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Recent advances in polymer nanoencapsulation of essential oils for multi-functional textile finishing

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Textile finishing is on the cusp of transformative change with the integration of the nanoencapsulation technique. Nanoencapsulation serves as a promising tool for incorporating therapeutic properties into various substrates, including textiles. Essential oils (EOs) are complex, heterogeneous, volatile and semi-volatile organic compounds with a broad range of biomedical applications, such as antimicrobial, antioxidant, anti-inflammatory and anticancer properties. However, essential oils are naturally biologically unstable and volatile, which limit their practical applicability. Nanoencapsulation acts as a barrier, providing physiochemical stability in natural environments. This review systematically explores various essential oils encapsulated in polymeric shells for the slow and sustained release of therapeutic agents functionalized on textiles for antimicrobial, insect repellent and skin care applications. Thus, it presents nanoencapsulation as a promising field in textile finishing and coating for potential biomedical and industrial applications.

1. Introduction

Nanoencapsulation of active functional biomolecules is one of the most significant advancements in nanotechnology. In the modern era, nanoencapsulation plays a significant role in the textile, food, and pharmaceutical industries. Nanoencapsulation of active ingredients improves bioavailability by increasing the surface-to-volume ratio.[1] Encapsulating active substances into nanoparticles to improve their functional performance has been one of the most prevalent and effective uses of nanotechnology.[2] Nanoencapsulation provides two types of core–shell structures: nanocapsules and nanospheres. In nanocapsules, the core or active material is enclosed in a membrane, while in nanospheres, active ingredients are uniformly distributed within a polymeric matrix.[3] The nanoencapsulation technique significantly reduces challenges by delivering the bioactive material in a specifically designed, advanced and versatile core–shell structure.[4]

The utilization of natural essential oils (EOs) with relevant and diversified functional activities has attracted researchers and consumers in diverse fields.[5] Essential oils represent intricate combinations of volatile chemical compounds produced as secondary metabolites in plants. These compounds play a key role in defining the plants' aroma, flavor, and scent. The biosynthesis of essential oils contributes to the distinct characteristics exhibited by various plant species.[6,7] Besides the unique composition of active compounds, aromatic properties, and diverse biological effects, essential oils represent a valuable source of natural soothing ingredients that can be incorporated into a wide range of cosmetic products. These products include cosmetic formulations, shampoos, hair-repairing conditioners, and pharmaceuticals.[8] Essential oils disrupt mitochondrial activity and increase oxidative effects, making them effective anticancer agents.[9] Natural oils are widely known for their anti-mutagenic and anti-carcinogenic properties.[10] The reported health benefits of consuming EOs and their compounds have been thoroughly studied.[11] Essential oils are increasingly being utilized in health, agriculture, food packaging, and the textile industry as well.[12–15] However, their hydrophobic nature, chemical instability, and volatility present challenges for many applications. These issues can often be addressed by encapsulating EOs within colloidal delivery systems.[16]

Nanoencapsulation involves encasing bioactive molecules, such as essential oils (EOs), within a protective shell, enhancing their stability and enabling controlled release.[17] Encapsulated EOs have shown increased potency by disrupting key bacterial functions, including ergosterol biosynthesis, essential ion leakage, and bacterial membrane stability.[18] Once inside microbial cells, these EOs or their bioactive components interfere with DNA synthesis or bacterial ribosomal activity, ultimately disrupting protein metabolism.[19]

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The nanoencapsulation of essential oils has gained significant attention in the textile finishing market. Textiles are made to provide comfort, wearable properties, smoothness and functional properties as antimicrobial, insect repellent, and aroma producing for consumers.[20] The choice of suitable encapsulation methods and wall materials plays a crucial role in the preservation and controlled release of essential oils (EOs), thereby increasing their antimicrobial efficacy.[21] The complex coacervation technique was utilized to synthesize citronella oil-encapsulated natural polymeric gelatin and gum Arabic microcapsules to fabricate mosquito repellent functional textile finishing. The optimized formulation of microcapsules was coated on polyester blended cotton textile *via* conventional padding and curing using acrylic binder for biomedical applications. The mosquito replant activity was analyzed by the cage test method before and after standard laundering cycles to check the durability.[22] Similarly, in another study, pepper mint EO-based microcapsules were prepared *via* complex coacervation to fabricate bug repellent functional finishing coated on polyester blended cotton *via* the pad-dry-technique.[23] The pad-dry-cure technique is considered effective to fabricate functional finished textiles in terms of washing durability utilizing commercially available binders. *Helichrysum* oil was encapsulated in beta-cyclodextrin *via* the solid diffusion method to produce antibacterial functional spherical capsules loaded with EO and cotton substrates were impregnated with a slurry of the capsules. The qualitative antibacterial activity of the resulting fabric was evaluated against *E. coli* and *S. aureus* with a maximum reduction in bacterial colonies, and it was found that its effectiveness was reduced after 5 standard laundering cycles. The washing durability of its antibacterial activity was attributed to the physicochemical interaction between the cotton and capsules through the formation of a complex without the need for commercial binders.[24] The use of commercial binder auxiliary agents can be restricted by utilization of the advanced layer-by-layer (LBL) coating method to fabricate sustainable functional textile finishing on a variety of textile substrates. LBL involves electrostatic interaction, hydrogen bonding and covalent interaction between polymeric nanoparticles and textile substrates to develop durable, semi-durable and temporary finished fabric for the corresponding industrial and biomedical applications.[25] Similarly, cosmetotextiles with skincare applications have emerged as a new advancement in functional textile finishing.[26] Imparting multi-functional properties to textiles *via* temporary, semi-permanent and permanent treatment is a promising approach for textile manufacturers.[27] In this case, the nanoencapsulation of active species offers several advantages, including enhanced chemical stability, durability, and controlled release for long-lasting effects.[17] Thus, EOs are the potential candidates to replace synthetic chemicals with plant-based naturally active molecules for multifunctional properties.[28,29]

The objective of this review is to explore the advancements in nanoencapsulated essential oils in functional textile finishing. The effects of different essential oils and the inherent properties of textiles are systematically evaluated to identify the challenges associated with polymer nanoparticles for the nanoencapsulation of essential oils in functional textile finishing. Also, we discuss scalable synthesis routes and fabrication techniques for the nanoencapsulation of EOs to produce multi-functional textile coatings. This will bridge the gap between existing knowledge and future advancements for potential industrial applications. These findings will not only contribute to the understanding of innovative approaches but also provide valuable insight for researchers and industry professionals, aiming to incorporate nanoencapsulated essential oils for multi-functional textile finishing. Its significant applications include biomedical and healthcare, pharmaceutical, cosmeceutical, fashion clothing, sportswear, footwear and smart hi-tech textile manufacturing. A graphical representation of nonencapsulated essential oils for textile finishing is shown in Fig. 1.

2. Challenges in the direct use of essential oils

The application of essential oils is limited by their volatility and susceptibility to chemical instability against external stimuli such as light, heat, and moisture, as shown in Fig. 2.[30] Essential oils are sensitive to temperature due to oxidative reactions and undergo degradation during transportation, storage, and consumption.[31] Also, formulations containing essential oils are associated with stability issues in the natural environment, leading to their degradation and oxidation.[32] Oxidation reactions can lead to substantial physicochemical alterations in essential oils (EOs), resulting the loss of their therapeutic efficacies and functional properties.[33] Moreover, essential oils are poorly soluble in water, which also limits their industrial application in food, cosmetic, textile and pharmaceutical products.[34]

In general, light exposure has a significant impact on the stability and possible functions of EOs. Storage of marjoram EO in light for more than 3 months resulted in significant changes in its chemical composition, with the formation of oxidative chemicals and loss of organoleptic qualities, making it unfit for usage. In contrast, storage in the dark did not produce any significant changes in its chemical and physical properties, suggesting that light accelerates the reactions and affects its stability.[36] However, the stability of some essential oils is not affected by light.

