. Chitosan is also used extensively in textiles for antibacterial, coloration, UV resistance, thermal stability, and so on [32,33]. It is one of nature's most important organic biomaterials with outstanding cationic characteristics. It plays a significant role in trapping material along with long-lasting effects by controlling the release rate. The most common interest of chitosan for textiles encapsulation is in the applications of thermal comfort, aroma finishes, antibacterial functioning, and insect repellency. The entire designing process of textiles needs to be healthier, sustainable, cheaper, and safer for consumers. Chitosan and chitosan-capped nanoparticles like silver have significantly been practised for functionalizing textiles [32,34–36]. Additionally, chitosan is used as a binder to finish the textile fabrics against degradation by maintaining the mechanical properties and as the binder for printing or even as the dyeing auxiliaries. The active substances could be delivered over the textiles by changing the shell permeability or from external stimuli (like temperature, pressure, diffusion via polymer wall coating, friction, biodegradations, and so on) degradations [37].

Moreover, chitosan-based microencapsulation is advantageous for the following reasons: (1) the polycationic nature in acidic conditions makes the basement for versatility and potential applications, and (2) it facilitates chemical modification through covalent bonding [34,36]. The chemical feature of chitosan provides superior antibacterial performances. However, it is affected by environmental conditions like temperature, pH, and/or ionic strength. Chitosan is a positively charged material and can easily react with negatively charged substrates. Due to its nontoxic properties, chitosan is often used as the shell material of microcapsules. Therefore, Chen et al. [38] reported phase change in the chitosan-based microcapsule, which was initially prepared using a single coagulation technique, later strawberry chitosan microcapsules were prepared through grafting photochromic microcapsules with chitosan microcapsules (Fig. 3). Interestingly, changing antimicrobial and colour could be regulated by adjusting nanocapsules on the chitosan cover factor [38].

3.2. Gelatin-based microencapsulated textiles

Gelatin also possesses excellent biocompatibility, water retention, anti-carcinogenicity, and film-formation capabilities. Gelatins are produced through mixing poly and oligopeptides obtained through collagens partial hydrolysis containing 18 amino acids [11]. The amino acids in collagen are bonded with peptide bonds by linking together and building larger chains. By applying the complex coacervation method, Li et al. [52] encapsulated moxa oil into gelatin-Arabic gum microcapsules to improve antibacterial performances. They have investigated the moxa oil containing microcapsules (loaded 0.2 ± 0.01 mg/ml) in terms of particle size (6.42 μm, spherical), surface morphology, drug loading,

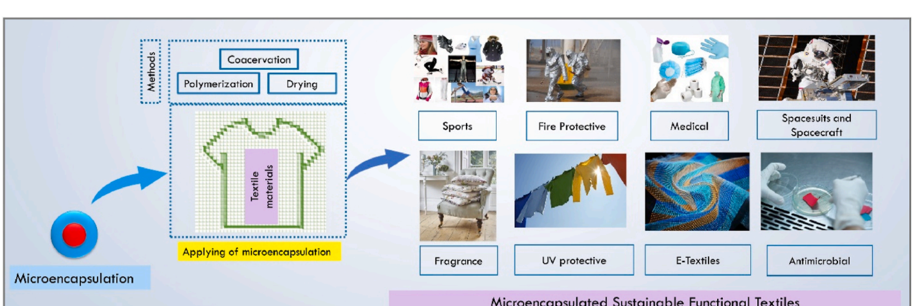


Fig. 2. Microencapsulated sustainable functional textiles.

Table 1
Surface modification techniques for textiles.

Methods	Application areas							
	Sports textiles	Medical textiles	E-textiles	UV protective textiles	Antimicrobial textiles	Fire protective textiles	Fragrance textiles	Spacesuits textiles
Nanoparticles	✓	✓	✓	✓	✓	✓	✓	–
Hydrogel	–	✓	–	✓	✓	–	✓	–
Aerogel	–	✓	✓	–	✓	–	–	✓
Plasma	✓	✓	✓	✓	✓	✓	–	–
Nanotubes	✓	–	✓	–	–	✓	–	✓
Radiation	✓	✓	–	✓	✓	✓	–	–
Enzyme	–	–	✓	✓	✓	–	–	–
Sputtering	–	✓	✓	✓	–	✓	–	–
Laser treatment	–	✓	✓	✓	–	✓	–	–
Microencapsulation	✓	✓	✓	✓	✓	✓	✓	✓

Table 2
Application of sustainable microencapsulation for functional textiles.

