Journal of Textiles, Coloration and Polymer Science
https://jtcps.journals.ekb.eg/
Egyptian Society for Textile Science and Technology
الجمعية المصرية لعلوم وتكنولوجيا النسيج

Microencapsulation Techniques for Functional Textile Products

Lobna N. Allam [a], Lamiaa S. Abd-Elaal [a], Abdallah N. El-Wekil [a], Amany G. Maraae [a], and Ahmed G. Hassabo [b]*

[a] *Benha University, Faculty of Applied Arts, Textile Printing, Dyeing and Finishing Department, Benha, Egypt*
[b] *National Research Centre (Scopus affiliation ID 60014618), Textile Research and Technology Institute, Pre-treatment, and Finishing of Cellulose-based Textiles Department, 33 El-Behouth St. (former El-Tahrir str.), Dokki, P.O 12622, Giza, Egypt*

Abstract

Based on consumer demand, the textile industry is moving toward the creation of value-added functional textile products. As a result, various novel finishing processes have been developed to functionalize textile substrates. In this way, the microencapsulation technique is one of the sophisticated technologies that has been utilized to give functional features to textiles such as flame-retardant fabrics, antibacterial activity, mosquito repellency, UV protection, and thermoregulation. The volatile and non-volatile components can be contained inside a thin polymeric film in microencapsulation, resulting in a delayed release of the chemical and a long-lasting functional impact Various active compounds, such as essential oils, enzymes, and insecticides, have been effectively entrapped inside polymeric microcapsules. There are several papers in the literature that deal with the functionalization of textiles utilizing microencapsulated materials. This review article discusses the principles of microencapsulation, its primary techniques, the materials used in microencapsulation and its morphology, its factors, and the relevant research that has been published in this field. The key essential oils utilized in microencapsulation are also discussed, as well as their functional benefits. The current and future research tendencies in this crucial field of textile chemical processing are addressed.

Keywords: Microencapsulation, antimicrobial, mosquito repellent, natural oils

Introduction

Microencapsulation is the process of encapsulating one material within another, resulting in microscopic capsules ranging in size from one micron to several hundred microns. Polymer concentration, solvent solubility, solvent removal rate, and organic solvent solubility in water all influence the effectiveness of microparticles, microspheres, or microcapsules. Microencapsulation includes confining chemicals within capsule walls for a set period, or they can be released gradually via the capsule walls, a process known as controlled release or diffusion, or when the capsule walls burst, melt, or dissolve. Microencapsulation can be accomplished using a variety of approaches. Micro-encapsulation is a process that involves surrounding tiny droplets with a coating to form miniature capsules. These capsules are simply spheres with a homogeneous wall, with the substance within being the core, internal phase, or fill, and the wall is a shell, coating, or membrane. Microcapsules are a technology used to encapsulate active compounds in micron-sized capsules of barrier polymers such as gelatin, plastic, or wax, with sizes ranging from a few micrometers to a few millimeters. These capsules transform liquids into solids, segregate reactive substances, preserve the environment, and improve material handling qualities. Microcapsules, unlike simple spheres, can have a core of crystals, jagged particles, emulsions, solid suspensions, or smaller microcapsule suspensions, as well as numerous walls. **[1-5]**

The issue is, 'Why employ microencapsulation technology?' Microencapsulation technology is used in a variety of sectors, encapsulating active chemicals for a variety of objectives, depending on the final application. The aim of encapsulation differs according to the industry:

a) Turning liquids into powders to reduce clumping and facilitate mixing.

* Corresponding author: Ahmed G. Hassabo, E-mail: aga.hassabo@hotmail.com, Tel. 00201102255513
Received date: 31 December 2023, **Revise Date**: 15 February 2024, **Accept Date**: 27 February 2024
DOI: 10.21608/jtcps.2024.259768.1319

b) Preventing active components from being harmed by environmental conditions such as moisture, heat, oxidation, acidity, alkalinity, or evaporation.

c) This entails preventing components from reacting with other molecules, which might result in polymerization or destruction.

d) Certain compounds have an unpleasant taste or odor.

e) Improving the management of ingredients before processing.

f) Controlled release of active substances

g) shielding persons or entities from exposure to harmful chemicals.

Microcapsule qualities are used in a variety of textile applications, including clothing, sportswear, outdoor wear, medicinal textiles, and engineering textiles. However, most textile firms, particularly those that make garments, do not normally undertake development programs to create microencapsulated formulations. A business with experience in encapsulation technology, such as flavorings or textile auxiliaries, might contact a textile producer to discuss the potential benefits of their formulations and demonstrate how microcapsules can be applied to textiles using current equipment. The textile sector is dominated by microencapsulation firms, which are largely focused on the application of long-lasting scents and skin softeners, as well as phase change materials antimicrobial agents, UV protectors, flame retardants, dyes, vitamins, and pharmaceuticals. **[6]** This article takes an in-depth look into microencapsulation, covering its materials, morphology, methods, purposes, advantages, release mechanism, and application domains.

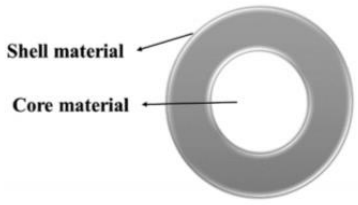

Fig (1): Microcapsule with Core and Coat

Microencapsulation

Microcapsule types (morphology)

There are two general types of microcapsules: **core-shell and matrix.**

A core-shell capsule: is similar to an egg, having a solid continuous shell around the liquid or solid active substance as the center. The active component is released by shattering, melting, or digesting the shell, resulting in a quick one-time release. The capsule can be polynuclear or multi-shell.

A matrix capsule: is more akin to a sponge in that it has the structure's pores that maintain the active substance in place by capillary action. The capsule fill is released to the surroundings outside by diffusion, which is more continuous. If a different release mechanism is needed, matrix capsules can be covered with a shell. An organic polymer known as alginic acid (produced from brown seaweeds) is a popular substance utilized in the formation of matrix capsules. When calcium ions are present, alginic acid chains cross-link, generating a gel that can be soluble or insoluble.**[7]**

The form of the microcapsules is determined by the sort of core material used. If the inner substance is crystal or solid, the resulting microcapsules will be uneven in shape. Spherical microcapsules may be produced by the liquid core. Many fine substance cores are evenly dispersed in an outer material of a matrix construction. **[8]**

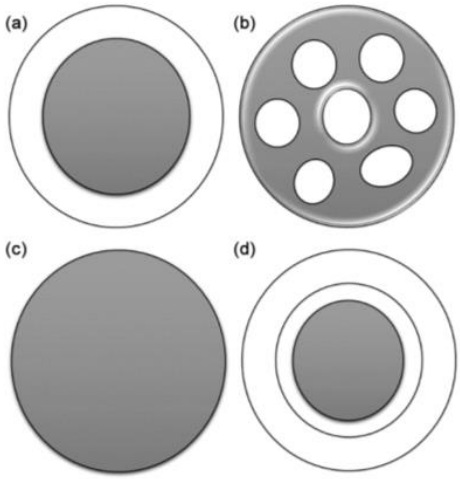

Fig 2: (a) reservoir capsule. (b) polynuclear capsule (C) matrix capsule. (d) multi-shell.

Core and shell Materials

Core Material

The substance that will be coated might be:

- Liquid or solid
- Liquid core, dissolved material, or dispersed material
- organic (natural oil) or inorganic (permethrin) **[1]**

Coating Material (shell or wall)

should be such that it is

- Capable of forming a coherent layer on the core and stabilizing it.
- Offer strength to the capsules.
- The product does not have a distinct flavor.
- coatings of suitable thickness on the core
- Compatibility with the main substance

- Inert toward active substances.
- Controlled release of substances under particular circumstances.
- The coating might be flexible, brittle, rigid, thin, or any combination of these characteristics.
- It is abundant and inexpensive.
- May be organic or inorganic [9] as shown in the following table1 [9, 10]

Tabel l: Organic and inorganic Coating

Organic Coating materials	**Inorganic Coating materials**
Gums (Gum Arabic, sodium alginate, Carrageenan)	poly (melamine-urea-formaldehyde)
Carbohydrates (Starch, dextran, sucrose)	Poly (melamine - formaldehyde)
Proteins (Gelatin, albumin)	Poly (urea-formaldehyde)
Lipids Beeswax, stearic acid, Phospholipids	Poly (methyl-methacrylate)
Celluloses and their derivatives Plant cells	Polystyrene
Chitosan Shells of crustaceans	Polyurethane
Organo-Silica	Inorganic Silica

