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Nanomaterials to Encapsulate Bacteria for Biological Applications

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Authors' contributions

This work was carried out in collaboration among all authors. Author RK collected literature and prepared the first draft of the manuscript. Author KA assisted preparation of the whole manuscript. Author KV conceived the study, planned and prompted the manuscript. All authors read and approved the final manuscript.

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Review Article

ABSTRACT

Nanotechnology has developed as a ground-breaking field with enormous potential for a wide range of applications, including biotechnology, medicine, and environmental cleanup. One intriguing use is encasing bacteria in nanomaterials to improve and control their biological functions. In order to modify the biological functions of bacteria, various forms of nanomaterials are employed to encapsulate them. Through the goal of utilizing bacteria-encased nanoparticles for targeted drug delivery, bioremediation, and biotherapeutic interventions, researchers have been investigating various nanomaterials in recent years. Due to their changeable surface characteristics, metallic nanoparticles, such gold and silver nanoparticles, enable precise control over bacterial contact. Additionally, encapsulated bacteria benefit from the protective habitats provided by polymeric nanomaterials like liposomes, micelles, and hydrogels, which improves their survival and activity.

The use planned and the desired interaction with the bacteria that are enclosed influence the choice of nanomaterial. The viability and activity of encapsulated bacteria can be affected by a variety of

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encapsulation methods, including physical adsorption, covalent bonding, and layer-by-layer construction. Researchers may design novel systems that harness bacteria's biological activity for a variety of purposes by using the features of nanomaterials and improving encapsulation methods. To turn these encapsulation technologies into useful and secure applications, there are still issues to be solved, including as long-term stability, biocompatibility, and regulatory concerns. In conclusion, the integration of bacteria with nanomaterials opens up new avenues for manipulating their biological functions. As nanotechnology continues to evolve, the synergy between nanomaterials and encapsulated bacteria holds great promise for revolutionizing fields such as medicine, biotechnology, and environmental science.

Keywords: Nanomaterials; encapsulation of bacteria; nanomedicine; nano-bioremediations.

1. INTRODUCTION

The word "Nanotechnology - terminology and definitions for the “nano-objects", i.e. Nanoparticle, nanofiber and nanoplate" [40] depends on a particular structure at the nanoscale, which is often defined as 100 nanometers (100 millionths of a millimeter or 100 billionths of a meter) or less. It encompasses materials with incredibly microscopic structures as well as gadgets or systems created by manipulating individual atoms or molecules [1,3]. One of the most intriguing examples of nanotechnology in the ancient world was presented by the Romans in the fourth century AD, who employed nanoparticles and structures. One of the most remarkable accomplishments in the ancient glass industry is the Lycurgus cup, which is part of the British Museum collection [1,39]. Encapsulation is the process of encapsulating a bioactive molecule in its liquid, solid, or gaseous state within an inert matrix or substance, often a polymer [38], A prospective point of convergence between nanotechnology and microbiology is bacteria-encapsulated nanomaterials. Potential applications for this developing sector may be found in a number of industries, including healthcare, agriculture, and industrial operations as well as environmental cleanup. The goal of this review paper is to give a general overview of the processes that lead to bacterial encapsulation inside nanomaterials and their possible uses [40,1,3].

2. NANOMATERIAL IN FOOD SECTOR

With new techniques that promise to boost food production sustainably, nanotechnology has advanced the food sector in the modern era. It also believed that it was about to begin to drive the economy. The use of nanotechnology in agriculture has the potential to lower input costs, improve soil quality by absorbing nutrients, control plant diseases, and identify disease outbreaks. Food packaging, additives, and food preservation are just a few of the consumer items that have been affected by food nanotechnology. The acceptance of this cutting-edge technology has improved food processing and storage practices that ensure food safety. Numerous traditional compounds used as packaging or food additives have also been shown to partially exist at the nanoscale scale. As an illustration, food-grade TiO_2 NPs have recently been discovered up to around 40% in the nanoscale range [1,2].

