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REVIEW **Open Access**

Exploration of different strategies of nanoencapsulation of bioactive compounds and their ensuing approaches

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Abstract

Background Nanotechnology has gained rapid popularity in many fields, such as food science. The labile bioactive is enclosed in a shield that protects it from harmful environmental factors. It also allows for targeted delivery to specific areas. Bioactive compounds in foods are slowly degraded or can change due to external or internal factors such as oxidation. Innovative technologies and novel edible packaging materials can be used to reduce bioavailability. One promising technology for overcoming the problems above is encapsulation.

The main body of the abstract Nanostructure systems enhances a number of properties, including resistance to degradation and improvements of physicochemical functions like solubility, stability, and bioavailability, among others as the nanosize increases surface area and, consequently, activity. A recently emerged nanoencapsulation technologies, including electro spraying, nano-fluidics, complex coacervation, electrospinning, polymerization, etc. have been briefly discussed. Different bioactive molecules can be nano encapsulated by absorbing, incorporating, chemically interacting, or dispersing substances into nanocarriers. There have also been other characterization techniques and different physico chemical parameters investigated to evaluate the characteristics of encapsulated bioactives. The current article highlights numerous bioactive substances utilized for nanoencapsulation using cutting-edge methods.

Short conclusion This review examines how different encapsulating bioactive materials can improve encapsulating films or coatings. The advent of nanotechnology has opened up a wide range of possibilities for the development, design, and formulation of innovative pharmaceuticals. The food and pharmaceutical industry can focus its attention on products that have added value through the various enhancements offered by nanoencapsulation.

Keywords Nanoencapsulation, Nanotechnology, Bioactive material, Bioavailability encapsulated bioactive compound

Background

Widespread bioactive substances, also referred to as secondary metabolites, are found in plant matrix, and over the past few decades, numerous in vitro as well as in vivo researches comprises of epidemiological and cohort designing, have provided the indication that eating plant-based food protects against a number of ailments.

The nanoencapsulation process provides a protective barrier around bioactive substances [1]. It is a system where a suitable nano-carrier, resistant to enzymatic degradation [2], especially in the gastrointestinal tract,

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including chitosan, zein, and alginate, is widely used to encapsulate bioactive compounds employing several delivery methods [3], including association colloids, nano-particles, nano-emulsions, nano-fibres/nano-tubes, and nano-laminates.

Research on innovative formulation methods, particularly the creation of biological capsules, is encouraged by the rising demand for biological products in agriculture [4].This has happened because these bioproducts are more stable and their active components are more reactive, which reduces volatility losses [5].

According to these circumstances, bioactive constituents (volatile oils, metabolites from fungi, different extracts from plants etc.) can be shielded from outside influences and deterioration by being enclosed in food and agricultural zones. The encapsulation enables the products' biological integrity and maintains the environment during storage, maintaining the active ingredients' long-term vitality [6].

Upon UV exposure and high temperatures, for instance, microbial compounds are vulnerable to abiotic and biotic variables that decrease the efficiency of these living things and metabolites of those, results in the loss of toxin integrity and spore viability [7].

Encapsulation functions as a substitute for these difficulties in this way. It enables, among other things, the reduction of volatility-related losses, the improvement of biological integrity, enhancement of efficacy, enhancement ofcommercial viability, and enhancement of stability of different formulations in the agricultural sector [8–10].

Numerous polymers are employed as wall materials for encapsulation in order to safeguard the core, which is typically created by bioactive chemicals. For this, a variety of substances are employed, including chitosan, maltodextrin, gums (such as shellac, gum arabic, gum acacia, and), whey protein, starch, sodium alginate, pectin, cellulose and,sodium caseinate, zein, pullulan, galactomannan [11–15].

Before a new encapsulated product is developed, it is essential to conduct preformulation studies on the materials to be used for encapsulation in order to accommodate the physicochemical behaviour of the active ingredient and produce the desired encapsulation efficiency, as well as the size of the shell or capsule, the surface morphology and functionalities of the capsule, and the behaviour of the encapsulated active ingredient. Encapsulating pharmaceuticals with the appropriate encapsulating material(s) can greatly increase the bioavailability of both currently available and upcoming poorly soluble drugs [16].

For encapsulation, natural polymers are ideal materials. Natural polymers, which are macromolecules with high molecular weights that are derived from nature, are favoured because of their adaptability to change, biodegradability, biocompatibility, renewability, and low toxicity [17].