Polymers	Preparation method	Textile materials	Application	Ref
Chitosan	Pad-dry-cure	Cotton	Antimicrobial and thermoregulating textiles	[39]
Chitosan	Padding	Viscose	Advanced medical textile, antimicrobial textile	[40]
Chitosan	Pad-dry-bake	Wool	Antimicrobial and insect-resistance	[41]
Chitosan	Padding	Cellulose	Antimicrobial and insect-resistance	[42]
Gelatin	Complex coacervation	Cotton	Durable and aroma finishes	[43]
Gelatin	Pad dry	Cotton	Antibacterial	[44]
Gelatin	Complex coacervation	–	Insect repellent	[45]
Alginate	Pad-dry-bake	Cotton	Biomedical and sports	[46]
Alginate	Printing	Cotton	Antibacterial and aroma finishes	[47]
Alginate	Padding	Cotton	Colorimetric detection of urea	[48]
Cellulose	Emulsion-solvent evaporation	–	Thermal reliability	[49]
Ethyl cellulose/ silica hybrid microcapsules with lavender fragrance	Emulsion-solvent diffusion on	Commercial cotton	High UV-resistance (159 UPF value) and durable aroma finishes (90 days)	[50]
Ethyl cellulose microcapsules and rosemary lavender	Phase separation method	Cotton	Durable fragrances, Antibacterial agent, skin softeners, and phase-change materials	[51]

and antibacterial characteristics and found significant performances. Moreover, the moxa oil was gradually released from the microcapsules, and the cotton fabrics treated with the same oil microcapsule provided strong inhibition growth against staphylococcus aureus bacteria [52]. The higher loading of moxa oil microcapsule (50 $\mu g/cm^2$) showed a higher inhibition zone (7.5 ± 0.5 mm) than that of lower loading (25 $\mu g/cm^2$) [52]. In another study [53], a gelatin microcapsule encompassing vitamin C was developed by implementing an emulsion hardening method for cosmetic textiles. The cosmetic textiles were prepared by grafting the gelatin microcapsules in the fibers [53].

Singh et al. [54], proposed an interaction mechanism of chitosan/gelatin microcapsules formation through a two-step methods procedure where, as being a cationic character of chitosan (acidic condition) made reaction with negatively charged gelatin at pH 4.8 (isoelectric point) due to electrostatic interactions (Fig. 4a). The same study also revealed that the finished fabric contains microcapsules due to the peaks present within 3000 to 2500 cm^{-1}, which correspond to the O–H bond for the carboxylic acid group of gelatin (Fig. 4b) [54].