In order to develop new characteristics in materials, nanotechnology often involves manipulating materials, processes, and research related to chemical compositions, physical states, and molecular interaction. The majority of businesses, including those in the food sector that deal with food processing, packaging, and storage, have seen significant improvements in productivity because to nanomaterials [5]. In order to produce superior crops, long-lasting plants, flowers, fruits, and seeds, nature has generally employed a wide variety of nanotechnology in plant growth, flowering, fruit production, preserving nutrients, and safety of plants. The fundamental uses of nanotechnologies are in the encapsulation of food products to increase their flavor and nutritional content. Nanotechnology has also studied structural and composite modification to create various nanomaterials with distinct features [3,4].

Nanoparticles are used in many foods to improve flavor, stability, and color during processing and lengthen shelf life. For instance, anticaking agents like aluminosilicate compounds are frequently used in processed foods that are powdered or granulated. Anatase titanium dioxide, on the other hand, is a common food brightener and whitener component found in desserts, sauces, and cheeses. One of the most crucial elements of the food system, flavors provide sensory awareness of taste and scent to enhance the entire eating experience. The release and preservation of flavors, as well as the creation of a balanced flavor profile, have all been improved with the use of nanoencapsulation technology.

The shelf life of products can be extended using nanotechnology techniques by keeping them in packaging materials that release antimicrobials or restrict moisture and air interaction with. Food packaging has to have precise physical, chemical, and biological qualities in addition to protection and tamper resistance.The majority of nanoparticles used in food packaging have antimicrobial properties, serve as carriers for antimicrobial polypeptides, and prevent microbial degradation. There have been several different metal and metal oxide nanoparticles suggested as antimicrobials. Their innate physicochemical characteristics encourage the production of reactive oxygen species, which causes oxidative stress and subsequently damages bacterial cells.

3. SAFETY IN FOOD NANOTECHNOLOGY

Nanotechnology has had a significant impact on several industries, which has led to a significant increase in the market for items incorporating nanoparticles. Fast reproduction is just one of the many benefits of nanotechnology in food science; other benefits include questions of ethics, regulation, and policy, as well as public and environmental safety [37].

Depending on the circumstances of the gastrointestinal tract (GIT) and their susceptibility to hydrolysis by digestive enzymes, nanocarriers' fate in the GIT varies. Evaporation is a procedure that should be used to get rid of these organic solvents, but it might leave behind unwelcome residual solvents that are harmful and cannot be taken out of the finished product. There has to be more risk analysis done on the safety concerns related to nanoparticles and the pertinent dangers. It is important to research the effects of nanoscale materials on the human body, both indirect and direct, as well as their fate in biology after digestion, potential interactions with biological systems, and GIT behavior. The usage of nanomaterials in the food industry is significant.

Research in this area has seen significant advancements in terms of regulatory a fairs, despite the current lack of risk management and particular rules for nanotechnology. The safe use of nanomaterials in the food sectors will be ensured by new, particular nanotechnology rules, which will be made possible by information openness.

Nano particles using in food sectors:

Major Usages in Food

- ✓ Food processing
- ✓ Food additive

Food processing: One of the most important measures in ensuring food safety is food packaging. Food packaging's main goals are to avoid spoiling and contamination, improve sensitivity by facilitating enzyme action, and minimize weight loss. Nanomaterials are highly suited for use as transporters, preservatives, or taste or color additions in food supplement products. Engineered nanoparticles' special qualities provide significant benefits for food processing as additives or supplements [42-46]. Functional nanomaterials with physicochemical enhancements, such as better mechanical strength, durability, flexibility, and moisture and temperature stability, can be used to create superior food packaging. Nanomaterials with active properties, such as those with antimicrobial, antioxidant, and UV protective properties, as well as nano sensors with smart or intelligent properties for the detection of gases and small organic molecules, active stage, and product identification, can both improve packaging. With the addition of bionanomaterials, bio-based improvements such as biodegradability, biocompatibility, low-waste, and eco-friendly packaging (Bio-based packaging) may also be made [6]. Bio-based packaging, such as biodegradable and biocompatible packaging, may be used in place of non-biodegradable plastic polymers, which are often used as the actual packaging [37].

ensuring the ethical and secure production of animal products worldwide. The U.S. FDA has officially classified copper oxide, iron oxide, and zinc oxide as nutritious dietary supplements that are "generally recognized as safe" (GRAS) [7].

