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Review Article

ENCAPSULATION OF BIOACTIVE COMPOUNDS INTO CHITOSAN- BASED MATERIALS MAINLY FOR FOOD APPLICATIONS: A MINI-REVIEW OF NANO ENCAPSULATION IN COMPARISON WITH CONVENTIONAL ONE

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Abstract: Bioactive compounds (BCs) possess several interesting properties and health benefits. However, poor bioavailability, low solubility, low stability and fast releasing rate, and susceptibility to oxidative deterioration, limit their applications. Encapsulation procedure protects them from different types of deteriorations. Chitosan, a biopolymer exhibits several interesting properties such as antioxidant and antimicrobial properties. Chitosan-based materials have been considered as promising frameworks for encapsulation bioactive compounds for food applications. In this study, encapsulation of BCs into chitosan- based materials having bulk, micro or nano sized was made a review. The effectiveness and performance of nano-encapsulated BCs into chitosan were compared with both their free forms and conventional encapsulation procedure. Use of nanotechnology has a great promise for addressing some issues such as improving bioavailability, solubility, stability from different deteriorations. The rate of releasing of nanomaterials from the encapsulated systems depends on the size of nanomaterials. Chitosan-based materials with nano-sized have higher encapsulation efficiencies compared to the conventional ones. The encapsulation of BCs in chitosan as food packaging systems contributes significantly to the extension of the shelf life of perishable food products

1. Introduction

Polyphenols, essential oils (EOs), carotenoids, flavonoids, curcumin, quercetin and vitamins are bioactive compounds (BCs) that have been well established to have several properties and health promoting effects. These compounds exhibit antioxidant, antimicrobial and anti-inflammatory activity. However, their low solubility, poor stability and low bioavailability limit their proper use in functional foods and nutraceuticals (Avila et al., 2022; Zahra et al., 2026) . Polysaccharides and proteins exist in many forms in the nature and being biocompatible, biodegradable and non-

toxic, and play important roles in physiological functions such as carriers and nano-carriers ǂ (Faridi Esfanjani, and Jafari, 2016) ǂ. Chitosan a polysaccharide derived from chitin, soluble under acidic conditions, insoluble at neutral to alkaline pH, enabling pH-responsive behavior ǂ (Li et al., 2016) ǂ. The unique cationic nature and presence of amino groups contribute to a wide range of remarkable properties including antioxidant activity (AOA), antimicrobial activity (AMA), muco-adhesion, ease of functionalization for targeted delivery, and permeation enhancement. These characteristics make chitosan highly versatile, with applications across various fields of food and medicine (Liu et al., 2025). The cationic nature and high density of amino and hydroxyl groups enable strong electrostatic and hydrogen-bond interactions with negatively charged or polar volatile compounds, which are critical for control of releasing of BCs. Encapsulation technologies enable controlled release of BCs such as EOs. Encapsulated BCs have great potential for various food applications (Pérez-Álvarez et al., 2020). Chitosan-based nanomaterials (NMs) are efficient for encapsulation of BCs and their transportation to food products and pharmaceutical systems (Faridi Esfanjani, and Jafari, 2016; Li et al., 2024; Liu et al., 2025; Pérez-Álvarez et al., 2020).

Different materials are utilized as the wall materials in nano-encapsulation must provide core stability to preserve biological activity. It is beneficial for these materials to be economically viable; they may be organic, inorganic, synthetic, or a mixture of them (Mondéjar-López et al., 2024). Nanotechnology is rapidly advancing across various sectors, and has become one of the most promising scientific disciplines in recent decades especially in food, pharmaceuticals, cosmetics, and agriculture (Kumar et al., 2026). Nanotechnology has been studied as an alternative to minimize the sensitivity and increase the bioavailability and solubility of BCs. Nanoencapsulation facilitates the development of functional foods with enhanced nutritional value and improved sensory properties. The novel nanoencapsulation technique entails enclosing BCs in nanoscale carriers (Yousefi et al., 2024). This method has drawn a lot of interest from the food industry, because it can improve the stability, bioavailability, and regulated release of sensitive nutrients, especially BCs that come from both plant and animal sources (Taouzinet et al.,2023)

In this study, encapsulation of BCs into chitosan- based nanocarriers has been made a review. The effectiveness and performance of nano-encapsulated of BCs into chitosan were compared with both their free forms and conventional encapsulated forms. This work was highlighted the potential of chitosan and chitosan- based materials as carriers of bioactive compounds, particularly in food applications.