Microcapsules preparation by (solvent extraction/evaporation) method

A multitude of techniques have been used to generate microspheres, each having competing and complementary features. Many microencapsulation techniques are variants of the three major processes: solvent extraction/evaporation, phase separation (coacervation), and spray drying. Although spray drying is a simple and high-throughput method, it should not be used for temperature-sensitive compounds. Furthermore, managing particle size is challenging, and yields for small batches are low. Coacervation is typically hampered by residual solvents and coacervating compounds found in microspheres. It is also inappropriate for producing microspheres with diameters smaller than one micrometer. The use of supercritical gases as phase separating agents was extensively researched to reduce the amount of potentially harmful residues in the microspheres, resulting in processes such as Precipitation with Compressed Antisolvent (PCA), Gas or Supercritical Fluid Anti-Solvent (GAS or SAS), and Aerosol Solvent Extraction System (ASES) **[11]**. For solvent extraction/evaporation, no extreme temperatures or phase separation-inducing compounds are required. Particle sizes can be adjusted in the nano to micrometer range, however careful encapsulation conditions and material selection are necessary to achieve high encapsulation efficiencies and a low waste solvent content. Microspheres are produced via solvent extraction. Evaporation is comprised of four major phases: (i) solubility or dispersion of the bioactive factor, usually in an organic solvent containing matrix-forming material; (ii) This organic phase's emulsification in a second continuous (often continuous) aqueous phase is identical to the first.; (iii) The continuous phase is transformed by solvent extraction from the dispersed phase, which may or may not be followed by solvent evaporation., (iii) The droplets are harvested into solid microspheres, then the microspheres are dried. **[12-14]**

Incorporation of bioactive compounds:

Bioactive compounds can be introduced to the matrix material solution by co-dissolution in a common solvent, dispersion of finely pulverized solid material, or emulsification of an aqueous solution of the bioactive chemical that is immiscible with the matrix material solution. [15] Codisolution may necessitate a schematic description of the four major process phases in solvent extraction/evaporation microsphere formation. Cosolvent to completely dissolve the substance in the matrix's solvent. Ultrasonication, impeller or static mixing, high-speed rotor-stator mixing, or microfluidization can all be used to disperse the solid or dissolved bioactive ingredient in the matrix-containing solution.

Droplet formation by Stirring

Stirring is the most fundamental method for creating droplets of the material/matrix dispersion for removing the solvent during the continuous extraction phase. The extraction phase is put into a jar and agitated by an impeller in the most basic manner. The material/matrix dispersion is subsequently added drop by drop or all at once while being stirred quickly enough to create the desired droplet size. Obviously, in the continuous phase, the impeller speed is the major parameter for defining the droplet's diameter of the drug/matrix dispersion. Raising the mixing speed diminishes the microsphere in general. **[12-14]**

Solvent Removal

The dispersion phase solvent, such as the material/matrix dispersion, must be a little soluble in the continuous phase in both solvent extraction and evaporation so that partitioning into the continuous phase can occur, resulting in matrix material precipitation. In solvent evaporation, the capacity of the continuous phase is inadequate to dissolve the whole volume of the dispersed phase solvent. As a result, to generate suitably hardened microspheres, the solvent has to evaporate from the surface of the dispersion. In solvent extraction, both the quantity and the composition of the continuous phase are chosen so that all of the amount of the dispersion phase solvent may be dissolved. Generally, a non-

solvent continuous phase is better for the micro-encapsulated bioactive chemical. While aqueous solutions are appropriate for lipophilic compounds, the use of hydrophobic, organic liquids as a continuous phase for the encapsulation of hydrophilic substances is more sensitive. Hydrophobic extraction fluids may be hard to remove from the final product, perhaps leaving undesired residues. As a result of this, aqueous solutions are frequently used as continuous phases in many applications, including microencapsulating hydrophilic compounds. In this instance, bioactive compound loss is often avoided by raising the quantity of the matrix material solution; the increased viscosity prevents bioactive component migration from the solidifying microspheres to the exterior phase via decreased diffusion and improved stability.

Microsphere harvest and drying

Filtration or centrifugation are commonly used to separate the solidified microspheres from the continuous phase. After that, the particles can be washed with suitable solvents to remove any clinging compounds, such as dispersion stabilizers or nonencapsulated pharmaceuticals. To limit the quantity of leftover solvent in the microspheres, rinsing may require using high temperatures or extraction agents. Finally, the microspheres are dried at room temperature or under decreased pressure, heat, or lyophilization to produce a free-flowing powder. The drying technique eliminates not only the continuous phase and wash fluid that has adhered to the surface of the microspheres, but also residues of solvents and continuous phase from the inside of the particles. Thus, the drying conditions and pace determine the quantity of solvent and moisture residue, microsphere shape and porosity, as well as drug recrystallization within the spheres, and are thus likely to alter the final product's release behavior. **[16]**

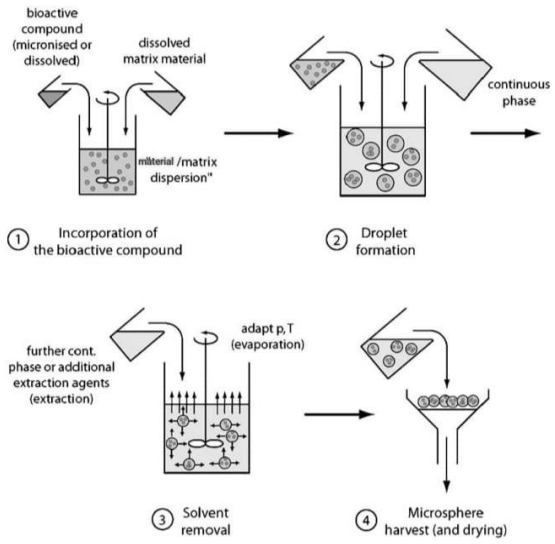

Fig.3. A diagram depicting the four major process phases in microsphere production by solvent extraction/evaporation

Factors affecting encapsulation

Capsule structure

The active material and the matrix polymer, which govern the rate of diffusion, are the two most significant components of a microcapsule. Understanding the shape, structure, physicochemical compatibility, and thermodynamics of the two active and matrix polymers is crucial. The microcapsule coat can perform a variety of different stability functions:

- Sensitive active components such as minerals vitamins, flavours, essential oils, unsaturated fats, and salts are protected from water, oxygen, and light.
- Changing difficult-to-manage liquids to powdered systems allows for easier processing.
- Two components separate during the storage hold time.

From a structural or morphological standpoint, the microcapsules' type, size, form, and payload all have an impact on stability and release. Functional moiety and surface charge, temperature, solubility, Active molecular weight wettability, and concentration are all important properties. **[17, 18]**

Capsules Types

Morphological configurations such as microcapsule morphology, which contains the active ingredient in a microcapsule with a distinct matrix wall that surrounds the active ingredient, or microsphere morphology, which contains the active ingredient in several little discrete droplets dispersed in the matrix material, can have a major effect on the active ingredient's stability and release. A microsphere's microscopic droplets may also be so minute that the active is spontaneously dissolved in the matrix polymer. The figure demonstrates the different structural designs of micro-encapsulated systems and how the active component is dispersed in the matrix polymer; nevertheless, both microsphere and microcapsule morphologies have to be devoid of flaws, pinholes, or high curvatures to give better stability. Defects can cause oxidative or hydrolyzed breakdown to occur over time. **[17, 18]**

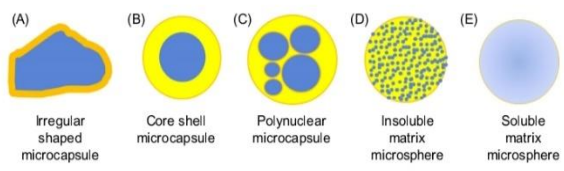

Fig. 4. Microcapsule (A, B, and C) versus microsphere (D and E) morphology

The molecular weight of the active agent

It is generally hard to adjust the size of a product once its active ingredient has been defined. It is just essential to grasp that the size of the component that is active is crucial in this situation. Most food-active compounds have molecular weights of less than 500 Da. These molecules are capable of passing through the tortuousness of the matrix polymer interstitial space or, in the example of a liposome, the polarized heads of the phospholipids due to their small molecular dimensions. As molecular size increases, diffusion decreases exponentially. As a result, larger molecules cannot disperse as quickly. **[17, 18]**

Charge of surface

The active component's ionic surface charge can dramatically decrease diffusion by electrovalently attaching to matrix polymer moieties. When the active ingredient's solubility is, the ionic properties in the matrix phase change. Thermodynamics also has an impact on microcapsule stability and release. Solubility, Concentration, temperature, and interfacial characteristics are all significant thermodynamic factors in the performance and stability of the microcapsule. **[17, 18]**