To prevent food-borne illnesses, better food that is minimal in fat, sugar, and salt is produced using nanotechnology. According to a study, silicon dioxide ($SiO2$) and titanium dioxide ($TiO2$) were both permitted as food additives in bulk (E551 and E171, respectively). The bionanoencapsulated quercetin (biodegradable poly-D,L-lactide) has enhanced the shelf life of tomatoes, and this strategy should be used to extend the shelf life of other fruits and vegetables. nutritional supplements Neosino capsules, Canola active oil, and Aqua Nova (micelle to increase the solubility of vitamins (A,C, D, E, and K, and NutraLeaf (fortifying nanocarriers to carry nutraceuticals and medications) are some of the most popular marketed nanotechnology-based goods on the market. Similarly, there are a few commercially available nano-processed foods on the market that are extensively distributed in the USA, Australia, China, and Japan. These include fortified fruit juices, oat nutritional beverages, nano teas, nano capsules containing tuna fish oil in breads, and nanometals slim shakes. Commercial nanofood items are produced using nanotechnology [5,6,8].

Food additives: The encapsulation of various nutrients, including vitamins, antioxidants, and proteins, has the advantage of regulating how and where they are released into the body [17]. Better vitamin delivery has the potential to be extremely beneficial. A significant portion of vitamins consumed in non-encapsulated form do not reach the areas of our bodies that require them [47-52].

Depending on their size, shape, composition, aggregation state, and electrical charge, nanoparticles can have quite different properties. This indicates that case-by-case risk assessment is required. Nanoparticles are dangerous because of their tiny size, which makes them more reactive and enables them to cross biological barriers like cell membranes. In the serious scenario, if they are bio-accumulating, this might result in cellular malfunction [18,19].

4. NANOMATERIALS IN AGRICULTURAL FORMULATES

Agronomy, soil science, entomology, plant pathology, and other agricultural fields, forestry, a environmental issues like urbanization in cities, energy issues in society, and sustainable use of natural resources all have a great deal of potential to benefit from nanotechnology [13].

Nanomaterials, which are smaller than 100 nm in size and have a large specific surface area, are one of the most varied and well-liked families of materials. Engineered nanomaterials (ENMs) have a smaller size that allows them to thoroughly enter a variety of biological tissues, including plant tissues and the blood-brain barrier. Due to their capacity to be fine-tuned, which can significantly improve their physicochemical characteristics, nanomaterials have a vast array of commercial uses. In a number of industrial applications, including those in agriculture, cosmetics, aviation, pharmaceutics, and other fields, these unique features of nanomaterials have been utilized [15].

Best tools for agriculture today are nanotechnology, which is also predicted to soon become a major economic force. In order to implement agricultural production, nanotechnology uses a variety of chemical agents, and it has the ability to require less agrochemicals overall. It could provide more accurate answers to the present issues facing the agricultural industry [9,52].

Nanotechnology's potential use in agriculture Nano-5 and Nano-Gro as plant growth regulators; nanopesticides, nanoherbicide encapsulated in nanoparticles for controlled release; nano emulsions for great control of pests, e.g. Allosperse delivery system, Nano revolution-2, adjuvant, and surfactant will improve the efficiency of agricultural input use [13].