3. Nanoencapsulation as an efficient way to improve the therapeutic efficiency of essential oils

Nanoencapsulation presents an innovative way to overcome the limitations in utilizing the therapeutic efficacies of EOs for functional textile applications.[37] Several nano-formulations have been developed with EOs encapsulated in a biodegradable polymeric shell to improve their bioavailability, bio-efficacy and shelf-life with high cellular uptake.[38] Depending on the nature

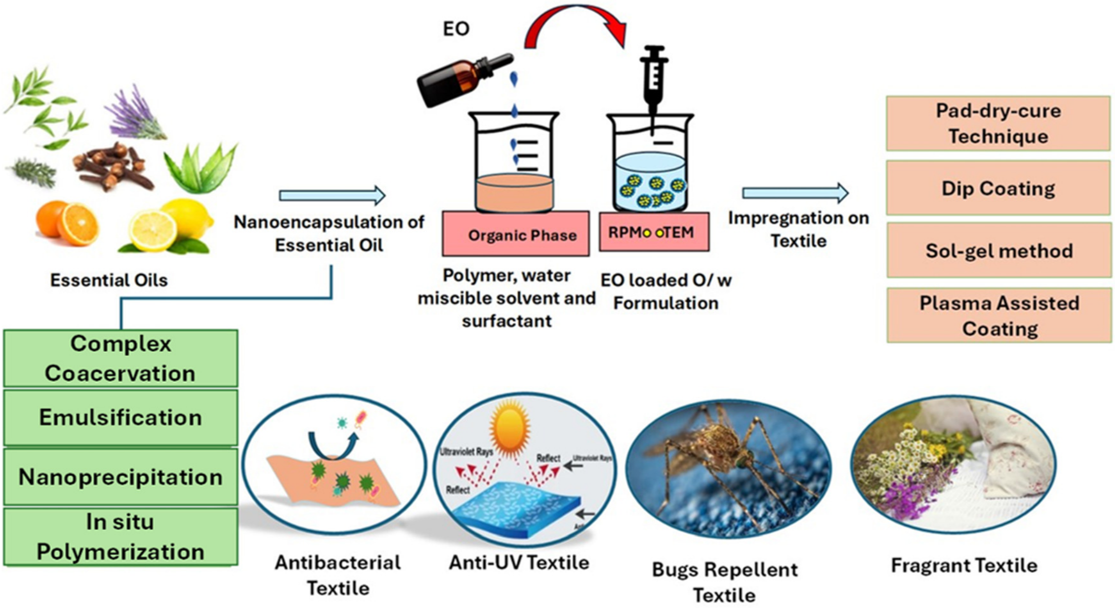

Fig. 1 Nanoencapsulation strategies for loading essential oils (EOs) in polymeric nanoparticles, showcasing the formation of oil-in-water (O/W) formulations, followed by their impregnation into multifunctional textile finishing.

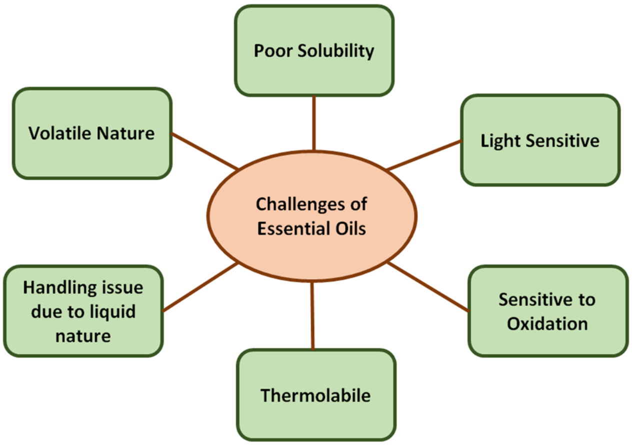

Fig. 2 Limitations of essential oils, including poor solubility, light sensitivity, susceptibility to oxidation, thermolability, handling issues due to their liquid nature and volatility.[35]

of functionalization and synthesis method, EO as the core encapsulated in a polymeric shell can be either a nano-sphere or nano-capsule, as shown in Fig. 3(a) and (b), respectively. Alternatively, the choice of a suitable polymer as the wall material is based on its non-toxicity, biodegradability, biocompatibility, and safety, as listed in Fig. 3(c). Various types of EOs as the core can be encapsulated in natural and synthetic polymers to achieve the slow and sustained release of active species to develop uni-functional, bi-functional, and multi-functional properties in textile substrates.[39,40] The nanoencapsulation of EOs in a polymeric shell is realized through various techniques including coacervation or ionic gelation, nano-precipitation (solvent evaporation or solvent displacement), solvent diffusion, spray drying, and emulsification. The choice of encapsulation technique depends on the stability and size of the active molecule, area of application, mechanism of *in vitro* and *in vivo* release and overall cost.[41] A suitable polymer is selected to encapsulate EO as the lipophilic core, depending on their solubility in a same solvent. According to Fessi *et al.*, polymeric nanoparticles synthesized through nanoprecipitations are comprised of two immiscible phases such as aqueous and organic phase with suitable ionic and non-ionic surfactants to acquire compatibility and stability between them. The polymer and active molecule are chosen based on their solubility in the organic solvent, while two aqueous and two organic phases with two surfactants can also be used.[42] Various process parameters need to be optimized besides the polymer, EO (as the active core) and surfactant concentration including stirring time, stirring speed, and temperature. Coacervation is considered another effective technique to encapsulate EOs in both natural and synthetic polymers including chitosan, alginate, casein, whey proteins, enzymes, polycaprolactone (PCL), polylactic acid (PLA) and polyvinyl alcohol (PVA).[6] The coacervation technique involves the formation of polymeric nanocapsules based on a nano-emulsion *via* high shear mixing. A lateral polyelectrolyte is added to the nano-emulsion to initiate the coacervation of a polymer thin film and facilitate the formation of a crosslinked structure between the polymer shell and active material. Coacervation has been widely studied by researchers for encapsulating EOs as an oil in water (O/W) nano-emulsion with multiple therapeutic activities. Cotton and polyester were selected as reservoirs to fabricate functional microencapsulated fabrics *via* padding and exhaustion and investigate the release kinetics for the slow and sustained release of EO for skin benefits. The study conclusions indicated that to achieve the controlled and prolonged release of EO to the skin, it is important to consider the type of polymer shell, nature of each

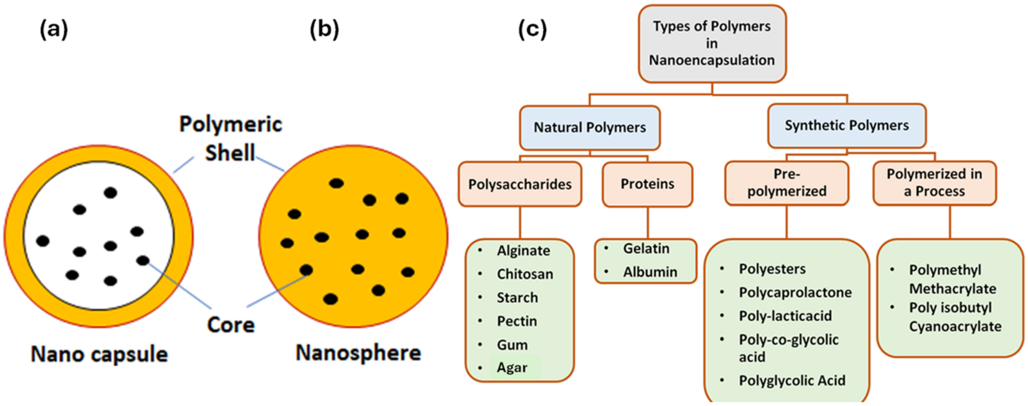

Fig. 3 Classifications of polymer nanoparticles in nanoencapsulation: (a) nanocapsules with an active material confined in a polymer shell, (b) nanospheres with an active material dispersed in a polymer matrix and (c) classification of polymers used in nanoencapsulation as natural and synthetic for encapsulating essential oils.[45,46]

chemical, type of fabric, and application technique.[43] Nanoencapsulation is a versatile tool to realize the enhanced efficacy and bioavailability of EOs and its significant properties are as follows:[44]

- Dissociation occurs more quickly.
- Provides greater surface to volume ratio.
- Significant intra cellular uptake.
- Reduces the amount of core shell material used.
- Physical stability.

