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Review Paper

Microencapsulation Technologies: Recent Advances in Drug Protection, Controlled Release and Targeted Therapeutics

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ABSTRACT

Active pharmaceutical ingredients, biologics, or living organisms are incased in protective polymeric, lipid, protein-based, or hybrid coatings in microencapsulation, a sophisticated drug delivery method. Microcapsules, which are typically between 1 and 1000 μm in size, shield delicate materials from light, moisture, oxygen, temperature, and pH fluctuations. Additionally, they avoid medication incompatibilities, hide offensive taste and odor, turn liquids into powders, and offer targeted, controlled, or prolonged drug release. Release can happen by osmosis, diffusion, dissolution, degradation, or reactions to temperature and pH. Ionic gelation, fluidized-bed coating, solvent evaporation, spray drying, interfacial polymerization, and coacervation are common preparation techniques. While synthetic polymers like PLGA, PLA, PCL, and Eudragit provide greater mechanical qualities and tunable release profiles, natural polymers like alginate, chitosan, gelatin, and pectin offer biocompatibility and biodegradability. Microscopy, particle-size analysis, FTIR, DSC, TGA, XRD, zeta-potential measurement, drug-loading investigations, and stability testing are all used to characterize microcapsules. Oral, topical, injectable, implantable, probiotic, vaccine, cosmetic, food, agricultural, and industrial delivery methods are among their uses. Personalized medicine, AI-assisted formulation design, 3D printing, and stimuli-responsive polymers are examples of recent developments.

INTRODUCTION

Over the past few decades, the pharmaceutical industry has seen tremendous changes in drug

delivery systems, with microencapsulation emerging as a key technique. By incorporating active pharmaceutical ingredients (APIs) in polymeric matrices, this method produces

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microcapsules that range in size from 1 to 1000 μm . Microencapsulation's main goal is to solve important issues with conventional drug administration, such as poor stability, insufficient solubility, and low release kinetics. By protecting medications from environmental elements including moisture, light, and oxygen, microencapsulation extends their shelf life and preserves their medicinal efficacy. In addition to providing protection, this method provides regulated release mechanisms that may be adjusted to certain physiological situations, increasing therapeutic efficacy and reducing adverse effects^[1]

Specifically, solid materials, liquid droplets, or gaseous molecules are trapped inside an inert shell composed of synthetic and/or bioinspired materials that can isolate chemically and thermally unstable active ingredients from environmental factors. Microencapsulation is commonly used to encapsulate essential oils, colorings, flavorings, sweeteners, microbes, and other substances in a variety of industries, including the pharmaceutical, agricultural, medical, and food sectors^[2]

The development of "smart" delivery methods that react to certain biological stimuli, such as pH shifts, enzyme activity, or temperature variations, has been the focus of recent advances in microencapsulation. These developments have greatly increased the therapeutic index of traditional medicines by enabling more accurate medication targeting to certain tissues or organs. The combination of nanotechnology and conventional microencapsulation techniques has created new opportunities to improve medicine delivery efficiency as the area develops^[3]

2.HISTORY AND EVOLUTION OF MICROENCAPSULATION -

Microencapsulation is the process of encasing small liquid or solid particles in a continuous polymer coating, allowing for controlled release

and protection of active compounds. Originating in 1931 by Bungenburg de Jon and Kan, it evolved primarily to enhance medication stability and regulate release rates. Initially applied in pharmaceuticals, methods advanced over decades to increase therapeutic efficacy using sophisticated polymeric barriers and innovative carrier systems, marking significant developments in drug delivery techniques.^[5,6]

3.NEED FOR MICROENCAPSULATION IN DRUG DELIVERY -

The main feature of microcapsules is their large surface area due to their small particle size. Notable advantages of this larger surface area include greater light scattering, chemical reaction facilitation, and increased absorption and desorption sites. The creation of different dosage forms, such as converting liquids into solids, is made possible by microencapsulation methods. This change tackles a major microencapsulation problem: protecting against environmental effects. It also improves the handling qualities of materials and helps separate reactive medicinal components^[2]

A crucial development in DDs, microencapsulation—which uses microspheres or microcapsules—is intended to solve a number of issues with traditional formulations. This method guarantees constant therapeutic levels and lowers the frequency of dosage by enabling regulated and prolonged medication release. By shielding them from environmental elements including light, moisture, and pH changes, it improves the stability of delicate medications. Additionally, by enabling targeted distribution to certain locations, microencapsulation reduces systemic adverse effects and increases patient compliance. Microencapsulation has become as a crucial method in modern pharmaceutical research to optimize medication solubility, BA, and release kinetics. In certain instances, the primary goal is to



regulate the release of medications in the surrounding environment, which can be accomplished by microencapsulation, rather than to isolate the core from the external environment. In general, microencapsulation improves product functioning across a variety of industries.^[7]

- Reasons for microencapsulation-^{[4][8]}
 1. Liquid medications can be transformed into free-flowing powders via microencapsulation.
 2. Microencapsulation helps avoid drug-drug and drug-excipient incompatibilities.
 3. It is possible to stop volatile oil from vaporizing.
 4. To accomplish prolonged or sustained drug release.
 5. To increase patient compliance by masking the bad taste and odor of medications.
 6. It may be possible to lessen the toxicity and GI discomfort caused on by different medications.
 7. This method helps stabilize medications that are susceptible to the environment.
 8. By modifying the release profile and focusing on particular absorption sites, microencapsulation can increase the bioavailability and effectiveness of medications.

4. DIFFERENT MECHANISMS FOR CONTROLLED RELEASE OF THE CORE MATERIAL-

Microencapsulation is most successful when the core material is shielded until intended release. The core material is released by a variety of mechanisms. These consist of degradation, diffusion, dissolution, pressure application, and pH and temperature changes. The characteristics of the wall material and the core determine the mechanisms that are employed.^{[9][10]} Below is a description of a few of the techniques:

A] Diffusion: Diffusion of the core often happens when a fluid passes through the intact microcapsule wall and dissolves in it, the core substance, and spreads via the pores.^[9]

B] Dissolution: In this case, the wall material's solubility in the dissolving fluid determines the core's release. When the wall comes into contact with the fluid, it dissolves and releases the core; it is no longer intact. The characteristics of the wall material, the dissolving fluid, and the wall's thickness all affect the rate of release.^[9]

C] Osmosis: The microcapsule wall functions as a semipermeable barrier during the osmotic release of the core material, allowing an osmotic pressure differential to form on either side of the wall. The core material shifts from within the capsule to outside as a result of this pressure differential.^[9]

D] Degradation: This method of core release breaks the wall and releases the core by using enzymes like lipases and proteases to break down the proteins and lipids in the wall material.^[10]

E] Change in pH: Changes in pH can impact the solubility of the wall material, which can result in the release of core. When the pH is changed, a wall material may become soluble in alkaline circumstances while remaining intact in acidic ones.^[10]

F] Changes in temperature: By varying the temperature at which the microcapsules are exposed, core release can be induced. Two distinct processes are involved in temperature-mediated core release: (a) One is known as temperature-sensitive release, in which the wall material expands and collapses when exposed to a temperature known as the critical temperature. (b) The alternative method, known as fusion-activated release, releases the core when the wall material begins to melt in response to an elevated temperature.^[10]



5. CLASSIFICATION OF ENCAPSULATION SYSTEM:

Microencapsulation systems can be classified according to several criteria, including the nature of the core material, shell or wall material, capsule structure, and encapsulation technique.^[2] This classification helps in selecting an appropriate microencapsulation strategy based on the physicochemical properties of the drug, desired

release profile, stability requirements, and target site of delivery. Recent advances have further expanded this classification to include smart stimuli-responsive systems, hybrid polymeric carriers, and biofilm-based encapsulation, which offer improved drug protection, controlled release, and site-specific delivery.^[11]

Classification of Microencapsulation Systems Based on Composition, Structure and Encapsulation Techniques.^[12,13]

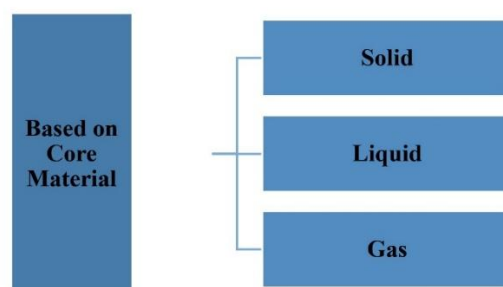


Fig 1 : Classification Based on Core Material

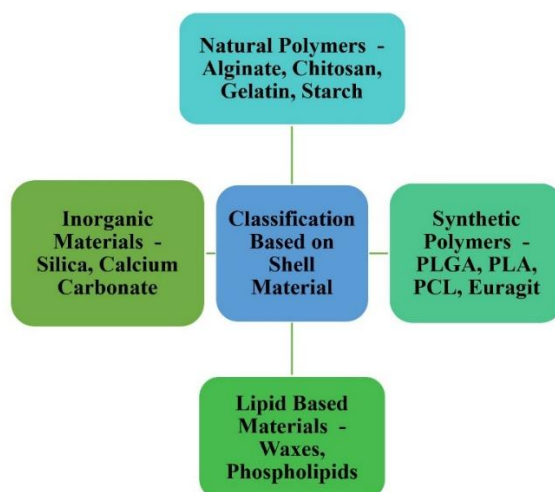


Fig 2 : Classification Based on Shell Material

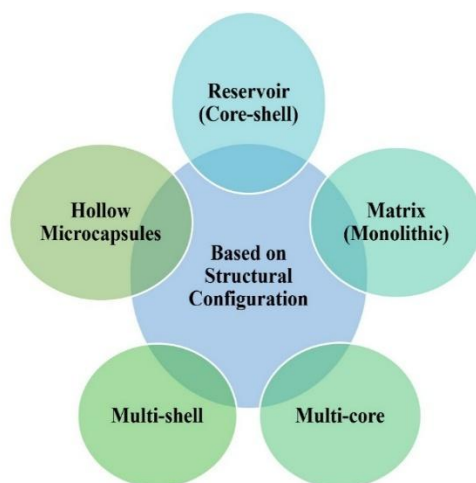


Fig 3 : Classification Based on Structural Configuration

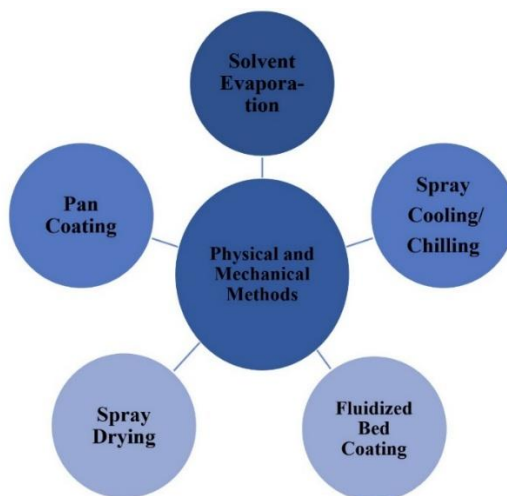


Fig 4 : Physical and Mechanical Methods

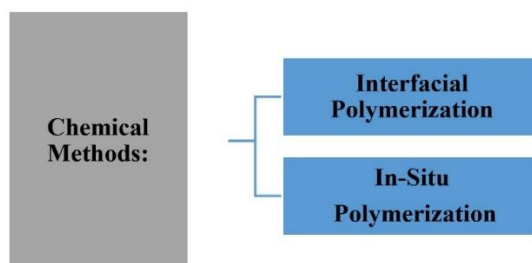


Fig 5 : Chemical Methods

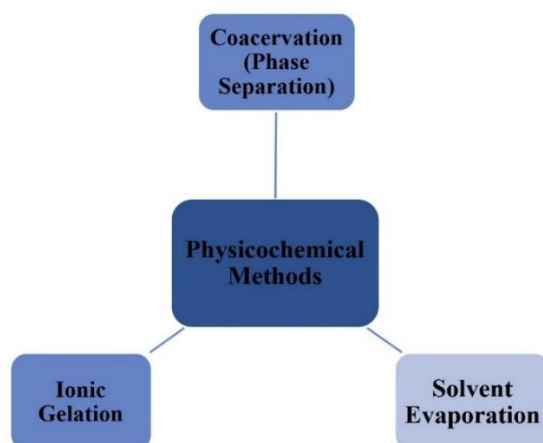


Fig 6 : Physicochemical Methods

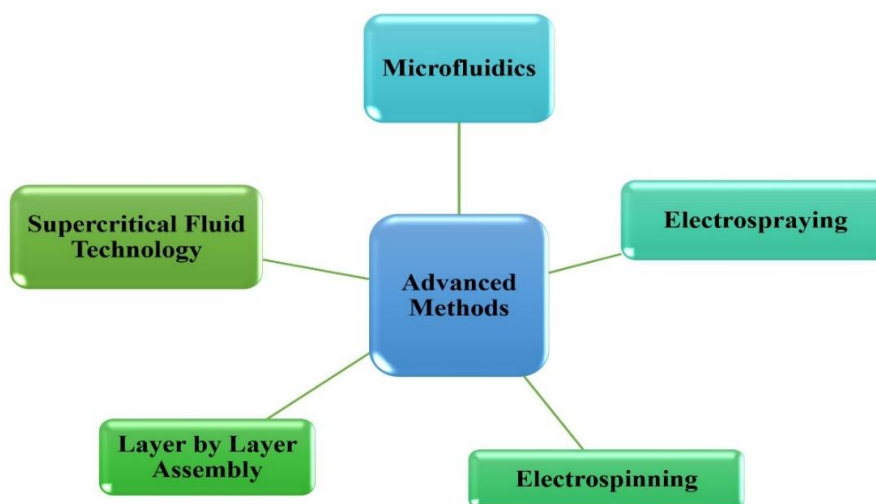


Fig 7 : Advanced Methods

6.ADVANTAGES AND DISADVANTAGES

Advantages : ^[7]

1. Encapsulated compounds are protected from destruction caused by moisture, light, and oxygen.
2. Masks the drug's bitter taste, which improves palatability and patient compliance.
3. Avoids medicine combinations that are incompatible.
4. Allows for regulated release of active substances.
5. Reduces major adverse effects such as toxicity and GI irritation.
6. Converts free-flowing liquids into solids or pseudosolids for easier handling and storage.
7. Preserves the inner core's compound volatility.
8. Enhances the flow property of the core medication.
9. Masks unpleasant scents from certain drugs.