Main text

Bioactive composites derived from plant

Plants have always been a benediction for maintaining a healthy lifestyle from the dawn of time since them not only offer a safe place to live but also, and perhaps most significantly, food and bioactive components for therapeutic use [18]. Plants and foods derived from them were first employed as a source of food and for its nutritional value; subsequently, their therapeutic properties, which might treat ailments, were discovered and Fig. 1 has shown various types of bioactive compounds from plant for nanoencapsulation [19]. Furthermore, these substances are categorised as follows depending on their clinical and toxicological characteristics:

Alkaloids

Alkaloids are heterocyclic chemicals with a small distribution in the plant kingdom that have a bitter taste and can retain nitrogen. Tropane alkaloids having anticholinergic characteristics are found in the Solanaceae family of

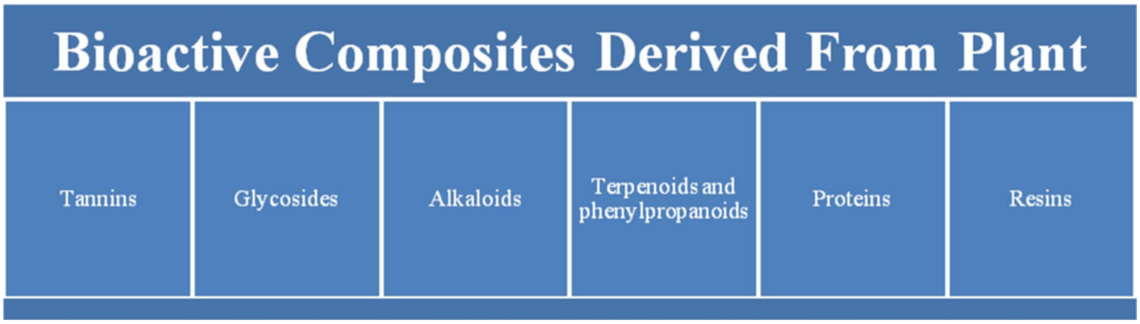

Fig. 1 Bioactive compounds from plant

plants, which also includes *Atropa belladonna*, *Datura spp.*, and *Hyoscyamus niger.* Alkaloids are the focus of research on plant-based drugs. The investigation of alkaloids from herbal and medicinal plants showed antiproliferative effects and antineoplastic properties in vitro and in *vivo* for a wide range of cancers. The databases that were accessible electronically have been screened for antiproliferative properties in lung cancer treatment [20]. It is frequently employed to lessen muscle pain. Additionally, pyrrolizidine alkaloids are found in Senecio species and other Asteraceae and Boraginaceae plants. With huge application including the treatment of cancer cells, boosting bone marrow leucocyte production, and increasing cardiac contraction. Additionally, *Theobroma cacao* and *Coffee arabica* both contain methylxanthine alkaloids [21].

Glycosides

They are usually attached with a monosaccharides or oligosaccharides or sometimes with uronic acids. Glycone is the portion that is attached to saccharide, while aglycone is the portion that is made up of pentacyclic triterpenoids and tetracyclic steroids. The main subcategories of glycosides are saponins, anthraquinones,cyanogenics, glucosinolates, and cardiac glycosides.

These substances are glycosylated, and the aglycone moieties, which are connected to uronic acid or monosaccharide or oligosaccharide, are constituted of vitamins, terpenoids, alkaloids, polyphenols, steroids, antibiotics, and other substances [22]. The glycosides' glycosidic residue is thought to be the cause of their biological effects [23]. The cardiac glycosides, diterpenoid glycosides, cyanogenic glycosides, and anthraquinone glycosides are among the classes of glycosides that are frequently harmful. Cardiac glycosides are known to produce hyperkalaemia, a disease that results in blood potassium ions that are greater than normal [24].

The $Na+/K+$-ATPase activity of bio-membranes is inhibited by the cardiac glycoside derivatives digitalis and strophanthus, such as ouabain [25, 26]. Diterpenoid glycoside consumption has been linked to renal proximal tubule necrosis in both humans and animals, as well as centrilobular hepatic necrosis. Adenine nucleoside carriers are hampered by diterpenoid glycosides, which have been connected to the inhibition of oxidative phosphorylation in mitochondria [27].

More than 2,650 plant species produce the cyanogenic glycosides, which are -linked glycosides of -hydroxy nitriles.Plants containing this class of glycosides produce hydrogen cyanide into the bloodstream, which impairs the efficient utilisation of oxygen in the peripheral tissues by reducing the activity of cytochrome oxidase in the mitochondrial electron transport chain. Aside from goitre and congenital hypothyroidism in children, irreversible paralysis, angular stomatitis, damage of the optic nerves, tropical ataxic neuropathy, sensorineural hearing loss, and sensory gait ataxia are further harmful outcomes of cyanide use. Examples of cyanogenic glycosides that can be found in edible plant parts are linamarin and lotaustralin, both of which are present in *M. esculenta* [28].

Tannins

Tannins are bioactive bitter polyphenolic chemicals that bind to and precipitate proteins, alkaloids, and other substances. They are soluble in water. Numerous plant species contain tannins, particularly those in the Polygonaceae and Fagaceae families. Condensed tannins and hydrolysable tannins are the two main categories. Condensed tannin groups are composed of bigger polymers of flavonoids, whereas hydrolysable tannin groups are composed of glucose clusters coupled to various catechin derivatives. Tannin molecules and protein molecules commonly engage in random interactions. Larger groups of tannins are used as drugs to treat skin bleeding, diarrhoea, and transudates [29].