The distribution of nutrients, insecticides, agrochemicals and herbicides, smart packaging, nanosensors, veterinary care, fisheries and aquaculture, and nutrient deficiency diagnosis are only a few direct uses of nanotechnology in the agriculture industry. Nowadays, nano-fertilizers are employed as an alternative to fertilizers used in large quantities and to lessen soil and water contamination caused by various agrochemicals. In order to reduce nutrient loss and improve nutrient usage efficiency, nanofertilizers aid in the delayed and steady release of micro and macronutrients. In addition to increasing nutrient utilization efficiency and lowering environmental protection expenses, slow-release fertilizers are a great alternative to soluble fertilizers [9,10].

About 40% to 60% of the world's total food production depends on the use of fertilizers, which are essential for plant nutrition and crop quality. The use of the fewest particles feasible by nanotechnology gives hope for enhancing agricultural productivity while tackling issues that cannot be handled traditionally [10]. By enabling the optimal management and resource conservation inputs for plant and animal production, nanotechnology applications have a significant potential to change agricultural production [9].

4.1 Agricultural Nanomaterial Synthesis

The preferred qualities of the resulting nanomaterials, such as their size and other physicochemical traits, are often taken into consideration while choosing the process of ENMs production. As a result, top-down techniques and bottom-up approaches to nanomaterial synthesis may be broadly categorized based on the kind of applications. These approaches are often distinguished by the phase of the starting materials. While the reactants in top-down procedures are frequently solids, liquid or gaseous reactants are typically utilized in bottom-up methods [10,12,41].

4.2 Nanomaterials in Soil Relationship

The soil contains a number of naturally occurring nanomaterials, including clay, organic matter, and a number of metal and metal oxide nanoparticles. Several million tons of different metal and metal oxide nanoparticles, including Ag, Au, SiO2, ZnO, TiO2, and CNT (carbon nanotube) fullerenes, are produced annually across the world, according to various estimations. Intentionally or accidentally, these nanomaterials are discharged into a variety of habitats [10,11], during the preparation, use, while they are disposed of in the environment [27].

4.3 Nanomaterials in Plant Relationship

It is commonly known that ENMs are taken up by higher living things like plants and interact with many biomolecules. Due to well researched nano-phytotoxicity, the interaction of ENMs with plants inside the soil may have an impact on plant physiology and possibly food security [9]. The capacity of ENMs to migrate within the soil, from the soil to plants, and to various tissues within the plant, as well as their ability to do so, are key factors in determining how ENMs affect plant growth. To accurately estimate the real impact of ENMs on plant growth, it is essential to have a clear understanding of how ENMs travel within the soil and inside the plant [10,41].

The investigation revealed that ENMs crossed the stem and reached the roots of the plants after entering the leaf through the stomatal channel [10,8]. Nanomaterials can travel via extracellular gaps, xylem vessels, or plasmodesmata in plants, respectively, in an apoplectic or symplastic manner [10].

4.4 Nanomaterials for Detoxification

Applications like aviation and space, chemical industry, optics, solar hydrogen, fuel cell, batteries, sensors, power generation, aeronautic industry, building/construction industry, automotive engineering, consumer electronics, thermoelectric devices, pharmaceuticals, and cosmetic industry have all benefited from the seamless integration of nanomaterials enabled technologies [15]. The creation of new nanomaterials that can offer the shortest reaction routes for the improvement of reaction kinetics is frequently required for clean energy and environmental applications [17].

This special issue's main goal is to highlight the key nanomaterials research paradigms and their prospective effects on clean energy production, storage, and use as well as waste heat recovery, environmental detoxification, and process sustainability [17,27].

Table 1. Nanomaterials used for the study

Nanofertilizers	Nano zinc, nikil, silica, iron and titanium dioxide, different core shell gold nanorods, Quantum Dots (QDs).	Nano fertilizer should be endorsed for controlled release to improve quality.	[12]
Nanoherbicides	Silver, copper,carbon nanotubes, graphene, zinc oxide, titanium dioxide.	Nanoherbicides refer to herbicides that incorporate nanotechnology to enhance their efficacy in controlling or eliminating unwanted plants (weeds).	[12]
Nanopesticides	Nanoemulsions,nanocapsules (e.g., with polymers) and nanoclays.	These products can be used to enhance the use efficacy of existing pesticide active ingredients or to improve sustainability.	[12]

A platform for delivering cargos *In vivo* is provided by nanoparticles, giving them potential uses in detoxification [15].