Disadvantages : ^[7]

1. Expensive because of the materials and advanced machinery.



2. Changes in process parameters such as temperature, pH, or solvent evaporation have an impact on core particle stability.
3. more stringent standards for quality control.
4. deterioration of the polymer matrix brought on by heat, hydrolysis, or biological factors.
5. low drug-loading capacity and a complicated production process.
6. shortens the hygroscopic medications' shelf life.
7. The method is not suitable for every kind of medication.
8. incidence of a discontinuous coating.
9. It is not possible to apply a single approach to every core material.
10. Scaling up production processes can be challenging, whether on a small and large scale.
11. Due to size limitations, it might not be appropriate for parenteral routes.

7. CORE AND COATING MATERIALS USED IN MICROENCAPSULATION

7.1. Selection Criteria for Core and Coating Materials

The choice of a suitable coating (wall) and core (active ingredient) material is the main factor influencing microencapsulation performance. Encapsulation efficiency, stability, drug release behavior, and targeting capabilities are all determined by the physicochemical compatibility of the core and shell. Excellent biocompatibility,

biodegradability, mechanical strength, chemical stability, and the capacity to create a consistent protective barrier around the core are all desirable qualities for a coating material. Similarly, the core substance should retain its therapeutic action while remaining chemically stable during encapsulation and storage. [14,15,16]

The intended route of administration, drug properties, release kinetics, and manufacturing technique should all be taken into consideration when choosing encapsulating materials, according to recent studies. [14,15,16]

7.2. Core Materials Used in Microencapsulation

The active ingredient included in the microcapsule is known as the core material. Pharmaceutical medications, proteins, peptides, probiotics, vaccines, nucleic acids, essential oils, and imaging agents are examples of substances that can exist in solid, liquid, or gaseous form. Encapsulation efficiency, stability, and release characteristics are all influenced by the nature of the core. While hydrophobic medications work better in lipid-based or hydrophobic polymer systems, hydrophilic pharmaceuticals frequently need hydrophilic polymer matrices. The variety of core materials has been broadened by recent pharmaceutical research to include biologics including mRNA, gene-editing components, and monoclonal antibodies. [2,16,17]

Table 1. Classification of Core Materials

Core Material	Examples	Purpose
Small Molecule Drugs [18]	Ibuprofen, Aspirin, Diclofenac	Sustained Release
Antibiotics [19]	Amoxicillin, Ciprofloxacin	Controlled Delivery
Anticancer Drugs [16]	Doxorubicin, Paclitaxel	Targeted Therapy
Proteins & Peptides [20]	Insulin, Growth Hormone	Protection From Degradation
Vaccines [16]	Antigens, Mrna Vaccines	Enhanced Immune Response



Probiotics ^[21]	Lactobacillus Spp.	Improved Gastrointestinal Survival
Essential Oils ^[22]	Curcumin Oil, Fish Oil	Stability Enhancement
Nucleic Acids ^[16]	Dna, Sirna, Mrna	Gene Delivery

7.3 Coating Materials Used in Microencapsulation

Controlling medication release, enhancing stability, and shielding the encapsulated agent from environmental deterioration are all accomplished by the coating or wall material, which creates a protective shell around the core. Excellent film-forming ability, biocompatibility, biodegradability, low toxicity, and compatibility with the medicine being encapsulated are all desirable characteristics of the wall material. While synthetic polymers are still necessary to achieve accurate and long-term regulated release, recent research has concentrated on natural polymers because to their superior safety profile and environmental sustainability. ^[23,24]

Classification of Coating Materials

A. Natural Polymers

Natural polymers come from plant, animal, or microbial sources and are non-toxic, biodegradable, and biocompatible. Because they may create protective shells around active medicinal ingredients, increasing medication stability, regulating drug release, and boosting bioavailability, they are frequently utilized as coating materials in microencapsulation. ^[23] They are appropriate for oral, topical, and targeted drug delivery systems due to their superior safety profile, mucoadhesive qualities, and environmental sustainability. Alginate, chitosan, gelatin, pectin, gum arabic, starch, cellulose derivatives, carrageenan, hyaluronic acid, xanthan gum, and pullulan are examples of common natural polymers. They may show batch-to-batch

variability and lower mechanical strength than synthetic polymers, despite benefits like low toxicity and biodegradability. ^[24,25]

Examples

- Sodium alginate
- Chitosan
- Gelatin
- Pectin
- Carrageenan
- Gum arabic
- Xanthan gum
- Hyaluronic acid
- Cellulose derivatives
- Starch
- Pullulan

B. Synthetic Polymers

In microencapsulation systems, synthetic polymers man-made polymers are intended to deliver drugs in a regulated, sustained, and targeted manner. Their exceptional mechanical strength, repeatability, chemical stability, and adjustable degradation rates make them widely employed. Synthetic polymers provide greater control over drug release kinetics, encapsulation efficiency, and large-scale production when compared to natural polymers. In addition to being biodegradable and biocompatible, many synthetic polymers can be used in oral, injectable, ophthalmic, and implantable drug delivery systems, among other pharmaceutical applications. ^[26]

Examples

- PLGA – Poly (lactic-co-glycolic acid)
- PLA - Polylactic acid



- PCL - Polycaprolactone
- Eudragit®
- EC - Ethyl cellulose
- PVA - Polyvinyl alcohol
- PEG - Polyethylene glycol
- PVP - Polyvinylpyrrolidone

C. Lipid-Based Materials ^[16]

Examples

- Beeswax
- Carnauba wax
- Stearic acid
- Glyceryl behenate
- Lecithin
- Phospholipids

Applications

- Lipophilic drugs

- Taste masking
- Controlled release

D. Protein-Based Materials ^[24]

Examples

- Gelatin
- Albumin
- Whey protein
- Zein
- Casein

Applications

- Protein delivery
- Vaccine delivery
- Tissue engineering

7.4. Properties of an Ideal Coating Material ^[23]

Table 2 : Properties of an Ideal Coating Material

Property	Importance
Biocompatibility	Safe For Biological Use
Biodegradability	Eliminates Need For Surgical Removal
Non-Toxic	Reduces Adverse Effects
Film-Forming Ability	Produces Uniform Capsule Shell
Chemical Stability	Protects Drug During Storage
Mechanical Strength	Prevents Rupture
Controlled Permeability	Regulates Drug Release
Ease Of Processing	Supports Scalable Manufacturing
Cost Effectiveness	Facilitates Industrial Production

8.CHARACTERIZATION OF MICROCAPSULES

The encapsulation efficiency, particle size and shape, surface properties, stability, and release behavior of microcapsules are assessed. The shape, surface texture, and structural integrity of the microcapsules are evaluated using morphological examination, which is often performed using SEM. The amount of active substance that is effectively trapped within the coated material is indicated by encapsulation efficiency. While release tests assess the regulated release and functional performance of the

encapsulated item in the intended application, stability investigations ascertain the microcapsules' capacity to shield delicate compounds from deterioration during storage. ^[27]

8.1. Particle Size and Size Distribution

Particle size and size distribution are important factors that affect microcapsule performance, stability, and quality. Consistent release properties are ensured and encapsulation efficiency is increased using smaller, evenly distributed microcapsules. Variables in formulation and processing, including viscosity, emulsifier



concentration, stirring rate, and stirring time, have an impact on particle size. While high viscosity or emulsifier content might increase particle size, increasing the stirring rate and duration generally results in smaller and more homogeneous microcapsules.^[28]

Determined using:

- Image Analyzer
- Optical Microscopy
- Dynamic Light Scattering (DLS)
- Laser Diffraction

8.2. Morphology and Surface Characteristics

The stability, release behavior, encapsulation efficiency, and structural integrity of microcapsules are all influenced by their morphology and surface features. The encapsulation method and formulation conditions affect the morphology of microcapsules, which are typically spherical in shape with smooth or slightly rough surfaces.^[29] Successful encapsulation is indicated by uniform surface morphology, which also improves the microcapsules' mechanical and thermal stability.^[30]

Determined using:

- Scanning Electron Microscopy (SEM)
- Optical Microscopy
- Energy Dispersive Spectroscopy (EDS) (surface elemental analysis)
- Atomic Force Microscopy (AFM) (surface topography)

8.3. Encapsulation Efficiency and Drug Loading

Two important metrics used to assess the effectiveness of microencapsulation systems are drug loading (DL) and encapsulation efficiency (EE). Drug loading is the quantity of drug included per unit weight of the microcapsules, whereas encapsulation efficiency is the proportion of medication properly entrapped within the carrier.

Drug protection, stability, controlled release, and therapeutic efficacy are all enhanced by high EE and DL. Following the quantification of the free and encapsulated medication, these parameters are typically ascertained using UV-visible spectrophotometry or High-Performance Liquid Chromatography (HPLC). Vacuum spray drying achieved a maximum encapsulation efficiency of 91.56% and a drug loading efficiency of 5.45% in the reviewed study, indicating that curcumin was effectively trapped within the pectin matrix.^[31]

Determined using:

- UV-Visible Spectrophotometry
- High-Performance Liquid Chromatography (HPLC)

8.4. Chemical Characterization (FTIR)

FTIR, or Fourier Transform Infrared Spectroscopy, is frequently used to determine the functional groups found in microcapsules, wall polymers, and core materials. By identifying distinctive chemical linkages and potential interactions between the drug and the encapsulating substance, it verifies successful encapsulation. Additionally, FTIR guarantees that no unwanted chemical changes take place during the microencapsulation process and aids in determining the compatibility of formulation components.^[32]

Determined using:

- Fourier Transform Infrared Spectroscopy (FTIR)

Purpose:

- Identifies functional groups
- Confirms successful encapsulation
- Detects drug-polymer interactions
- Evaluates compatibility between core and wall materials
- Verifies chemical stability of microcapsules



8.5. Thermal Characterization (DSC, TGA)

In order to assess the stability and thermal behavior of microcapsules throughout manufacturing and storage, thermal characterisation is crucial. While Thermogravimetric Analysis (TGA) analyzes weight loss and degradation temperature to evaluate thermal stability, Differential Scanning Calorimetry (DSC) is used to quantify the melting point, crystallization behavior, glass transition temperature, and enthalpy of encapsulated materials. These methods guarantee that microcapsules stay stable under heat stress and validate the protective function of the encasing substance.^[33,34]

Determined using:

- Differential Scanning Calorimetry (DSC)
- Thermogravimetric Analysis (TGA)

Purpose:

- Determines melting and crystallization behavior
- Measures enthalpy (heat storage/release)
- Evaluates thermal stability and degradation temperature
- Confirms the protective effect of the encapsulating shell
- Assesses suitability for processing and storage

8.6. Crystallinity (XRD)

The crystalline or amorphous state of microcapsules is assessed using X-ray diffraction (XRD). It assists in confirming effective encapsulation and determining the crystallinity of the medication and wall material.^[35] While variations in crystallinity affect the durability, solubility, and drug release behavior of the microcapsules, the absence or diminution of the core material's distinctive diffraction peaks signifies its successful integration into the polymer matrix.^[36]

Determined using:

- X-ray Diffraction (XRD)

Purpose:

- Determines crystalline or amorphous structure
- Confirms successful encapsulation
- Evaluates changes in crystallinity
- Assesses stability and solid-state properties
- Predicts drug release and storage behavior

8.7. Surface Charge (Zeta Potential)

Zeta potential, or surface charge, is a crucial metric for assessing the stability of microcapsule dispersions. It helps forecast the propensity of microcapsules to aggregate by measuring the electrical charge on their surface. Stronger electrostatic repulsion between particles is indicated by a greater absolute zeta potential value, which improves colloidal stability and decreases aggregation. Additionally, successful surface modification or layer-by-layer coating of microcapsules is confirmed by changes in zeta potential.^[37]

Determined using:

- Zeta Potential Analyzer (Electrophoretic Light Scattering)

Purpose:

- Determines surface charge of microcapsules
- Evaluates colloidal stability
- Predicts particle aggregation or dispersion
- Confirms successful surface coating or functionalization
- Assesses storage stability of microcapsule suspensions

8.8. Stability Studies

The capacity of microcapsules to shield the encapsulated active substance during manufacturing and storage is assessed by stability tests. They evaluate the encapsulated material's retention in several environmental settings, including pH, temperature, light, and humidity.^[38] High stability means that the wall material is



protecting the microcapsules effectively, extending their shelf life and improving their performance. Anthocyanin-loaded microcapsules in the reviewed study demonstrated the efficacy of

complex coacervation in maintaining the bioactive chemical under both room temperature (37 °C) and refrigerated (7 °C) storage settings.^[39]



Fig 8 : Overview of Microcapsule Characterization

9. PREPARATION TECHNIQUES OF MICROENCAPSULATION

Microencapsulation is the technique of creating tiny capsules by encasing solid, liquid, or gaseous core constituents in a protective shell.^[2] The type of core material, shell material, required particle size, encapsulation efficiency, release properties, and intended use are all taken into consideration while choosing a preparation method. Physical (Mechanical), Physicochemical, and Chemical methods are the general categories into which microencapsulation techniques fall.^[40,41]

9.1. Physical and Mechanical Methods

In both mechanical and physical microencapsulation techniques, a covering material is physically deposited around the core material without the active ingredient being chemically altered. To create the capsule shell, these methods rely on mechanical forces such

atomization, fluidization, or drying. They are popular for industrial applications in the pharmaceutical, food, cosmetic, and biotechnology industries due to their easy operation, affordability, scalability, and compatibility with heat-stable materials.^[42]

9.1.1. Solvent Evaporation:^[2,6,7]

One of the most popular techniques for microencapsulating both hydrophilic and hydrophobic medications is solvent evaporation. In this method, the core material and polymer are dissolved or dispersed in a volatile organic solvent to form an emulsion. As the solvent evaporates, the polymer precipitates around the core material, generating stable microcapsules with regulated particle size and sustained-release features.^[41] Oil-in-water (O/W) and water-in-oil-in-water (W/O/W) emulsion systems are frequently employed in this approach, which is extensively

utilized in biotechnology, biomedical, and pharmaceutical applications.^[43,44]

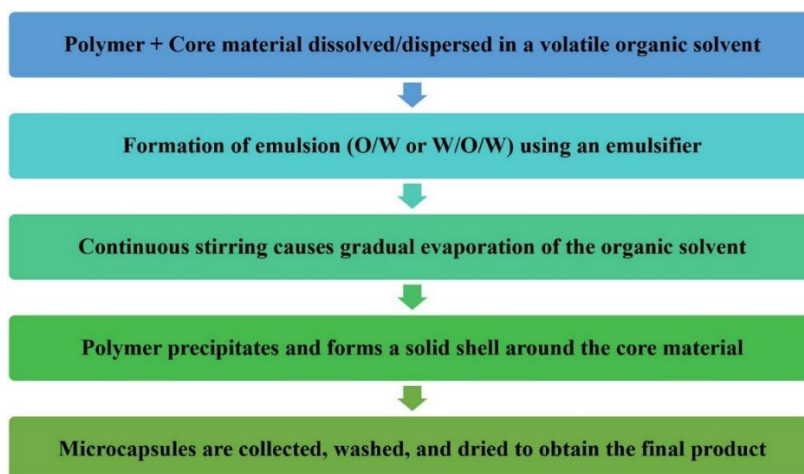


Fig 9 : Working Principle of Solvent Evaporation Technique

9.1.2. Pan Coating

One of the earliest and most basic mechanical techniques for microencapsulation is pan coating, which is generally used to solid particles larger than 600 μm . Using this method, the coating material is sprayed or poured over the surface of

the core particles while they are in a spinning coating pan. In order to evaporate the solvent and create a consistent protective layer surrounding every particle, warm air is concurrently delivered. The pharmaceutical industry uses this technology for pellet and tablet coating because it is straightforward, affordable, and very effective.^[45]

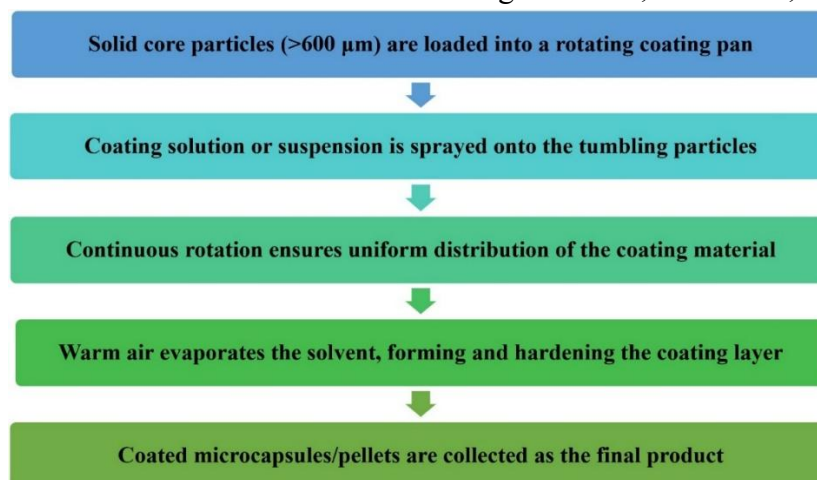


Fig 10 : Working Principle of Pan Coating

9.1.3. Spray Drying:

One of the most popular physical microencapsulation techniques for turning liquid feed into dry, free-flowing microparticles is spray drying. In order to create microcapsules, the core

material is combined with an appropriate wall material, atomized into tiny droplets, and quickly dried using hot air.^[46] It is favored due to its ease of use, affordability, speed of processing, scalability, reproducibility, and capacity to create

stable powders with regulated particle sizes and longer shelf lives. [47]

Example : Curcumin from turmeric (*Curcuma longa*) is commonly microencapsulated by spray

drying using gum arabic, sodium alginate, or modified chitosan as wall materials to improve its stability, solubility, and controlled release. [48]

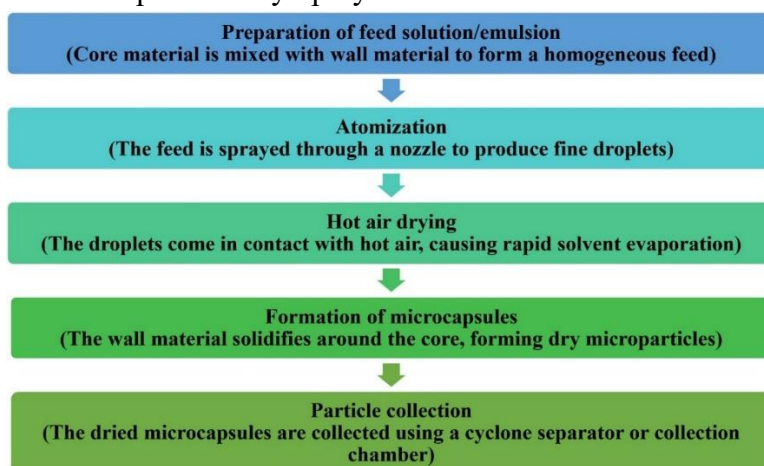


Fig 11 : Working Principle of Spray Drying

9.1.4. Fluidized Bed Coating

Fluidized bed coating is a mechanical microencapsulation method where a coating solution is sprayed onto the surface of solid particles suspended in an upward air stream. [49] Uniform coating is ensured by the particles'

constant motion, and concomitant drying quickly eliminates the solvent to create a protective shell surrounding every particle. This approach is one of the most popular for microencapsulation because it provides good control over coating thickness, high encapsulation effectiveness, and uniform particle coating. [50]

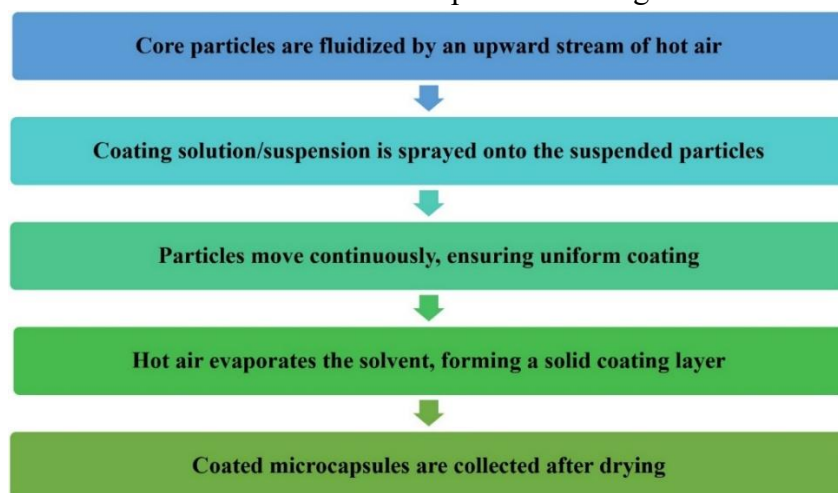


Fig 12 : Working Principle of Fluidized Bed Coating

9.1.5. Spray Cooling/Chilling :

A physical microencapsulation approach called spray cooling/chilling involves atomizing a molten

mixture of the active ingredient and carrier material into a cooled chamber. The droplets quickly solidify into microspheres or microcapsules as they cool below the carrier's

melting point. This method is appropriate for encasing heat-sensitive and lipophilic chemicals because it does not require solvent evaporation like spray drying does. A straightforward, economical, and high-throughput method, spray cooling/chilling frequently uses lipid-based

carriers like fats, waxes, and other biodegradable substances.^[51]

Example - Vitamin D₃ encapsulated in lipid-based microspheres by spray cooling to improve stability and controlled release.^[52]

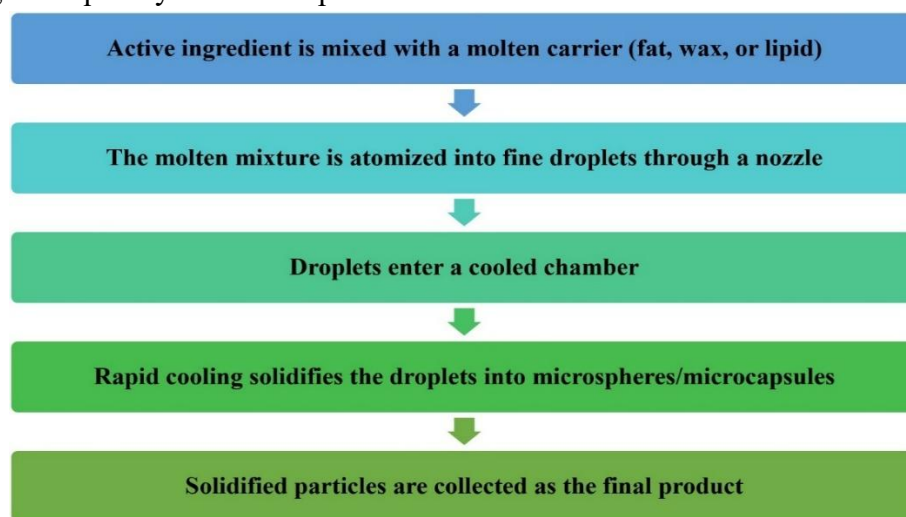


Fig 13 : Working Principle of Spray Cooling/Chilling

9.2. Chemical Methods of Microencapsulation :

Chemical polymerization or cross-linking events are used in chemical microencapsulation techniques to create a polymeric shell surrounding the core material. With exact control over capsule size, wall thickness, and drug release, these methods yield robust, stable, and homogeneous microcapsules. Chemical techniques are frequently utilized to create microcapsules with enhanced stability, protection, and controlled-release characteristics in pharmaceutical, biomedical, and industrial applications.^[53]

9.2.1. Interfacial Polymerization:

In the chemical microencapsulation process known as interfacial polymerization, two reactive monomers that have been dissolved independently in the aqueous and oil phases react quickly at the oil–water interface to create a thin polymeric shell

surrounding the core material. Because the polymerization is limited to the interface, core-shell microcapsules with superior mechanical strength, controlled-release characteristics, and high encapsulation efficiency are produced. This method is frequently used for the encapsulation of medications, insecticides, cosmetics, scents, and phase-change chemicals because of its quick reaction, large loading capacity, and simplicity of processing.^[54]

Fast interfacial polymerization (FIP) produces self-stabilized microcapsules without the need for extra surfactants by facilitating the quick creation of stable polymer shells at the oil–water interface.^[55]

By controlling the shell thickness and compactness of microcapsules during interfacial polymerization, the shuttle effect enhances controlled release and lowers environmental losses of the encapsulated active ingredient.^[56]