3.1. Release mechanism of essential oil-loaded polymeric nanoparticles

Nanoencapsulation protects essential oils from the external environment, which are released after exposure to a specific chemical trigger.[47] When triggered by an external reaction, the essential oil is released by one or more different mechanisms, as shown in Fig. 4. Diffusion is the most common method for releasing essential oils.[48] This mechanism relies on a concentration gradient from high concentrated medium to low concentrated medium. Also, the weight of the core material and loaded material and particle size affect the rate of diffusion.[49] Thermal stimulus is based on providing heat, which melts the outer wall, and then the essential oil is released. In the case of chemical stimuli, the essential oil is released from the wall upon a change in temperature or pH or dissolving in some solvent. Mechanical stimuli provide some frictional or pressure force, causing the essential oil to be released from the wall material.[50–53]

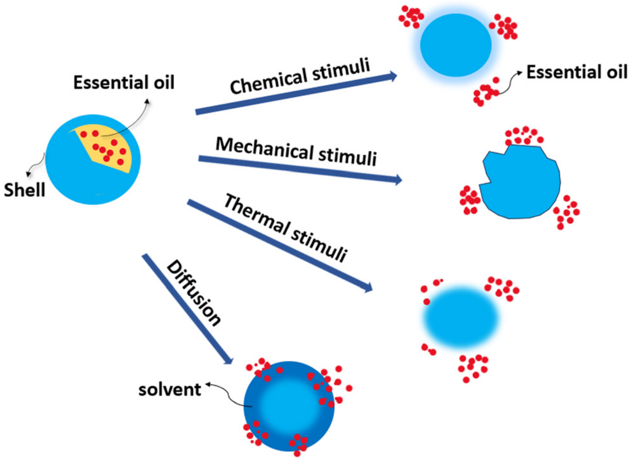

Fig. 4 Release Mechanisms of essential oils from polymeric nanocapsules.[54]

4. Essential oils associated with multiple therapeutic efficiency

Essential oils can be classified depending on their chemical composition and variety of extraction sources.[55] The composition of essential oils extracted from a specific plant exhibits significant properties based on factors such as age, growing temperature, plant organs, and soil composition.[56] Generally, EOs can be categorized into two major classes based on their biosynthetic chemicals. Terpenes and terpenoids make up the first category, whereas aromatic and aliphatic components make up the second. These two categories collectively constitute 20–85% of the composition of essential oils EOs, while other components are frequently present in much lower quantities or at negligible levels.[57] Essential oils have diverse applications in cuisine, medicine, cosmetics, textiles, agriculture, food, and packaging.

4.1. Peppermint essential oil

Peppermint EOs have antifungal, antiviral, antibacterial, insecticidal, and repellant properties and have found applications in skin care products, medicine, and the food industry. Menthone (about 30%) and menthol (25%) are believed to be the main components of peppermint essential oils.[58]

4.2. Sage leaves essential oil

The aromatic sage (*Salvia officinalis*) leaves are renowned in Mediterranean cuisine for their use as a classic seasoning. Sage leaves possess hollow surface fibers saturated with essential oils, imparting a potent fragrance to the plant.[59] The stem and leaves of sage contain more than 50 distinct chemicals known for their antioxidant, radical-scavenging, and antimicrobial activity. The primary active ingredient is thujone, present in 50% of the stems, 30% of the leaves, and 18% of the flowers. Other significant essential oil components of sage include α-pinene, β-pinene, camphene, camphor, β-humulene, β-caryophyllene, and viridiflorol.[60]

4.3. Rosemary essential oil

Rosemary (*Rosmarinus officinalis*) is a highly branched and fragrant semi-shrub plant having leaves containing 1% to 2.5% EO, primarily composed of triterpenes such as ursolic acid. Rosemary extract predominantly consists of phenolic diterpenoids with notable antioxidant effects, including carnosol, carnosic acid, rosmanol, epirosmanol, rosmadial, and methyl-carnosate, as well as flavonoids such as genkwanin and cirsimaritin. These constituents contribute to the potent antibacterial, antimutagenic, anticancer, anti-allergic, and antioxidant properties of rosemary.[61]

4.4. Oregano essential oil

Oregano is a flavorful, medicinal plant with a historical benefit in medicine and cuisine for thousands of years. The genus *Origanum*, belonging to the family Lamiaceae, constitutes 39 species. The primary phenolic components found in oregano are thymol (35%) and its isomer carvacrol (32%), which are known for their antibacterial, antiviral, and antifungal effects.[62]

4.5. Thyme essential oil

Thyme is a genus of the Lamiaceae family and is similar in appearance to basil, oregano, marjoram and wild thyme. Two types of EOs can be derived from thyme plants. The first category of oils is comprised of monoterpene molecules such as thymol and carvacrol, as well as their biosynthetic precursors p-cymene and y-terpinene. The primary constituents of the second category are monoterpene hydrocarbons. Thyme is a popular spice having a pleasant odor and strong antioxidant, antimicrobial, and therapeutic action.[63]

4.6. Basil essential oil

Basil essential oil has antiviral, antioxidant, anti-inflammatory, and anti-diabetic properties. Basil essential oil is known to have antibacterial action against Gram positive and Gram negative bacteria, yeast, and molds due to the presence of linalool, methyl chavicol, and methyl cinnamate.[64]

4.7. Lavender essential oil

Lavender EO has applications in cosmetics, medicines, food, environmental products, and agriculture. Lavandula plants are rich in phenolic compounds, with the discovery of 8 anthocyanins and 19 flavones. The essential oil composition varies across *Lavandula* species,[6] with over 300 terpenes (mono- and sesquiterpenes) identified.[65]

4.8. Lemongrass essential oil

Lemongrass essential oil, belonging to the family Poaceae, is characterized by its high industrial demand in various sectors such as food, cosmetics, textiles, and medicine. The most active ingredient in lemongrass essential oil is myrcene, followed by limonene and citral, together with geraniol, citronellol, geranyl acetate, neral, and nerol, all contributing to human health. Lemongrass essential oil has demonstrated potential benefits in diabetic wound healing, tissue repair and regeneration, and addressing arthritis and joint discomfort.[66]

4.9. Aloe vera essential oil

Aloe vera is a perennial green herb known for its vibrant yellow tubular blooms, which is commonly found in North Africa, the Middle East of Asia, the Southern Mediterranean, and the Canary Islands. The active compounds in aloe vera are aloe-emodin, aloin, aloesin, emodin, and acemannan with significant anti-inflammatory, antibacterial, and wound healing properties. Aloe vera EO is extensively utilized for the treatment of skin injuries, including burns, wounds, insect bites, and eczemas, as well as for addressing stomach disorders.[67] Some common essential oils and their therapeutic benefits are summarized in Table 1.

Table 1 Some common essential oils, their scientific names, sources or origin and their potential health benefits

S. no.	Essential oil	Scientific name	Source of essential oil	Potential health benefits	Ref.
1.	Oregano	*Cinnamomum zeylanicum*	Leaves and shoots	Antioxidant, antibacterial, anticarcinogenic, and anti-inflammatory	68
2.	Lemongrass	*Cymbopogon citratus*	Leaves and stems	Antibacterial	69
3.	Thyme	*Thymus vulgaris*	Leaves and flowers	Antibacterial	70
4.	Peppermint	*Mentha x piperita*	Flowering parts and leaves	Antioxidant	71
5.	Citral	*Citrus limon*	Lemon, lemongrass, citrus fruits	Antibacterial	72
6.	Eucalyptus	*Eucalyptus globulus*	Fresh leaves	Larvicidal	73
7.	Clove oil	*Eugenia caryophyllus*	Leaves, flowers, and stems	Efficient in regrowth of hairs or treating *Alopecia areata*	74
8.	Virgin coconut oil	*Mangostin extract*	Stone fruit	Antibacterial, antioxidant	75
9.	Orange peel oil	*Origanum vulgare*	Orange peel	Antibacterial	76
10.	Flax	*Linum usitatissimum*	Flaxseeds	Antioxidant, antibacterial	77
11.	Nutmeg oil	*Myristica fragrans*	Leaves	Phyto-repellant	78

5. Essential oil-loaded nanoparticles for functional textile finishing

In recent years, the quest for creative materials to fabricate functional textiles has increased to meet consumer expectations and demands. Textile or textile-based functional fibers are necessary to humans for comfort and wellbeing.[79] However, textile fabric provides a large surface area and capacity to hold moisture, thus serving as an ideal habitat for microbial growth. The harmful microbial growth on fabric not only deteriorates textile materials but causes unpleasant odors and poses a considerable risk to consumer health.[80] In this case, polymeric nanoparticle-encapsulated EOs have potential for textile functionalization.[81] EOs loaded in a polymeric shell can provide slow and sustained release of functional characteristics immobilized on textile and fabric. EOs provide significant properties to textiles to fabricate self-purifying, UV-protective, insect repellent, hydrophobic, hydrophilic, and antimicrobial-resistant textiles, as shown in Fig. 5.[82,83] A brief overview of nano/microencapsulated EOs with their specific core–shell structure, synthesis and methods for impregnating and coating in functional textile finishing is presented in Table 2.