Nanoparticles can also serve as a platform for targeted detoxification of action mechanisms. Pathologies' main virulence factors are pore-forming toxins (PFTs), which can harm the cellular membrane [17] Despite the fact that these nanoparticle-assisted detoxification techniques have proven to be effective in capturing target substances, there are a number of issues that restrict their use. As was already indicated, the adsorption of drug molecules to the outer surface of the particle happens during extraction using microemulsions and ligand-based nanoparticles. However, the presence of significant numbers of serum proteins, for which medicines have a high binding affinity, significantly lowers the extraction efficiency *In vivo* [15].

4.5 Characterization Techniques

In order to analyze and comprehend the characteristics, structure, composition, and behavior of materials at the nanoscale (usually spanning from 1 to 100 nanometers), a group of analytical techniques and instruments are utilized. These methods are essential for researching and working with nanomaterials, which are very small objects with special features [21,32,33].

Almost every branch of research and engineering is represented in the new and expanding subject of nano size science and technology. with quick developments in fields including molecular electronics, artificial biomolecular motors, DNA-based self-assembly, and scanning tunneling microscope-based atom manipulation [21,22]. These methods can be combined, or they can be used exclusively for the research of a certain attribute. We compare each of these methods, taking into account things like their accessibility, cost, accuracy, non-destructiveness, ease of use, and affinity for particular compositions or materials. Despite the large number of approaches offered here, each one is carefully examined. There are methods based on microscopy [23], Spectroscopic Analysis (UV-Visible Spectroscopy), Transmission Electron Microscopy (TEM), Dynamic Light Scattering (DLS), Zeta Potential, Inductively Coupled Plasma Mass Spectrometry (ICP-MS), Dark Field Microscopy, Aerodynamic Particle Sizer (APS), Scanning Mobility Particle Sizer (SMPS), Matrix-assisted Laser Desorption/Ionization Mass Spectrometry (MALDI-MS), X-ray-based techniques (XRID), X-ray Photoelectron Spectroscopy (XPS), Small-Angle X-ray Scattering (SAXS), Extended X-ray Absorption Fine Structure (EXAFS), Neutron Scattering, Magnetic Force Microscopy (MFM), Surface-Enhanced Raman Spectroscopy (SERS), Near-Field Scanning Optical Microscopy (NSOM), High-Resolution Atomic Force Microscopy (HR-AFM) [21,22,23, 24].

4.6 Nanomaterials Dimensions

Through the multidisciplinary study of nanotechnology, we are able to create new materials with novel, intriguing, and practical features. These novel materials are nanoparticle-derived nanomaterials [25]. Due to their adaptable physicochemical properties, such as melting point, wettability, electrical and thermal conductivity, catalytic activity, light absorption and scattering, which result in improved performance over their bulk counterparts, nanoparticles and nanomaterials have gained prominence in technological advancements. 50% or more of the particles in the number size distribution have one or more exterior dimensions that fall within the size range of 1-100 nm [25,26,29]. This may be achieved by regulating the form, size, and internal order of the nanostructures [29].

Nanomaterials are very tiny, with at least one dimension being 100 nm or less. The nanoscale can be one, two, or three dimensions for nanomaterials. They come in spherical, tubular, and irregular shapes and can be found alone, fused, aggregated, or agglomerated [28,33].