2.General Aspects

2.1.Definition and principles of encapsulation and nanoencapsulation

Encapsulation is a process in which active agents are capped or coated by carrier materials in order to form capsules in different sizes including micrometer and nanometer scales. This process enhances bioavailability, stability, and solubility of BCs (See Table 1). The active agents are designated as core or internal phase, while the coating materials that can be one or multiple materials are formed shell or external phase and are known as carrier or wall materials (Devi et al., 2017). The encapsulation safeguards BCs by forming protective barriers against light, oxygen, heat, pH, moisture, shear stress, and other damaging factors and extreme conditions. Additionally, encapsulation assists in masking undesirable odors and flavors, while preserving and enhancing the properties of BCs (Ali Redha et al., 2024; Devi et al., 2017; Hosseini, and Jafari, 2020; Shishir et al., 2018). Furthermore, the encapsulation contributes in reduction of evaporation or volatility loss, enhancement of reactivity of barrier for BCs, and improvement of physical stability, biological activity of BCs, and extension of shelf life for food products (Aguiar et al., 2016; de

Souza Simões et al., 2017; Jia et al., 2016). Encapsulation plays an important role to preserve and enhance the functionality of BCs. Encapsulation offers a viable option to improve the application of active ingredients in food products or protects them from adverse environmental conditions (Ali Redha et al., 2024; Devi et al., 2017). Various roles of encapsulation in food science and technology are illustrated in Figure 1.

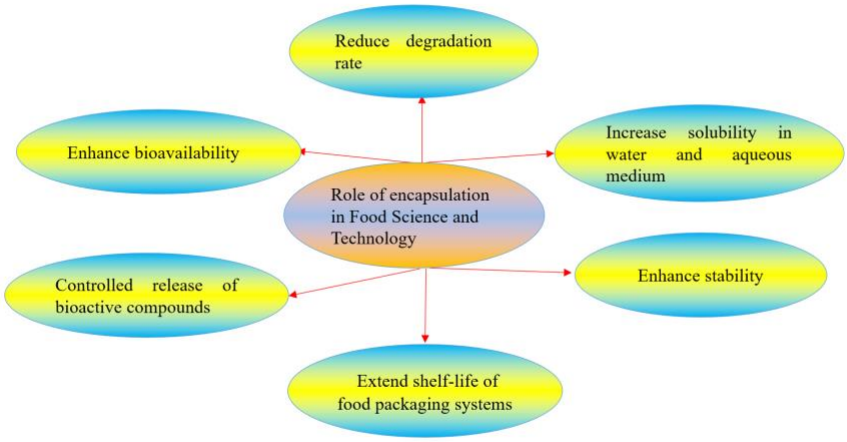

Figure 1. Illustrates various roles of encapsulation in food science and technology

Nanotechnology has emerged as a groundbreaking field with immense potential to transform industries, particularly in biomedicine and food science. One of the most promising applications is nanoencapsulation of BCs- a revolutionary technique that enhances stability, enables controlled release, and facilitates targeted delivery (Wani & Naik, 2025). Nano-encapsulation enhanced significantly stability, solubility, protection against degradation, and target delivery of bioactive components in comparison with conventional encapsulation (Khezerlou et al., 2021; Lin et al., 2019). The encapsulating layer creates a protective barrier around BCs, prevents degradation and regulates BCs release during processing or digestion. This technology is especially advantageous for the efficient delivery of health-enhancing components, like vitamins, antioxidants, and probiotics, within food items (Rezagholizade-shirvan et al., .2024). The stability of BCs against environmental factors like light, heat, and oxygen has been improved by nanoencapsulation. This is essential for preserving the nutritional integrity of food stuffs over time (Singh et al., 2023). The nanoencapsulation facilitates the regulated release of encapsulated substances at designated locations inside the gastrointestinal (GI) tract, and enhances their absorption and efficacy (McClements, 2018). The incorporation of nano-encapsulated components into functional foods is increasing. The food components are formulated to offer health advantages that exceed fundamental nutrition, frequently addressing health concerns such as cholesterol regulation or antioxidant enhancement (Vignesh et al., 2024). Nanoencapsulation is employed both in food processing products and food packaging.

BCs, ranging from functional food ingredients, pharmaceutical drugs and nutraceuticals to agricultural chemicals, often face challenges such as instability, poor

solubility, limited bioavailability, and inefficient delivery. Nanoencapsulation addresses these issues by enveloping bioactive molecules in protective nanoscale carriers, shielding them from degradation, improving their solubility, and ensuring precise release at desired sites. This capability opens new frontiers across multiple disciplines (Wani & Naik, 2025).

2.2.Micro, sub-micro and nano encapsulations

Nanotechnology offers powerful tools for enhancing the functional properties of edible coatings, particularly through micro- and nanoencapsulation. This technique improves stability, facilitates targeted release, and enhances the delivery of BCs. Microcapsules (1–1000 μm), submicron-capsules (less than 1 μm), and nano-capsules (1 to several hundred nanometers) are produced through micro or nano- encapsulation technique. Microencapsulation involves the encapsulation of BCs or nutrients in a carrier, such as polysaccharides, proteins, lipids, or synthetic polymers, to form microcapsules. These capsules act as protective shells that shield the BCs from environmental stressors such as heat, oxygen, light, and moisture (See Table 1). Microencapsulation also allows for controlled and sustained nutrient release, which is a crucial for preserving the nutrients' effectiveness over time. For instance, vitamins or EOs can be encapsulated in edible carriers, providing long-term protection and enhancing the coating's performance (Chaudhary et al., 2021).