5.1. Nanoencapsulated EOs in antibacterial textile finishing

EOs extracted from a variety of plants have antimicrobial bio-efficacy for various biomedical, cosmeto-textile and industrial applications. Many naturally active substances have been extracted and utilized to fabricate antibacterial textiles finishing. Essential oil-loaded polymeric nanocapsules have been applied in controlling infectious diseases, wound healing, and antimicrobial activity.[100] The mechanism of action of EO-loaded antibacterial nanocapsules is shown in Fig. 6.

A combination of *Moringa oleifera* leaf extract and silver nanoparticles (AgNPs) was formulated as a biodegradable antibacterial agent for carboxymethyl cellulose and cationic fiber.[101] AgNPs were synthesized with particle sizes in the range of 15 to 25 nm in a reducing environment using polyvinyl alcohol (PVA). *Moringa* EO was immobilized on the surface of a fabric *via* the pad-dry-cure technique and the finished fabric was characterized through UV-visible spectroscopy, transmission electron spectroscopy (TEM), and X-ray diffraction (XRD). Its surface morphology was further examined using scanning electron microscopy (SEM), and its mechanical properties were assessed. The antibacterial efficacy of the functional fabric was assessed through qualitative and quantitative methods. An agar disk diffusion and bacterial count colony system was used to determine the bacterial reduction percentage. The results demonstrated that the *Moringa* oil and silver nanoparticles immobilized on the textile exhibited a significant zone of inhibition against both Gram-positive *S. aureus* and Gram-negative bacteria *E. coli*. This indicates the potential utility of EO to develop antibacterial finished cellulosic fabrics. Similarly, polymeric nanocapsules synthesized through the nanoprecipitation method were coated on cotton textile *via* the dip coating technique for antibacterial and anti-UV functional finishing, as shown in Fig. 7. Dip coating of nanoformulations is another advancement towards multi-functional textile finishing, which is achieved through electrostatic attraction between a polyelectrolytic solution of nanocapsules and pre-modified fabric surface. Dip coating provides a sustainable and eco-friendly method for textile finishing and dying without utilizing acrylic or non-acrylic binders.[80,102]

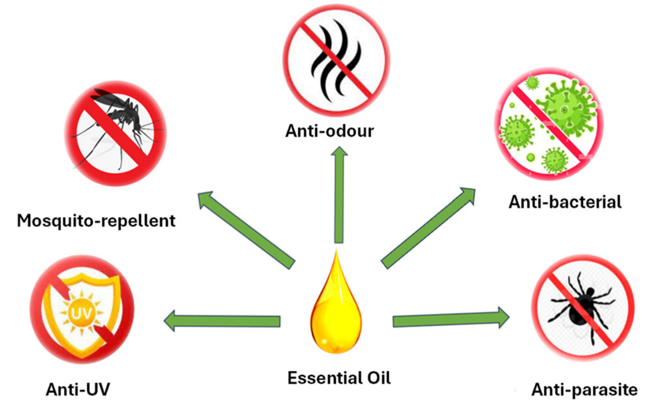

Fig. 5 Uses of essential oils in the textile industry.

B. S. Beşen *et al.*[103] developed tea tree oil microcapsules *via* the coacervation technique to fabricate disposable antibacterial textile. To achieve this, tea tree oil was encapsulated in a polymeric shell composed of different ratios of cyclodextrin, polyvinyl alcohol and Arabic gum and applied on nonwoven viscose fiber using a laboratory-scale padding method. The synthesized capsules were analyzed through scanning electron microscopy (SEM) and Fourier transform infrared spectroscopy (FTIR) to investigate their structural morphology. Further, the EO composition was studied *via* gas liquid chromatography. The microcapsule-immobilized non-woven viscose fiber was analyzed by SEM and FTIR for comparative analysis of the untreated and treated fibers. The antibacterial efficacy of the textile samples against two bacterial strains, *E. coli* and *S. aureus*, was systematically evaluated. The results demonstrated that the tea tree oil encapsulated within CD, PVA, and GA capsules can be efficiently applied to knitted and non-woven fabric with potential significance for medical and cosmetic textiles. The treated fabric samples exhibited varying degrees of antibacterial activity, with their efficacy dependent on the specific wall materials used in the encapsulation process.

Cerempei *et al.*[104] developed a natural antibacterial material suitable for application in barrier materials, hygiene products, plasters, and bandages. The material was designed by encapsulating different essential oils with beeswax and blend of beeswax and chitosan. An EO-based emulsion was synthesized by employing a suitable stabilizing agent. The resultant emulsion was coated on cotton fabric *via* the pad-dry-cure technique. The stability of the emulsion was investigated using optical microscopy, focusing on the impact of the oil, wax, and chitosan concentrations. UV/Visible spectrophotometric studies were performed to assess the controlled release of essential oils, including *Eucalyptus*, tea tree, and sage from the wall material. Furthermore, the antibacterial activity of the emulsions and

Table 2 Summary of types of essential oils and polymers as core and shell, techniques for encapsulation and methods for fabricating functional textiles with multiple health benefits

Essential oil composition as core	Polymers as shell	Technique of encapsulation	Fabrication method/coating technology	Functionality induced in textile	Ref.
Lemon and *Litsea* EO	Chitosan–alginate shell Average particle size: 1.5 μm Particle size distribution: 0.5 μm Stability profile: 14 days, while long term stability is less	Micro-emulsification process	Soak-pad-dry-cure technique	Antimicrobial antifungal and mosquito-repellant functional cotton textile finishing	84
Citronella EO	Gelatin	Complex coacervation	Pad-dry-cure technique	Mosquito-repellent cotton textile finishing	85
Limonene, camphor, linalool, menthol	Sodium alginate	Emulsion-extrusion	Pad-dry-cure technique	Mosquito-repellent Polyester-cotton textile finishing	86
Carvacrol and thymol	Chitosan	Complex coacervation	Pad-dry-cure technique	Antimicrobial finishing for cotton lab-coats	87
Ginseng and soyabean EO	Melamine-formaldehyde prepolymers	*In situ* polymerization	Pad-dry-cure technique	Antibacterial, antioxidant, functional nylon-polyurethane textile finishing	88
Rosemary and *Litsea* EO	Sodium alginate-chitosan	Complex coacervation	Soak-pad-dry-cure technique	Antibacterial and mosquito repellent cotton and polyester textile finishing	89
Lemon peel EO	Chitosan–alginate	Complex coacervation	Pad-dry-cure technique	Antimicrobial gauze fabric finishing	90
Cinnamon EO	Chitosan–gelatin	Spray-drying	Pad-dry-cure technique	Antibacterial, mosquito repellant, fragrant and antioxidant cosmeto-textile finishing for linen fabric	91
Limonene in lime peel EO	Alginate–gelatin	Complex coacervation	Pad-dry-cure technique	Anti-bacterial cotton textile finishing	92
Limonene and vanilla EO	Chitosan-gum Arabic	Complex coacervation	Easter bond formation with temperature cured grafting without binder	Aroma producing and antibacterial cosmeto-textile finishing	93
Strawberry EO	Melamine-formaldehyde prepolymers	*In situ* polymerization	Pad-dry-cure coupled with plasma assisted under nitrogen and oxygen environment	Fragrant cotton textile finishing	94
Jasmine EO	Melamine-formaldehyde prepolymers	*In situ* polymerization	Pad-dry-cure technique	Fragrant jute-cotton blended textile finishing	95
Coconut and curry leaf EO	Nanoemulsion with polysorbate 20 as surfactant	High-shear Emulsification	Batch and continuous padding and exhaustion	Antibacterial and antifungal cotton textile finishing	96
Lemon EO and nanoparticles	Pectin and gelatin	High-shear emulsification	Pad-dry-cure technique	Antimicrobial, mosquito repellent and anti-UV functional cotton and wool textile finishing	97
Lavender EO	Polyethylene-co poly-lactic acid block copolymer	Nanoprecipitation	NA	Antibacterial textile finishing for foot industry	98
Oregano EO	Polycaprolactone	Nanoprecipitation	Padding and exhaustion	Antibacterial and hydrophilic polyester textile finishing	99

treated cotton fabric was evaluated against *S. aureus* and *E. coli*. Further, a comparative analysis of the antibacterial treatment was conducted using variants containing different concentrations of wall and core materials for encapsulation. Among them, a higher concentration of EOs exhibited the most promising antimicrobial activity and the highest *in vitro* release.