According to several dimensions, which pertain to the structural characteristics that Through the multidisciplinary study of nanotechnology, we are able to create new materials with novel, intriguing, and practical features. These novel materials are nanoparticle-derived nanomaterials [25]. Due to their adaptable physicochemical properties, such as melting point, wettability, electrical and thermal conductivity, catalytic activity, light absorption and scattering, which result in improved performance over their bulk counterparts, nanoparticles and nanomaterials have gained prominence in technological advancements. 50% or more of the particles in the number size distribution have one or more exterior dimensions that fall within the size range of 1-100 nm [25]. This may be achieved by regulating the form, size, and internal order of the nanostructures.

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5. APPLICATIONS IN VARIOUS AVENUES

Nano encapsulation in food sector: In order to meet increased consumer concerns and expectations for natural, nutrient-dense, and wholesome food products, nanotechnology is a developing subject in the food business. The most effective use of nanotechnology to increase stability, solubility, and bioavailability of natural compounds may be nanoencapsulation. When producing, processing, packing, and securing food, the nanostructure can be used. Highly unsaturated edible oils (like fish oils), vitamins, enzymes, and other flavors are all enclosed in food grade proteins and polysaccharides to extend their shelf life and/or cover up the unfavorable flavor or taste [8]. This study intends to identify various nanoencapsulation techniques (chemical, physicochemical, and physicomechanical), emphasize environmentally acceptable strategies, and group the nanoencapsulation systems (polymer, lipidic, and metallic) into these categories [1,34]. Microencapsulation (ME) is the process of encasing microscopic solid particles, liquid droplets, or gas atoms in a covering (1-1000 um). Essential oils (EOs) and plant extracts containing polyphenols with well-known antibacterial characteristics can be effectively entrapped using ME [2]. Nanoencapsulation technologies may be able to address issues facing the food sector, such as the effective delivery of health-promoting substances and the regulated release of taste components. Applications of nanotechnology in food for the targeted distribution of bioactives, such as coenzyme Q10, vitamins, carotenes, omega-3 fatty acids, and plant polyphenols [2]. The main benefit of encapsulation is that even in challenging environmental conditions, the hidden component may be reliably transported to the desired site. The liposome is one type of nano-based carrier used for nano encapsulation. Nano-liposomes are useful in achieving controlled and targeted dispersion of the system's numerous components [3,30]. They have been demonstrated to transport a wide range of bioactive molecules such as minerals, nutraceuticals, enzymes, antimicrobials, vitamins, and additives [34]. Electrospinning, a revolutionary encapsulation process, is being used to encapsulate gallic acid into zein fibers. The zein fiber keeps the lipids from degrading as they travel to the delivery location. This novel strategy may find broad application in the food packaging industry. Lipid-based encapsulation techniques are far better to other encapsulation systems due to the improved specificity and solubility of the components [3,4].

Advantages of encapsulation In food sector:

- ✓ The bioavailability of flavors and food components may improve with an increase in surface area. This is crucial for flavor compounds with poor solubility and/or low flavor and odor detection thresholds. An example of improving the solubility of poorly water soluble substances is the micelle-based solubilization of omega.
- ✓ Nanoemulsions and microemulsions with oil droplet sizes of less than 100 nm are optically transparent, which is significant in beverage applications.
- ✓ During spray drying, there is more component retention (a decrease in volatile organic carbon).
- ✓ molecular inclusion complexes based on amylose and cyclodextrins, for instance, are closer to a genuine molecular solution (homogeneity in system parameters, such as density).
- ✓ Higher degrees of active component encapsulation, such as antimicrobials in nanoemulsion or microemulsion forms.
- ✓ Keeping the active ingredients in a carrier material, encapsulation is a beneficial technique to enhance the transfer of bioactive molecules (antioxidants, minerals, vitamins, phytosterols, lutein, fatty acids, lycopene, etc.) and live cells (probiotics, etc.) to meals.
- ✓ The microencapsulation technology transforms liquid flavoring compounds into stable, freely flowing powders that are simple to utilize in powdered meals [9,30].