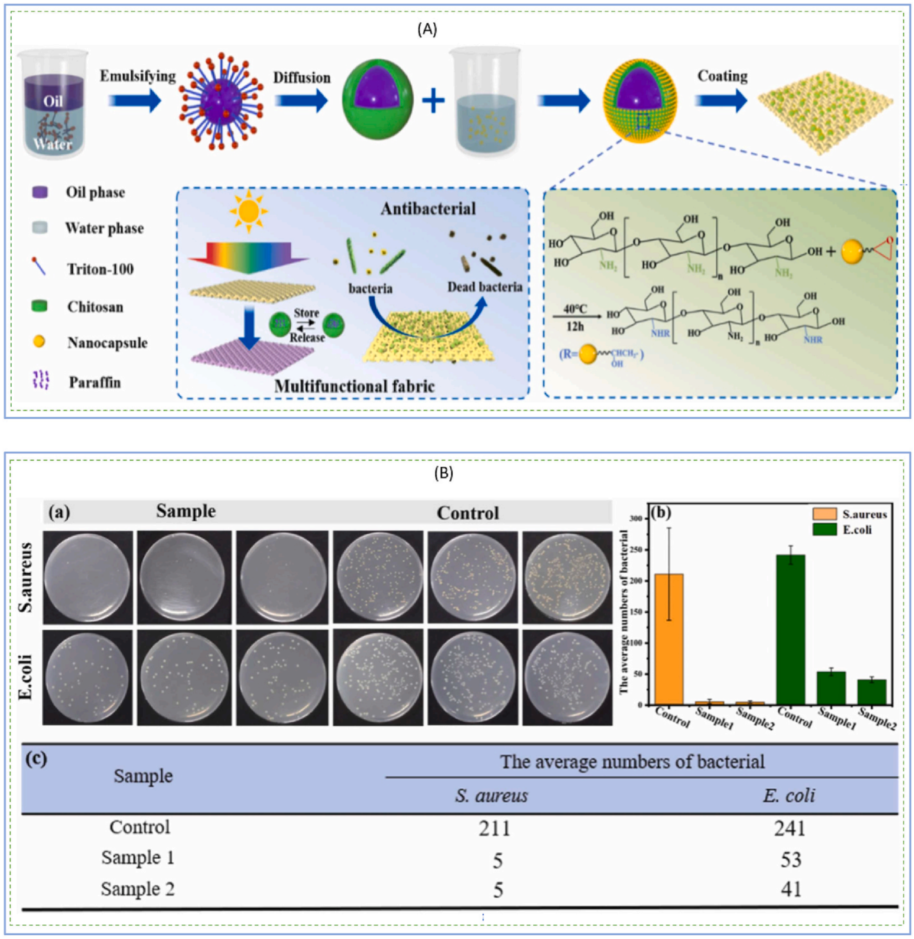
3.3. Alginate-based microencapsulated textiles

Alginate is also another tremendously studied biopolymer used for microencapsulation. It is grown in brown algae, which is like a skeleton component. It is considered one of the most efficient microencapsulation over various materials, which could be performed by applying different methods. This is a linear polysaccharide (anionic) which consists of α-L-guluronate and β-D-mannuronate residues, generally linking through (1,4)-glycosidic bond in an irregular block-wise form [11,55]. Microcapsules could be formed using the combination of chitosan and alginate. Alginate contains a carboxylic acid group with negative surface charges, which strongly facilitates a spontaneous reaction with the chitosan's amide group when both polymers are mixed together. The most common reactions are hydrogen bonds, electrostatic, and dipole-dipole associations. Interestingly, the developed complexes can resist pH variations, have stability against any leakage from the loaded material, and provide better mechanical performances. Alginates have a higher gelling capability, low toxicity, and biocompatibility; therefore, they are utilized in the case of oil encapsulations, especially beside the other polymers used in membranes [56]. The alginate macromolecules create crosslinking for forming a three-dimensional network when present with Ca^{2+} (calcium ions) called hydrogel. However, such a process of encapsulation can be carried out in three ways: Internal gelation mechanisms, External gelation mechanisms and Inverse gelation mechanisms.

In the case of textiles, the chitosan-alginate complex exists applications for medical products like cotton-gauges and antibacterial peptides. The side effects of the multifaceted application of medical textiles toward human health are minimized when naturally derived products are incorporated. Therefore, Rehan et al. developed a microcapsule comprising a starch core and guava leaf powder (bioactive compounds were extracted by ultrasonic method), where calcium alginate was used as the membrane material [57]. The same study revealed that the developed products contain outstanding antibacterial, UV-resistance, wound healing, and antioxidant characteristics [57]. Moreover, sodium alginate and other reagents are also getting attention for treating the effluents discharged from textile industries [58].