In the pursuit of novel antimicrobial wound dressings, a groundbreaking approach was reported by Quartinello *et al.*,[105] where they fabricated pH-responsive human serum albumin/silk fibroin nanocapsules immobilized on cotton/polyethylene terephthalate (PET) blends. Eugenol, an antimicrobial phenylpropanoid derived from clove oil, was encapsulated as the core material for significant antimicrobial activity. The eugenol-loaded nanocapsules exhibited a hydrodynamic radius in the range of 319.73 to 574.00 nm, accompanied by a zeta potential in the range of 10.39 mV to 12.11 mV. Recognizing the significance of sweat glands in wound re-epithelialization, investigations into eugenol release were conducted in artificial sweat formulations with varying pH. The formulations featuring 10% silk fibroin with a lower breakdown degree displayed the maximum release of 41% at pH 6.0. The functionalized cotton/PET blend-immobilized nanocapsules demonstrated impressive capability to inhibit 81% bacterial colonies. The notable antibacterial activity observed against both strains was

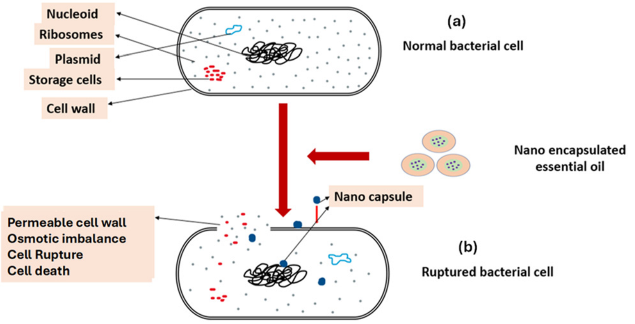

Fig. 6 (a) A normal bacterial cell with a nucleus at its center and a cell wall and (b) bacterial cell death occurring due to the mechanism of action of essential oil-loaded polymeric nanocapsules, affecting the cell nucleoid and rupturing the bacterial cell wall.

attributed to the particle homogeneity, silk fibroin content, and high surface-area-to-volume ratio of the generated nanocapsules. This innovative approach underscores the potential of developing antimicrobial fabrics utilizing nanocapsules containing active natural components, offering a promising alternative to conventional antiseptics and mitigating concerns associated with antibiotic resistance.

Gopalakrishnan *et al.*[106] applied *Coleus amboinicus* extract to cotton fabric *via* exhaust microencapsulation and nanoencapsulation processes. The antimicrobial efficacy of the finished fabric was qualitatively analyzed by standard test methods, which showed a significant reduction in bacterial colonies of both Gram-positive bacteria (*S. aureus*) and Gram-negative bacteria (*E. coli*). The standard washing or laundered test procedure was conducted on the fabric to check the durability of the finished samples. It was found that after several washing steps, the finishing applied to fabric using exhaust, microencapsulation, and nanoencapsulation processes demonstrated high antibacterial activity. Notably, the nanoencapsulation method displayed significant antibacterial activity against both Gram-positive and Gram-negative bacteria even after 30 washes, indicating its sustained effectiveness in microbial reduction over multiple laundering cycles. Thus, nanoencapsulations serve as an effective method for enhancing and prolonging the antimicrobial properties of cotton fabric treated with *Coleus amboinicus* EO.

Chandrasekaran *et al.*[107] develop a novel approach to enhance the medicinal properties of textiles by developing nanocapsules containing extracts from various herbs known for their medicinal benefits. The fabric samples included cotton, bamboo, and cotton/bamboo merged with woven textiles. EOs of neem, wild turmeric, and tulsi were formulated for their potential in controlling psoriasis. The fabric was pre-modified without using any synthetic chemicals. Herbal extracts were obtained using methanol solvent and the textile sample was coated using pad-dry cure technology with carefully optimized process parameters for the uniform immobilization of nanocapsules on the textile. The resulting textiles were evaluated for their antibacterial activity against *S. aureus* and *E. coli* by means of a bacterial inhibition assay. Remarkably, all the treated textiles exhibited high antibacterial activity against both bacterial species. The presence of active components was confirmed through Fourier transform infrared spectroscopy, demonstrating the incorporation of medicinal plant extracts. Furthermore, the presence of nanocapsules on the fabric structure was confirmed using electron microscopy. Statistical analyses of the antibacterial tests, mechanical tensile testing analysis and comfort properties were performed through standard procedures. Among the various fabricated textile samples, 100% bamboo fabric emerged as the most effective in terms of antibacterial efficacy and durability. Thus, comprehensive research not only imparts medicinal properties to textiles but also highlights the potential of bamboo fabric as a superior choice in terms of antibacterial activity and overall comfort properties.

P. Venkatraman *et al.*[108] introduced a distinctive and innovative method for the development, optimization and comparative analysis of two varying concentration-based nano-emulsions. In the first phase, a *Moringa oleifera*, curry leaf, and coconut

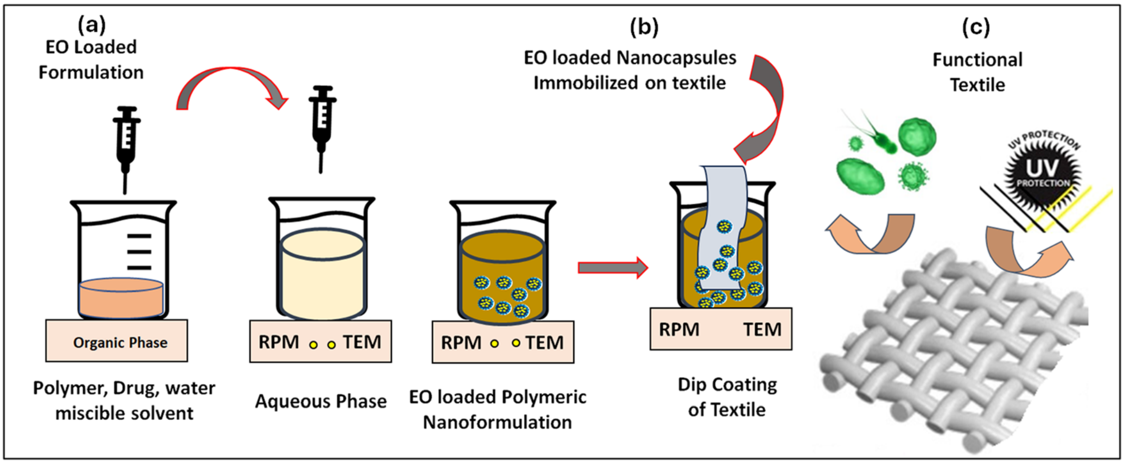

Fig. 7 (a) Synthesis of essential oil (EO)-loaded polymeric formulation *via* nanoprecipitation technique using organic and aqueous phases, (b) fabrication of EO-loaded nanocapsules on textile through dip coating and (c) functional textile showing anti-bacterial and anti-UV properties.

oil-based formulation was synthesized, while in the second phase, *Aegle marmelos* with curry leaf and coconut oil was formulated. The optimization was performed by varying process parameters such as pH, thermal stability, particle size, and zeta potential of the nano-emulsions. Cotton textiles with weights of 20 and 60 GSM were coated with these nano-emulsions using both continuous and batch processes. The surface morphology of the treated textiles was thoroughly examined through scanning electron microscopy, energy dispersive X-ray analysis, and Fourier transform infrared spectroscopy. Subsequently, the textiles underwent testing for antimicrobial resistance against both Gram-positive *S. aureus* and Gram-negative *E. coli* using the standard test procedures. The resultant nano-encapsulated finished textiles exhibited significant antibacterial and antifungal properties with wash fastness even after 20 washing cycles. These EO-based nano-emulsions provide durable and effective antimicrobial functional textiles finishing particularly suitable for healthcare applications.