Concentration

Molecules are continually moving and prefer to move from high-concentration locations to low-concentration areas. Microcapsules are no exception. The active component moves from places with high concentrations of that material to areas with low concentrations of that substance. As the concentration difference between the surrounding outside and the inside of the microcapsules develops, so does the rate of diffusion. This is relevant from two points of view. To begin with, the microcapsule's initial concentration gradient is steep, which adds to the burst effect. In addition, when the concentration gradient decreases, so does the driving force related to release, creating a first-order release in such a system.**[17, 18]**

Solubility

Most product development operations include determining whether the active component should be solubilized or dispersed. When the active is dissolved, it is released more quickly. Microcapsules with dispersed active components demand a trade-off between release rate and stability. This is especially significant when the activity in the product into which the microcapsule is put is poorly soluble. The active component may move more easily through the matrix as it is dissolved in the matrix increases**. [17, 18]**

Temperature

Temperature is the most significant thermodynamic factor determining active component release. In most cases, increased temperatures cause molecules to move faster, boosting diffusion. The temperature also allows the matrix to entropically relax from a metastable to an optimum state. As density increases, the molecule has fewer points of collisions, allowing for faster diffusion. Similarly, lowering the temperature lowers the diffusion rate by lowering the energy of each particle. Microcapsules maintained under refrigeration or room temperature are thus more stable in comparison to those stored at high temperatures. Because temperature is a regulated property, it affects matrix polymers. Temperature-dependent phase transitions occur often in polymer matrices, transitioning from solid to molten, sol to gel, glassy to rubbery, and crystalline to amorphous. In each of the transitional periods. [19]

Benefits of microencapsulation

Microencapsulation is used to protect reactive cores from chemical harm, separate cores from their surroundings, safeguard vitamins from oxygen destruction, delay volatile core evaporation, enhance sticky handling of materials, and protect sensitive cores from chemical attack. In certain cases, the goal is to control the core's release rate instead of completely isolating it, similar to controlled drug or pesticide release. This might range from as simple as masking the flavor or smell of the core to as complex as improving the selectivity of an adsorption or extraction process. Capsules are designed and manufactured with the properties of the core material, intended for the product usage, and storage environment in mind. Microcapsule-based goods have characteristics such as size, shape, chemistry, degradability, quality, permeability, and biocompatibility. These factors are important when deciding on the initial materials and microencapsulation technologies for distinct applications. Microencapsulation, which is distinguished by impermeable coats, is used in products to isolate active substances, which are then released rapidly under specified conditions. Impermeable microcapsules offer various advantages, including the capacity to isolate reactive components, protect sensitive compounds from external impacts, minimize volatile substance volatility, turn liquid materials into solid forms, conceal flavor and odor, and reduce toxicity. Porous-walled microcapsules, on the other hand, allow for the prolonged release of active molecules into the surroundings of the microencapsulated compound's immobilization with limited activity. Microencapsulated fertilizers and pesticides with limited release to avoid groundwater leaking, and additionally microencapsulated enzymes, are examples of later improvements. **[1]**

Microencapsulation in Textiles

The textile business and research have been constantly developing during the last 30 years. Traditional textile goods, which were initially created to cover or conceal the individual's body, developed into more technical products in the 1990s, becoming more smart functional, and multifunctional textiles that met customer needs and environmental standards. Smart fabrics are garnering greater attention in terms of research and development, as well as prospective capabilities, delivering significant added value and rising market opportunities. In this instance, using microencapsulation technologies to create functional and smart-coated fabrics is critical. As a result, as compared to other industries, employing Microencapsulation as a possible method for functionalizing textile supports was introduced late in the manufacturing process. Today, it is used in a variety of textile applications such as medical, technical, beauty products, and cosmetics for aesthetic impacts, protection, comfort, and skin care, and various properties such as functional coatings, which offer additional benefits without changing the product structure or its characteristics, are becoming increasingly important in the competitive textile market. **[20]** Commercial uses of microencapsulation in the textile industry are developing in the twenty-first century, particularly in North America, Western Europe, and Japan. The development of developed nations into novel characteristics and additional value, such as technical and medical textiles, has spurred this growth, making microencapsulation procedures more viable and cost-effective. **[6]**

Insects' repellency with microencapsulation

Many investigations on pesticide repellents incorporated into fabrics and clothing suited for outdoor activities have been done in recent years. **[21]** In most cases, insect-repellent textiles are created by correctly treating the cloth in its final state with repellent chemicals. In this instance, suitable binder compositions that can stick to the textiles while also supporting the mosquito-repellent agents should be utilized to fix the insect-repellent agents on the fabrics. **[22]** insect-repellent textiles may be made before material preparation by adding repellent chemicals into the substance of fiber or yarn. In this situation, insect repellents are used throughout the fiber-spinning process.

Mosquito repellency with limonene & permethrin Capsules

For preparing mosquito repellent fabrics. Permethrin and Limonene were encased with an ethyl cellulose shell to compare bio-based and manufactured mosquito-repellent agents. Coacervation was used, which is an easy and repeatable encapsulation process with high production efficiency. Morphological examination revealed that the capsules had smooth outsides and a spherical form. Laser diffraction analysis confirmed the capsules' homogeneous size distribution. The capsules had a limited size distribution, with the mean size of the particles of the limonene and permethrin optimal formulations being 1 and 1.3 m, respectively. The size of the capsules generated was deemed adequate for textile applications. **[22]** The FTIR results indicated a chemical structural similarity between capsules and shell material. Cotton textiles were individually treated with limonene and permethrin capsules via the padding method. After 20 washing cycles, the existence of capsules on the materials was confirmed. Insecticide activity was assessed against common house mosquitos (Culex pipiens) using the World Health Organization's cone bioassay. Mosquitoes were seen to avoid treated textiles, with fatality rates of 41% and 54% for limonene and permethrin, respectively. Even though fabric efficacy declined with increasing washing, the materials retained repellency after 20 washing rounds. The capacity of mosquitoes to fly or stand was similarly reduced when they came into contact with materials containing both active chemicals. **[22]**Fabrics carrying limonene capsules were shown to have decreased mortality toward Culex pipiens in comparison to those containing permethrin. Insecticides are assured with a significantly low dose of insecticides when active ingredients are used in capsular form. Furthermore, because the active component is surrounded by a polymer, the end-user is not in continual touch with these agents, as is the case with several other products on the market (such as insect repellent sprays and lotions). As a result, both acute and long-term negative effects can be avoided. Furthermore, because the active components are resistant to oxidation and washing with encapsulating information the new product would not require repeated application. End users are going to be able to reduce or discontinue their usage of topical products in this manner. The results showed that textile materials treated with capsules carrying limonene and permethrin have acceptable insect-repellent characteristics, and they might be an effective and promising alternative to market items**. [22]**

Mosquito repellency with Coleus aromatic extraction capsules

The Box Behnken experimental design technique was used to improve the combination of antibacterial and mosquito-repellent treatment on woven cotton fabrics using Coleus aromaticus capsules. **[21]** The basic extract of Coleus aromaticus was prepared using methanol-based solvent extraction. Gum acacia was used as the outer layer and Coleus aromaticus extract as the core material to make the microcapsules. The pad-batch approach was used to apply these capsules to the Cotton fab-

ric. Three process parameters were chosen for optimization: microcapsule concentration (GPL), BTCA concentration, and curing temperature. The treated textiles were tested for antibacterial activity and mosquito repellency. Following that, a polynomial equation was created for both antibacterial activity and mosquito repellency behavior. **[21]** The impacts of each process variable on how it responded were examined using RSM analysis. The best process parameters were the microcapsule concentration of 40gpl, the BTCA concentration of 67.5gpl, and a temperature for curing of 116°C. The total desirability coefficient was determined to be 0.792. Following that, SEM and FTIR experiments were carried out to establish the efficiency of microencapsulated therapy. Both antibacterial activity and mosquito repellency required the development of a polynomial equation. The model of regression was significant for both antibacterial activity and mosquito repellency, with 98.10% and 98.10% adequacy, respectively ANOVA revealed that all of the coefficients of linearity of the process factors in both models were significant. The interaction coefficient of microcapsule (GPL) concentration and BTCA concentration was significant for the regression model of antimicrobial activity, while the interaction coefficient of BTCA concentration and temperature of cure was significant for the model of regression of mosquito repellency. **[21]**

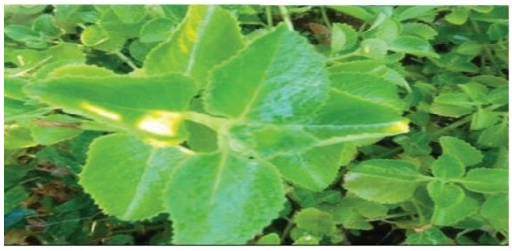

Fig.5: Plant leaf of Coleus aromatics.