Table 2. Encapsulation method

Encapsulation Method	Purpose of Usage	References
Freeze drying	○ Antimicrobial food packaging. ○ Packaging stability.	[9]
Spray cooling	○ Packaging stability and flavor application in foods.	[9]
Electro spray	○ Food enrichment.	[9]
Coacervation	○ Food enrichment. ○ Foods enriched with EGCG products. ○ Food packaging films.	[9]

Table 3. Viability and survival and enhanced colonization of the rhizosphere and roots of plants

Microorganism	Carrier	Purpose	Plant	References
Pseudomonas putida	Sodium alginate + paraffin	Plan growth promotion	soybean and corn plants	[11]
Pseudomonas fluorescens	Sodium alginate and Sodium alginate + soybean oil	Polychlorinated biphenyl degradation bioremediation Biocontrol of Fusarium solani.	Potato and tomatto	[11]
Trichoderma viride	Sodium alginate And Alginate	Plant nutrition And Biocontrol of Rhizoctonia solani and plant growth promotion	Beans	[11]
Bacillus subtilis	Sodium alginate	Plant growth promotion	Lettuce	[11]
Bacillus megaterium	Chitosan + maltodextrin	Bioremediation of salinized soils	Mouse Ear Cress	[11]
Pseudomonas putida	Sodium alginate + paraffin	Plant growth promotion	Arabidopsis thaliana	[11]
Pseudomonas fluorescens + Pseudomonas putida	Eudragit + methacrylic copolymer	Biofertilizer	Tomatto plants	[11]
Bacillus subtilis + Pseudomonas corrugata	Sodium alginate	Plant growth promotion	Maize	[11]
Pseudomonas fluorescens + Burkholderia cepacia	Sodium alginate	Biofertilizer in salinized soil	Wheat	[11]
Pseudomonas putida + Bacillus subtilis	Sodium alginate	Plant growth promotion	Lettuce	[11]

Nano encapsulation in agriculture sector: Current agricultural practices employ toxic and harsh fertilizers and pesticides in excessive and unregulated amounts, which harms the environment and poses threats to the health of both humans and animals [11]. Microorganism encapsulation is gaining popularity as a way to increase the effectiveness of helpful microorganisms. In order to safeguard the viability and activity of the microbes, layers of various materials are coated on particles containing active bacteria [7]. Current agricultural practices employ toxic and harsh fertilizers and pesticides in excessive and unregulated amounts, which harms the environment and poses threats to the health of both humans and animals. A potential bioformulation that protects the actions of PGPMs linked to plant growth promotion is their immobilization inside biodegradable polymers or encapsulation. This results in maximal cell viability and survival and enhanced colonization of the rhizosphere and roots of plants [6,36]. In order to safeguard the viability and activity of the microbes, coatings of other materials are coated on particles containing active bacteria. [7]. Application of existing methods for disease detection and treatment, improved plant nutrient absorption capacity, and other aspects of agriculture can be changed through nanotechnology. Due to nano-based crystals, which are currently being produced, herbicides and insecticides will be more effective at lower doses [10,36]. A possible bioformulation that protects the actions of PGPMs linked to the stimulation of plant development is their immobilization inside biodegradable polymers or encapsulation. This results in maximal cell viability and survival and enhanced colonization of the rhizosphere and roots of plant [11,31].