S. Ghayempour *et al.*[109] proposed the application of antibacterial *Aloe vera oil* on cotton textile for wound healing. The cotton fabric underwent a simultaneous process of encapsulation with *Aloe vera* oil as the core in a natural tragacanth gum with a suitable stabilizer. The surface morphology of the nanocapsules immobilized on cotton fabric was analyzed by scanning electron microscopy, which revealed spherical shapes with an average size in the range of 55 to 70 nm. The *Aloe vera* oil-loaded Tragacanth nanoparticles immobilized on cotton textile exhibited notably high antibacterial and antifungal properties. Specifically, bacterial reductions of 70% to 80% were observed against *E. coli*, *S. aureus*, and *C. albicans*, respectively. Furthermore, the treated fabric demonstrated suitability as cotton bandages for wound healing benefits. This innovative approach suggests the potential of utilizing nano-encapsulated *Aloe vera* oil in cotton bandages for wound healing antibacterial and antifungal applications.

S. Subair *et al.*[110] employed two natural bioactive chemicals, carvacrol and thymol, encapsulated in chitosan nanoparticles to provide robust protection against four human infections, achieving a 99.99% reduction in bacterial count. These bacteria are commonly encountered in biohazard laboratory lab coats. The treated textiles exhibited remarkable durability for up to ten wash cycles with a substantial 90% bacterial reduction, aligning with the intended application requirements. To accurately assess the efficacy of antibacterial lab coats and model the potential fate of unintentional bacterial spills that necessitate rapid neutralization, the researchers modified the existing standard fabric tests. These modifications aimed to better replicate real lab coat usage conditions, offering a more realistic evaluation of their antibacterial effectiveness. The novel study concluded the potential of chitosan nanoparticle-encapsulated carvacrol and thymol for creating durable and highly effective antibacterial lab coats suitable for challenging laboratory environments.

M. Sumithra *et al.*[111] has formulated micro and nanoencapsulation of three herbal oils, *Ricinus communis*, *Senna auriculata*, *and Euphorbia hirta* to enhance the antibacterial efficacy by applying methanol extracts of these herbs to denim fabric. A combination of herbal extracts, specifically *Ricinus communis*, *Senna auriculata* and *Euphorbia hirta* was applied directly to denim fabric by using the pad-dry-cure technique according to the standard test protocols to enhance the durability of the finished fabric. Their study revealed that the treated fabric exhibited robust resistance to bacteria even after undergoing 30 industrial washes, demonstrating its enduring antibacterial properties against the test bacterial strains. This approach suggests the potential of using micro- and nanoencapsulation to impart long lasting antibacterial efficiency to denim fabrics treated with herbal extracts.

O. G. Allam *et al.*[112] aimed to enhance the bacterial resistance of wool and viscose textiles by incorporating lemon peel oil and its derivatives. This involved the production of lemon peel essential oil, followed by nanoencapsulation in a natural nanoclay. Essential oil from lemon peel was extracted *via* the conventional extraction technique and a stable formulation was synthesized by encapsulating EO in clay using a surfactant. The volatile bioactive components in the oil were identified using gas chromatography-coupled mass spectrometry (GC/MS), while high-performance liquid chromatography (HPLC) was employed to assess phenolic chemicals qualitatively and quantitatively. The size, shape, and size distribution of the oil and nano clay nanoparticles were investigated using TEM, and SEM. The morphological changes in the coated textiles were examined using SEM and energy dispersive X-ray analysis (EDX). The antibacterial results demonstrated that the textiles coated with citrus oil and its derivatives exhibited a significantly better performance against *S. aureus* than the untreated fabrics. This innovative approach highlights the potential of incorporating citrus oil and its derivatives as nanoemulsions to enhance the antibacterial properties of wool and viscose textiles.

5.2. Nanoencapsulated EO in insect repellant textile finishing

Natural insect repellants are becoming increasingly popular compared to synthetic ones because of their lack of side effects. Due to global warming, many insects are moving towards temperate and high-altitude regions. These insects are great vectors and cause diseases such as malaria, yellow fever, and dengue. Thus, insect repellant functional textiles or textile substrates are considered the most significant consumer demand for textile manufacturers. There are two major types of insect repellant groups, bio insect and synthetic repellants. However, considering that synthetic insect repellants are toxic, natural oils and extracts are preferable.[113] Different approaches have been developed to achieve insect repellant textiles.

G. C. Türkoğlu *et al.*[114] fabricated mosquito repellent functional fabric using a coacervation method to encapsulate limonene and permethrin in an ethyl cellulose shell. This approach aimed to contrast organic and manufactured mosquito inhibitors. The morphological analysis and laser diffraction confirmed the smooth surface, spherical size, and homogeneous size distribution of the capsules. FTIR spectroscopy unveiled the structural similarity among the capsules and wall material. Cotton textiles were processed individually with the capsule blend of limonene and permethrin using the padding strategy.

After subjecting the treated fabrics to 20 washing cycles, the presence of capsules on the materials was confirmed. Insecticidal activity was assessed against common house mosquitoes using the World Health Organization cone testing method. The treated textiles exhibited mosquito repellency, with fatality rates of 41% for limonene and 54% for permethrin. Despite the decline in fabric effectiveness with an increase in the number of wash cycles, the textiles retained repellency even after 20 washing cycles. This study suggests that the formulated functional finishing can serve as a substitute for existing treatments in the market for preventing mosquito-borne infections.

A. L. Mohamed *et al.*[97] conducted an investigation into the application of various metal and EO nanoparticles encapsulated in a biopolymer material on cotton and wool textile with or without the presence of lemon oil. The goal was to develop fabrics with mosquito-repellent, aroma producing, and antimicrobial functionalities. Lemon oil was encapsulated by biopolymers using a mechanical homogenizing mixing method. Various treatments for textile materials were devised with or without metal nanoparticles, employing a pad-dry-packing technique. Organic polymers were utilized at three different concentrations (3%, 5%, and 10%), with different concentrations of encapsulated oil for each polymer. The mechanical and physical properties of the treated textiles were assessed through various methods. This study revealed that the textiles coated with silver (Ag) nanoparticles encapsulated in gelatin biopolymer exhibited strong antibacterial activity. Titania (TiO_2) nanoparticles encapsulated in pectin biopolymer provided robust mosquito-repellent behavior, while zinc oxide (ZnO) nanoparticles loaded in gelatin biopolymer offered greater ultraviolet protection (UPF) values. In comparison to the untreated fabric, the treated textiles demonstrated improved physical and mechanical properties, showcasing the potential of these treatments to enhance the functionality of textiles for various applications.

A. Kamari *et al.*[115] explored the use of poly(-caprolactone) nanocapsules containing betel essential oil as the active ingredient as mosquito inhibitory spray compositions for cotton and polyester fabrics. UV-visible spectrophotometry was employed to assess the dissemination and preservation of the betel essential oil on the textiles after successive washing and heating. The repulsive properties of the cotton and polyester textiles were tested against *Aedes aegypti* mosquitoes in an excito chamber. The results indicated that the nanocapsules exhibited a high encapsulation efficacy and maintained stability for up to 60 days. Encapsulating the betel essential oil in the lipid polymeric nanocapsules enhanced its durability against washing and heating. The textiles retained good resistance, up to 47% even after five consecutive washing cycles. This suggested that betel essential oil-loaded lipid shell nanocapsules can be a promising alternative to insect repellent sprays for manufacturing insect protective textiles.

S. Kala *et al.*[116] addressed the challenges associated with the prolonged usage of synthetic pesticides for combating mosquito-borne infections by exploring plant-based insecticides. They suggested an ecofriendly approach by encapsulating cedarwood essential oil in natural pectin. This study evaluated the shape, size, encapsulation effectiveness, and thermal stability of formulated nanocapsules. The EO-loaded cedarwood nanocapsules were impregnated on small cotton tea bags and provided a ready-to-use formulation for treating insect breeding areas with simplicity and ease of handling. The insecticidal performance of the bags treated with pectin-cedarwood nanocapsules was evaluated against the malaria vector *Anopheles culicifacies* with a 98% mortality rate achieved after 4 weeks. Thus, the results indicate the potential and ease of use of plant-based insecticidal formulations, presenting a promising and environmentally friendly approach to combat mosquito-borne infections.