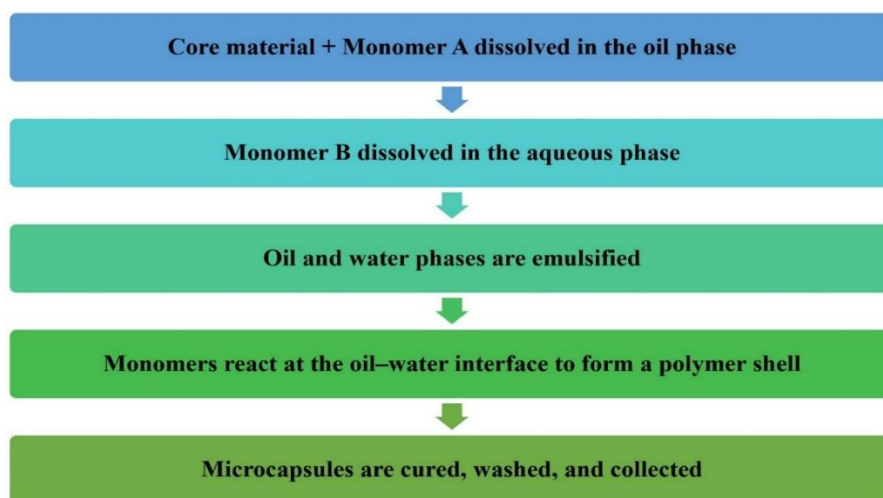


Fig 14 : Working Principle of Interfacial Polymerization

9.2.2. In Situ Polymerization

Shell-forming monomers polymerize directly in the continuous phase during in situ polymerization, a chemical microencapsulation process, and deposit around scattered core droplets to create a homogenous polymeric shell. Phase change materials (PCMs), medicines, self-healing agents, and functional bioactive chemicals can all be encapsulated using this technology because of its high encapsulation efficiency, strong mechanical strength, regulated particle size, and exceptional temperature stability.^[57]

By using in situ polymerization, paraffin was effectively encapsulated with a melamine-urea-

formaldehyde (MUF) shell, resulting in a 77.1% encapsulation efficiency and superior thermal energy storage capabilities.^[57]

In situ polymerization was used to encapsulate epoxy resin in poly(urea-formaldehyde) (PUF) microcapsules, resulting in self-healing coatings with enhanced corrosion protection and excellent encapsulation efficiency.^[58]

In situ polymerization was used to create butyl stearate-containing photochromic polyurea microcapsules with reversible light-to-heat conversion, high thermal energy storage, and outstanding thermal stability.^[59]

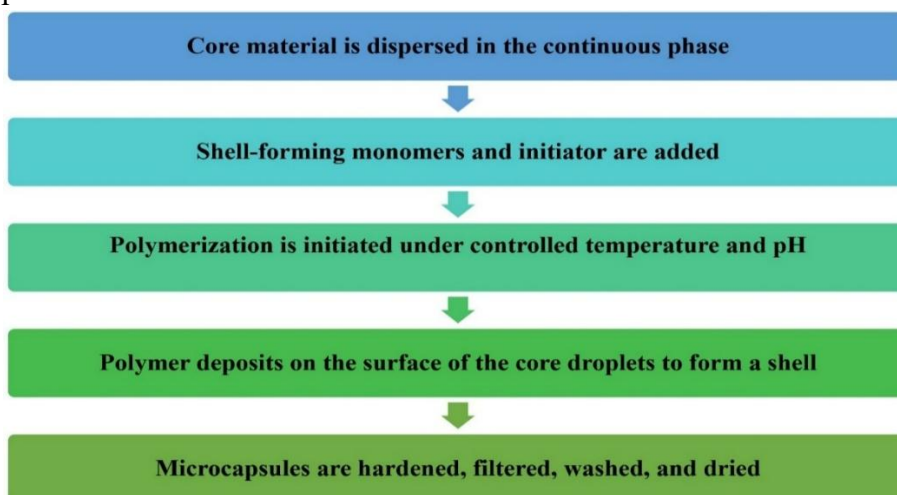


Fig 15 : Working Principle of In Situ Polymerization

9.3. Physicochemical Methods of Microencapsulation

Sensitive bioactive chemicals are coated or trapped inside a polymer matrix or shell via physicochemical encapsulation techniques, which rely on chemical and physical interactions such as electrostatic attraction, phase separation, solubility alterations, ionic cross-linking, and interfacial tension manipulation. [60]

The microencapsulation of phenolic compounds and carotenoids can benefit from the ionic gelation approach since it is solvent-free and only requires moderate temperatures, which increases the process's feasibility and reduces its cost. [61]
Ionic gelation (IG) is a potential method for microencapsulating oils and oleoresins that include ASX. [62]

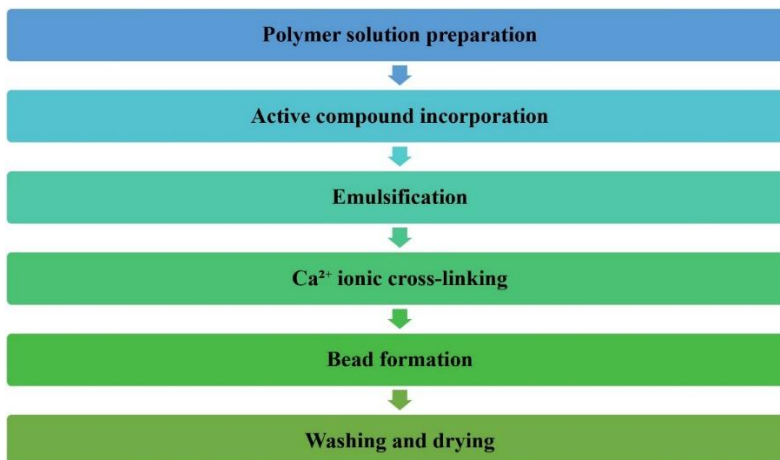


Fig 16 :Working Principle of Ionic Gelation

9.3.2. Coacervation [Phase separation]

One of the earliest and most used encapsulating methods is coacervation. Comparable to a modified emulsification process, it is a reasonably easy procedure. The hydrocolloid is separated from the primary solution and then agglomerates

into a distinct liquid phase known as "coacervate" as part of this process mechanism. The "continuous phase" refers to the coacervates, whereas the "equilibrium solution" refers to the second phase. [63]

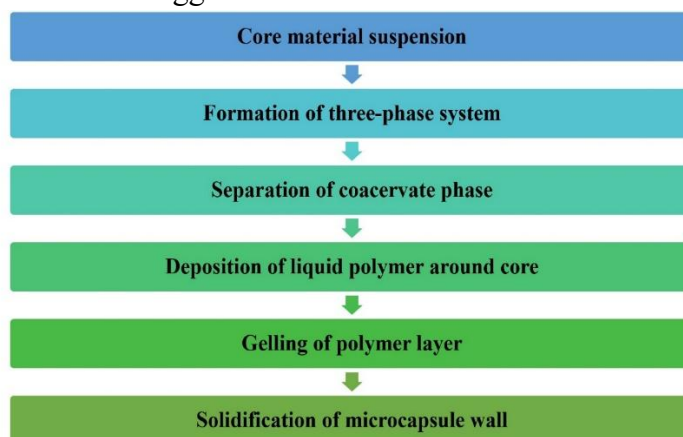


Fig 17 : Working Principle of Coacervation [Phase separation]

10.THERAPEUTIC APPLICATIONS OF MICROENCAPSULATION

API delivery routes play a crucial role in determining their efficacy. Microencapsulation has been widely used for oral API delivery, and microencapsulated APIs are formulated as oral dosage forms, such as tablets, syrups, or capsules, that offer several advantages over conventional formulations. For example, microencapsulation protects APIs from degradation in the gastrointestinal tract, leading to improved bioavailability and enhanced variability of living organisms.

Microencapsulation has been used for topical API administration. By adding microencapsulated APIs to creams, gels, or sprays, their effectiveness and skin delivery can be improved. Additionally, microencapsulation can increase the stability of APIs in topical formulations, resulting in improved patient compliance and a longer shelf life. Microencapsulated APIs can pass through the skin thanks to transdermal API delivery. Applying transdermal patches enables APIs to enter the systemic circulation by penetrating the epidermis, the skin's outermost layer. By applying transdermal patches to the skin, APIs are able to enter the systemic circulation through the epidermis, the skin's outermost layer. Convenience and prolonged release are two benefits of transdermal delivery for APIs with a limited therapeutic window, such as hormone replacement and pain relief. Injectable API delivery involves

administering APIs directly into the body through various routes, such as intravenous, intramuscular, and subcutaneous injection. This allows for quick absorption and distribution by bypassing obstacles like the gastrointestinal tract. While intramuscular and subcutaneous injections offer prolonged release and localized effects, intravenous injections enable instantaneous API administration into the bloodstream. Implantable API delivery systems are used for long-term therapy, where sustained release or pulsatile release is required, such as pain management, contraception, and treatment of chronic diseases. These devices can be reservoir-based or matrix-based, releasing APIs through diffusion, osmotic pressure, or other forces^[16]

10.1. Microencapsulation of Small APIs

Small APIs include substances with low molecular weight, such as aspirin, ibuprofen, and cannabidiol. Most of them that are consumed orally taste harsh. One of the main issues, especially with pediatric APIs for kids, is masking the bitter taste. Their effectiveness and compliance are significantly reduced when they are bitter. One popular API used to treat hypokalemia orally is potassium chloride (ICI). However, the taste is unbearable.

Compared to the commercial KC syrup, it exhibits two times better taste-masking after being microencapsulated with Eudragit E100 by fluid bed coating.^[16]



Table 3 : Microencapsulation of Small APIs^[16]

API	Polymer	Encapsulation technology	Pharmaceutical application
Morphine, Amikacin, Cytrabine	Tricaprylin, phosphatidylcholine, cholesterol, and triolein	Liposome	Epidural analgesia, neoplastic meningitis, and antibacterial
CBD, THC	Alginate, cyclodextrin, and chitosan.	Hydrogelation	Anxiolytic, antipsychotic, anticonvulsant, analgesic, anti-inflammatory, and antioxidant
Nicotine	Protein, gelatin, polyphosphate, and polysaccharide	Spray drying , coacervation	treating or avoiding nicotine addiction.
Nimodepin, felodipine, and o-vanillin	Poly-(ethylene glycol)PEG 4000	Supercritical fluid expansion	The dissolution rate of APIs improve .
5-FluorouracilTr etinoin	Dimethicone , crosspolymer , Methyl methacrylate glycol dimethacrylate	Microsponge	Multiple acne keratoses, acne vulgaris
Vitamins	Proteins , polysaccharides and lipids	Spray drying , molecular encapsulation and coacervation	Beri-beri , rickets, anemia , scurvy ,nightblindness ,osteoporosis and excessive bleeding

2. Microencapsulation of medium size APIs

Active pharmaceutical ingredients (APIs) in pharmaceutical delivery systems are generally divided into three categories based on their molecular size and structural complexity: medium APIs (intermediate molecular weight biologics),

small APIs (low molecular weight synthetic drugs like aspirin or ibuprofen), and living organisms (probiotics, bacteria, and viruses). Particularly, medium-sized APIs include biomolecules like peptides, proteins (including insulin, albumin, and toxoids), nucleic acids (like mRNA), and antibodies.^[16]

Table 4 : Microencapsulation of medium size APIs^[16]

API	major wall materials	encapsulation technology	pharmaceutical applications
Insulin	Chitosan, alginate, triolein, trilinolein, paraffin, methacrylic acid copolymer, cyanoacrylate monomer, isopropyl myristate, ethyl cyanoacrylate, PEG-8 glycole octanoate, decanoate, chitosan, triacetin, cetyl palmitate, and poly alkyl cyanoacrylate	liposome, polymerization, emulsion, and lipid nanoparticles	diabetes; insulin administered orally, injected, and inhaled



Enzymes, antibodies, and amino acids	polyamide microcapsules	polymerization	Target delivery system and nanocarrier for anticancer APIs
albumin	Polylactic-co-glycolic acid and polycaprolactone	Extraction and solvent evaporation	API delivery system
toxoid	polylactic-co-glycolic acid and polylactic acid	extrusion, emulsion, liposome, solvent evaporation, spray drying, and coacervation	multifunctional peptides, proteins, and vaccines
recombinant hepatitis B surface antigen	Cationic microcapsules comprising polylactic acid, polylactic-co-glycolic acid, and stearyl amine	spray drying, liposome, lipid nanoparticle, and emulsion	hepatitis B vaccine

3. Microencapsulation Of Micro-Organisms

A. Probiotics

Although live probiotics have important benefits such as gut microbiota control and pathogen defense, their oral delivery is hampered by significant viability loss during storage and transit through the gastrointestinal tract (GIT). To resolve this, microencapsulation using biopolymers, lipids, and layer-by-layer (LbL) coatings—such as

chitosan and alginate—protects bacteria from stomach acid, enhances muco-adhesion, and enables targeted release in the colon, often boosted by co-encapsulating prebiotics or polyphenols. Furthermore, microencapsulating recombinant probiotics via methods like centrifugal extrusion transforms them into robust oral vaccine platforms, protecting antigenic payloads through gastric and intestinal fluids to elicit strong systemic (IgG) and mucosal (IgA) immune responses^[16]

Table 5: Microencapsulation Of Probiotics^[16]

API	major wall materials	encapsulation technology	pharmaceutical applications
Lactobacillus acidophilus	Hydroxypropyl methylcellulose, chitosan, and sodium alginate	spray drying	protection, targeted release, and defense of mucoadhesive qualities
Lactobacillus plantarum	Gellan gum, xanthan, chitosan, and sodium alginate	spray drying and freeze-drying	stability, long-term preservation, protection, and targeted release
Lactobacillus reuteri	chitosan and alginate	spray drying	defense against heat stress and gastrointestinal disorders
Bifidobacterium bifidum	kepa carrageenan and sodium alginate	emulsification and emulsion	probiotic sustainability, protection, stability, and targeted release
Bifidobacterium breve	calcium lactate, chitosan, and sodium alginate	freeze-drying and emulsion	protection, probiotic fortification, and survival in GI conditions



B.Other living organisms

Live species like Bifidobacteria, Clostridia, and Salmonella are used in bacterial therapy as targeted drug delivery vectors. These species can colonize hypoxic tumor regions, boost antitumor immunity, and treat diseases like cancer, obesity, and gastrointestinal disorders. Intestinal bile salts and severe stomach acidity significantly lower

bacterial survivability and therapeutic efficiency in vivo, despite oral delivery being the most practical and compliant method.