Nano-capsules provide a greater surface area that enhance the solubility in comparison with microcapsules (Lević et al., 2015; Rodríguez et al., 2016). Nano-encapsules have a better contribution in bioavailability and drug release which enable precision targeting of the active compounds (de Souza Simões et al., 2017; Yang et al., 2017; Yao et al., 2016). Nanoencapsulation results in formation of nanocarriers, possessing a particle size with a diameter of less than 1 micron (1000 nm), and exhibit characteristics that are different from traditional encapsulation (Mahdi et al., 2022). Nanoencapsulation involves embedding nutrients within carriers that are nanometer-sized, including liposomes, nanoparticles (NPs), or nanogels. The reduced size of these carriers facilitates improved protection of the nutrients and a more effective controlled release mechanism. This technique is especially beneficial for fat-soluble vitamins, antioxidants, and polyphenols, which are often vulnerable to oxidation and environmental degradation. By integrating nutrients into edible coatings, there is a significant potential to enhance bioavailability, as these nutrients can more readily penetrate the food surface and be absorbed by the body (Chaudhary et al., 2021).

2.3.Various techniques of encapsulation and nanoencapsulation

Encapsulation/ nanoencapsulation techniques include precipitation, emulsification, coacervation, Pickering emulsions, emulsion-based methods, liposomal entrapment, spray drying, freeze drying, spray coating, electro-spinning, extrusion, and layer-by-layer assembly (Baig et al., 2021; Garavand et al., 2021; Hassen, and Ben Salah, 2026; Kandasamy, and Naveen, 2022; Timilsena et al., 2019; Weng et al. 2026, Zahra et al., 2026). Each procedure possesses particular advantages and limitations. These methods allow for accurate regulation of particle dimensions, structure, and encapsulation effectiveness, addressing particular application needs. These techniques enhance stability and efficacy of active components like vitamins, antioxidants, and ultraviolet (UV) filters, ultimately improving product effectiveness and consumer satisfaction (Casanova and Santos, 2016; Hassen, and Ben Salah, 2026; Weng et al., 2026; Xie et al., 2024).

2.4.Bioactive compounds and their carriers

BCs include polyphenols, carotenoids, flavonoids, vitamins, EOs, polyunsaturated fatty acids such as omega-3 fatty acids (see Figure 2). Natural BCs, particularly those sourced from plant matrices and rich in polyphenols, anthocyanins, flavonoids, and carotenoids, are well known for their antioxidant, anti-

inflammatory, and cardioprotective attributes, playing a significant role in health care attributes and in the prevention of chronic diseases (Alamgir, 2017; Bhatla and Lal., 2023; Dey et al., 2025; Pateiro et al., 2021). BCs commonly found as secondary metabolites in plant matrices, and have long been recognized for their potential health benefits.

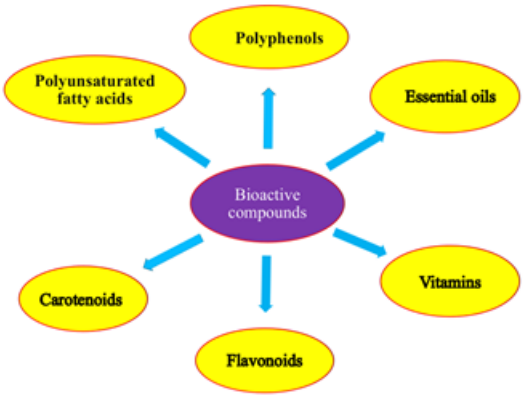

Figure 2. Illustrates various families of bioactive compounds

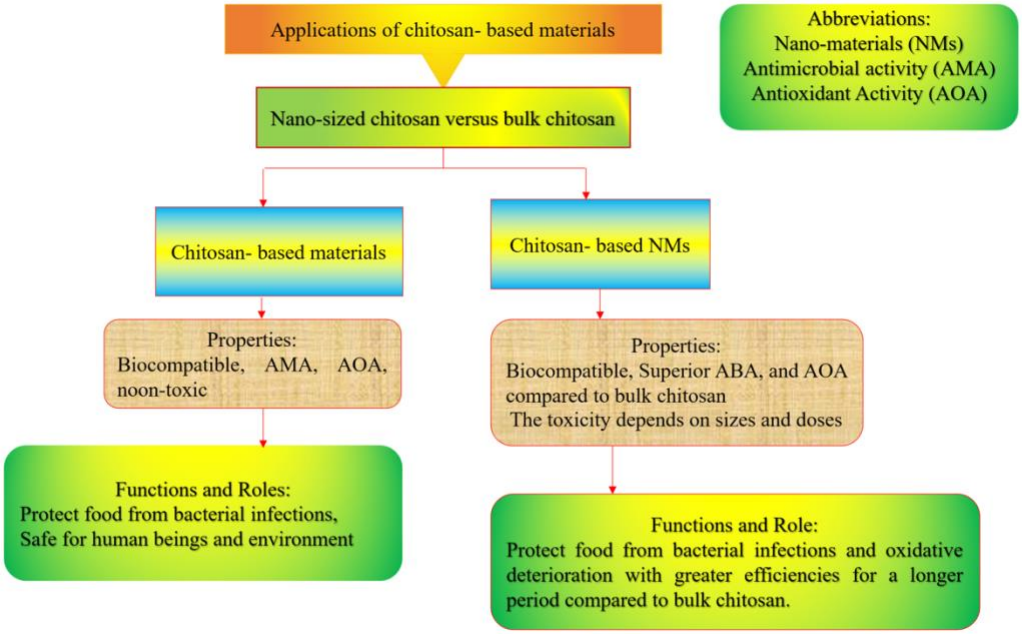

Figure 3. A comparison of nanosized chitosan versus bulk chitosan.