Mosquito repellency with lemongrass oil capsules:

Chitosan nanocapsules carrying lemongrass (Cymbopogon citratus) oil (LGO) were created in a gel form with acrylate (Ac) as a thickening and fabric binder. To obtain long-lasting and washable mosquito repellency, the gel was injected on cloth. FTIR and XRD were used to analyze the interaction of cotton fibers with gel. Using SEM and GC-MS, the wash resistance of gel was compared to that of chitosan nanocapsules with no acrylate (LGO-encap). SEM analysis demonstrated that acrylate-containing nanocapsules remained on the cloth after several washings. According to the GC-MS data, the percentage of oil components in fabric was found to be greater following a series of washings in acrylate-containing nanocapsules (LGO-encap-Ac), pointing to better wash resistance and capsule retention on fabric. The bio-efficacy findings of post-fifteen washing revealed 75% repellency against mosquitoes with the application of acrylate, but only 51% repellency was achieved in nanocapsules without acrylate. Furthermore, the repeated use of nanogel on Swiss albino mice for 36 days revealed no symptoms of skin harm. As a result, the formulation is appropriate for impregnating the clothing of military personnel and those who must undertake field duties and are at a higher risk of mosquito bites. **[23]**

Silverfish repellency with natural oils:

The article concentrated on the creation of microcapsules utilizing two essential oils. It suggests using eucalyptus oil and cedarwood oil as natural insecticides. The goal of this work is to show how created microcapsules may be used to transmit insect repellency on textile substrates. The publication chose an experimental investigation in which two essential oils and gum were used to produce microcapsules utilizing a simple co-aseravtion encapsulating approach. The produced solution was examined, including size and structural confirmation. To demonstrate enhanced capabilities as a repellent fabric, a developed finish was additionally applied to the substrate. The research focuses on the practical creation of microencapsulated cloth by combining gum acacia and eucalyptus oil as inner and coating materials. The created fabric repels silverfish better than the microencapsulated fabric made using gum acacia (coat) and cedarwood oil (basic). **[24]**

Due to a shortage of time and essential oil availability, only two oils were employed to investigate the repellent's behavior. **[24]**

This work addresses an identified requirement and has implications for the creation of a very effective natural pesticide to repel silverfish insects. This bug is a prevalent issue in textile closets and bookshelves; it mostly targets fabrics with cellulose content and starch. The use of these microencapsulated finished textiles will assist society greatly by repelling silverfish from their homes and keeping their apparel and books safe for a longer length of time. These essential oils' natural scent and medical properties should never be overlooked.

This study proposes a novel method for repelling insects such as silverfish from bookshelves and garment closets. In these shelves and wardrobes, an insect-repellent microencapsulated finishing cloth may be incorporated. It is an environmentally friendly strategy that uses natural essential oils rather than artificial pesticides. This experiment also showed that microencapsulated fabric using gum acacia + eucalyptus oil repelled silverfish better than microencapsulated fabric using gum acacia + cedarwood oil. **[24]**

Fig.6: Silverfish

Antimicrobial textiles with Micro capsulation

Antimicrobial finishing is a chemical treatment designed to kill or prevent the growth of microscopic organisms, however also causes functional, sanitary, and cosmetic issues. Antimicrobial protection in textiles can perform two distinct purposes. The first is to protect the user against infections or odor-producing microbes. The second step is to protect the cloth from mold, mildew, or rot-producing microbes.**[25]** In other words, the former is rot-proofing finishing, which offers material protection against physical deterioration or the use of various aesthetic finishes that control odor development; the latter is hygiene finishing, which focuses on the control of infections and unwanted bacteria. Furthermore, antimicrobial treatments in medical textiles aim to reduce harmful microorganism cross-contamination and the transmission of infectious illness through contaminated garments. Textile antimicrobial finishing has arisen as a significant market area that includes consumer and technical goods for healthcare and hygiene control.

Nosocomial infections in hospitals, as well as surface contamination with microorganisms, demonstrated the importance of antimicrobial finishing. Antimicrobial finished textiles were wanted to limit microbe development and transmission. The study on antimicrobial textile finishing resulted in a large volume of published research material. **[26]** This reflected an increase in the use of antimicrobial finishing chemicals and antimicrobial fibrous materials. However, an antibiotic that inhibits or causes the death of microorganisms may be detrimental to other living species, including humans. An antimicrobial contained in clothes, healthcare fiber products, and home textiles may come into touch with an individual's skin or harm any living species in the surrounding environment. As a result, understanding environmental problems is necessary to manufacture antimicrobial fibrous goods with acceptable environmental impact, such as Micro capsulation. **[21]**

Antimicrobial textiles with Thyme Oil Microcapsules

The goal of this research was to create antimicrobial agent-loaded microcapsules for use in medical textiles. [25] Thyme oil with antibacterial action was effectively encapsulated for this purpose utilizing a complicated coacervation technique using gelatin and gum Arabic as wall components. Images of optical microscopes were used to observe the production of microcapsules. The resulting microcapsules possessed a spherical form, a continuous core, and a continuous shell. The effects of the quantity of oil and the concentration of the wall material on encapsulation yield, mean particle size, and oil loading were examined. Encapsulation yield often increases with increasing amounts of oil. Similarly, increasing the concentration of wall material resulted in increased encapsulation yield up to a specific concentration. **[25, 26]**

There were no capsules created after that. As predicted, as the amount of oil grew, so did the size and oil content of the microcapsules, although they tended to clump together. Agglomeration was also generated by a high concentration of wall material. In the current investigation, it was determined that 10 mL of oil and 2% wall concentration produced the greatest results in terms of microcapsule size. Encapsulation yield was 74.72%, mean microcapsule size was 25.37 microns, and oil loading was 36.38% in these circumstances. Antibacterial activity studies demonstrated that thyme oil-filled microcapsules exhibited significant antibacterial action against E. coli. coli, S. aureus and C. Albicans. Following that, produced microcapsules were grafted at four different concentrations onto a nonwoven fabric to impart antibacterial properties to this fabric. The results demonstrated that even the lowest concentration (10 g/l) offered enough antibacterial action to the cloth.

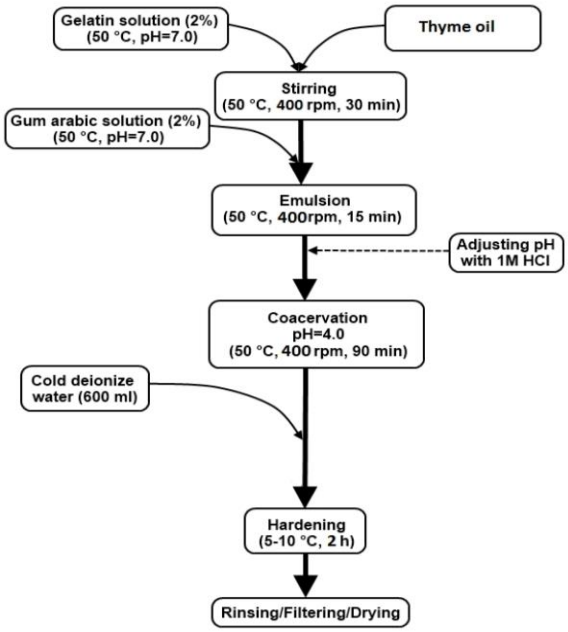

Fig.7: Flow chart of the microencapsulation process by complex coacervation.

Antimicrobial textiles with oil Mixture (Cinnamon oil & Cloves oil)

We provide an examination of the chemical components of essential oils extracted from the barks of Ceylon cinnamon and Syzygium aromaticum cloves, as well as research on their antibacterial activity. Oil components were identified using Gas Chromatography/Mass Spectrometry (GC-MS) analysis, and antibacterial activity was tested using the disk diffusion test. **[21]** The synergistic impact of a blend of essential oils (cinnamon oil and clove oil) was investigated. Cellulosic fibers were given antimicrobial characteristics via microencapsulation with citric acid as a green binding agent. Coacervation was used to encapsulate an essential oil combination utilizing chitosan as a wall material and sodium hydroxide as a hardening agent. The dimension of the microcapsules formed ranges between 12 and 48 m. Attenuated Total Reflectance-Fourier Transformed Infrared (ATR-FTIR) spectroscopy, optical microscopy, and scanning electron microscopy (SEM) examination were used to demonstrate the attachment of the generated microcapsules to the surface of cotton textiles. The findings reveal that microcapsules were successfully adhered to cotton fabric surfaces, imparting antibacterial activity without changing their qualities appreciably. The resultant cotton textiles have good mechanical and wettability qualities. **[27]**