Terpenoids and phenylpropanoids

The isoprenoids, often referred to as terpene derivatives, are made up of numerous combinations of terpene derivatives that are derived from five carbon isoprene units, which are combined together to form terpenoids. Instead of existing as low polar or none terpene aglycones, the majority of terpenoids exist as glycosidic forms [30].

An isoprene with penta carbons is used in the synthesis of terpenoids. Mono-terpenoids contain two isoprene units, whereas sesqui-terpenoids include three isoprene units. They are well-known for having a lower molecular weight and having a large number of groups more than 25,000. Though, phenylpropanoids are a class of compounds having a basic carbon structure that begins at nine and above, strong flavours, and a volatile tendency. These substances are frequently found in the *Lamiaceae* family and are known as volatile oils [31].

It has antibacterial, antiviral, and antitumor properties and is used as a natural medicine. Additionally, it supports gastric stimulation. Diterpenoids are also a cluster of 4 isoprene units with a strong flavour that is a lipophilic non-volatile (odourless) molecule. Since it has antioxidant properties, it is abundantly available in many plants, like coffee arabica [32].

Resins

Resins are the mixtures that include both volatile as well as non-volatile property chemicals, as well as a collection of compounds that are lipid soluble. While volatile resins have mono- and sesquiterpenoids, non-volatile resins are made up of diterpenoid and triterpenoid molecules. The antibacterial and wound-healing abilities of these resins, which are widely distributed in herbaceous plants, are well-known [33].

Proteins

Since proteins are a substantial source of nutrients for both animals and human, plant proteins have grown significantly in favour in the food and pharmaceutical industries. It is commonly known that the Fabaceae family, lentils, and the Euphorbiaceae family all have significant protein content [34].

Categorization of nanoencapsulation schemes

In the area of food science, nanoencapsulation has grown in favour recently. A bioactive substance is used as the core matrix and is encapsulated a wall matrix in inner part that can survive enzymatic and other degradation. Because bioactive substances are very susceptible to heat and the digestive enzymes found in the stomach and GI system of a person, using a substantial wall matrix/nano-carrier protects against them. Encapsulating bioactive compounds has been the subject of increasing research for various reasons. Encapsulations have been achieved using a variety of techniques, including electrospinning and coacervation. These encapsulations are known to enhance the physicochemical characteristics of bioactive compounds, increase bioavailability and stability, control the release, improve bioactivity and disguise flavour. The materials used include lipids and synthetic and natural polymers. They also influence performance and functionality. Additionally, these wall materials aid in sustaining the compound's nutritional activity and aid in disguising some compounds' unpleasant tastes [35]. Depending on how much energy is used to encapsulate these molecules, several methods are used, such as top-down and bottom-down procedures as well as their combination [36].

The top-down method of encapsulation uses equipment like spray-drying, ultrasonication, homogenizers, and many others, which results in high power consumption, as opposed to the bottom-up method, which uses techniques like precipitation, micro-emulsification, conjugation, atom exchange, etc., which use much less energy. Delivery release rate, solubility and stability of the nano-carrier, and manufacturing cost, are significant variables that are crucial in choosing a specific method for nanoencapsulation [37].

Bioactive agents and its encapsulating carriers

Hybrid nano-carriers

Internal (metal and polymer) and exterior (single/multi-lipid layer) networks make up the two main networks that make up hybrid nano-carriers [38]. This nanoparticle's outside coating serves as defence against degradation and water diffusion. These lipid-polymer and organic–inorganic carriers were primarily created for the regulated release of bioactive substances for the treatment of cancer cells.

Seyedabadi et al. reported that when compared to nano-liposomes without chitosan covering, slow-release encapsulated caffeine using chitosan wrapped in nano-liposomes performed better for the encapsulation of caffeine. [39]

Lipid-based nano-carriers

Niosomes, nano-liposomes, particulate carriers are lipid-based nano-carriers, also referred to as vesicular carriers. As a result of the interaction between the surfactant molecule and the aqueous solution, a spherical bilayer is formed. It is employed to encapsulate peptide among other bioactive substances. While liquid and solid lipid are mixed together to create nano-lipid particles, in internal phase solid lipid nanoparticles are created by combining solid lipid [37].

Chaudhari et al. studiedcompritol, a solid lipid, squalene, a liquid lipid, span 80, and tween 80 were used as emulsifiers and co-emulsifiers to encapsulate the compounds piperine and quercetin. For slow lipid wall matrix erosiveness (12 h), these bioactive chemicals were encapsulated and showed slower release [40].

Another research reported by Abd-Elhakeem et al. demonstrated about employing lipid-based nanoencapsulation to elevate the bioavailability and target delivery of eplerenone orally. After 24 h, rabbit intestinal permeability to eplerenone-loaded nano-lipid capsules were up to two folds higher than that of traditional aqueous medication [41].