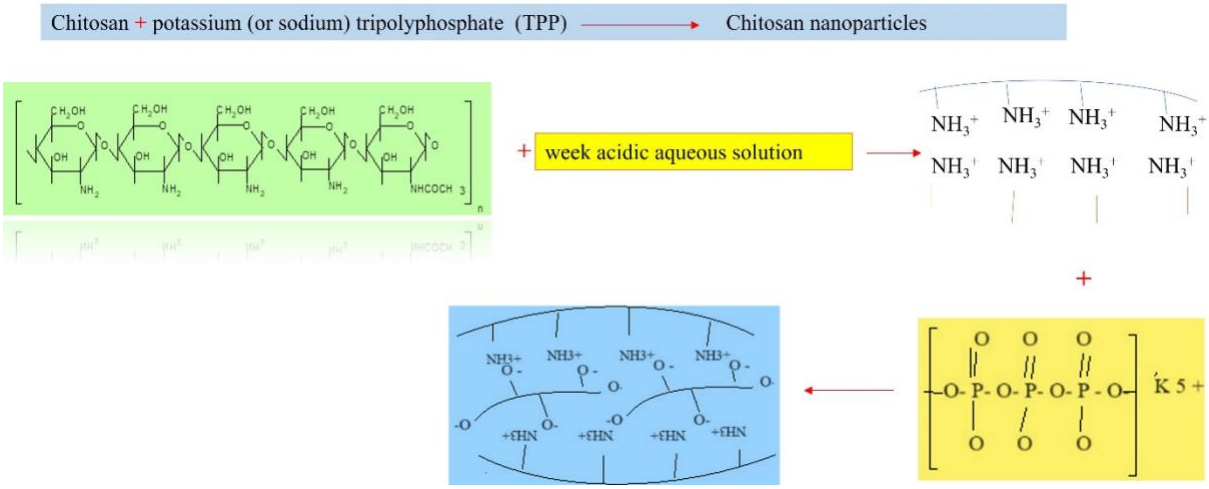

Figure 4. Fabrication of chitosan- nanoparticles from chitosan and sodium or potassium tripolyphosphate (TPP).

Several types of materials (biopolymers, BCs derived from plant extracts such as polyphenolic compounds, flavonoids, β-carotene, lycopene, EOs) demonstrate antioxidant effects. Oxidative and off-flavor compounds obtained from food products can be suppressed by antioxidants (Belitz et al., 2009). Carotenoids are sensitive to oxidation due to their characteristic conjugated double bond structure, and present chemical instability, when exposed to light, heat, and oxygen (Benbelkhir & Medjekal, 2022; Yin et al., 2024).

Biopolymers are the most commonly used materials to develop nanocarriers, as they allow for encapsulation, promoting BCs protection and controlled release, ensuring their effectiveness over time, as well as providing protection against environmental factors (Carvalho et al., 2025; Venkidasamy et al., 2025). Biodegradable polymers combined with nanofillers can prolong food shelf life by offering barriers to moisture and oxygen, while also potentially integrating antioxidant and antimicrobial capabilities (Gupta et al., 2024 a, b).

A comparison of nanosized chitosan versus bulk chitosan was illustrated in **Figure 3.**

Chitosan-based NMs, and chitosan- based nanofibers (NFs), have demonstrated promising potential to improve product stability, enhance delivery performance, and act as effective emulsion stabilizers (Ardekani-Zadeh et al., 2019; Haghighi et al., 2020; Liu et al., 2024; Vafania, et al., 2019). Chitosan NPs have been usually fabricated by a gelation procedure via electrostatic interactions between positively charged of amino groups ($-NH_3^+$) of chitosan and negatively charged of sodium tripolyphosphate (TPP) (Pateiro et al., 2021).