3.4. Cellulose-based microencapsulation textiles

Natural cellulose is the most common organic polymer. Plants are the primary biosource for cellulose. Cellulose, a polysaccharide composed of glucose monomers, is one of the primary components of plant cell walls. There are several cellulose derivatives available, including ethyl cellulose (EC), cellulose acetate (CA), cellulose acetate butyrate (CAB), cellulose acetate phthalate (CAP), trimethylsilyl cellulose (TMSC), etc. Industrial usage of cellulose derivatives is widespread because of their



Sample	The average numbers of bacterial	
	S. aureus	*E. coli*
Control	211	241
Sample 1	5	53
Sample 2	5	41

Fig. 3. (A) Strawberry microcapsule preparation process on treated fabrics and (B) antibacterial development over-treated and control fabrics: Samples 1 and 2 indicate treatment of strawberry/chitosan composite microcapsules. Reprinted with permission from Elsevier [38]. Copyright, Elsevier, 2022.

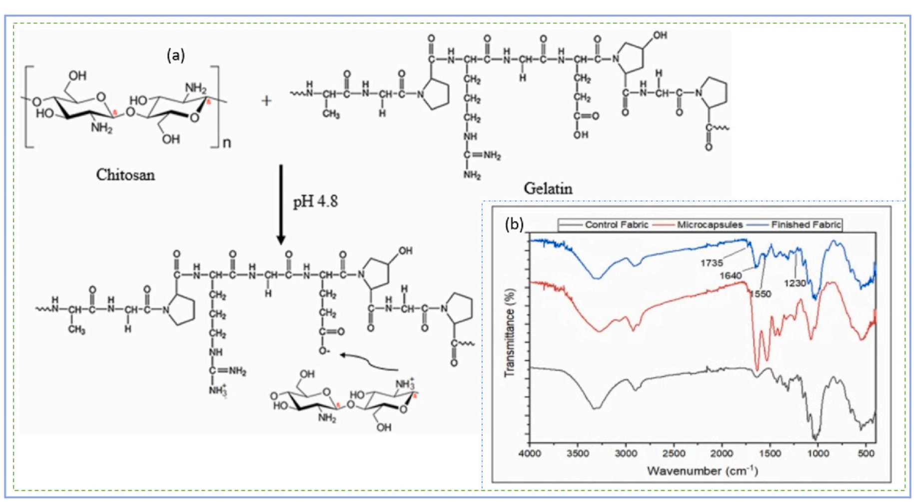


Fig. 4. (a) Probable interaction mechanisms between the gelatin and chitosan and (b) FTIR analysis. Reprinted with permission from Elsevier [54]. Copyright, Elsevier, 2022.

inexpensive cost, biodegradability, and low physical characteristics [59,60].

Recent work by Simões et al. [61] has successfully encapsulated eugenol in cellulose derivatives (EC, CA, CAB, and CAP) that have been successfully integrated into cotton textiles. The primary component of clove oil, eugenol, has potent antiseptic, antibacterial, and antiviral effects [62,63]. Producing these microspheres required solvent evaporation, and then they were applied to fabrics using padding methods (Fig. 5). The study findings they obtained indicate that CA-based microspheres were more effective. In conclusion, these microspheres performed well in storing and preserving hydrophobic active chemicals for potential textile applications. Later, a mesostructured reactor was

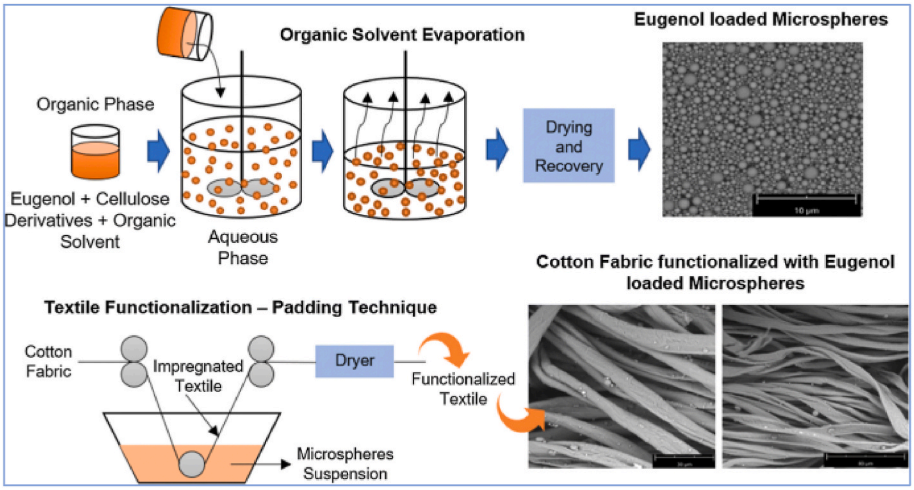


Fig. 5. Schematic representation of eugenol encapsulation by cellulose and its application on textiles. Adapted from Ref. [61] under the open access policy, Springer Nature, 2020.