Polymeric nano-carriers

They are thought to be an incredibly ideal part for encasing and delivering bioactive chemicals. Currently, natural-based nano-carriers such starch, chitosan, casein, albumin and whey protein are most frequently employed. Ravi et al. in 2018 utilised chitosan as a wall substance to enclose the marine carotenoid named fucoxanthin [42]. The bioactive compound's anticancer activity was improved, and caspase-3 activity was 25.8 times higher as a result.

Gagliardi et al. conducted a comparison study for the encapsulation of rutin using natural and synthetic nanoparticles, namely poly (lactic-co-glycolic acid), zein etc. According to the findings, poly release represented slower release (25%) after 60 h in comparison to zein along with 0.8% rutting [43].

Apart from this, in 2021, a research group from Portugal, Costa et al. bioactive extract from grape pomace was encapsulated with nanoparticles of chitosan and alginate, which increased the bioactivity and prevented the bioactive components from being hydrolysed in the gastrointestinal tract [44].

Systems of nanoencapsulation of biologically active composites

Capsulation of Bioactive substances is considereda more difficult technique than microencapsulation. It is broken down into three primary categories: low-energy, high-energy, and a combination of low and high. Low-energy processesinclude precipitation, micro-emulsification, conjugation, etc.[45]. Spray-drying, ultrasonication, homogenization, etc. will fall under the category of high-energyprocesses.

Delivery energy, release rate, solvability, solidity of the nano-carrier, and manufacturingprice are some of the variables that affect the decision of which method to adopt for designing nano-capsules. Several encapsulation methodshave been covered in the current review study [46].

Electro spraying

An alternative to the drying-encapsulation method is the electro-spraying process. At room temperature, it uses high-voltage electric current to operate. The fundamental idea behind electrospinning and electro-spraying is the same, but what sets these two techniques apart is the molecular adhesion of the polymers, which is less for electro-spraying causing the jet to break up into tiny droplets [47]. Due to the surface tension in the air, the jet particles acquire a spherical shape when exposed to it. It has been previously demonstrated that using zein as a wall material during electro spraying increases the permeability and bioactive release characteristics in green tea catechins. Later in 2019, it came to light that resveratrol achieves a 70% encapsulation efficiency when nano-encapsulated with the same wall material [48].

Micro-/nano-fluidics

The fundamental idea behind micro- and nano-fluidics is the interfacial contact between the fluids. It promotes droplet development delaying the emancipation of biologically active substances. Additionally, it aids in the creation of precise nano-droplets of a similar size. It comprises a polydimethylsiloxane glass foundation. This channel helps in transporting the fluid because it is related to all other channels [49]. A syringe is used to inject gas and liquid. This processutilizes nano or micro-fluidic appliances as emulsion devices. Micro fluidization was used to create a nano-emulsion system under ideal conditions, which included pressures between 40 and 65 MPa and 2–5 cycles. The research suggested that the nano-emulsion included smaller fish oil droplets. After a few years, the system was altered by utilizing micro fluidization and citrus pectin. The results exhibited that the qualities of the nano-emulsion were improved, thus safeguarding cholecalciferol against UV [50] degradation in comparison to the original pectin. Additionally, the modified pectin’s molecular weight and hydrodynamic diameter were both decreased to 235 kDa and 420 nm, respectively.

Complex coacervation

In the encapsulation process known as complex coacervation, two polyelectrolytes with opposing charges engage with one another in an aqueous media. The bioactive substance is encapsulated around a protein or carbohydrate compound [51]. This interaction only occurs at particular parameters like strength, polymeric concentration, biopolymer content, and biopolymer weight. This method enables the creation of particles that have a coating of a capsulating agent thus protecting the biologically active chemicals [52, 53].

Electrospinning

By applying high-voltage electricity to polymeric fluids to process fluids with electric charges, electrospinning creates dry micro- and nanostructures. The instrument essentially consists of three main components: syringe and pump, an electrified needle, and a collection plate [54]. When high-voltage electricity is applied to the nozzle or needle, the liquid is forced inside. The studies were conducted at room temperature, and the nanofibers were stored in a desiccator before being transported after being collected on an electric collector plate [48]. Nanofibers can be anything between one and many nanometers in diameter [55].

Blend, coaxial, emulsion, high-throughput, and polymer-free are among the five main types of electrospinning techniques. The biologically active component and the solutions of the polymerare assortedtogether using either a blend or emulsion approach, which is effective at managing the release of bioactive substances. Using this method, both hydrophilic and hydrophobic compounds can be easily enclosed [56]. On the other hand, a coaxial electrospinning arrangement utilizesa syringe connected to a single output pump producing enclosed fibers [57].