The TPP is non-toxic and thus the fabrication of chitosan NPs is a safe procedure. Chitosan NPs is much safer, when it is made with food-grade of TPP (Hosseini, and Jafari, 2020). Both chitosan: TPP ratio and pH of chitosan solution are affected the physicochemical characteristics [size, polydispersity index (PDI), zeta potential (ZP), surface charge)] of the NPs. Chitosan NPs or chitosan nanomaterials (NMs) create longer paths and stronger structures, and resulting nano- reinforced materials with enhanced MPs in comparison with conventional ones (Belitz et al., 2009; Benbelkhir & Medjekal, 2022)

Table 1: Resources, characteristics, properties, advantages, limitations, and disadvantages for chitosan, bioactive compounds in free form, encapsulation/ nanoencapsulation of bioactive compounds in chitosan, and their applications

NO	Item	Resources, Characteristics, Properties; Performances and Advantages	Limitations and Disadvantages	Overcome to limitations, Functions and Applications	References
1	Chitosan	Renewable resources; eco-friendly materials; biodegradable; biocompatible; non-toxic; film-forming, fiber forming; cationic nature, antioxidant and antimicrobial properties	Exhibits somewhat antioxidant and antimicrobial properties; the properties depend on degree of N-acetylation (DA) and molecular weight (M_w)	Suitable shell components or carriers for BCs; They used in food packaging systems, drugs, genes, nutrients, and cosmetics; Safe for use in food, medicine and healthcare settings;	Kasaai et al., 2020; Pérez-Álvarez et al., 2020; Torchilin, & Amiji,, 2020; Zhang et al., 2021
2	Nano-sized chitosan	Exhibits superior physical, chemical, and biological properties compared to its bulk counterpart	Safety and toxicity of nano-sized chitosan are needed to be determined	Nano-sized of chitosan or nanocomposite of chitosan has greater potential applications in different branches of food, medicine compared to bulk counterpart; Chitosan in nano-sized and as a free form has a greater efficiency in comparison with bulk counterpart;	Pérez-Álvarez et al., 2020; Zhang t al., 2021
3	Bioactive compounds (BCs)	Renewable resources; eco-friendly materials, safe; exhibit biological activity,	Their bioavailability, stability and solubility in water are low in free forms.	Encapsulation or nanoencapsulation is a suitable solution, Encapsulation enhances bioavailability and stability of BCs by diminishing volatility and augmenting chemical and thermal resistance; Encapsulation or nanoencapsulation is an advantageous method for safeguarding BCs from adverse environmental conditions (oxygen, light, moisture, pH); facilitates targeted release; nano-encapsulation enhances the delivery of BCs. Nanoencapsulation facilitates the development of functional foods with enhanced nutritional value and improved sensory properties. Nanoencapsulation technique involves enclosing BCs in nanoscale carriers	Chowdhury et al., 2024 ; Faridi Esfanjani et al., 2016 ; Sabaghi, et al., 2021; Wang et al., 2022; Yousefi et al., 2024.

3.Encapsulation of bioactive compounds in chitosan

Chitosan, presents a significant potential as a versatile and an effective material in delivery of BCs and drugs, providing numerous benefits (Bernkop-Schnürch, & Dünnhaupt, 2012; Desai et al., 2023; Naskar et al., 2019). The influence of chitosan (DA= 0.15, M_w = 650 kDa) protonation state and concentration on the physicochemical, rheological, thermal, and antioxidant properties of chitosan- based emulsions [conventional emulsion (CE) or Pickering emulsion (PE)] containing carotenoids from microalgae have been studied. All emulsions formed nano-capsules ranging from 265 to 470 nm. CEs stabilized by protonated chitosan, demonstrated higher zeta potentials and smaller increases in capsule size over a period of 30 days, indicating superior electrostatic stabilization. PEs exhibited gradual droplet growth over 30 days PE showed greater aggregation and lower zeta potential values, leading to reduced colloidal stability compared to conventional systems. Chitosan protonation influenced nano-capsule stability and bioactive release. PEs exhibited gradual droplet growth over 30 days. Thermodynamics showed strong chitosan–bioactive interactions. Dense interfacial layers delayed antioxidant release (de Farias et al., 2025). PEs stabilized by deprotonated chitosan, displayed lower surface charge and more significant capsule growth, implying particle clustering. Both types of emulsions (CEs and PEs) showed non-spontaneous, endothermic flow behavior. Antioxidant stability improved at higher chitosan concentrations in both systems, but via different mechanisms, (electrostatic interactions in CE and dense interfacial structuring in PE). Overall, increasing chitosan concentration resulted in enhanced emulsion stability and bioactive protection. These findings support the development of chitosan-based systems for encapsulating microalgal BCs (de Farias et al., 2025; Li et al., 2023).

Among the wide array of encapsulating materials, chitosan is an excellent one, due to its biocompatibility, biodegradability, AMA, AOA, and tunable physicochemical properties. Chitosan nanofibers (NFs), have demonstrated promising potential to improve product stability, enhance delivery performance, and act as effective emulsion stabilizers (Cui et al., 2020).

Chitosan coated with zein was used to encapsulate epigallocatechin gallate (EGCG) (the major polyphenol found in tea). EGCG-encapsulated in the composites exhibited antioxidant activity and has potential to be used as edible films to protect fatty foods against oxidative deterioration, as confirmed by the DPPH test (Liang et al., 2017). The encapsulated system may be used to release the bio-active compound (EGCG) in foods containing lipids.