Antimicrobial textiles with Silver capsulated Compositions

The efficiency of a technique for the manufacture of silver nanoparticles employing oxalic dialdehyde as a reducing agent and polyguanidine as a stabilizer is demonstrated. The authors report a study of photon correlation spectroscopy data describing the sizes of produced particles in the Ag-polyelectrolyte system. The biocidal impact of manufactured silver nanoparticles has been proven. The system of biodegradable polyelectrolytes chitosan-xanthan gum is chosen for the manufacture of the capsule shell with silver nanoparticles. This will allow stable polyelectrolyte capsule shells containing oyster mushroom mycelium extract to develop. The method of successive adsorption of chitosan polyelectrolytes and xanthan gum on calcium carbonate templates was used to create microcapsules. The capsule shell contains silver nanoparticles, while the center contains a physiologically active medication (oyster mushroom mycelium extract). **[27-35]**

The technical methodology of immobilization of complicated capsules on a textile material by the layer-by-layer method is explained. A system of polyelectrolytes, positively charged chitosan and negatively charged xanthan gum, is used to immobilize multilayer microcapsules on a fibrous substrate. The discovered multifunctional coatings enable the addition of antibacterial, antimycotic, and high-hygroscopic qualities to textile materials. Oyster mushroom mycelium was successfully employed as a model filling of the capsule core in this investigation. The suggested approach for the creation of microcapsules, the shells of which are doped with silver nanoparticles, provides for the most focused antibacterial action on the site of infection. The encapsulated oyster mushroom mycelium extract was released for a long period and offered a more effective wound-healing effect in this situation. Cellulose tissue samples coated with silver-containing microcapsules revealed significant antibacterial, antimycotic, and wound-healing action. **[27]** The ideal concentration of the microencapsulated medication for successful wound healing was discovered to be 1%-2% of the weight of the textile material. To heal the skin in the event of burn wounds, the material should be replaced at least every two weeks. Changing the capsule core filler (biologically active ingredient) allows you to impart a range of diverse qualities to the created medicine as well as the textile material with different sorts of final finishing**. [36]**

UV Protection textile with Micro capsulation

UV light is electromagnetic radiation with a wavelength ranging from 10 to 400 nanometers (nm). The UV spectrum has several effects on human health, both positive and negative. Increased UV light exposure, on the other hand, has negative consequences such as sunburn, inflammation, and skin cancer. Studies on UV wave blocking are primarily undertaken in the cosmetics industry; however, they are increasingly being conducted in the textile industry as well. **[37]** To provide textiles the capacity to block UV radiation, they are usually treated with an organic UV absorber. UV protection textiles are created by the use of an organic UV absorber and processes such as mixing, coating, adsorption, and microencapsulation. Durable UV protection textiles are created using the mixing procedures by adding a UV absorber during the spinning stages of synthetic fibers. **[32, 34-36, 38-44]**

Coating technologies lower the handling and air permeability of fabric and are consequently used in umbrellas and cold clothing. Adsorption techniques used to adsorb a UV absorber on the surface of cloth create skin issues since the wearer's body is exposed to it. Because the organic UV absorber employed as the core material is covered by shell material, microencapsulation technologies can reduce contact between the wearer's skin and the organic UV absorber. Furthermore, the use of microcapsules is not confined to a certain type of cloth.

UV Protection textile with Silica Microcapsules

The goal of this work was to create UV protection textiles using microencapsulation technologies,

silica microcapsules with an organic UV absorber as their core and silica as their exterior. In an O/W/O emulsion, spherical silica microcapsules were created using the sol-gel technique. Microcapsules were attached to cotton-knitted textiles to create UV protection materials. **[37]** For microencapsulation, the following conditions were used: 20% (w/v) UV absorber content, 0.5% (w/v) HPC (hydrophyl-cellulose) addition concentration, 6% (w/v) PEG (polyethyleneglycol) addition concentration, 6 h agitation time, and 1000 rpm agitation speed. The particle distribution of microcapsules generated under the proper circumstances ranged from 2 to 12 m, with an average particle size of 6.27 m. Given that the optimum microcapsule size for textile treatment is around 10 m, the capsules produced in this work would be acceptable for textile treatment. Regarding the thermal properties of the microcapsules, the first peak showed at 152°C, followed by the second peak at 250°C. Even after repeated washing, cotton-knitted textiles coated with silica microcapsules retained an 80-90% UV protection rate. **[37]**

UV protection textiles with (Lemon& AZO)

Using an aluminum-doped zinc oxide (AZO)-embedded lemon microcapsule and SiO2 dual-layer coating, multifunctional textiles with UV protection, thermal insulation, and superhydrophobic and aromatic performance were effectively created. Interfacial polymerization was used to create AZO-loaded lemon microcapsules with an average diameter of 1.5 mm. **[37]** The high concentration of the AZOembedded lemon microcapsule contributed to improved performance and visible and near-infrared light transmission, according to the results. Lemon extract included up to 2.789 mg/g (weight of essence: weight of fabric). The AZO's doped Al2O3 concentration was determined to be 13.5 wt%. As the number of AZO-embedded lemon microcapsules grew, the light transmittance dropped. When the AZO-embedded lemon microcapsule dose was 6%, the UV protection factor value reached 88.78. Given the research findings, cotton fabric coated with the AZO-embedded lemon microcapsule and SiO2 bi-layer composite coating might find use in water/oil purification and functional protective textiles. **[45]**

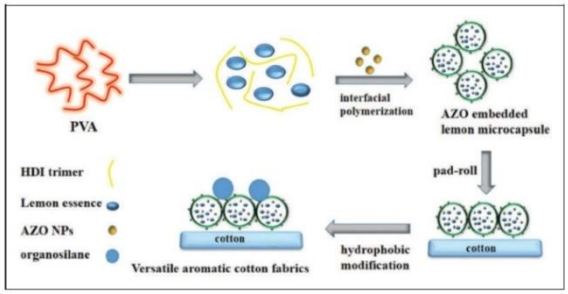

Fig.8.Schematic illustrating the preparation of versatile aromatic cotton fabrics.

AZO: aluminum-doped zinc oxide; NP: nanopigment; PVA: polyvinyl alcohol.

Flame retardant textile with Micro capsulation

Flame resistance can be a naturally occurring feature in fibers or developed by chemical treatments that provide the material with indirect immunity to combustion. Flame retardant yarns and textiles are used to make a variety of items such as ready-made clothes, industrial protective apparel, children's clothing, lint fabrics, upholstery fabrics, carpets, and curtains. **[45]** Cotton textiles are subjected to two types of treatments to achieve the attribute of resistance to combustion: First, there are non-permanent therapies. Second, there is permanent treatment. **[4, 5, 46-51]** Thus, the function of flame retardant materials is to avoid or limit the development of materials that aid in the continuation of fire or to alter the distribution of materials caused by thermal cracking.

Flame retardant textiles with RP(Red Phosphorus)

Red phosphorus (RP) particles are commercially accessible as a polymer flame retardant ingredient. RP is typically encased with a protective organic covering. In this paper, we suggest an alternate method for encapsulating RP with an inorganic SiO2 shell (SiO2@RP) for use in textiles. The silica shell was created in two phases by sol-geling a TEOS precursor in RP aqueous dispersion. **[45]** A uniform silica shell was regularly produced. Fourier Transform Infrared (FTIR) spectroscopy, X-ray diffraction (XRD), and scanning electron microscopy (SEM) were used to describe the chemical structure and morphology of the as-obtained powder. Through thermogravimetric coupled-differential thermal analysis (DT-TGA), the effect of the silica coating on the thermal stability of RP was evaluated, which demonstrated increased thermo-oxidative stability. The produced coated and uncoated RP are then studied as flame retardant additives for fabric back-coating. Only the textiles treated with SiO2@RP effectively self-extinguished the flame during the BS-5852 flammability test, attaining the no-ignition classification necessary for a practical application. The suggested entirely inorganic encapsulation technique opens the door to innovative and efficient RP-based flame retardant solutions that might be used in a variety of applications. **[46]**

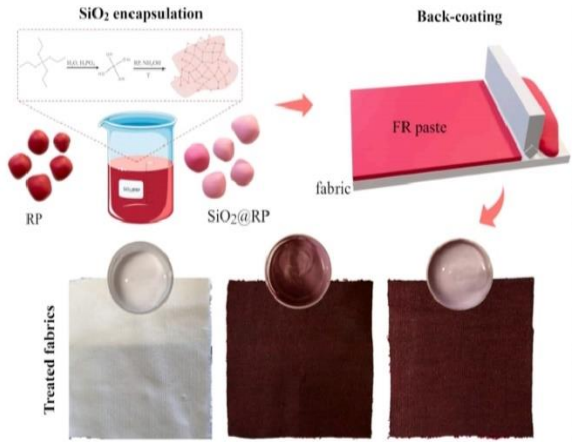

Fig.9: Scheme of RP coating with p-doped SiO2 by two-step sol-gel process and schematic view of the fabric back-coating with FR paste. Pictures of treated fabrics with FR pastes are provided at the bottom of the picture. Silica encapsulation results in faded red on the fabric's backside