High-throughput electrospinning, on the other hand, is a pointless process used to create ultra-thin fibers from emulsions. In 2018, a high-throughput process was utilized to create glycoconjugates. In addition to all of these methods, the polymer-free methodutilizes a solution of a polymer having high masswhich is incorporated by a pump to produce a greater yield than the traditional methods [58].

According to Xiao et al. [59], this method can create nanofibers varying from 80 to 50 nm, while Moreira et al. [60] claim that the polymer-free method can widely help the food industry. Additionally, Poornima et al. [61] successfully delivered controlled drug release using this method to capsulate resveratrol with caprolactone and lactic acid. While Zein was used to enclose resveratrol with the best encapsulation effectiveness (96.9%), they are the ideal one according to researchers [62].

Spray chilling

Ascorbic acid, a form of vitamin C, has been shown to have positive benefits in agriculture, including lowering the impact of nickel and cadmium on barley, reducing the stress of drought on sweet pepperand cucumber, and enhancing apple quality [63]. It makes it possible to lessen the effects of salt stress and promote better barley growth. In this regard, spray cooling has been reported as an efficient method for encapsulating ascorbic acid, displaying retentions above 80% [64]. The method entails melting the completely hydrogenated palm oil to 85 °C, mixing in the ascorbic acid, and then letting it instantly flow through the spray drier before being cooled to 4 °C.

Polymerization

In this method of nano-encapsulation, the bioactive ingredient is added after the aqueous fluid's monomers are polymerized to create nano-particles. Additionally, the nano-particles are cleansed during encapsulation by getting rid of excess stabilizer and surfactant that had accumulated on their surface. Typically, this method is used to create poly butyl cyanoacrylate nanoparticles [65].

Supercritical microencapsulation

Modern terminology for supercritical microencapsulation includes "micronization." Mild temperatures are used during supercritical micronization to prevent lowering the quality of bioactive substances. Water and carbon dioxide are the two most common solvents utilized in this method. To microencapsulate bioactive substances of relevance to the food and agricultural industries, carbon dioxide under supercritical circumstances has grown in popularity [53].

It is a different environmentally friendly technique for creating nanoparticles. Since CO_2 is non-toxic, inexpensive, and inflammable, it is frequently utilized as a supercritical fluid. In this procedure, a liquid solvent is used. This liquid solvent isassorted with supercritical liquid (CO_2). Instant precipitation now occurs as a result of the solute's insolubility non the supercritical fluid, which enhances the effect of the produced nanoparticles [66].

According to some studies, depending on the characteristics of the wall matrices and the active components, this method can be beneficial in a variety of contexts, including the creation of encapsulated products. The processing method employing supercritical CO_2 is chosen according to the main component and polymer to be capsulated. For instance, the way CO_2 reacts with the solvent, the wall material, and the active substance. The contact between CO_2 and the solution of polymer utilized in the biopolymer drug delivery system is crucial to the encapsulation process. While polymers, such as polylactide, are effective for SAS treatment, RESS is challenging to solubilize in supercritical CO_2 [67].

Ultrasonication

The term ultrasound refers to a group of sound waves that are louder than 16 kHz. There are two types of sound waves: low-intensity waves and high-sound waves. Low-intensity waves are utilized for the purpose of detection, butmolecules are modified utilizing high sound waves, including reducing their size and emulsification. It is employed in nanotechnology to create several types of nanostructures [68].

A generator, a transducer, and a titanium horn-shaped sound expeller make up the ultrasound system's components [69]. To create nano-emulsions, nano-liposomes, niosomes, and other types of nano-delivery systems utilizing ultrasound, a variety of nano-delivery strategies have been devised [70].

Homogenization

Homogenization is the process of creating homogeneous-sized nano-fragments at a particularly escalated pressure. It has a pressure range of 100 to 400 MPa, which is 10 to 15 times higher than a typical homogenizer. The study found that the milk and milk product industries frequently use this technique to improve the basic characteristics of the products while also enhancing the anti-microbial quality of certain microbes. At 250 & 350 MPa homogenization pressure and 40 and 50 °C inlet temperatures, a decrease of about 2 and 3 log cycles was found [71].

It also serves as an alternative to thermal processing since it effectively inactivates enzymatic and microbial characteristics [72]. The homogenization technique was also used to create a soy protein emulsion [73]. Figure 2 has shown various types of nanoencapsulation systems for bioactive compounds.