Microencapsulation methods enclose therapeutic bacteria (such as *E. coli*, *Bacteroides*, and magnetotactic strains) into protective matrices to maintain their activity and facilitate efficient targeted distribution in order to get over these physiological obstacles^[16]

Table 5: Microencapsulation Of Other living organisms^[16]

API	major wall materials	encapsulation technology	pharmaceutical applications
pancreatic cell clusters and placental tissue	Alginate-poly-L-lysine alginate, barium alginate, sodium alginate, and agarose	extrusion	type 1 diabetes mellitus
human umbilical cord blood cells hepatocytes	sodium alginate	extrusion	hepatic disease
Cardiac stem cells	alginate-poly-L-lysine alginate and sodium alginate	hydrogelation	cardiovascular disease
<i>Salmonella typhimurium</i>	L- α -phosphatidylcholine,	liposomal encapsulation	tumor therapy
<i>Magnetococcus marinus</i>	lipopolysaccharides and phospholipids	liposomal encapsulation	tumor therapy
bacteriophages	Sodium alginate, cholesterol, and phospholipids	extrusion and liposomal encapsulation	Foodborne illnesses and management of gut pathogen colonization
neurotrophic factor-secreting cells	alginate-poly-L-lysine alginate and sodium alginate, collagen	extrusion	Parkinson's disease and neurodegenerative diseases
genetically engineered <i>E. coli</i> DH5	alginate-poly-L-lysine alginate and polyvinyl alcohol	extrusion	uremia therapy

11.INDUSTRIAL AND COMMERCIAL APPLICATIONS

1.Food industry

Over the past 20 years, the idea of functional meals has drawn more attention due to customer desire for goods that offer both extra health advantages

and nutritional value. Bioactive substances including polyphenols, carotenoids, omega-3 fatty acids, essential oils, dietary fibers, or bioactive peptides are frequently added to functional foods. Numerous health-promoting qualities, such as antioxidant, anti-inflammatory, antibacterial, and cardioprotective activities, are linked to these substances. Therefore, incorporating them into



regular diets is thought to be a promising way to avoid chronic diseases linked to diet and to enhance general health. Incorporating bioactive compounds like polyunsaturated fatty acids and polyphenols into foods poses significant technological and sensory challenges due to their chemical instability (sensitivity to light, heat, oxygen, and pH), low solubility, poor bioavailability, and off-tastes like bitterness or astringency. To overcome these hurdles, microencapsulation techniques protect sensitive compounds, mask unpleasant flavors, improve stability, and enable targeted controlled release in the digestive system. While traditional methods like spray-drying and freeze-drying are widely used, innovative approaches—such as nanotechnology-based carriers, liposomes, electrohydrodynamic processes, and biopolymer matrices—offer enhanced functionality and scalability for food industry applications.^[64]

Beverages

The fortification of beverages with sensitive compounds such as polyphenols, carotenoids, and omega-3 fatty acids is highly challenging due to solubility and stability issues. Encapsulation technologies (e.g., nanoemulsions and cyclodextrin complexes) have enabled the incorporation of bioactives into fruit juices, functional waters, and dairy-based drinks while maintaining clarity, stability, and desirable sensory attributes. For example, nanoencapsulated β -carotene has been successfully applied in fruit juices, providing both enhanced stability and improved bioavailability.^[64]

Dairy items

Encapsulated bioactives are commonly found in yogurts, cheeses, and milk beverages due to their high fat content and favorable pH. During storage and gastrointestinal transit, probiotics enclosed in

whey or alginate protein matrices show increased survival rates. Similarly, fish oil encapsulated via complicated coacervation or spray-drying has been added to milk powders and yogurts to provide omega-3 fatty acids and lessen oxidative off-flavors.^[65]

Bakery Goods

Bioactive integration is severely hampered by the high processing temperatures used in baking. The antioxidant qualities of bread, biscuits, and muffins have been enhanced by the encapsulation of polyphenols, carotenoids, or essential oils in protective carriers, which have improved their thermal stability during baking procedures. Additionally, microcapsules can function as moisture regulators, improving the texture and shelf life of products.^[66]

While bread is a popular food, most commercial kinds are produced from refined flour, which lacks essential elements such as vitamins, minerals, and antioxidants, and are baked in ways that destroy sensitive bioactive ingredients. Researchers have looked into fortifying bread with fibers, fruit/vegetable extracts, and direct bioactive compounds to satisfy growing consumer demand for healthier options. However, these additions frequently result in off-flavors, decreased volume, increased firmness, and shortened shelf life. By enclosing bioactives like probiotics, vitamins, polyphenols, and omega-3s in protective matrices, encapsulation technology helps get around these problems by protecting delicate components from heat damage and hiding offensive flavors. Manufacturers must balance health benefits with dough rheology, final sensory qualities, shelf-life, and digestive bioaccessibility in order to commercially commercialize functional bread employing encapsulated chemicals.^[67]



Products Made from Meat

Essential oils (e.g., oregano, rosemary, thyme) and plant extracts encapsulated in biopolymer or lipid matrices are being utilized in meat and poultry to improve shelf life by lowering lipid oxidation and microbiological development. Antimicrobials and antioxidants that are encapsulated provide regulated release, guaranteeing progressive protection during distribution and storage. Bioactive peptides generated from meat proteins have recently drawn interest due to their antibacterial, antihypertensive, and antioxidant qualities, in addition to bioactives derived from plants. To increase product stability and nutritional value, these peptides can be added to meat compositions or utilized as natural preservatives. Additionally, encasing bioactive peptides in appropriate delivery systems can assist their progressive release during processing and storage, improve their bioavailability, and shield them against deterioration.^[68]

Plant-Based Foods

Encapsulated bioactives have a lot of potential in the expanding plant-based food industry. To improve the nutritional and functional qualities of plant-based drinks and dairy substitutes, polyphenols and phytosterols are added. Encapsulation stabilizes lipophilic bioactives in low-fat matrices and helps conceal bitterness from plant-derived substances.^[69]

2. Textile Industry

Biopolymer-based microencapsulation technology—utilizing natural, biodegradable polymers like chitosan, gelatin, alginate, and cellulose—offers a sustainable alternative to conventional formaldehyde-based synthetic coatings for developing multifunctional textiles. By enclosing active compounds like essential oils, dyes, antimicrobials, and phase-change materials

in protective micrometric membranes, this technique imparts durable functional properties (e.g., UV protection, aroma finishes, and thermoregulation) without altering the fabric's natural breathability or softness. Various application methods—including padding, spraying, printing, and UV or microwave curing—ensure effective binding and controlled active release. However, scaling this technology requires addressing key environmental concerns and technical challenges, such as post-laundry chemical leaching into ecosystems, poor wash durability, the need for safe binding agents, and the ecological impacts of biopolymer degradation.^[70]

Silk fibre

Although silk fiber is valued as a comfortable, skin-friendly natural protein, its susceptibility to photo-aging, yellowing, and wrinkling limits its application. Applying microencapsulation technology—using wall materials such as gelatin, starch derivatives, biopolymers, or regenerated silk fibroin to enclose active core substances like fragrances, phase change materials, dyes, and antimicrobials—overcomes the poor durability of direct functional treatments. Microcapsules can be applied to silk via finishing, printing, or electrospinning processes and are secured through intermolecular forces (electrostatic or hydrogen bonding) or chemical bonds (ionic or covalent) using crosslinking adhesives to withstand washing and friction. Despite current challenges regarding high material costs, size control, and single-functionality, microencapsulated silk offers promising high-value applications across smart textiles, cosmetic skin care, and medical drug-delivery devices.^[71]

3. Cosmetic Products

In cosmetics, polymer shells such as alginate are used for microencapsulation to protect active



ingredients and improve efficacy. With a size range of 1 to 1000 μm , microparticles (MPs) exert an action locally in contact with the skin barrier without deep penetration. Moreover, natural biopolymer shells naturally hydrate and protect the skin barrier. In the skincare and cosmetics, actives are microencapsulated to protect them from UV light, temperature or moisture while hiding scent. It greatly enhances formula stability and bioavailability by preventing degradation as well as avoiding interactions with preservatives. Today, a wide range of active ingredients are encapsulated for cosmetic application — vitamin C and E, astaxanthin, turmeric essential oil or lemon essential oil or citronella as examples. Specifically, one key prominent application of microencapsulation is for the delivery of live probiotics coordinate with topical treatment such as *Lactobacillus* strains in order to repair skin dysbiosis conditions caused acne. Whereas nanocapsules are too small to fit the relatively large bacterial cells, microcapsules and especially hybrid structures. These cosmetic microparticles are mostly made using methods including spray drying, emulsification, and extrusion. The most popular technique is extrusion since it is easy to use, economical, and doesn't require high temperatures or hazardous organic solvents, which makes it ideal for maintaining the viability of delicate components like probiotics. Because emulsification is so good at encasing hydrophobic substances like vitamins and essential oils, it is also widely utilized.^[72]

3. Application In Detergents

Green, environmentally friendly microcapsules that use a solvent evaporation technique to encapsulate the nonionic surfactant Span 20 as the core material inside a hydrophobic ethyl cellulose (EC) shell. In order to release the surfactant and lower the oil-water interfacial tension, the resultant spherical microcapsules exhibit an oil-

phase targeting capacity, remaining stable in aqueous conditions while rupturing quickly upon meeting oil surfaces. According to experimental findings, it is possible to modify particle size and mechanical properties (stiffness and elasticity) by varying important parameters including stirring speed, core-to-shell ratio, and polymer molecular weight. The microcapsules' strong resilience to salt and cold, as well as their ability to effectively separate and disperse oil droplets at low surfactant doses, underscore their promising potential in uses like detergents and enhanced oil recovery (EOR).^[73]

4. Application In Agrochemicals

To reduce environmental pollution and crop phytotoxicity, controlled-release polyurea microcapsules carrying the herbicide oxyfluorfen were created thru interfacial polymerization in the presence of a green solvent (N,N-dimethyldecanamide). The microcapsules, which were synthesized with toluene diisocyanate (TDI) and different polyamines, had the maximum encapsulation effectiveness of 98.2% when ethylenediamine (EDA) was used. The chosen amine and core-to-shell ratio had a significant impact on both release kinetics and encapsulation efficiency; increasing the core-to-shell ratio decreased encapsulation efficiency and accelerated release, whereas EDA and lower core-to-shell ratios produced thicker capsule walls that provided a sustained, slow-release profile. Morphological and thermal evaluations verified the creation of stable spherical microcapsules, averaging 20-50 μm in diameter and great thermal stability. Importantly, field experiments on paddy crops demonstrated that while standard commercial emulsifiable concentrates caused severe phytotoxicity and crop destruction, the microencapsulated oxyfluorfen allowed for quick crop recovery and improved growth, proving it to



be a safer, eco-friendly alternative for agricultural applications.^[74]

5.Application In Electric Circuits

To facilitate the autonomous restoration of conductive silver lines in flexible electronic circuits, poly(urea-formaldehyde) (PUF) microcapsules encapsulating an oleyl amine-dispersed carbon nanoparticle core in toluene demonstrated size-dependent healing mechanisms governed by mechanical fracture geometry. Under tensile stretching strain, which causes distributed micro-fissures typical of repeated flexural deformation, the smaller variants showed superior

restoration efficiency due to their higher numerical spatial distribution, increased probability of crack intersection, and local matrix plasticization effects. In contrast, during mechanical scratching tests that produced wide discrete gaps, the bigger microcapsules performed substantially better, recovering up to 96% of the initial electrical current by discharging a larger volume of core dispersion to physically bridge the broad channel.^[75]

12.RECENT ADVANCES IN MICROENCAPSULATION

1.Smart Polymers ^[76]

Polymer type	Primary stimuli Mechanism	Key Properties	Representative Examples	Major applications
Shape memory polymers	variations in temperature, humidity, or pressure.	Reverts to its original shape after deformation when attaining a transition temperature/pressure.	Polyurethane, polycaprolactone, polyvinyl alcohol, polyethylene	Lightweight automobiles, aircraft parts, and medical stents /catheters
Conductive Polymers	Electrical current through conductive additives (such as metals or carbon)	Excellent electrical conductivity, transparency, and stability in doped forms.	Polyaniline, pyrrole, thiophene, and polyacetylene	Displays, sensors, actuators, batteries, and power storage
Self-Healing Polymers	Repair processes are triggered when there is damage or fissures.	Up to 95% healing efficiency; self-repair thru microencapsulation, covalent bonding, or supramolecular interactions	Microencapsulated systems and dynamic covalent network polymers.	Self-healing concrete, long-lasting structural coatings, and aircraft panels.
Thermally Responsive Polymers	Temperature alterations	Modifies hydrophobicity, elastic modulus, or glass transition temperature at particular limits.	Poly(N-isopropylacrylamide) , Poly(ethylene glycol) (PEG) / Polycaprolactone (PCL), κ -Carrageenan or Pluronic F127,Ethyl Cellulose / Chitosan / Alginate	Cell culture, tissue engineering, and targeted drug delivery.



pH responsive polymers	Environmental pH variations	Ionization or protonation/deprotonation results in hydrophilic-to-hydrophobic transitions.	Methacrylic Acid Copolymers, Poly(acrylic acid) (PAA), Poly(2-vinylpyridine) (PVP), Chitosan / Alginate Polyelectrolytes	Regulated drug delivery, bioseparation, and water-oil separation
Light responsive Polymers	Exposure to Light	Adjusts refractive index (by 0.01-0.1), optical absorption, shape, swelling, or conductivity.	Spiropyrans, azobenzene polymers, Liquid Crystal Polymers (LCPs), and PDLCs.	optical data storage, optical switching, biomedical devices, optoelectronics.