Flame retardant textiles with diphenyl phosphate

A flame retardant nonwoven substrate was created using a microencapsulated flame retardant. **[46]** Melamine-formaldehyde polymer-shell microcapsules with Afflamit® PLF 280 (resorcinol bis(diphenyl phosphate) as the core substance were impregnated with an outer thermoplastic wall (polystyrene (PS) or poly(methyl methacrylate)). To connect the microcapsules to the textile fibers, the outside wall of the microcapsules was heated to the softening temperature of the thermoplastic shell. The thermogravimetric analysis was used to assess the thermal stability of the microcapsules. A scanning electron microscope was used to examine the textile samples, and the flame retardancy performance was assessed using the NF P92-504 standard. **[46]**

The findings reveal that the composition of the outer polymeric shell affects the thermal stability of the microcapsules, with particles with a PS shell being more stable. Furthermore, the microcapsules were more concentrated on the nonwoven surface without changing the sample thickness. According to the NF P92-504 test findings, the flame spread rate was reasonably modest for all of the evaluated formulations. Only the formulation with the lowest PS concentration was classed as M2, while the rest were classified as M3. **[52]**

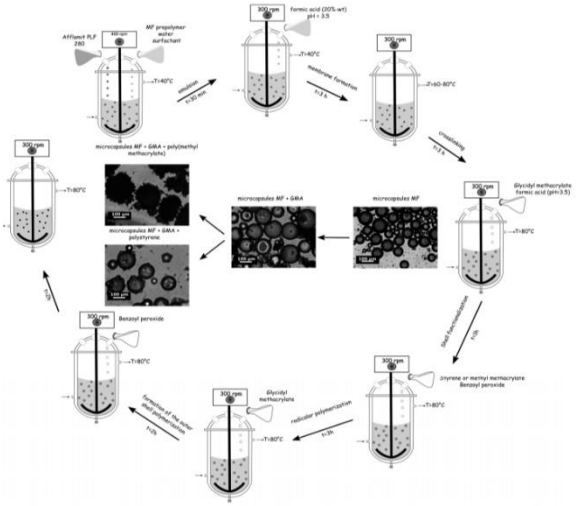

Fig.10: Schematic representation of the microencapsulation process

Phase change material with Micro capsulation

Fabric, being the first and most frequent layer in continuous touch with human skin, is an excellent interface for providing covering as well as heat and cold insulation. PCMs are organic and inorganic compounds that have the potential to absorb and release significant quantities of latent heat during phase transitions between solid and liquid phases at low temperatures. **[53]** Because PCMs undergo phase shifts (liquid-solid and solid-liquid transitions) while collecting and releasing thermal heat, they should be enclosed in polymeric shells, known as microcapsules, if they are to be used for an extended period. Microencapsulation and nanoencapsulation techniques have been developed to limit a PCM's reactivity with the outside environment, improving ease of handling, and lowering diffusion and evaporation rates. **[52]** The methods for incorporating PCMs into textiles, such as electrospinning and measuring thermal characteristics, were summarized. Because of their high thermal storage density, repeatability of phase change, thermal stability, small volume change during phase transition, chemical stability, non-toxicity, non-flammability, non-corrosiveness, and low cost, paraffin waxes appear to play an important role in confronting climate change and global warming. Textiles containing PCMs are influenced and react proportionally to the temperature of the ambient by changing the temperature of various regions of the body as well as the temperature of the environment. **[4, 50, 53-64]**

Because the physical state of PCMs (liquid-solid, solid-solid) changes under different heat settings, the employment of microencapsulation technology is required to conserve, protect, and optimize the usage of PCMs. Because the primary function of clothing is to protect the body from various temperature fluctuations, the introduction of microcapsules containing PCM (micro PCM) in textile production and finishing processes will considera-

bly improve and increase their thermoregulating properties. Microencapsulated phase change materials (mPCMs) undergo solid-liquid and liquid-solid transitions while receiving and storing thermal energy and releasing it. The process described above is known as phase transition (phase change). **[53]**

PCMs store thermal energy during the heating process and release previously stored thermal energy during the cooling phase, hence they are widely used in the manufacture and finishing of various fabrics. They can be used directly within fibers (acrylic fiber) and foams (polyurethane foam) as well as as a liner in the manufacture of different textiles. Naturally, the body can adjust to fluctuations in temperature under various climatic circumstances**. [65]**

Metal salt as phase change material:

Polyethoxysiloxane (PAOS) was used as a cross-linker to create pure inorganic silica capsules that contain inorganic hydrated salt. During this work, six different hydrated inorganic salts evaluated to be used as inorganic phase change materials (namely: calcium nitrate tetrahydrate ($Ca(NO_3)_2.4H_2O$), calcium chloride hexahydrate ($CaCl_2.6H_2O$), sodium sulfate decahydrate ($Na_2SO_4.10H_2O$), disodium hydrogen phosphate dodecahydrate ($Na_2HPO_4.12H_2O$), ferric nitrate nonahydrate ($Fe(NO_3)_3.9H_2O$), and manganese (II) nitrate hexahydrate ($Mn(NO_3)_2.6H_2O$)) in silica-based micro-capsules. Inorganic phase transition materials have been investigated for use in textiles. The best results are obtained using sodium sulfate decahydrate and disodium hydrogen phosphate dodecahydrate. **[52]** At the extrusion step, the microcapsules with good phase change properties were implanted in a polypropylene film. The novel material's basic mechanical characteristics are identical to those of pure polypropylene. Polypropylene (PP) is a very flexible polymer that is mostly utilized in interior textiles. This material was used to incorporate PCM silica capsules to increase its heat storage ability. The PP grains were combined with 5% PCM-silica capsules before being extruded at 200°C. **[53]**

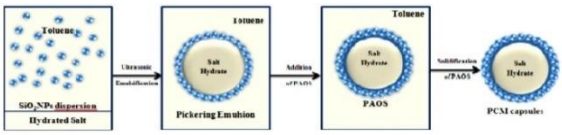

Fig.11: Schematic illustration of the preparation of the inorganic PCM capsules based on silica nanoparticles

Eicosan as Phase change material

In situ polymerization was used to create melamine-formaldehyde microcapsules containing eicosane. The microcapsules were characterized, including particle size and size distribution, shape, thermal characteristics, and stability. **[52]** To create thermoregulating textile materials, the produced microcapsules were applied to polyester knit textiles using a traditional pad-dry-cure procedure. The treated textiles' morphology, thermal characteristics, and washing qualities were also studied. The spherical microcapsules have melamine-formaldehyde shells encapsulating eicosane. The microcapsules were sturdy enough to withstand swirling in hot water and alkaline solutions. The heat storage capacity increased as the microcapsule concentration rose. The heat storage capacity of the thermoregulating textiles ranged from 0.91 to 4.44 J/g, depending on the concentration of the microcapsules. After five launderings, the treated textiles preserved 40% of their heat storage capacity. **[66]**

Solution		Retention of heat storage capacity (%)	
Temperature (°C)	pH	1 h	3 h
20	Neutral[a]	98	90
68	Neutral[a]	100	99
20	Alkaline[b]	99	97

Fig 12.Effect of the Water Temperature and pH on the Heat Storage Capacity of the Microcapsules

Summary

So far, various innovative finishing processes have been developed to functionalize textile substrates. In this respect, one of the modern technologies that has been utilized to give functional qualities such as antibacterial activity, scent, mosquito repellency, UV protection, and thermoregulation to textiles is microencapsulation. The volatile and non-volatile components can be contained inside a thin polymeric film in microencapsulation, resulting in a delayed release of the chemical and a long-lasting functional impact. Essential oils, enzymes, medicines, insecticides, and vitamins have all been effectively entrapped inside microcapsules constructed from various polymeric materials. Microcapsules provide a variety of advantages, including the ability to convert liquids to solids, separate reactive substances, provide environmental protection, and improve material handling qualities. After that, active ingredients are enclosed in micron-sized capsules made of barrier polymers (gelatin, plastic, wax, etc.). However, many microcapsules have little similarity to these basic spheres. The core might be a crystal, a jagged adsorbent particle, an emulsion, a solids suspension, or a microcapsule suspension. The microcapsule may even have numerous walls, which may be organic (gums, polysaccharides, proteins, etc.) or inorganic (polymelamine-formaldehyde, polystyrene, polyurethane, etc.).

Conflict of Interest

There is no conflict of interest in the publication of this article.

Acknowledgment

The authors thank the National Research Centre, Giza, Egypt for the financial support of this work and are also gratefully grateful to the Faculty of Applied Arts, Benha University.