Nano-encapsulation utilizes suitable nano-carriers such as chitosan, zein and alginate to resist enzymatic degradation, especially in the GIT to ensure controlled and sustained release of core BCs (Chowdhury et al., 2024). Different delivery methods associated with nano-encapsulation include nano-emulsions (NEs), NPs, association colloids, nanotubes, and nano-laminates. Nano-encapsulation is encouraged in the current scenario in agricultural and food applications, because of its higher stability and reduced volatility losses of BCs (Do Nascimento Junior et al.,2021). Moreover, BCs such as EOs and plant extracts are shielded from external environmental conditions like temperature, relative humidity, and light. The coating enables the biological integrity of the constituents and maintains their long-term vitality (de Oliveira et al., 2024).

The effect of chitosan alone and different formulations of chitosan grafted with karonda polyphenol extract (KPE) (chitosan-g-KPE) on the antioxidant machinery and quality attributes of plums during 40 days storage under cold storage conditions were investigated. The chitosan-*g*-KPE 1.0 % formulation retained the activity of enzymatic antioxidants defence including superoxide dismutase (SOD), catalase, and peroxidase compared to the uncoated and alone chitosan or KPE coated plums. Moreover, the functionalized chitosan coating with KPE significantly inhibited polyphenol oxidase (PPO), pectin

methylesterase and polygalacturonase activities. These results suggest that chitosan-*g*-KPE grafted coatings are a promising natural and innovative solution to extend plum shelf life, while preserving their nutritional quality (Jan et al., 2026). Black Golden prunus salicina fruits coated with chitosan- based showed delayed ripening and higher contents of non-enzymatic antioxidant contents like phenolic, flavonoids, anthocyanin, ascorbic acid and 2,2-Diphenyl-1-picrylhydrazyl (DPPH) activity, as well as enzymatic antioxidant activities such as ascorbate peroxidase and SOD (Adiletta et al. 2022). A variety of chitosan-BC combinations with nano-sized versus corresponding bulk combination counterparts were illustrated in **Figure 5.**

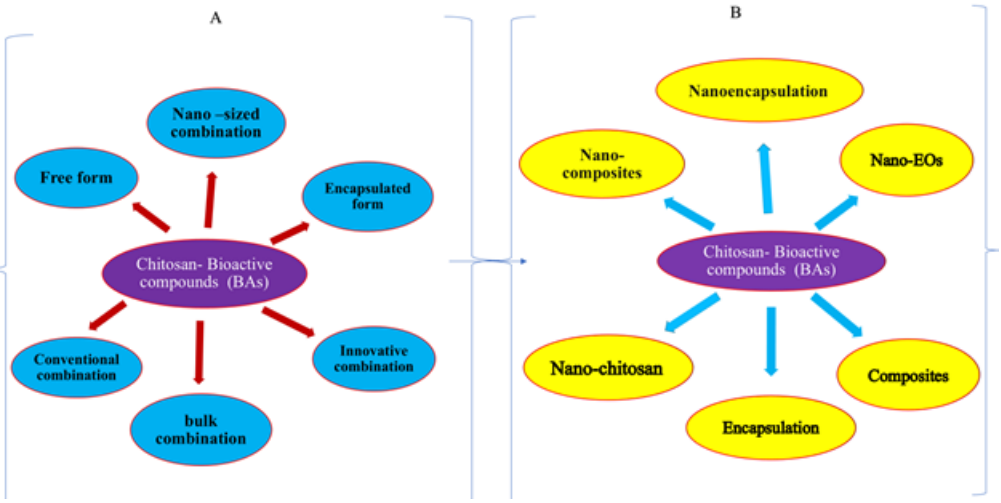

Figure 5. illustrates various chitosan- bioactive compound combinations with nano-sized versus bulk corresponding combination counterparts.

4.Applications of nanotechnology in encapsulation of bioactive compounds

Functional performance of BCs significantly was improved by their encapsulation into biopolymer-based films such as chitosan (Khezerlou et al., 2021). In pharmaceuticals, nanoencapsulation promises to revolutionize drug delivery by enhancing the bioavailability of poorly soluble therapeutics, minimizing side effects, and enabling targeted treatment of diseased tissues. Such advancements could redefine therapeutic efficacy and expand options for combating complex diseases. The nutraceutical and functional food industries stand to benefit significantly as well. By stabilizing and improving the bioavailability of bioactive ingredients, nanoencapsulation maximizes their health benefits, paving the way for innovative dietary supplements, fortified foods, and functional beverages that promote wellness. Beyond healthcare, nanoencapsulation holds promise for cosmetics, where it enhances the delivery of active ingredients for skincare, antiaging, and sun protection. In agriculture, it enables the precise delivery of agrochemicals, reducing environmental impact while boosting crop yields—a critical step toward sustainable farming (Wani and Naik, 2025). Chitosan was integrated with various bio NMs and BCs to enhance its hydrophobicity, mechanical strength, antimicrobial properties, antioxidant capacity, water vapor barrier (WVB), oxygen barrier (O_2B) characteristics, encapsulation efficiency, and to improve bioavailability for agricultural and food-related applications. For example, chitosan was combined with cellulose nanofibers to strengthen its MPs (Ventura-Cruz & Tecante, 2021). Copper NPs (Cu NPs) were incorporated into chitosan-polyvinyl alcohol (PVA) hydrogels and utilized in a native kidney-shaped tomato variety cultivated in greenhouse conditions. The impact of adding Cu NPs on the

postharvest behavior of the physicochemical components, including total soluble solids (TSS) and titratable acidity (TA), as well as BCs such as lycopene and β-carotene, and the levels of total phenols and flavonoids, along with the antioxidant capacity of the fruits during cold storage, was assessed (Hernandez-Fuentes, et al., 2023).