A. Kamari *et al.*[117] synthesized cinnamaldehyde-loaded poly(-caprolactone) lipid-core nanocapsules through the interfacial deposition of pre-formed polymer. The synthesized lipid capsules immobilized on a variety of fabric substrates including cotton, polyester and tetron offer a novel approach towards mosquito repellent textiles. FTIR and DLS analyses were conducted to evaluate the structure and particle size distribution of the capsules. The retention of the loaded capsules on the textiles before and after washing was investigated using SEM and UV-Vis spectroscopic techniques. The resistance of the textiles processed with the cinnamaldehyde-loaded nanocapsules against mosquitoes was tested in the lab using the Excito chamber method, as well as field studies on rubber fields. The SEM micrographs and UV-Vis spectroscopic data also demonstrated the durability of the textiles treated with the cinnamaldehyde-loaded nanocapsules and ethanolic cinnamaldehyde after washing cycles. Patch tests on individuals for 4 h indicated no skin discomfort from the treatment materials. Furthermore, the treated textiles exhibited strong mosquito repulsion and retained approximately 30% repulsion even after five washing and heating cycles. These findings suggest that the poly(-caprolactone) lipid-core nanocapsule-based formulation offers durability and permanence in mosquito-repellent functional textiles.

D. Rastogi *et al.*[118] employed neem oil as a mosquito repellent finish for textiles. They varied its concentration to optimize the formulation and determined the shelf life of the proposed formulation. Subsequently, the formulation was applied to various types of cotton textiles using two procedures. The effectiveness of the formulation was assessed through cage tests conducted on completed textiles at the National Institute of Malaria Research (NIMR) in Delhi. Additionally, the impact of the storage duration of the completed fabric on mosquito repellency was investigated. The neem oil composition demonstrated promising results, proving effective against mosquitoes. It was identified as a potential domestic finish for various fabrics, showcasing its applicability for mosquito repellency on textiles.

In the study by L. Bhatt *et al.*,[119] essential oils were utilized to create a cost-effective, safe, and efficient formulation with mosquito repellent and antibacterial effects. A high-shear method was employed to produce an O/W nanoemulsion using three separate essential oils based on lemongrass, eucalyptus, and chrysanthemum flower. The optimization of the nanoemulsion involved variable factors such as surfactant-oil ratio, stirring duration and time. This study was extended to the storage stability of the nanoemulsion, examining parameters such as particle size, pH, viscosity, and zeta potential at both ambient and refrigeration temperatures for a duration of six months. The efficacy of the nanoemulsion was assessed in controlling mosquito larvae, targeting both susceptible and resistant mosquito species. Additionally, the fabric was treated with the emulsion using the layer-by-layer dip-coating method. The treated textile samples were characterized against mosquito bioassays, microbiological growth tests, and aroma retention tests. The wash resilience and durability of the treated samples were investigated, followed by a laundering process. This study demonstrated that the treated materials exhibited excellent mosquito repellency and aroma retention.

5.3. Nanoencapsulated EO in cosmeto-textile finishing

The increased usage of cosmetic items reflects a growing awareness of personal appearance, aesthetics, and wellbeing. Cosmetics have evolved beyond basic soaps and lotions, now encompassing sophisticated products such as anti-aging, skin whitening, and anti-acne formulations, which dominate the market. This trend suggests a heightened focus on skincare and beauty, with consumers seeking products.[120] In addition, consumers are concerned about the origin, odor, and color of these products, as well as technical advancement. Most synthetic formulations are comprised of surfactants and fatty acids, which cause bad odor and skin allergies. Thus, the cosmetic industry and manufacturers are focused on the use of natural plant-based EOs to produce cosmetics and cosmeceuticals. Natural EO-based formulations provide non-toxic, fragrant, therapeutic efficacies, which are ecofriendly and curtail the risks associated with the use of synthetic cosmetics.[121–123] Functionalized cosmeto-textiles play a crucial role in skincare by providing protection and addressing dermal problems. Thus, EO-loaded polymeric formulations can provide a variety of functional finishes for cosmeto-textiles such as anti-UV, anti-wrinkle, moisture management, hydration, antibacterial, hypoallergenic, and skin-healing.[124,125] Essential oil-loaded polymeric formulations have emerged as a major field to address the present and future challenges in cosmeto-textile applications and cosmeto-pharmaceuticals.

F. S. Ghaheh *et al.*[126] employed a pad-dry-cure method for coating cotton textile with protein-based nanoparticles containing vitamin E oil. The fixation and stability of the nanoparticles on the cellulosic textile were evaluated through FTIR, SEM, and air permeability studies. The antioxidant activity of the coated textiles was determined using 2,2′-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) to reduce free radicals. The strongest antioxidant activity was observed in the samples coated with nanoparticles carrying a large amount of encapsulated vitamin E. The protein-based coating showed stability after ten laundering cycles, indicating the durability of the immobilized nanoparticles on the cotton surface through the pad-dry-cure method. However, the basic crockmeter rubbing in the presence of moisture and protease demonstrated a method for nanoparticle release from the coated surfaces and transfer to other substrates. The synergistic impact of sweat/protease and abrasion facilitated the transportation and release of a significant quantity of products to various substrates, such as fabrics and skin. Thus, the developed coating and release approach suggests that vitamin E-loaded nanoformulations can offer notable advantages as skin protection, anti-aging, or skin moisturizer in various cosmetic and cosmeceutical applications.

5.4. Nanoencapsulated EO in anti-UV textile finishing

In the last decade, ozone layer depletion due to anthropogenic activities has resulted in the penetration of an increasing amount of UV radiation in the tropospheric level, causing serious health risks including skin allergies, premature ageing, pigmentation and skin cancer.[127] Long-term exposure to short-wavelength electromagnetic radiation has the potential to harm several substances including plants, animals, and humans. Increased exposure to short-wave UV radiation elevates the Earth's atmospheric temperature and can cause severe health disorders such as respiratory, nervous, heart and dermal and skin problems.[128]

The textile industry has been driven by a growing demand for smart and multi-functional fabrics for personal protective clothing including the medical, healthcare and fashion industry. Among the crucial technical elements of functional finishes, solar radiation resistance or anti-UV textile finishing has gained prominence.[129] The level of ultraviolet UV protection offered by textiles depends on the type and chemical composition of fabrics, together with their intended use. Essential oils providing anti-UV, antioxidant and antibacterial properties loaded in a polymeric nanoformulation can be applied directly to textiles as a multifunctional finishing, as illustrated in Fig. 8. In various industrial processes, anti-UV finishing can be applied during fiber finishing treatment or coated directly to the textile in later treatment at certain stages.[130,131]

M. I. H. Mondal *et al.*[132] developed an anti-UV and antibacterial finishing for cotton textile by employing *Aloe vera* oil/chitosan extract *via* a pad-dry-cure technique. *Aloe vera* and chitosan extracts were applied in a concentration-dependent manner. The finished textile was characterized for its structural, morphological, and thermal properties by FTIR, XRD, SEM, TGA and DSC. Alternatively, its mechanical stability was determined by measuring its tensile strength. Fabric whiteness index, water and air permeability, weight percent before and after coating treatment, and soil degradation tests were also conducted. The abrasion resistance creased recovery angle of the coated finished fabric showed an improvement compared to the unfinished fabric. Also, soil degradation tests demonstrated the biocompatibility of the treated sample. The successful integration of chitosan and *Aloe vera* on the surface of cotton fabric was examined using FTIR, XRD, and thermal analysis. Scanning electron microscopy demonstrated roughness and agglomeration on the surface of the treated and untreated textiles. The air permeability, water vapor permeability, and thermal conductivity tests revealed that the finishing treatment had no significant impact on thermal comfort. Quantitatively, anti-UV activity was measured by calculating UPF factors