2.AI And ML in Microencapsulation

Gaussian Process Regression (GPR) models are used to successfully forecast the dynamic viscosity of thermal energy storage solutions including microencapsulated phase change materials (MPCMs) and MXene particles. By categorizing twelve GPR hyperparameters into three distinct groups based on sensitivity and evaluating them using the Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and Marine Predators Algorithm (MPA), the researchers discovered that optimizing all twelve hyperparameters simultaneously via GA yielded the highest predictive accuracy with an R-value of 0.999224. The parametric analysis indicated that as MPCM concentration increases and temperature decreases, dynamic viscosity increases dramatically. Finally, these optimized computer models offer a cost-effective alternative to costly laboratory experiments in heat management and engineering applications.^[77]

3.MICROENCAPSULATION IN FUEL

In both the petroleum and fuel cell industries, microencapsulation serves as an effective mechanism for protecting reactive core materials and controlling their interaction with surrounding environments, though it introduces distinct operational trade-offs. Within the petroleum

sector, microencapsulated additives—such as delayed-release gel breakers for hydraulic fracturing, self-healing core agents for cement sheaths, and long-acting corrosion inhibitors—rely on controlled release via shell rupture, dissolution, or diffusion to maintain fluid performance and repair subterranean structural damage^[3]. Conversely, in proton exchange membrane fuel cells (PEMFCs), encapsulating platinum nanoparticles within thin carbon or silica layers protects the catalyst core against dissolution and carbon support corrosion. However, evidence demonstrates a critical trade-off between activity and durability: while robust graphitic shells significantly enhance catalyst lifespan, they restrict mass transport to the underlying active platinum sites, diminishing initial oxygen reduction reaction kinetics and altering reaction selectivity.^[78]

4.PERSONALIZED MEDICINE

3D printing technologies ("nanoprinting") improve personalized medicine by incorporating microencapsulation and nanovehicles—such as polymeric nanocapsules, liposomes, SNEDDS, and microreservoirs—into solid dosage forms, targeted scaffolds, and microneedles to achieve precise, patient-specific drug delivery and controlled release profiles. Furthermore, 3D



printing enables the continuous manufacturing of these micro/nano-encapsulated formulations by fabricating high-throughput microfluidic chips, tho wide clinical translation still faces challenges regarding particle aggregation, post-processing solvent/monomer removal, high equipment costs, and changing regulatory standards.^[79]

13.RECENT CLINICAL TRIALS

The current stage and advancement of clinical research assessing the safety, effectiveness, and therapeutic advantages of medications or bioactive chemicals administered by microencapsulation

technology is referred to as the clinical trial status of microencapsulation. Enclosing active chemicals in a protective layer to improve stability, regulate release, and boost BA is known as microencapsulation. In order to make sure they satisfy legal standards for human usage, clinical trials in this sector evaluate their uses in areas like targeted medication administration, sustained-release formulations, and protection of sensitive substances. The details of the numerous clinical trials carried out for microencapsulation nanocarriers, such as microspheres and microcapsules, are listed in the table below. ^[7]

Title of Study	Type of Study	Current Situation	Conditions	Interventions
Data Collection on Yttrium Y 90 Resin Microspheres in Incurable Liver Cancer: The RESIN Study (RESiN)	Observational	Completed	Localized Adult Liver Carcinoma That Is Incurable	Microspheres of Yttrium-90 Resin
Comparison of Uterine Artery Pain Gelatin Microsphere or Tris-acryl Gelatin Microsphere Embolization	Interventional		Uterine Myoma, Uterine Fibroid	Gelatin microsphere (NexsphereTM) Device: Embosphere
Pharmacokinetic-Pharmacodynamic Progesterone Microspheres (PK-PD) Examine	Interventional	Phase-I	Infertility	Progesterone
A Comparison of Tretinoin Gel Microsphere, 0.1% with RETIN-A MICRO® Gel Microsphere, 0.1% for Acne Vulgaris Treatment	Interventional	Early Phase I	Acne Vulgaris	0.1% Tretinoin Gel Microsphere
Crizotinib Encapsulated Microsphere Formulation Bioequivalency Study (eMS)	Interventional	Phase 1	Participants in Good Health	Crizotinib
Chemotherapy Patients' Injection of Docetaxel Lipid Microsphere (DT-LM)	Interventional	Phase 1	Advanced Cancer	Docetaxel and DT-LM
Assess the Taste and Comparative Bioavailability of Two Crizotinib Microsphere Formulations in Healthy Individuals	Interventional	Phase 1	Healthy Volunteers	Treatment A,B,C etc.

The study in the field of microencapsulation was concluded and all clinical trials were explained. Preclinical research, Phase I (safety), Phase II (efficacy), and subsequent phases for more

comprehensive assessments are frequently covered by these trials.



14. REGULATORY CONSIDERATION

GRAS Status and EFSA/FDA Perspectives ^[80]

One of the biggest obstacles to industrial adoption is still the regulatory assessment of encapsulated bioactive chemicals, especially when nanostructured or microstructured systems are involved. In the US, the Food and Drug Administration (FDA) uses the Generally Recognized as Safe (GRAS) framework to evaluate new delivery methods and food additives. For a drug to be classified as GRAS, it must be proven to be safe under the intended conditions of use, either by a history of widespread usage in food or by publicly available scientific data that has been examined by qualified experts. GRAS status has already been obtained for encapsulating matrices such as maltodextrins, gum Arabic, modified starches, or certain proteins. The status of GRAS has already been determined. However, a case-by-case analysis is necessary when encapsulation involves unique nanostructures (such as nanoliposomes, nanocrystals, or polymeric nanoparticles), concentrating on elements including particle size distribution, surface charge, solubility, digestibility, and possible accumulation in tissues.

The EFSA is responsible for overseeing innovative micro- and nanoencapsulation technologies in the EU. According to EFSA, nanomaterials are manufactured structures with one or more exterior dimensions in the 1–100 nm size range. Materials outside of this range may nevertheless be taken into consideration if they have nano-specific characteristics. Safety dossiers must contain the following, according to the EFSA Guidance on the Risk Assessment of Nanomaterials in the Food and Feed Chain (2021) Safety dossiers may include:

- a thorough physicochemical analysis of the substance that is enclosed and its carriers,
- verified techniques for solubility and size distribution,

- profiles of invitro degradation and digestion,
 - Research on absorption, distribution, metabolism, and excretion (ADME) in toxicology.
- The EFSA examination, in contrast to the GRAS idea, is centrally controlled and necessitates a complete pre-market authorization for each novel encapsulating substance that isn't already on the Union list of authorized food additives. Crucially, safety demonstration is rigorous and data-intensive, particularly for persistent or non-biodegradable carriers; yet, nanoencapsulation is not automatically barred from approval.

Labeling and Consumer Communication

To preserve consumer confidence and promote adoption of foods containing encapsulated bioactive chemicals, clarity in labeling and communication is crucial. Regulation (EU) No 1169/2011 on food information to consumers in the EU mandates that engineered nanomaterials used as ingredients be clearly indicated in the ingredient list, using the word "nano" in brackets after the chemical name (e.g., silicon dioxide [nano]). This guarantees that customers are aware of the existence of nanoscale structures, but if it is not appropriately contextualized, it may also cause worries. Labeling of encapsulated compounds is less regulated in the United States. The Federal Food, Drug, and Cosmetic Act requires businesses to give accurate and non-misleading information, although the FDA does not need a specific "nano" classification. To improve consumer comprehension, voluntary communication techniques including concise explanations of functional advantages (such as enhanced stability, lower dosage, or regulated release) are advised. Consumer perceptions of nanotechnology in food are consistently mixed. While acceptance is higher for obvious health benefits (such as increased nutrient bioavailability or decreased use of artificial preservatives), skepticism emerges when the technology is thought to be artificial, covert, or



poorly regulated. Consequently, industry-consumer communication have to concentrate :

By highlighting regulatory clearances and safety evaluations,

- emphasizing observable advantages for consumers (nutrient stability, flavor preservation, less chemicals),
- ensure clear language that communicates the functional role of encapsulation while avoiding excessively technical jargon.

Therefore, ethical labeling and proactive communication are essential for both compliance and building public trust in the use of cutting-edge encapsulation technologies.

15.FUTURE PROSPECTIVE :

The prospectus for novel nanocarriers in the future:^[7,81]

The potential of microencapsulation to transform DDs. Creating more effective, targeted, and controlled-release formulations is made possible by the combination of nanocarriers with microencapsulation . Future developments might concentrate on

- **Enhanced Precision Medicine:** Development of personalized therapeutic approaches using nanocarriers tailored for specific diseases or patient needs. Nanocarriers and microencapsulation technologies are paving the way for personalized medicine, allowing therapies to be tailored to individual patients based on their genetic profiles, disease conditions, and specific needs. By enabling targeted drug delivery, these systems reduce off target effects and improve therapeutic outcomes, making treatments more effective and safer for patients.
- **Enhanced Drug Stability:** Creating encapsulation techniques to shield medications from deterioration, extending

their shelf life and improving their therapeutic effectiveness. By protecting bioactive molecules from environmental elements including light, oxygen, and moisture, microencapsulation improves their stability. This protective layer increases overall therapy success 100 by maintaining drug potency, extending shelf life, and guaranteeing that the therapeutic chemicals stay active until they reach their target site.

- **Growing Applications:** Used to address unmet clinical requirements in a variety of domains, such as neurology, oncology, and vaccine administration. Because of its adaptability, nanocarrier microencapsulation can be used in many different domains, including neurology for blood-brain barrier crossing, oncology for targeted cancer therapy, and vaccine administration for controlled antigen release. Unmet clinical demands are being addressed by these technologies, especially in difficult treatment domains where traditional methods frequently fall short.
- **Emerging Technologies:** Using AI and 3D printing to quickly prototype new enclosed systems and optimize formulation design. The design and prototyping of encapsulated medication systems are being revolutionized by the combination of 3D printing and artificial intelligence (AI). While 3D printing makes it possible to quickly and precisely fabricate complex nanocarrier systems, AI algorithms optimize formulation parameters, promoting innovation and shortening development timelines.
- These developments may result in medical advances that offer safer and more efficient therapies for a range of illnesses 102. The numerous difficulties include a number of technical, legal, and clinical trials, which are covered as follows:



- **Manufacturing and Scalability:** Making the switch from laboratory-scale to large-scale Production of nanocarriers. It is difficult and resource-intensive to produce nanocarriers and microencapsulated systems while preserving uniformity and quality.
- **Stability Problems:** It is very difficult to guaranty the long-term stability of encapsulated medications, especially for delicate bioactive compounds. Advanced encapsulation techniques and stabilizers 103 are required since variables such chemical degradation, aggregation, or leakage of the encapsulated material can affect the formulation efficacy and shelf life.
- **Regulatory Barriers:** Clinical approval is hampered by the strict regulatory frameworks governing nanotechnology-based systems. Due to the lack of precise, widely recognized regulatory criteria, these technologies frequently delay commercialization and necessitate lengthy safety, effectiveness, and biocompatibility assessments.
- **Complexity in Patenting:** Overlapping discoveries make patent claims unclear in the very competitive intellectual property market for nanocarrier technology. This frequently results in disagreements, filing delays, or difficulties obtaining exclusive rights, all of which can impede the development and use of novel formulations.
- **Clinical Translation:** It takes a lot of time and money to show that nanocarrier systems are safe and effective in human clinical trials. The translation of these technologies into practical applications may be further delayed by high failure rates brought on by unanticipated toxicity, a lack of notable therapeutic advancements, or insufficient scalability.