created to continuously manufacture cellulose acetate microspheres used in textile impregnation [64].

Microencapsulation of essential oils in EC [51] was also explored. These oils included rosemary, lavender, and sage. Microcapsules containing essential oils were manufactured using the phase separation process and then used to treat fabrics for odor control. Essential oils may be used as a relaxant, an antimicrobial, and a deodorant. In addition, they managed the microcapsule sizes by varying the stirring speed throughout the encapsulation process (350–1000 rpm). The microcapsules produced with the greatest stirring speed were the tiniest and smoothest on the outside.

By combining ethyl cellulose and silica in microcapsule form, Chen et al. [50] established a water-based fabric coating with a wide range of applications. Hybrid microcapsules of ethyl cellulose and silica-containing lavender fragrance oil (LFO) were created by dispersing LFO in a solvent to form an emulsion. These microcapsules include a core-shell design with UV absorbers and silica grafted with methacrylic acid in the outer shell and have a diameter of 30 m. To create fabric coverings with various uses, these hybrid microcapsules were added to polysiloxane resins that were dissolved in water. Performance tests revealed that cloth treated with cellulose/silica hybrid microcapsules infused with lavender fragrance oil (LFO-CSHM) retained scents for far longer than fabric treated with LFO alone. This occurs when the lavender oil used to scent the capsules is released gradually. This coating may be applied to outdoor textiles such as sportswear, curtains, and upholstery.

In response to certain wavelengths of light, photochromic dyes undergo rapid and reversible color changes. There has been a recent uptick in interest in using these dyes for smart and practical textiles. Coacervation and *in situ* polymerization techniques were used to microencapsulate two photochromic dyes [65]. Shells were made of ethyl cellulose and melamine-urea-formaldehyde. Characterization revealed that photochromic microcapsules were round, smooth, and uniform in composition. Microcapsules were successfully printed onto cotton fabric. It didn't take long after printing for the colors of the materials to shift drastically when seen in various lighting conditions. These textiles have strong fatigue resistance and a reversible photochromic reaction. The outcomes of the mechanical and physical tests and the color fastness tests' findings are all very promising. The authors propose that photochromic microcapsules are viable for securing textile brands and warding against counterfeits.

Microencapsulation shells made from cellulose and cellulose derivative polymers are becoming popular because of their biodegradability. However, the use of cellulose microcapsules in the textile industry is still in the experimental stages. As global environmental and sustainability concerns grow, sustainable microencapsulated functional textiles made from cellulose should be developed by the textile science and technology community.

4. Sustainability considerations: environmental perspective

This review has shown how biopolymers may be used in a variety of ways and explored how they can be used as inputs in the development of sustainable microencapsulation. There are substantial information gaps concerning the environmental effect of designed microcapsules that need to be addressed before bringing these concepts from the lab to the real world, even though the notion of sustainable microencapsulation for functional textiles applications may seem to be an appealing solution at first sight [66]. Once discharged into the environment (laundry washing), i.e. soil, air, and water, it is predicted that the majority of the novel microcapsules are highly mobile, quickly dispersible, and extremely reactive, potentially endangering human health (Fig. 6) [67,68].