5.Critical Analysis of reported the existing Knowledge

By encapsulation of BCs in chitosan can overcome bioavailability issues, a major limitation for many hydrophobic BCs (dos Santos Oliveira et al., 2026). The nano systems had been employed to encapsulate BCs including phenolic compounds, EOs, vitamins, metal NPs, curcumin and quercetin, enabling controlled and sustained release (Avila et al., 2022). Chitosan nanofiber represents a suitable biopolymeric carrier for delivery of BCs, owing to its inherent biocompatibility, biodegradability, and biological (antioxidant or antimicrobial) activity, tunable pore sizes, chemical stability. Its porous structure allows for efficient encapsulation of BCs. However, solubilization in water and a low water vapor barrier (WVB) property can lead to a low performance and low encapsulation efficiency (dos Santos Oliveira, et al., 2026). To address these challenges, chitosan is frequently modified with hydrophobic polymers like zein and is additionally functionalized with polymeric compounds to create cross-links. These modifications enhance encapsulation efficiency and loading capacity (Kasaai, 2022; Kasaai, 2025). For instance, modification of chitosan-sodium caseinate combination with zein resulted in an increase in the encapsulation efficiency (Zhang et al. 2014). Curcumin was also encapsulated in chitosan-zein composites. The encapsulation efficiency of curcumin depends on the composite formulations (Jiang et al., 2020; Li et al., 2018).

Bioactive extracts from grape (jaboticaba, and hibiscus by-products) were nano-encapsulated using chitosan-tripolyphosphate (TPP) NPs. The nano encapsulated in preserving natural antioxidants, promote the valorization of fruit by-products, and advance the development of sustainable, thermally stable, and clean label food ingredients (dos Santos Oliveira et al., 2026). Chitosan NPs coated with zein have emerged as a promising system for encapsulating and delivering hydrophilic nutrients, enhancing their bioactivities. Additionally, a hydrophobic nutrient, α-tocopherol (TOC), was encapsulated within the chitosan-zein complex. The fabrication parameters, including zein concentration, zein-chitosan weight ratio, and TOC loading percentage, were thoroughly examined. Physicochemical and structural analyses indicated that electrostatic interactions and hydrogen bonds were the primary forces driving the formation of the chitosan-zein complex. Scanning electron microscopy (SEM) analysis revealed that the morphology of the chitosan-zein complex was spherical with a smooth surface. The encapsulation of TOC was further confirmed by differential scanning calorimetry (DSC). The particle size and zeta potential of the complex ranged from 200 to 800 nm and +22.8 to +40.9 mV, respectively. The kinetic release profile of TOC exhibited an initial burst effect followed by a gradual release. In comparison to zein NPs, the zein-chitosan complex offered superior protection for TOC and its release under GI conditions, attributed to the chitosan coating. The zein-chitosan complex represents a promising delivery system for the supplementation or treatment of hydrophobic nutrients or drugs. By coating TOC-zein NPs with chitosan, the particle size was significantly reduced, and the zeta potential was increased, depending on the specific formulations used. The chitosan coating did not impact the encapsulation efficiency but significantly enhanced the controlled release properties of TOC in both phosphate buffer saline (PBS) and simulated GI tract conditions, suggesting that the TOC-zein-chitosan complex can be developed for TOC (Luo et al., 2011).

A gastro-mucoadhesive matrix composed of ultrafine fibers was created using a composite of zein-poly (ethylene oxide) (PEO)- chitosan in a