16. CURRENT CHALLENGES AND LIMITATIONS OF MICROENCAPSULATION TECHNIQUES – [82,83]

1. Premature Core Leaching & Imperfect Barrier Properties-

Most polymeric shell materials are innately porous, resulting to passive diffusion and leaching of active substances during storage (shelf-life deterioration).In pharmaceuticals, leaching causes improper dosage or premature drug release.

2. Environmental Sustainability and Regulatory Compliance-

Because of their great mechanical strength and chemical stability, microcapsules have traditionally relied on synthetic, non-biodegradable polymers such acrylic resins, polyurethanes, and melamine-formaldehyde.Industries are forced to phase out non-biodegradable polymeric shells due to restrictions on purposefully added microplastics (such those imposed by the European Union).

3. Standardized Testing for Biodegradability-

The final microcapsule assembly, which is frequently cross-linked with formaldehyde, glutaraldehyde does not always biodegrade under actual environmental circumstances (soil, marine, or wastewater systems) only by utilizing a biodegradable starting polymer (e.g., chitosan or polylactic acid).It is still difficult and costly to conduct standardized, widely recognized testing procedures that confirm complete environmental breakdown of intact core-shell microcapsules.

4. Energy Use in Manufacturing and Process Scalability-

High-Energy Emulsification: The formation of fine emulsions using high-shear homogenizers, microfluidics, or ultrasonic cavitation—processes with extraordinarily high energy requirements—is typically necessary to produce uniform microcapsules.



Thermal deterioration: Heat-sensitive active ingredients (such as proteins, probiotics, and volatile essential oils) are subjected to severe thermal stress during processes like spray-drying or melt-extrusion, which causes deterioration.

• **Limitations-** [4,84]

1. Expensive manufacturing procedures: When applied on a bigger scale, certain microencapsulation techniques might be costly.
2. Release Control Issues: Maintaining exact control over the rate of release of encapsulated materials can be challenging and may affect performance.
3. Reduced shelf life for hygroscopic substances: Hygroscopic materials contained

inside the microparticles may have a reduced shelf life due to potential moisture absorption.

4. Materials Incompatibility Issues: Some chemicals may not be suitable for encapsulation due to process limitations or incompatibility with covering materials.
5. Uneven coating: Inconsistent microencapsulation coating may affect the release of encapsulated materials, leading to performance variability.
6. Stability Problems: Microcapsules may break down or become unstable in unfavorable conditions like high temperatures or humidity.

17. MARKETED ENCAPSULATED PRODUCTS

Brand Name	Type of microencapsulation	Polymer/coating	Therapeutic Application
Lantus® (Insulin Glargine) [85]	Biodegradable microsphere encapsulation	Biodegradable polymer (PLGA microspheres)	Sustained insulin release for diabetes
Depo-Provera® (Medroxyprogesterone acetate) [86]	Injectable microspheres	PLGA (poly-lactic-co-glycolic acid)	Long-acting contraception
Lupron Depot® (Leuprolide acetate) [87]	Controlled-release microspheres	PLGA microspheres	Treatment for prostate cancer and endometriosis
Sandimmune Neoral® (Cyclosporine) [88]	Lipid microencapsulation	Lipid-based microcapsules	Immunosuppression for organ transplant patients
Ritalin LA® (Methylphenidate) [89]	Coated multiparticulate microcapsules	Ethylcellulose coating	Extended-release treatment for ADHD

CONCLUSION

Microencapsulation has shown to be an essential platform for industrial therapies and contemporary pharmaceutical medication delivery. It effectively solves traditional formulation challenges such as poor stability, undesired volatility, undesirable organoleptic qualities, and quick degradation by

encasing sensitive solid, liquid, or gaseous actives within customized polymeric, lipid, or hybrid shells. The technology enables flexible release mechanisms—ranging from passive diffusion and dissolution to smart, stimuli-responsive triggers like pH and temperature—facilitating precise, sustained, and tailored release profiles across oral, topical, and injectable delivery routes. The



synergistic choice of core and shell materials and appropriate fabrication techniques, including as spray drying, solvent evaporation, interfacial polymerization, and coacervation, are critical to the success of microencapsulation. To ensure particle integrity, high encapsulation efficiency, and batch consistency, rigorous physicochemical analysis (such as SEM, FTIR, DSC, and XRD) is still necessary.

Key obstacles still exist despite notable clinical and commercial success, including core leaching, high manufacturing costs, scaling difficulties, and complicated regulatory environments pertaining to nanomaterials and environmental microplastics. It will be crucial to overcome these obstacles with cutting-edge technologies like smart biopolymer engineering, 3D printing, and formulation design aided by artificial intelligence.

REFERENCES

1. Chaturvedi P, Sharma P. A review on microencapsulation as method of drug delivery. In BIO web of conferences 2024 Feb 19 (Vol. 86, p. 01033). EDP Sciences.
2. Choudhury N, Meghwal M, Das K. Microencapsulation: An overview on concepts, methods, properties and applications in foods. *Food Frontiers*. 2021 Dec;2(4):426-42.
3. Sonali M, Jadhav B, Gaware V. MICROENCAPSULATION -A NOVEL APPROACH IN DRUG DELIVERY SYSTEM. 2024 [cited 2026 Aug 12];9:814. Available from: <https://www.ijnrd.org/papers/IJNRD2411179.pdf>
4. Tejas M, Sansare, Babasaheb J. A Review: Microencapsulation. © 2025 JAAFR | [Internet]. 2025 [cited 2026 Aug 12];3:487. Available from: <https://rjwave.org/jaafr/papers/JAAFR2512292.pdf>
5. Agnihotri N, Mishra R, Goda C, Arora M. Microencapsulation-A Novel Approach in Drug Delivery: A Review. *Indo Global Journal of Pharmaceutical Sciences*. 2012 Mar 1;2(1):1.
6. Yadav R, Gogate S, Morya R, Saxena SK. *Journal of Scientific Research in Allied Sciences*.
7. Tressa A, Singh A, Pal R, Kumar N. Novel Nanocarriers Microencapsulation: Current, Patents and Clinical Trials Comprehensive Review. *Journal of Drug Delivery & Therapeutics*. 2025 Apr 1;15(4):188.
8. Mankar SD, Shaikh SB. Microencapsulation: is an advance technique of drug formulation for novel drug delivery system. *Research Journal of Science and Technology*. 2020;12(3):201-10.
9. Singh MN, Hemant KS, Ram M, Shivakumar HG. Microencapsulation: A promising technique for controlled drug delivery. *Research in pharmaceutical sciences*. 2010 Jul;5(2):65.
10. Jeyakumari A, Zynudheen AA, Parvathy U. Microencapsulation of bioactive food ingredients and controlled release-a review.
11. Jia H, Zhang J, Li Y, Qu B, Zhao F, Zhao Q, Jiang Y. Probiotic biofilms: A novel encapsulation system for bioactive modalities. *Journal of Controlled Release*. 2026 Jan 21:114651.
12. Pasarkar NP, Yadav M, Mahanwar PA. A review on the micro-encapsulation of phase change materials: classification, study of synthesis technique and their applications. *Journal of Polymer Research*. 2023 Jan;30(1):13.
13. Xu Y, Yan X, Zheng H, Li J, Wu X, Xu J, Zhen Z, Du C. The application of encapsulation technology in the food Industry: Classifications, recent Advances, and



- perspectives. *Food chemistry: X*. 2024 Mar 30;21:101240.
14. Yeşilyurt MK, Nadaroglu H, Çomaklı Ö. Materials and selection thereof for encapsulated phase change materials for heat transfer applications. *International Journal of Innovative Research and Reviews*. 2019 Dec 15;3(2):16-22.
15. Sparks RE, Jacobs IC. Selection of coating and microencapsulation processes. In *Controlled-release delivery systems for pesticides* 2023 Jan 13 (pp. 3-29). Routledge.
16. Yan C, Kim SR. Microencapsulation for pharmaceutical applications: a review. *ACS applied bio materials*. 2024 Feb 6;7(2):692-710.
17. Zhao H, Fei X, Liang C, Xian Z, Cao L, Yang T. The evaluation and selection of core materials for microencapsulation: A case study with fragrances. *Flavour and Fragrance Journal*. 2021 Nov;36(6):652-61.
18. Drapińska P, Skulmowska-Polok K, Chałupka J, Sikora A. Sustained-release oral delivery of NSAIDs and acetaminophen: advances and recent formulation strategies—a systematic review. *Pharmaceutics*. 2025 Sep 26;17(10):1264.
19. Said FA, Bousserhine N, Alphonse V, Michely L, Belbekhouche S. Antibiotic loading and development of antibacterial capsules by using porous CaCO₃ microparticles as starting material. *International Journal of Pharmaceutics*. 2020 Apr 15;579:119175.
20. Ma G. Microencapsulation of protein drugs for drug delivery: strategy, preparation, and applications. *Journal of Controlled Release*. 2014 Nov 10;193:324-40.
21. Kiprono S, Wambani J, Rono J, Langat V, Shi Z, Raballah E, Yang G. Microencapsulation of probiotics and their applications: a review of the literature. *ES Food and Agroforestry*. 2024 Mar 5;17(2):1106.
22. Sousa VI, Parente JF, Marques JF, Forte MA, Tavares CJ. Microencapsulation of essential oils: A review. *Polymers*. 2022 Apr 23;14(9):1730.
23. Saadi S, Nacer NE, Chenaker H, Ariffin AA, Ghazali HM, Saari N, Mohammed AS, Anwar F, Hamid AA. A review on trends in microencapsulation of bioactive compounds: coating materials, design, and applications. *European Food Research and Technology*. 2023 Dec;249(12):3123-39.
24. Muñoz-More HD, Nole-Jaramillo JM, Valdiviezo-Marcelo J, Espinoza-Delgado MD, Socola-Juarez ZM, Ruiz-Flores LA, Espinoza-Espinoza LA. Microencapsulated iron in food, techniques, coating material, efficiency, and sensory analysis: a review. *Frontiers in Sustainable Food Systems*. 2023 Jul 19;7:1146873.
25. Akpo E, Colin C, Perrin A, Cambedouzou J, Cornu D. Encapsulation of active substances in natural polymer coatings. *Materials*. 2024 Jun 6;17(11):2774.
26. Parente JF, Sousa VI, Marques JF, Forte MA, Tavares CJ. Biodegradable polymers for microencapsulation systems. *Advances in polymer technology*. 2022;2022(1):4640379.
27. Rocha GA, Fávaro-Trindade CS, Grosso CR. Microencapsulation of lycopene by spray drying: Characterization, stability and application of microcapsules. *Food and bioproducts processing*. 2012 Jan 1;90(1):37-42.
28. Gray A, Egan S, Bakalis S, Zhang Z. Determination of microcapsule physicochemical, structural, and mechanical properties. *Particuology*. 2016 Feb 1;24:32-43.
29. Tian Y, Liu Y, Zhang L, Hua Q, Liu L, Wang B, Tang J. Preparation and characterization of



- gelatin-sodium alginate/paraffin phase change microcapsules. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 2020 Feb 5;586:124216.
30. Xue K, Li H, Pan L, Li C, Zhang X, Zou JJ. Preparation and performance characterization of functionalized boron-based energetic-microcapsules with uniform size. *Chemical Engineering Journal*. 2023 Aug 1;469:143917.
31. Hartini N, Ponrasu T, Wu JJ, Sriariyanun M, Cheng YS. Microencapsulation of curcumin in crosslinked jelly fig pectin using vacuum spray drying technique for effective drug delivery. *Polymers*. 2021 Aug 4;13(16):2583.
32. Attaei M, Calado LM, Taryba MG, Morozov Y, Shakoor RA, Kahraman R, Marques AC, Montemor MF. Autonomous self-healing in epoxy coatings provided by high efficiency isophorone diisocyanate (IPDI) microcapsules for protection of carbon steel. *Progress in organic coatings*. 2020 Feb 1;139:105445.
33. Niu S, Kang M, Liu Y, Lin W, Liang C, Zhao Y, Cheng J. The preparation and characterization of phase change material microcapsules with multifunctional carbon nanotubes for controlling temperature. *Energy*. 2023 Apr 1;268:126652.
34. Niu S, Cheng J, Zhao Y, Kang M, Liu Y. Preparation and characterization of multifunctional phase change material microcapsules with modified carbon nanotubes for improving the thermal comfort level of buildings. *Construction and Building Materials*. 2022 Sep 12;347:128628.
35. Klonos PA, Chronaki K, Vouyiouka S, Kyritsis A. Effects of high crystallinity on the molecular mobility in poly (lactic acid)-based microcapsules. *ACS Applied Polymer Materials*. 2024 Jan 10;6(2):1573-83.
36. Ledari SA, Milani JM, Shahidi SA, Golkar A. Comparative analysis of freeze drying and spray drying methods for encapsulation of chlorophyll with maltodextrin and whey protein isolate. *Food Chemistry: X*. 2024 Mar 30;21:101156.
37. da Cunha AB, Leal DA, Santos LR, Riegel-Vidotti IC, Marino CE. pH-sensitive microcapsules based on biopolymers for active corrosion protection of carbon steel at different pH. *Surface and Coatings Technology*. 2020 Nov 25;402:126338.
38. Zhang W, Qi X, Yang X, Dong Y, Fan B, Liang L. Fabrication of high-stability Ni-PSF@ PAO40 microcapsules and their lubricating properties in polyamide 6. *Friction*. 2022 Dec;10(12):1985-99.
39. Devi LM, Das AB, Badwaik LS. Effect of gelatin and acacia gum on anthocyanin coacervated microcapsules using double emulsion and its characterization. *International Journal of Biological Macromolecules*. 2023 Apr 30;235:123896.
40. Zhu J, He J, Zhou J, Yang Z, Li X, Li Y, You Z. Recent progress in microencapsulation technology and its applications in petroleum industry. *Journal of Molecular Liquids*. 2024 Aug 1;407:125162.
41. Venkatachalam CD, Damodaran S, Natarajan A, Shahulhameed MA, Ravichandran SR, Sengottian M. Microencapsulation techniques: A comprehensive review. *Food and Feed Research*. 2026 Jan 1;53(1):107-31.
42. Hassan ME, Tamer TM, Valachová K, Šoltés L. Microencapsulation process: methods, properties, and applications. *Polymer Bulletin*. 2025 Nov;82(17):11593-624.
43. Ahangaran F. Microencapsulation: solvent evaporation. In *Principles of Biomaterials Encapsulation: Volume One* 2023 Jan 1 (pp. 377-392). Woodhead Publishing.