Although biopolymers are considered biodegradable, some additives incorporated into the process make it more viable in a toxic environment through the leaching phase. A stable binding procedure carried out during the fabric's finishing stage may, thus, reduce the likelihood of leaching. Sustainable manufacturing also necessitates efficiently using the energy, water, and other natural resources needed to produce these goods [69,70]. Achieving this objective depends on how well the several functional agents are integrated into the substrates. It may permanently attach these active substances to the fibers or remove them easily. Positive end-user engagement is possible through an assembly process that considers a lower level of integration with relatively low negative environmental consequences, which is a supportive route for recycling and reuse, cleaning and washing, and ever-evolving technology. Additionally, using sustainability factors, such as ecological risk assessment, life cycle assessment, and possible hazard identification, may be an effective technique to advance microencapsulation-based sustainable textile technology [71].

5. Challenges and perspective

Microencapsulation coatings on textiles made from natural sources are an exciting area of research with significant potential for the textile industry in the future. Microencapsulated textile products based on biopolymers have allowed manufacturers to produce high-quality textiles that satisfy customer demand by maintaining safety, human health,

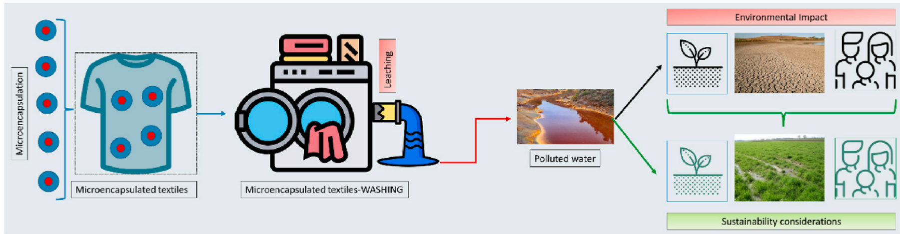


Fig. 6. Schematic representation of microencapsulation leaching from textiles into surroundings with environmental impact and sustainability considerations.

or environmental sustainability. Nevertheless, various concerns must be resolved before commercial applications can be created with a long-term focus.

- Environmental degradation of microcapsules is a significant issue for biopolymers-embedded microencapsulated textiles since it may occur in a variety of contexts, including natural media, mechanical agitation, and photodegradation.
- Unlike traditional synthetic polymers, biodegradable polymers may rapidly discharge a large number of microcapsules into the ocean or a river.
- Consequently, an alternate way to solid development might be the use of binding agents instead of the coating process. They may be more long-lasting if chemical finishing is added following the microencapsulation process.
- The relative importance of biopolymer microcapsules in multi-functional textiles is nuanced and still requires convincing and significant data.
- Post-use processing of the biopolymer microcapsule is an important consideration.

Microcapsules made from biopolymers are expected to gain popularity shortly for usage in a wide range of niche scientific and textile industry applications. We also anticipate the widespread use of biopolymer-based microencapsulation in the not-too-distant future. These particles will aid in advancing the high performance and give a deeper insight into and enhanced qualities of textile materials. Researchers will be incentivized to develop nanoencapsulation based on biopolymers, which would enhance the properties of textiles. Furthermore, we are certain that cutting-edge, environmentally friendly, and user-friendly synthesis techniques will be developed to fully use biopolymers-based microcapsules. We hope this review will stimulate additional studies into developing and implementing microcapsules based on biopolymers for use in textiles.

6. Conclusions

Microencapsulation is utilized in the production of eco-friendly functional textiles to improve upon already present attributes or to introduce entirely new ones; this increases the utility and monetary value of the finished products. Microencapsulation has the ability to make major strides forward as a subject of study, notably in eco-friendly formulations, thanks to the factors of active ingredient choice, polymer membrane structure, textile finishing for attaching particles, and support functionalization. The application of microcapsules to textiles presents a number of technological challenges that need to be addressed in future research. These include the necessity for fixing agents, the short lifespan after washing, and the altering of textiles' physical properties. It is expected that the growth and development of multifunctional textiles will soon lead to additional growth and the introduction of new possibilities, including the use of microencapsulated materials in the functionalization of textiles. To solve this challenge, insight into this crucial area of chemistry is required. In the future, microencapsulation and its use in textiles will necessitate cutting-edge engineering and modern production processes. This review effort can help to solidify the potential of further research into the microencapsulation production of eco-friendly textile products for the textile community.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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