Funds

There is no funding

References

1. Jyothi, S.S., Seethadevi, A., Prabha, K.S., Muthuprasanna, P. and Pavitra, P. Microencapsulation: A review, *Int. J. Pharm. Biol. Sci*, **3**(2) 509-531 (2012).
2. Nada, A.A., Hassabo, A.G., Mohamed, A.L., Mounier, M.M. and Abou Zeid, N.Y. Liposomal microencapsulation of rodent-repelling agents onto jute burlaps: Assessment of cytotoxicity and rat behavioral test, *JAPS*, **6**(8) 142-150 (2016).
3. Abdel-Aziz, E., Bakr, M., Zayed, M., Othman, H. and Hassabo, A.G. Microencapsulation and its application in textile wet processing: A review, *J. Text. Color. Polym. Sci.*, **19**(2) 189-202 (2022).
4. Marey, A.G., Allam, L.N., Abd-Elaal, L.S., El-Wekil, A.N. and Hassabo, A.G. The applications of microencapsulation in different textile finishing, *J. Text. Color. Polym. Sci.*, - (2024).
5. Mohamed, H.A., Gaafar, Z.S., Roshdy, Y.A.E.-m., El-Shamy, M.N. and Hassabo, A.G. Microencapsulation and its application in textile industry, *J. Text. Color. Polym. Sci.*, **22**(1) 81-87 (2025).
6. Nelson, G. Microencapsulation in textile finishing, *Review of Progress in Coloration and related Topics*, **31** 57-64 (2001).
7. Reis, C.P., Neufeld, R.J., Ribeiro, A.J. and Veiga, F. Nanoencapsulation ii. Biomedical applications and current status of peptide and protein nanoparticulate delivery systems, *Nanomedicine: Nanotechnology, Biology and Medicine*, **2**(2) 53-65 (2006).
8. Singh, N. and Sheikh, J. Microencapsulation and its application in production of functional textiles, (2020).
9. Choudhury, N., Meghwal, M. and Das, K. Microencapsulation: An overview on concepts, methods, properties and applications in foods, *Food Frontiers*, **2**(4) 426-442 (2021).
10. Maiti, T.K., Dixit, P., Suhag, A., Bhushan, S., Yadav, A., Talapatra, N. and Chattopadhyay, S.P. Advancements of organic and inorganic shell materials for the preparation of microencapsulated phase change materials for thermal energy storage applications, *RSC Sustainability*, (2023).
11. Jung, J. and Perrut, M. Particle design using supercritical fluids: Literature and patent survey, *The Journal of supercritical fluids*, **20**(3) 179-219 (2001).
12. Mateovic, T., Kriznar, B., Bogataj, M. and Mrhar, A. The influence of stirring rate on biopharmaceutical properties of eudragit rs microspheres, *Journal of microencapsulation*, **19**(1) 29-36 (2002).
13. Sansdrap, P. and Moës, A.-J. Influence of manufacturing parameters on the size characteristics and the release profiles of nifedipine from poly (dl-lactide-co-glycolide) microspheres, *International journal of pharmaceutics*, **98**(1-3) 157-164 (1993).
14. Yang, Y.-Y., Chung, T.-S. and Ng, N.P. Morphology, drug distribution, and in vitro release profiles of biodegradable polymeric microspheres containing protein fabricated by double-emulsion solvent extraction/evaporation method, *Biomaterials*, **22**(3) 231-241 (2001).
15. Herrmann, J. and Bodmeier, R. Biodegradable, somatostatin acetate containing microspheres prepared by various aqueous and non-aqueous solvent evaporation methods, *European Journal of Pharmaceutics and Biopharmaceutics*, **45**(1) 75-82 (1998).
16. Freitas, S., Merkle, H.P. and Gander, B. Microencapsulation by solvent extraction/evaporation: Reviewing the state of the art of microsphere preparation process technology, *Journal of controlled release*, **102**(2) 313-332 (2005).
17. Mehta, R.C., Thanoo, B.C. and Deluca, P.P. Peptide containing microspheres from low molecular weight and hydrophilic poly (d, l-lactide-co-glycolide), *Journal of controlled release*, **41**(3) 249-257 (1996).
18. Schlicher, E.J.A.M., Postma, N.S., Zuidema, J., Talsma, H. and Hennink, W.E. Preparation and characterisation of poly (d, l-lactic-co-glycolic acid) microspheres containing desferrioxamine, *International Journal of Pharmaceutics*, **153**(2) 235-245 (1997).
19. Vasisht, N. Factors and mechanisms in microencapsulation, Microencapsulation in the food industry, Elsevierpp. 15-24, (2014).
20. Massella, D., Giraud, S., Guan, J., Ferri, A. and Salaün, F. Manufacture techniques of chitosan-based microcapsules to enhance functional properties of textiles, *Sustainable Agriculture Reviews 35: Chitin and Chitosan: History, Fundamentals and Innovations*, 303-336 (2019).
21. Boominathan, S., Magesh, G. and Balakrishnan, S. Antimicrobial and mosquito repellent finish on cotton fabric using coleus aromaticus leaf extract, *Journal of Natural Fibers*, **19**(12) 4707-4717 (2022).
22. Türkoğlu, G.C., Sarıışık, A.M., Erkan, G., Yıkılmaz, M.S. and Kontart, O. Micro-and nano-encapsulation of limonene and permethrin for mosquito repellent finishing of cotton textiles, *Iranian Polymer Journal*, **29** 321-329 (2020).
23. Kala, S., Agarwal, A., Sogan, N., Naik, S.N., Nagpal, B.N., Patanjali, P.K. and Kumar, J. Chitosan-acrylate nanogel for durable anti mosquito finishing of cotton fabric and its dermal toxicity

profiling on swiss albino mice, *Colloids and Surfaces B: Biointerfaces*, **181** 789-797 (2019).