44. Mady O. Application of solvent evaporation technique for pure drug crystal spheres preparation. *Particuology*. 2022 Aug 1;67:79-89.
45. Sedighi M. Encapsulation: Pan-coating. In *Principles of Biomaterials Encapsulation: Volume One* 2023 Jan 1 (pp. 235-252). Woodhead Publishing.
46. Pudžiuvėlytė L, Petrauskaitė E, Stabrauskienė J, Bernatoniene J. Spray-drying microencapsulation of natural bioactives: Advances in sustainable wall materials. *Pharmaceuticals*. 2025 Jun 26;18(7):963.
47. Nguyen TT, Le TV, Dang NN, Nguyen DC, Nguyen PT, Tran TT, Nguyen QV, Bach LG, Thuy Nguyen Pham D. Microencapsulation of essential oils by spray-drying and influencing factors. *Journal of Food Quality*. 2021;2021(1):5525879.
48. Lucas J, Ralaivao M, Estevinho BN, Rocha F. A new approach for the microencapsulation of curcumin by a spray drying method, in order to value food products. *Powder Technology*. 2020 Feb 15;362:428-35.
49. Frey C. Fluid bed coating-based microencapsulation. In *Microencapsulation in the food industry* 2023 Jan 1 (pp. 83-115). Academic Press.
50. Dehghani F, Farhadian N. Encapsulation: Fluidized bed coating technology. In *Principles of Biomaterials Encapsulation: Volume One* 2023 Jan 1 (pp. 143-156). Woodhead Publishing.
51. Abdul-Al M, Saeinasab M, Sefat F. Encapsulation techniques overview. In *Principles of biomaterials encapsulation: Volume one* 2023 Jan 1 (pp. 13-36). Woodhead Publishing.
52. Karami A, Babaloo H, Farhadian N. Encapsulation: Spray chilling and cooling. In *Principles of biomaterials encapsulation: Volume one* 2023 Jan 1 (pp. 109-130). Woodhead Publishing.
53. Khandbahale SV. Microencapsulation-A novel approach in drug delivery: a review. *Asian J. Res. Pharm. Sci.* 2020 Mar 7;10(1):39-50.
54. Ricardo F, Pradilla D, Luiz R, Alvarez Solano OA. A multi-scale approach to microencapsulation by interfacial polymerization. *Polymers*. 2021 Feb 22;13(4):644.
55. Lian X, Liao S, Xu XQ, Zhang S, Wang Y. Self-stabilizing encapsulation through fast interfacial polymerization of ethyl α -cyanoacrylate: from emulsions to microcapsule dispersions. *Macromolecules*. 2021 Nov 14;54(22):10279-88.
56. Zhang T, Sun H, Yang L, Zhang P, Zhang Y, Bai J, Liu F, Zhang DX. Interfacial polymerization depth mediated by the shuttle effect regulating the application performance of pesticide-loaded microcapsules. *ACS nano*. 2023 Oct 6;17(20):20654-65.
57. Han S, Chen Y, Lyu S, Chen Z, Wang S, Fu F. Effects of processing conditions on the properties of paraffin/melamine-urea-formaldehyde microcapsules prepared by in situ polymerization. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 2020 Jan 20;585:124046.
58. Zotiadis C, Patrikalos I, Loukaidou V, Korres DM, Karantonis A, Vouyiouka S. Self-healing coatings based on poly (urea-formaldehyde) microcapsules: In situ polymerization, capsule properties and application. *Progress in Organic Coatings*. 2021 Dec 1;161:106475.
59. Sun S, Gao Y, Han N, Zhang X, Li W. Reversible photochromic energy storage polyurea microcapsules via in-situ polymerization. *Energy*. 2021 Mar 15;219:119630.



60. Huang K, Yuan Y, Baojun X. A critical review on the microencapsulation of bioactive compounds and their application. *Food reviews international*. 2023 Jul 4;39(5):2594-634.
61. Santos AP, Andreola K, Alvim ID, de Moura SC, Hubinger MD. Microencapsulation of Pitanga extract (*Eugenia uniflora* L.) by ionic gelation: Effect of wall material and fluidized bed drying. *Food Research International*. 2025 May 1;209:116304.
62. Vakarelova M, Zanon F, Donà G, Fierri I, Chignola R, Gorrieri S, Zoccatelli G. Microencapsulation of astaxanthin by ionic gelation: effect of different gelling polymers on the carotenoid load, stability and bioaccessibility. *International Journal of Food Science and Technology*. 2023 May;58(5):2489-97.
63. Napiórkowska A, Kurek M. Coacervation as a novel method of microencapsulation of essential oils—A review. *Molecules*. 2022 Aug 12;27(16):5142.
64. Shen, Z.; Augustin, M.A.; Sanguansri, L.; Cheng, L.J. Oxidative Stability of Microencapsulated Fish Oil Powders Stabilized by Blends of Chitosan, Modified Starch, and Glucose. *J. Agric. Food Chem*. 2010, 58, 4487–4493.
65. Jeyakumari A, Kothari DC, Venkateshwarlu G. Microencapsulation of fish oil-milk based emulsion by spray drying: Impact on Oxidative Stability. *Fishery Technology*. 2014;51(1):31-7.
66. Bińkowska W, Szpicer A, Stelmasiak A, Wojtasik-Kalinowska I, Półtorak A. Utilization of microencapsulated polyphenols to enhance the bioactive compound content in whole grain bread: recipe optimization. *Applied Sciences*. 2024 Nov 6;14(22):10156.
67. Tolve R, Bianchi F, Lomuscio E, Sportiello L, Simonato B. Current Advantages in the Application of Microencapsulation in Functional Bread Development. *Foods*. 2022 Dec 24;12(1):96.
68. López-Pedrouso M, Zaky AA, Lorenzo JM, Camina M, Franco D. A review on bioactive peptides derived from meat and by-products: Extraction methods, biological activities, applications and limitations. *Meat Science*. 2023 Oct 1;204:109278.
69. Wen C, Tang J, Cao L, Fan M, Lin X, Liu G, Liang L, Liu X, Zhang J, Li Y, Xu X. Strategic approaches for co-encapsulation of bioactive compounds: technological advances and mechanistic insight. *Foods*. 2025 Jun 7;14(12):2024.
70. Peng X, Umer M, Pervez MN, Hasan KF, Habib MA, Islam MS, Lin L, Xiong X, Naddeo V, Cai Y. Biopolymers-based microencapsulation technology for sustainable textiles development: A short review. *Case Studies in Chemical and Environmental Engineering*. 2023 Jun 1;7:100349.
71. Xiao Z, Liu H, Zhao Q, Niu Y, Chen Z, Zhao D. Application of microencapsulation technology in silk fibers. *Journal of Applied Polymer Science*. 2022 Jul 5;139(25):e52351.
72. Alves TF, Morsink M, Batain F, Chaud MV, Almeida T, Fernandes DA, da Silva CF, Souto EB, Severino P. Applications of natural, semi-synthetic, and synthetic polymers in cosmetic formulations. *Cosmetics*. 2020 Sep 25;7(4):75.
73. Yu H, Xue C, Qin Y, Wen Y, Zhang L, Li Y. Preparation and performance of green targeted microcapsules encapsulating surfactants. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*. 2021 Aug 20;623:126733.
74. Rao J, Chandrani AN, Powar A, Chandra S. Design and application of polyurea microcapsules containing herbicide



- (oxyfluorfen). Designed Monomers and Polymers. 2020 Jan 1;23(1):155-63.
75. Hsieh TL, Li CC, Lin PC, Hsu YC. Encapsulating well-dispersed carbon nanoparticles for applications in the autonomous restoration of electronic circuits. *ACS applied materials & interfaces*. 2020 Aug 5;12(34):38690-9.
 76. Sahayaraj AF, Dhamotharan S, Sandeep D, Ramachandran P, Jenish I, Divakaran D, Suyambulingam I, Sanjay MR, Siengchin S. Sustainable smart polymer composite materials: a comprehensive review. *InE3S Web of Conferences 2023 Sep (Vol. 428, p. 02014)*. EDP Sciences.
 77. Hai T, Basem A, Alizadeh AA, Sharma K, Jasim DJ, Rajab H, Ahmed M, Kassim M, Singh NS, Maleki H. Optimizing Gaussian process regression (GPR) hyperparameters with three metaheuristic algorithms for viscosity prediction of suspensions containing microencapsulated PCMs. *Scientific Reports*. 2024 Aug 31;14(1):20271.
 78. Ji SG, Kwon HC, Kim TH, Sim U, Choi CH. Does the encapsulation strategy of Pt nanoparticles with carbon layers really ensure both highly active and durable electrocatalysis in fuel cells?. *ACS Catalysis*. 2022 Jun 3;12(12):7317-25.
 79. Serrano DR, Kara A, Yuste I, Luciano FC, Ongoren B, Anaya BJ, Molina G, Diez L, Ramirez BI, Ramirez IO, Sánchez-Guiraes SA. 3D printing technologies in personalized medicine, nanomedicines, and biopharmaceuticals. *Pharmaceutics*. 2023 Jan 17;15(2):313.
 80. Arkadiusz Szpicer, Weronika Bińkowska, Stelmasiak A, Iwona Wojtasik-Kalinowska, Czajkowska A, Sylwia Mierzejewska, et al. Innovative Microencapsulation Techniques of Bioactive Compounds: Impact on Physicochemical and Sensory Properties of Food Products and Industrial Applications. *Applied Sciences*. 2025 Nov 9;15(22):11908–8.
 81. Pal R, Pandey P, Khadam VK, Chawra HS, Singh RP. *INTERNATIONAL JOURNAL OF PHARMA PROFESSIONAL'S*.
 82. Lobel BT, Baiocco D, Al-Sharabi M, Routh AF, Zhang Z, Cayre OJ. Current challenges in microcapsule designs and microencapsulation processes: a review. *ACS applied materials & interfaces*. 2024 Jul 23;16(31):40326.
 83. Lalarukh, Hussain SM, Ali S, Yilmaz E, Zahoor AF, Javid A, Alshehri MA, Shahzad MM, Naeem A, Mahrukh. Microencapsulation: An innovative technology in modern science. *Polymers for Advanced Technologies*. 2025 Jan;36(1):e70066.
 84. Hassan ME, Tamer TM, Valachová K, Šoltés L. Microencapsulation process: methods, properties, and applications. *Polymer Bulletin*. 2025 Nov;82(17):11593-624.
 85. Dunn CJ, Plosker GL, Keating GM, McKeage K, Scott LJ. Insulin Glargine. *Drugs*. 2003;63(16):1743–78
 86. Westhoff C. Depot-medroxyprogesterone acetate injection (Depo-Provera®): a highly effective contraceptive option with proven long-term safety. *Contraception*. 2003 Aug;68(2):75–87.
 87. Dlugi AM, Miller JD, Knittle J. Lupron depot (leuprolide acetate for depot suspension) in the treatment of endometriosis: a randomized, placebo-controlled, double-blind study. *Fertility and Sterility*. 1990 Sept;54(3):419–27.
 88. Beauchesne PR, Chung NSC, Wasan KM. Cyclosporine A: A Review of Current Oral and Intravenous Delivery Systems. *Drug Development and Industrial Pharmacy*. 2007 Jan;33(3):211–20.



89. Biederman J, Quinn D, Weiss M, Markabi S, Weidenman M, Edson K, et al. Efficacy and Safety of Ritalin?? LA???, a New, Once Daily, Extended-Release Dosage Form of Methylphenidate, in Children with Attention Deficit Hyperactivity Disorder. *Pediatric Drugs*. 2003;5(12):833–41.

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