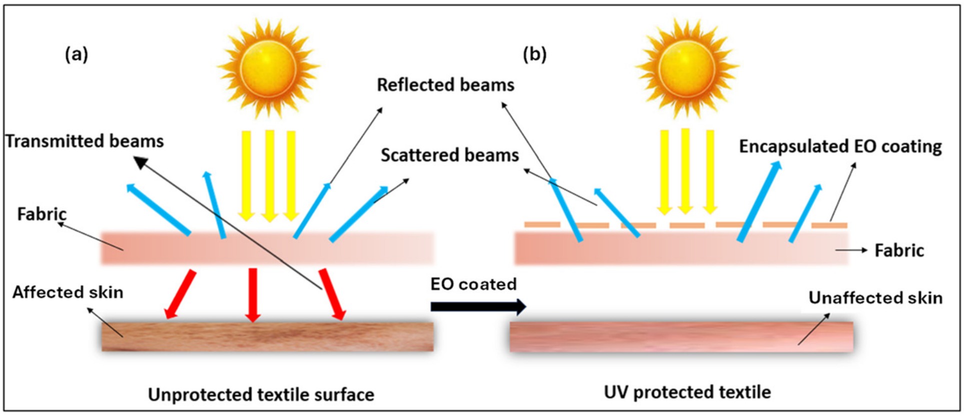

Fig. 8 (a) Pristine textile enabling the penetration of UV radiation, which reaches the skin, and (b) anti-UV finished textile impregnated with essential oil (EO)-loaded polymeric formulation, causing the transmittance of UV radiation and inhibiting it from reaching the skin.

according to the standard test method, which showed a significant improvement in UPF by absorbing harmful UV radiation in the finished cotton fabric.

5.5. Nanoencapsulated EO in fragrant textile finishing

Textile fragrance finishing has grown dramatically and is now utilized for domestic and industrial applications. Fragrance may be chemically manufactured, but it is also present in natural and inorganic forms. N. Singh *et al.*[133] conducted an investigation into the collective effects of perfume and antibacterial finishing on cotton textile using lavender oil. This was achieved using β-cyclodextrin, chitosan citrate, and β-cyclodextrin/grafted chitosan applied *via* the pad-dry technique. This study investigated the formation of ester bonds between β-cyclodextrin/grafted chitosan and cotton cellulose, which was confirmed by FTIR. Standard test procedures were employed to evaluate the fragrance release rate and antibacterial activity in the finished fabric samples. The fallouts indicated that β-CD was vastly solvable in a 0.6 gpl NaOH solution, and solutions containing 80 gpl β-CD and 6% essential lavender oil were identified as the optimal combination for aroma and antibacterial finishing. FTIR analyses demonstrated the existence of a carboxylic ester linkage between cotton and β-cyclodextrin/grafted chitosan, as indicated by the presence of an ester peak at 1730 cm^{-1}.

A. Danila *et al.*[134] developed polysaccharide-based emulsions containing lavender essential oil as an O/W emulsion. Various process parameters were optimized to obtain a stable formulation, which was employed on cellulose to fabricate hydrophilic cotton patches. Lavender essential oil with antibacterial properties was utilized as the core in chitosan-coated O/W polymeric emulsions. The lavender essential oil-based formulation was quantitatively analyzed by gas chromatography–mass spectrometry (GC/MS) to analyze its chemical composition. Seven different O/W emulsions having lavender oil in chitosan/agar polymeric blends were synthesized for cosmeto-textile applications. Further these emulsions were assessed for their rheological and microbiological properties. The cellulosic support coated with stable O/W emulsion was characterized for the controlled release of the active chemicals, toxicity, antibacterial efficacy, and skin analysis in healthy participants. The results revealed that the cellulosic supports treated with O/W emulsions were non-irritating, soft, and hydrating.

6. Challenges and future perspective

The nanoencapsulation of EOs in a polymeric shell as functional textile finishing is considerably significant for sustainable textile coating and can potentially alleviate the problems regarding commercial finishing agents in the textile industry. EO-loaded polymeric nanoparticles bind to a variety of textile substrates without damaging the softness, comfort and integrity of the textile, paving the way for nanoencapsulated multifunctional textiles on consumer demand. However, compared to conventional textile finishing, which has been in use for some time, nanoencapsulated textile finishing is quite advanced and has prompted some concerns for long-term industrial use. The major concern arising with the fabrication of EO-loaded polymeric nanoparticles on textiles is their durability to washing, which has been explored by many researchers but after 5 or more washing cycles their leached out, thus restricting their long-term commercial use and creating environment sustainability problems. The natural degradation process of polymeric nanoparticles is controllable but unnatural or uninvited external stimuli (rubbing, agitation or photochemical decomposition) can degrade the polymeric shell more quickly and the uncontrolled release mechanism limits their applicability.[135] Also, the excess use of chemicals, auxiliary agents, energy, water and commercial binders for impregnating nanoparticles on textiles raises energy and sustainability concerns regarding the ecosystem. Furthermore, the leaching of nanoparticles during textile finishing and before and after laundering at the user end stimulates serious environmental concerns.[136]

More sophisticated, long-lasting, and environmentally friendly methods of fixing multifunctional biomolecules to textiles are needed for the development of multifunctional textiles by nanoencapsulation; sol–gel, nanocoating and plasma or UV-curing are taking the place of padding and curing. Plasma or UV curing for the fixation of polymeric nanoparticles for durable functional finishing is considered a cost-effective and green solution without the utilization of excess water and energy. Furthermore, layer-bi-layer (LBL) dip coating is another multifaceted, reproducible, economical and cost-effective technique for coating nonencapsulated polymeric nanoparticles on a variety of textiles, eliminating the use of acrylic and toxic binders.[25] LBL coating facilitates the alternating deposition of oppositely charged EO-loaded polymeric formulations for multi-functional textile finishing to develop a robust linkage among deposited layers and the textile substrate. Researchers have explored LBL coating treatment as an eco-friendly solution towards durable functional textile finishing, which is accomplished by favorable chemical bonding including electrostatic charge attraction, hydrogen bonding and coordinate covalent bonding between the polymeric formulation and variety of textile substrates.[137] The development of strong chemical bonds during LBL coating avoids the use of commercial binders for longevity of functional textile finishing at the final stage.

Efficient encapsulation efficiency (EE), increased loading capacity (LC) and stability of EO-loaded polymeric nanoparticles with optimized experimental parameters and suitable finishing treatment such as plasma, sol gel and LBL coating are considered the benchmark toward durable cost-effective and sustainable textile finishing for present and future textile manufacturers.

EO-loaded polymeric nanoparticles are required to fabricate multi-functional and user friendly nonencapsulated smart textiles for various pharmaceutical and cosmeceutical, sports, automotive, construction, footwear, fashion clothing and household applications. Furthermore, the nano-encapsulation of EOs as sustainable source of functionality paves a way toward a broader perspective including sportswear, automotive, household, decorative and fashion clothing. This review will enable future researchers to focus on more elaborate, sustainable and ecofriendly solutions toward durable EO-loaded natural polymeric nanoparticles for advanced high-tech textile applications.

7. Conclusion

The use of nonencapsulated EO-loaded polymeric nanoparticles in sustainable, multipurpose textile finishing was examined in this review. A short description about the nanoencapsulation of EOs in a variety of natural and synthetic polymer shells was provided, with their possible sustained release mechanisms explored. A variety of EOs comprised of several components with therapeutic activity can be applied in functional textile finishing. Nanoencapsulated EO-loaded polymeric nanoparticles are considered potential candidates for multi-functional textile finishing. They offer the slow and sustained release of encapsulated EOs for a prolonged period, thus reducing their toxicity and enhancing their bioavailability. Nanoencapsulated EOs have demonstrated substantial advancements in providing antimicrobial, bug repellent, anti-UV, and cosmeto-textile functional finishing for natural and synthetic textile materials. The immobilization of EO-loaded polymeric nanoparticles in both woven and non-woven textiles furnished by conventional pad-dry-cure and dip coating techniques was studied in detail. The excess used of synthetic binders in conventional pad-dry-cure techniques restricts their use in sustainable textile applications. Moreover, in the future, researchers in the field of textiles should focus more on the issues of durability, stability, and targeted release related to EO-loaded polymeric nanoparticles for functional textile finishing. The use of advanced nano-coatings such as the LBL and sol–gel techniques can alleviate the problems associated with durability and eco-toxicity with significant reproducibility. Thus, nanoencapsulation serves as a scientific tool to develop sustainable multifunctional high-performance textiles for present and future textile consumers.

Data availability

The data can be made available upon request, as this manuscript received no funding and is not in open access.

Conflicts of interest

The authors declare no conflict of interest.

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