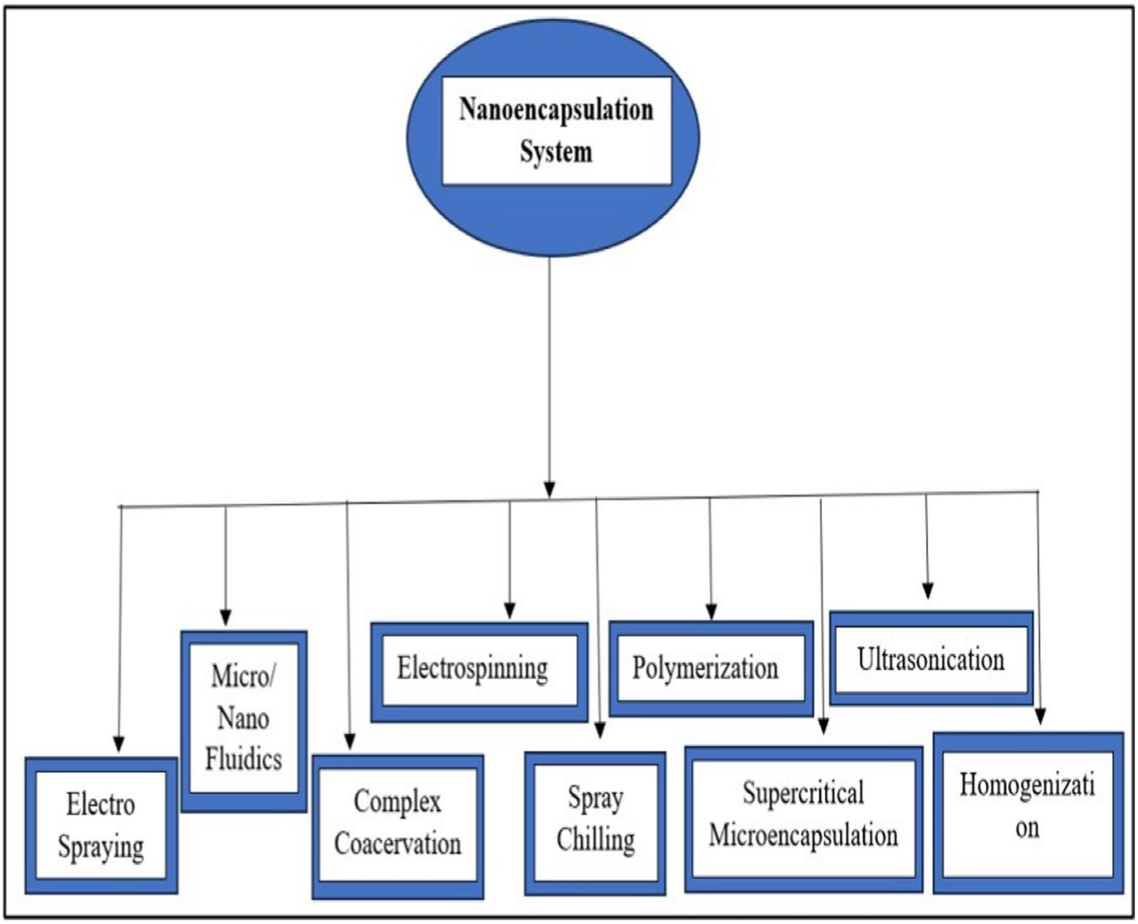

Fig. 2 Types of nanoencapsulation systems for encapsulation of bioactive composites

Nano encapsulated bioactive agents and its physicochemical features

Encapsulation efficiency and loading capacity

The amount of bioactive compounds encapsulated within the matrix wall is what we call it. Quantifying the amount of mixture in a nanoparticle can be done using UV–Vis spectrum analysis [74]. The perfect nanoparticle has the maximum loading capacity of the compound with minimal wall materials. The incorporation or absorption of bioactive compounds can be done in two ways. Entrapment capacity mainly depends on the solubility and molecular mass of the bioactive compounds encapsulated within the material of the wall [75]. The maximum entrapment capacity is reported for macromolecules and proteins at an isoelectric level.

Particle size

These properties are conscientious for the quality of the nanoparticles, as well as their delivery capability, stability and viscosity [76]. The intracellular capacity of nanoparticles is higher than that of micro-particles due to their relative size and mobility [77].

The size and shape of nanoparticles can be detected using a variety of microscopes. Optical properties of nanoparticles and nano-capsules or micro are determined by laser diffraction & scanning electron microscope techniques. The surface study, which requires extremely powerful analyzers like transmission electron microscopes to determine the quantity of pores, is needed. Mixing fluorescent dyes with the bioactive compounds makes it possible to detect multiple locations using fluorescence or confocal microscopy. The photon correlation spectrum, or dynamic light scattering, is widely used to determine the size of nanoparticles in the 1000 nm range. This helps to determine the particle range and its concentration within a matrix [78]. The charge characteristics of nanoparticles are identified. The electrical properties of nanoparticles can be altered by altering the compounds in the fluid. A nanoparticle with a Zeta Potential greater than (±) 30 mV is stable. It is interesting to note that the Zeta Potential process can identify whether partition materials are encapsulated within the nano-capsule or if they cover its outer arrangement [64, 79].

Stability

The nanoparticles' stability is the ability to stay intact within the matrix wall until they are released at the time and location desired. The nano-emulsions are more stable caused by the morphological structures of small droplets. The stability of bioactive compounds can also be tested by placing them into various modified environments, such as high/low temperatures, fluids with different ionic charges, and pH levels [80].