Nano encapsulation in pharmaceutical sector: A kind of microencapsulation known as "nano encapsulation" encloses bioactive substances in a nanoscale shell consisting of lipids and biodegradable polymers [12]. Natural, semi-synthetic, or synthetic combinations, often of a lipid origin, are utilized as encapsulating materials. The most often employed lipid materials for the loading of active medicinal substances in micro/nanoparticles include acids and fatty alcohols, triglycerides, and waxes with a high melting point [14]. Coacervation, solvent evaporation, solvent emulsion, ionic gelation, extrusion, high-pressure homogenization, spray drying, and spray cooling (also known as spray congealing and spray chilling) are the most widely used Encapsulation technologies used in the production of delivery systems for active pharmaceutical ingredients [15,32]. Nanoparticles of a submicron size provide a variety of benefits over microparticles, including a considerably greater intracellular absorption rate. In terms of intestinal uptake, in addition to their particle size, the nature of the nanoparticles and their charge characteristics appear to have an impact on the uptake by intestinal epithelia [16]. More hydrophilic particles may be quickly removed because the uptake of nanoparticles made from hydrophobic polymers appears to be greater than that of particles with more hydrophilic surfaces. Uncharged and positively charged poly(styrene) nanoparticles typically have an affinity for follicle-associated epithelia and absorptive enterocytes, while negatively charged poly(styrene) nanoparticles have only weak affinities for all types of intestinal tissues. Contrarily, negatively charged, hydrophilic nanoparticles exhibit a considerable increase in bioadhesive qualities and are taken up by both M cells and absorptive enterocytes. The gastrointestinal uptake appears to be positively impacted by a combination of improved hydrophilicity of the matrix material and nanoparticle surface charges [17,18]. To improve their effectiveness and specificity, many kinds of medications have been encapsulated on liposomes. Methotrexate, an anticancer drug, was enclosed in the liposomes' inner aqueous phase. Doxorubicin, a different medication, has been used to treat malignancies of the bladder, stomach, ovary, lung, thyroid, and other organs. However, it has been shown that using it might lead to toxicities such mucositis, alopecia, and gastrointestinal myelosuppression. Doxorubicin was placed on liposomes for encapsulation, which extended retention duration and decreased doxorubicin toxicity. With a 45% loading efficiency, ciprofloxacin was also effectively loaded on liposomes. The addition of cysteine to the dithiobenzyl urethane connection between the lipid and the PEG in liposomes controlled the release rate of the drug that was encapsulated mucositis, baldness, and myelosuppression. Doxorubicin was placed on liposomes for encapsulation, which extended retention duration and decreased doxorubicin toxicity. With a 45% loading efficiency, ciprofloxacin was also effectively loaded on liposomes. The addition of cysteine to the dithiobenzyl urethane connection between the lipid and the PEG in liposomes controlled the release rate of the drug that was encapsulated [19]. Probiotics have been successfully microencapsulated for use in both the food and pharmaceutical sectors. Probiotics are protected by microencapsulation by being enclosed in tiny capsules. The capsule protects probiotic bacteria from harm by creating a useful barrier between the cells and environment, increasing the viability of probiotics. Environmental elements like oxygen and pH won't have an unfavorable effect on encapsulated cells as they travel to the site of action. By shielding probiotic cells from the stomach's acidic environment, microencapsulation can also increase their survivability throughout gastrointestinal digestion. A significant number of probiotics, including Lactobacillus rhamnosus and Bidobacterium longum, have been demonstrated to be seriously harmed by the stomach's low pH and the intestine's high bile salt conditions before entering the colon [20,31].

Advantages of encapsulation in pharmaceutical sector:

1. To make pharmacological drugs more bioavailable.
2. To make medicinal agents more stable.
3. To administer drugs with precision.
4. To slow down the rate at which the core material evaporates.
5. We can quickly and simply supply the pharmaceutical ingredient at a chosen pace and at a greater concentration to a sick spot.

6. Their ability to alter drug release from polymeric nanoparticles and choice of polymer make them attractive candidates for the administration of vaccinations and cancer treatments.
7. Contraceptives and the use of certain antibiotics.
8. The characteristics of the substance that is encapsulated can also be changed (for example, to hide flavors or odors.
9. Industrial operations, such as the conversion of liquid into solid, can be facilitated or enhanced [35].

6. CONCLUSION

The integration of bacteria with nanomaterials opens up new avenues for manipulating their biological functions. As nanotechnology continues to evolve, the synergy between nanomaterials and encapsulated bacteria holds great promise for revolutionizing fields such as medicine, biotechnology, and environmental science.

DATA AVAILABILITY

All datasets analyzed in this study are included in the manuscript.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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