ratio of 87.5:10:2.5 through the process of electrospinning. Mucoadhesive nanofibers loading α-TOC were electro-spun from zein–PEO- chitosan composite. The inclusion of α-TOC at a concentration of 20 wt % into the fiber matrix markedly enhanced the muco-adhesive of the composite fibers without affecting their morphology. Release characteristic studies revealed that the release of α-TOC in SGF at pH 1.2 with pepsin was initiated by degradation, while the release in simulated gastric fluid (SGF) at pH 2 without pepsin was triggered by rapid swelling followed by diffusion. SEM analysis showed the degradation and fusion of certain fibers, which reduced the release surface area at a later stage. The gastro-mucoadhesive and release properties of the composite electro-spun fibers suggest their potential use for delivering hydrophobic compounds to the GI tract (Wongsasulak et al., 2014). Typically, polymer solutions characterized by significant entanglement of polymer chains demonstrate elevated viscosity, facilitating the creation of larger electro-spun fibers. Additionally, a polymer solution with reduced electrical conductivity generally results in a diminished electrical repulsive force of the electrospinning jet, further contributing to the production of larger electro- spun fibers (Weiss et al., 2012; Wongsasulak et al., 2010; Wongsasulak et al., 2014). Chitosan films containing EO encapsulated in zein NPs can be applied in the preparation of active packaging films to prolong shelf-life of foods (Xavier et al., 2021). Chitosan-chlorogenic acid (CA) conjugate was developed with a substitution of CA on chitosan of 103.5 mg. $g.^{-1}$ Curcumin encapsulated in the chitosan-CA conjugate showed better heat stability than that in CA at temperatures 25 and 95 °C ($p < 0.05$). The release of curcumin was inhibited by the chitosan-CA conjugate. The total release amount of curcumin from chitosan and chitosan-CA-conjugate NPs were 70.5 and 61.7%, respectively ($p < 0.05$). A methyl thiazolyl tetrazolium (MTT) assay showed that the antiproliferative activity of curcumin in chitosan-CA NPs was remarkably higher than that in chitosan NPs, because of the higher chemical stability (Fan et al., 2017). The results suggest that chitosan- based NPs are promising candidates for the encapsulation, chemical stabilities and controlled release of hydrophobic BCs (Fan et al., 2017; Kasaai, 2026; Liu et al., 2026).

6.Conclusions

This review highlighted encapsulation of BCs in chitosan- based materials having different sizes encompassing bulk, micro-and nano-sized for different industrial applications. BCs possess several interesting properties and offer numerous health advantages. Nevertheless, they exhibit both chemical and physical instability, making them vulnerable to various forms of degradation. The limited solubility, inadequate bioavailability, and rapid release rates of BCs restrict their applications in food and pharmaceutical formulations. The encapsulation process protects BCs from biological deteriorations, environmental stressors, enhances their physicochemical properties, and boosts their health-promoting and anti-disease effects. Research conducted both *in vitro* and *in vivo* have shown that treatments utilizing nanotechnologies, NMs, nanocarriers, and nano-encapsulation methods are more effective than conventional technologies and bulk substances.

Among a wide array of encapsulating materials, chitosan is a unique one, due to its biocompatibility, biodegradability, AMA, AOA, positive charges, and tunable physicochemical properties. Chitosan stabilizes BCs (EOs, probiotics, enzymes, and flavors), enabling controlled release in the food products Chitosan- based materials has been employed in various fields of life sciences and technologies. Nanoencapsulation and co- nanoencapsulation of BCs in chitosan -based materials versus their corresponding conventional counterparts for different branches of food, medicine, nutrition and agriculture have been also compared. Studies conducted *in vitro* and *in vivo* have demonstrated that the treatment using nanotechnologies, NMs, nanocarriers, and nano-

encapsulation techniques were more effective than traditional technologies and bulk materials.

7.Future perspectives

Conventional technologies result in a low efficacy, whereas many potential benefits can be achieved from nanotechnology and NMs. Despite a variety of benefits, NMs, induced potential toxicity on human health. There exists a critical knowledge gap regarding their safety. The toxicity of NMs should be experimentally determined both *in vitro* and *in vivo*. The results can lead to the identification of safe dosage levels, a defined range of safety, and the potential risks linked to the applications of certain nano-sized NMs. Thus, the range of safety for each component should be experimentally determined. The toxicity of BCs and drugs was minimized by their encapsulation in NEs. The delivery of BCs to the targeted organs using encapsulation in chitosan and nanotechnology via encapsulation has been significantly improved.

8.References

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Abbreviations with their full names

Abbreviation	Expression, Term	Abbreviation	Expression, Term
AMA	Antimicrobial activity	NEs	Nano-emulsions
AMPs	Antimicrobial properties	NM	Nanomaterial
AOA	Antioxidant activity	NMs	Nanomaterials
AOPs	Antioxidant properties	NP	Nanoparticle
BC	Bioactive Compound	NPs	Nanoparticles
BCs	Bioactive compounds	O_2	Oxygen
CA	Chlorogenic acid	O_2B	Oxygen barrier
CE	Conventional emulsion	PBS	Phosphate buffer saline
CEs	Conventional emulsions	PDI	polydispersity index
Cu	Copper	PE	Pickering emulsion
DA	Degree of N-acetylation	PEO	poly (ethylene oxide)
DPPH	2,2-Diphenyl-1-picrylhydrazyl	PEs	Pickering emulsions
DSC	differential scanning calorimetry	PPO	polyphenol oxidase
EF	Encapsulation efficiency	PVA	polyvinyl alcohol
EGCG	epigallocatechin gallate	SEM	Scanning electron microscopy
EO	Essential oil	SGF	Simulated gastric fluid
EOs	Essential oils	SOD	Superoxide dismutase
GI	Gastrointestinal	TA	Titratable acidity
KPE	Karonda polyphenol extract	TOC	α-Tocopherol
M_W	Molecular weight	TPP	Tripolyphosphate
MTT	Methyl thiazolyl tetrazolium	TSS	Total soluble solids
MPs	Mechanical Properties	UV	Ultraviolet
NE	Nano-emulsion	WVB	Water vapor barrier