Control release

The release of bioactive agents depends on several factors, like as solubility of the mix, the surface binding/adsorption, and the diffusion of the matrix. Other aspects include matrix degradation or a combination of matrix degradation, diffusion, and degradation. The release of nano-spheres containing bioactive compounds in an even distribution is mainly due to erosion of the wall material. Diffusion is the only way to control release if wall degradation occurs slowly. Quick release can lead to poor wall materials or small binding ability [65]. The mixing technique has been reported to play a crucial role in the release profile for nano-capsules, as it slows the release [81]. If the coating is polymer, the release will be by diffusion from the inside of the matrix to the outside. Several other techniques, such as reverse dialysis bags, dialysis bags, and synthetic or artificial membrane diffusion, can release the compound.

Applications of nano-encapsulated compound

The most common encapsulation material is natural or synthetic polymers. Food encapsulation is a technique that has been used for many years in the food industry [82]. Encapsulation is a technique that aims to deliver bioactive compounds directly to target organism tissues. The bioactive compounds are more stable and bioavailable, and their benefits to the body increase [83]. Table 1 shows the various applications of nano-encapsulated compounds in food. Other compounds useful for food encapsulation include dyes and flavors, vitamins, antioxidants, enzymes and bioactive peptides.

Other substances, such as those found in essential oils and herbal extracts with insecticidal and antimicrobial properties, are being encapsulated [84]. Biotechnology faces a difficult task in controlling volatile oils and extracts.

The essential oil of savoury leaves was combined with natural polymers like apple pectin and gum arabic. All polymers showed a higher efficiency of encapsulation. The herbicidal effect of amaranth, tomato and other plants was subsequently increased [85]. Pepper oil was encapsulated, and its antibacterial activity was tested long-term. Encapsulating this oil with gum arabic/malt dextrin had an inhibitory action against *Pseudomonas aureus, Enterococcus Faecali* and *Staphylococcus aureus.*

Table 1 Applications of nano-encapsulated compound in the food industry

Sl. No	Nano-encapsulated compound	Nanomaterials	Functions	Food materials	References
1	Vitamin D3	Potato proteins	encouragement of human health	beverages solutions	[96]
2	Vitamin E	Edible mustard oil	Health supplement antioxidant	Mango juice	[97]
3	α-Tocopherol	Canola oil and tween 80	Antioxidant agent	Fish sausages	[98]
4	Quinoa peptide	Soyphosphatidylcholine and cholesterol	Natural food preservative	Fresh beef burgers	[99]
5	Pears peel fruit	Sodium alginate-chitosan	Preservative	Guava juice	[100]
6	Olive leaf phenolicsoleuropein	Lecithin cholesterol	Functional food product	Yogurt	[101]
7	Nisin and garlic extract	Phosphatidylcholine and oleic acid	Antimicrobial agent	Whole UHT milk	[102]
8	Nisin and lysozyme	Phosphatidylcholine pectin	Natural antimicrobials	Whole UHT milk	[103]
9	Fish skin peptide	Lecithin	Preservative and vehicle for Entrapping fishy smell	Pork patties	[104]
10	Fish oils	Lecithin sunflower oil	Improvement of the nutritional value	Bread	[105]
11	Chlorogenic acids	β-cyclodextrin	Phenolic compounds Supplementation on aroma volatile profile	Bread, cookies, caramel cottage cheese, nutty filling, and mushroom or meat stuffing	[106, 107]

The Supercritical Anti-solvent method encapsulated curcumin from turmeric using polymer matrices. This dye contained turmeric extracts. These polymers were Eudragit L100 and Pluronic F127 or mixtures thereof. In this field, economic evaluations were also developed to help boost the application of the technology on a larger scale and to transfer it to an industrial scale.

Gas anti-solvent was used to create poly (caprolactone), containing resveratrol, with heterogeneous properties. The encapsulation process was successful because the resveratrol's chemical structure or antioxidant activity did not change. The microparticles also maintained their release over 48 h [86].

The use of non-hydrolyzed polymers in agriculture has increased due to their accessibility and price. Hydrolyzed starches are the most effective agents for encapsulating pesticides (metabolites made by *Bacillus-thuringiensis*) because they protect environmental factors while improving the formulation. Encapsulation is a viable method for formulating biopesticides and/or biofertilizers for agricultural fields. Encapsulation has several uses in agriculture [87] and pharmaceutical, which are shown in Tables 2 and 3

Trichoderma Harzianum is a very effective biological control agent for agricultural purposes. Its live spores make it highly sensitive to both biotic and non-biotic factors. Encapsulation improves the activity of phytopathog*ens, such as Sclerotinia sclerotiorum. Another study encapsulated spores from the* Trichoderma genus in biologically-based lignin to treat diseases in the vine trunk. In vitro tests showed that the spores remained at rest until the fungus triggered germination at the right time.