24. Sharma, R. and Goel, A. Development of insect repellent finish by a simple coacervation microencapsulation technique, *International journal of clothing science and technology*, **30**(2) 152-158 (2018).
25. Abdel-Aziz, E., Bakr, M., Zayed, M., Othman, H. and Hassabo, A.G. Microencapsulation and its application in textile wet processing: A review, *Journal of Textiles, Coloration Polymer Science*, **19**(2) 189-202 (2022).
26. Deng, X., Nikiforov, A.Y., Coenye, T., Cools, P., Aziz, G., Morent, R., De Geyter, N. and Leys, C. Antimicrobial nano-silver non-woven polyethylene terephthalate fabric via an atmospheric pressure plasma deposition process, *Sci Rep*, **5** 10138 (2015).
27. Dridi, D., Bouaziz, A., Gargoubi, S., Zouari, A., B'chir, F., Bartegi, A., Majdoub, H. and Boudokhane, C. Enhanced antibacterial efficiency of cellulosic fibers: Microencapsulation and green grafting strategies, *Coatings*, **11**(8) 980 (2021).
28. Hassabo, A.G., Nada, A.A., Ibrahim, H.M. and Abou-Zeid, N.Y. Impregnation of silver nanoparticles into polysaccharide substrates and their properties, *Carbohydrate Polymers*, **122** 343-350 (2015).
29. Mohamed, A.L., El-Naggar, M.E., Shaheen, T.I. and Hassabo, A.G. Laminating of chemically modified silan based nanosols for advanced functionalization of cotton textiles, *Int. J. Biol. Macromol.*, **95** 429–437 (2017).
30. Mohamed, A.L., Hassabo, A.G., Shaarawy, S. and Hebeish, A. Benign development of cotton with antibacterial activity and metal sorpability through introduction amino triazole moieties and agnps in cotton structure pre-treated with periodate, *Carbohydrate Polymers*, **178** 251-259 (2017).
31. Hassabo, A.G., El-Naggar, M.E., Mohamed, A.L. and Hebeish, A.A. Development of multifunctional modified cotton fabric with tri-component nanoparticles of silver, copper and zinc oxide, *Carbohydrate Polymers*, **210** 144-156 (2019).
32. Hassabo, A.G., Shaarawy, S., Mohamed, A.L. and Hebiesh, A. Multifarious cellulosic through innovation of highly sustainable composites based on moringa and other natural precursors, *Int. J. Biol. Macromol.*, **165** 141-155 (2020).
33. Mohamed, A.L. and Hassabo, A.G. Cellulosic fabric treated with hyperbranched polyethyleneimine derivatives for improving antibacterial, dyeing, pH and thermo-responsive performance, *Int. J. Biol. Macromol.*, **170** 479-489 (2021).
34. Hassabo, A.G., Reda, E.M., Ghazal, H. and Othman, H.A. Synthesis of agnps and znonps using tea leaves extract and their utilization to improve dyeability, printability and functionality of cotton and wool fabrics, *Inorg. Chem. Commun.*, **150** 110525 (2023).
35. Mohamed, A.L., El-Zawahry, M., Hassabo, A.G. and Abd El-Aziz, E. Encapsulated lemon oil and metal nanoparticles in biopolymer for multifunctional finishing of cotton and wool fabrics, *Indust. Crop. Prod.*, **204** 117373 (2023).
36. Petrova, L., Kozlova, O., Vladimirtseva, E., Smirnova, S., Lipina, A. and Odintsova, O. Development of multifunctional coating of textile materials using silver microencapsulated compositions, *Coatings*, **11**(2) 159 (2021).
37. Hong, S.A., Kim, I.Y., Kim, H.R. and Song, W.S. Manufacture of UV absorbers and UV protection fabrics using microcapsules, *Fibers and Polymers*, **12** 491-498 (2011).
38. Ibrahim, N.A., Nada, A.A., Eid, B.M., Al-Moghazy, M., Hassabo, A.G. and Abou-Zeid, N.Y. Nano-structured metal oxides: Synthesis, characterization and application for multifunctional cotton fabric, *Adv. Nat. Sci.: Nanosci. Nanotechnol.*, **9**(3) 035014 (2018).
39. Mohamed, A.L., El-Naggar, M.E. and Hassabo, A.G. Preparation of hybrid nano-particles to enhance the electrical conductivity and performance properties of cotton fabrics, *Journal of Materials Research and Technology*, **12** 542-554 (2021).
40. Zayed, M., Othman, H., Ghazal, H. and Hassabo, A.G. Psidium guajava leave extract as reducing agent for synthesis of zinc oxide nanoparticles and its application to impart multifunctional properties for cellulosic fabrics, *Biointerf. Res. Appl. Chem.*, **11**(5) 13535 - 13556 (2021).
41. Hassabo, A.G., Ragab, M.M. and Othman, H.A. Ultraviolet protection of cellulosic fabric, *J. Text. Color. Polym. Sci.*, **19**(1) 51-61 (2022).
42. Zayed, M., Ghazal, H., Othman, H. and Hassabo, A.G. Psidium guajava leave extract for improving ultraviolet protection and antibacterial properties of cellulosic fabrics, *Biointerf. Res. Appl. Chem.*, **12**(3) 3811 - 3835 (2022).
43. Zayed, M., Ghazal, H., Othman, H.A. and Hassabo, A.G. Synthesis of different nanometals using citrus sinensis peel (orange peel) waste extraction for valuable functionalization of cotton fabric, *Chem. Pap.*, **76**(2) 639-660 (2022).
44. Mohamed, A.L., Khattab, T.A., Rehan, M.F. and Hassabo, A.G. Mesoporous silica encapsulating zns nanoparticles doped cu or mn ions for warning clothes, *Results in Chemistry*, **5** 100689 (2023).
45. Wang, W., Liang, Y., Yang, Z., Zhang, W. and Wang, S. Construction of ultraviolet protection, thermal insulation, superhydrophobic and aromatic textile with al-doped ZnO–embedded lemon microcapsule coatings, *Textile Research Journal*, **89**(18) 3860-3870 (2019).
46. Gibertini, E., Carosio, F., Aykanat, K., Accogli, A., Panzeri, G. and Magagnin, L. Silica-encapsulated red phosphorus for flame retardant treatment on textile, *Surfaces and Interfaces*, **25** 101252 (2021).
47. Mohamed, A.L. and Hassabo, A.G. Flame retardant of cellulosic materials and their composites, in: P.M. Visakh, Y. Arao (Eds.), Flame retardants, Springer International Publishingpp. 247-314, (2015).
48. Hassabo, A.G. and Mohamed, A.L. Novel flame retardant and antibacterial agent containing mgo nps, phosphorus, nitrogen and silicon units for

functionalise cotton fabrics, *Biointerf. Res. Appl. Chem.*, **9**(5) 4272 - 4278 (2019).

49. Yousef, M.Y. and Hassabo, A.G. Environmentally friendly inorganic materials for anti-flammable cotton fabrics, *J. Text. Color. Polym. Sci.*, **18**(2) 97-110 (2021).
50. El-Wekil, A.N., Marey, A.G., Allam, L.N., Abd-Elaal, L.S. and Hassabo, A.G. Micro/nano capsulation: Textile functional features and application, *J. Text. Color. Polym. Sci.*, - (2024).
51. Hesham, N., Maged, S., Nabil, N., Ahmed, T., Omar, M., Maamoun, D., Hassabo, A.G., Abdelrahman, M.S. and Khattab, T.A. Flame retardant and water repellent finishing of polyester fabric, *J. Text. Color. Polym. Sci.*, **21**(1) 97-102 (2024).
52. Butstraen, C., Salaün, F., Devaux, E., Giraud, S. and Vroman, P. Application of flame-retardant double-layered shell microcapsules to nonwoven polyester, *Polymers*, **8**(7) 267 (2016).
53. Hassabo, A.G., Mohamed, A.L., Wang, H., Popescu, C. and Moller, M. Metal salts rented in silica microcapsules as inorganic phase change materials for textile usage, *Inorganic Chemistry: An Indian Journal*, **10**(2) 59-65 (2015).
54. Popescu, C., Vinokur, R., Hassabo, A.G., Beginn, U. and Möller, M. Phase change materials (pcm) for textiles, 4th Aachen-Dresden International Textile Conference, Dresden, Germany, (2010).
55. Hassabo, A.G. New approaches to improving thermal regulating property of cellulosic fabric, *Carbohydrate Polymers*, **101**(0) 912-919 (2014).
56. Hassabo, A.G. and Mohamed, A.L. Enhancement the thermo-regulating property of cellulosic fabric using encapsulated paraffins in modified pectin, *Carbohydrate Polymers*, **165** 421-428 (2017).
57. Hassabo, A.G. and Mohamed, A.L. Enhancement of thermo-regulating textile materials using phase change material (pcm), *Evolution in Polymer Technology Journal*, **2**(1) 180009 (1-11) (2019).
58. Ali, M.A., Seddik, K.M. and Hassabo, A.G. Polyester fibres enhanced with phase change material (pcm) to maintain thermal stability, *Egy. J. Chem.*, **64**(11) 6599 - 6613 (2021).
59. Ali, M.A., Hassabo, A.G., Seddik, K.M., yahia, s. and Mohamed, N. Characterization of the thermal and physico-mechanical properties of cotton and polyester yarns treated with phase change materials composites, *Egy. J. Chem.*, **65**(13) 21-37 (2022).
60. Fathallah, A.I., El-Sadek, H., Youssef, B.Y., Amin, M.G., El-Kambashawy, Y.M., Abd El-Kader, B.M., Halawa, O. and Hassabo, A.G. Intelligent pcm composite for enhancing the thermoregulated properties of different cotton/polyester fabric constructions, *J. Text. Color. Polym. Sci.*, **20**(1) 113-123 (2023).
61. Fathallah, A.I., Youssef, B.Y., El-Sadek, H., Amin, M.G., Abd El-Kader, B.M., El-Kambashawy, Y.M., Halawa, O.E. and Hassabo, A.G. Alginic/stearic/octadecane as phase change material (pcm) for enhancing the thermal comfort-ability of different polyester fabrics constructions, *Egy. J. Chem.*, **66**(4) 167-177 (2023).
62. Hassabo, A.G., Eid, M.M., Mahmoud, E.R. and Asser, N.A.H., A. Innovation of smart knitted fabrics for functional performance of sportswear upon treatment using phase change material, *Egy. J. Chem.*, **66**(3) -133-156 (2023).
63. Zayed, M., Abd El-Aziz, E., Ghazal, H., Hassabo, A.G. and Othman, H. Phase change materials (pcm) for sustainable textile materials: Design, characteristic, performance and application, *J. Text. Color. Polym. Sci.*, - (2024).
64. Zayed, M., Abd El-Aziz, E., Ghazal, H., Othman, H. and Hassabo, A.G. Construction of intelligent bio-pcm matrix for cotton fabrics to improve thermal comfortability and human protection, *Egy. J. Chem.*, **67**(13) 109-119 (2024).
65. Ahrari, M., Khajavi, R., Dolatabadi, M.K., Toliyat, T. and Rashidi, A. A review on application of phase change materials in textiles finishing, *International Journal of Materials and Metallurgical Engineering*, **11**(5) 400-405 (2017).
66. Shin, Y., Yoo, D.I. and Son, K. Development of thermoregulating textile materials with microencapsulated phase change materials (pcm). Ii. Preparation and application of pcm microcapsules, *Journal of Applied Polymer Science*, **96**(6) 2005-2010 (2005).