The Pickering emulsion microencapsulated *Metarhizium conidia* were found to have a better distribution of cells in the leaves and greater control over the *Spodoptera Littoralis* pest [88]. In a separate study, *Bacillusthuringiensis aizawai* was encapsulated in Pickering emulsion water-in-oil. It was found that *Spodoptera thuringiensis aizawa* larvae of the first instar were killed with 92% efficiency [89].

Similarly, inoculating potatoes with two strain of *Pseudomonas fluorescens* by an alginate/gelatin capsule led to a larger level of safeguard from harmful soil conditions and a greater establishment in the Rhizosphere. The antifungal effect of salicylic acids containing zinc oxide was shown when the bacteria were encapsulated with sodium alginate.

Azadirachtin, a natural insecticide found in neem trees (*Azadirachta indica*), was nano-emulsified with whey isolate. The strategy significantly affected the death of *Spodoptera frugiperda*, a pest caterpillar that attacks soybean crops. The encapsulated orange essential oil also positively affects the mortality of *Spodoptera frugiperda*, affecting soybean crops [90].

Peel inhibits the growth of *Escherichia colitis* and *Staphylococcus aureus* [91]. A study on the encapsulation of biofertilizers showed formulations with *Burkholderia*

Table 2 Applications of nano-encapsulated compound in the agricultural industry

Sl. No	Nano-encapsulated bioproducts in agriculture	Functions of nano-encapsulated compound
1	Biofertilizer	1. Enhanced formulation stability 2. Better biological properties 3. Slow release of encapsulated bioproducts 4. Reduction of volatility 5. Enhanced in efficiency 6. Increase in commercial viability 7. Protection of encapsulated materials
2	Bioherbicide	
3	Biofungicide	
4	Bioinsecticide	
5	Plant extracts	
6	Essential oil	

Table 3 Application of nano-encapsulated compound in pharmaceutical industry

Sl. No	Nano-encapsulated bioactive compound	Applications
1	Phenolic compounds	Protection, improvement of their antioxidant and other functional activities, target delivery
2	Carotenoids	Stabilization, efficient controlled release, expansion of their industrial applications
3	Essential fatty acids	Stabilization, better solubility, decrease volatility, use of lower doses, favorable impact on the sensory quality of the final product
4	Vitamins	Protection to oxidation
5	Peptides and enzymes	Improved antimicrobial or antioxidant activity, better absorption
6	Probiotics and prebiotics	Increment of viability, promotion of gastrointestinal health

spp. and Pseudomonas alginate encapsulated in phosphate-alginate provided superior environment for the growth of wheat plants under semi-arid or salt-stressed environments [92]. A study showed that biofertilizers containing *Pseudomonas cepacia* and *Azosprillum brasilense*, encapsulated in polymers made of clay mineral and sodium alginate, led to a higher level of formulation control [93]. The study also showed that the slow release of active compounds positively affected wheat plants' growth, with increased biomass.

Future directions

Nanoencapsulation-based bioactive compounds are unique and current; their operation in both the food and pharmaceutical areas results in new opportunities for commercialization. Their application is primarily the creation of nanostructured ingredients for food and pharmaceutical product, which allows the enhancement of solubility and stability, flavour, texture, and colour of foods. Encapsulation can be used to mask unpleasant aromas or flavours. It also increases the bioavailability of nutrients and allows for controlled release in both food and pharmaceutical products. At the same time, the volatility of compounds encapsulated is reduced. In the near future, food and pharmaceutical industries can gain from incorporating NPs into their new products [94, 95].

Conclusions

It is necessary to strengthen our immune systems to combat the rapid spread of deadly diseases. This can only be achieved by consuming bioactive substances extracted from plants. Nanoencapsulation technologies are unique and recent; their action in both the food and pharmaceutical areas effects in new opportunities for commercialization. The nanoencapsulation with carriers of bioactive compounds is an approach that can be used to improve their bioavailability, stability, and use within the pharmaceutical industry. Nanotechnology used to encapsulate microbial compounds with bioactive properties has many obvious advantages, from packaging to food processing. These include improved bioavailability and stability. The controlled release and defence of bioactive substances also offer safety benefits. To facilitate the safe marketing of health-beneficial new nanotechnology products, global legislation is needed to recognize the safety and toxicology of these nanomaterials. In other words, it is necessary to develop and implement novel extraction and encapsulation technologies for highly effective microbial bioactives that can be used in different industries, such as the food, pharmaceutical and cosmetic industries. Further, it is necessary to understand the safety and toxicology of nanoencapsulation, as well as to implement global legislation to ensure safe marketing and use.

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Author contributions

Dr. SC conceived the idea and outlined the content; Dr. KK collected information, reviewed the literature and developed the manuscript; Dr. SC and Dr. RM proof read and edited the manuscript. All authors read and approved the final manuscript for submission.

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Availability of data and materials

All necessary data generated or analyzed during this study are included in this published article. Any additional data could be available from the corresponding author upon request.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

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