FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 10 No. 21, November, 2026, pp 235 – 244
DOI: https://doi.org/10.33003/fjs-2026-1021-6402

Zerovalent Iron Curcumin Chitosan Encapsulated Nanocomposite Beads: A Narrative Review of Stabilization Strategies, Synthesis and Characterization

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Received: 17 Oct. 2026
Accepted: 23 Oct. 2026
Published: 02 Nov. 2026

ABSTRACT

The zerovalent iron (ZVI) nanoparticles are highly promising materials for catalysis and environmental remediation due to their low cost, high surface reactivity and strong reducing power. However, their practical performance can be restricted as a result of rapid oxidation, passivation and agglomeration. This narrative review reveals ZVI stabilization and encapsulation, which focused on chitosan and curcumin as potential components of the biopolymer-based matrices. The literature is discussed thematically in relation to the stabilization mechanisms, synthesis and encapsulation strategies, characterization techniques, applications and the outstanding research gaps. The reviewed studies show that chitosan can offer a structural matrix and metal-binding functional groups, while the curcumin exhibits antioxidant properties that may contribute to the stabilization of the nanoparticle. Encapsulation in bead-based matrices may also facilitate handling of material and influence the transport and release behavior. However, the proof concerning these components individually or in a separate nanoparticle system does not establish that their combination improves the ZVI stability or treatment performance. Direct experimental evidence on incorporated chitosan-curcumin-encapsulated ZVI systems remains limited, revealing the need for systematic comparative studies. Future research should compare combined matrices with chitosan and curcumin individually systems, adopt complementary characterization methods to verify the composition, encapsulation and stability, evaluate the performance of contaminant removal, oxidation resistance, environmental status and safety under realistic conditions. This review revealed the potential of naturally derived encapsulating matrices while emphasizing that the advantages of the combined system require rigorous experimental validation before its practical suitability can be established.

Keywords: Zerovalent Iron, Chitosan, Curcumin, Encapsulation, Nanocomposite Beads, Characterization

INTRODUCTION

Nanotechnology has reshaped many scientific and industrial fields, including medicine, materials science and environmental remediation. A central outcome of this progress is the nanocomposite: a material that combines two or more components at the nanoscale to improve physicochemical properties, stability and performance (Aththanayaka et al., 2022). Such engineered materials have enabled advances in pollutant removal, targeted drug delivery and advanced manufacturing.

Among the nanomaterials under study, zerovalent iron (ZVI) nanoparticles have drawn particular attention because of their high surface reactivity, low cost and strong reduction capacity (Zeng et al., 2024). They can degrade or immobilize a wide range of contaminants, including heavy metals, chlorinated solvents and organic pollutants, which makes them valuable in water treatment and environmental remediation (Liu et al., 2019). Despite this potential, several inherent limitations hinder their practical use. ZVI nanoparticles oxidize readily on exposure to air and water, and the resulting oxide shell passivates the surface and markedly lowers reactivity (Pandey & Saha, 2022; Xu et al., 2022). Their high surface energy also favors agglomeration, which reduces the effective surface area available for reaction and therefore their efficiency as remediating agents (Kouhiyan Afzal et al., 2017). In addition, the behavior of unprotected ZVI toward pollutants under real environmental conditions is difficult to control, which can lead to uneven pollutant removal and raises concern about secondary environmental effects.

To overcome these drawbacks, further research has successfully encapsulated ZVI nanoparticles within biopolymers and other active compounds (Pandey & Saha, 2022). Chitosan, a naturally occurring polysaccharide with high adsorption capacity, biocompatibility and biodegradability, is an attractive stabilizer for this purpose (Jiménez-Gómez & Cecilia, 2020). By forming a matrix around the nanoparticles, chitosan can limit oxidation, improve dispersion and support controlled release, while its reactive functional groups promote interaction with contaminants.

Curcumin, a polyphenolic compound from turmeric, offers further functionality. Its antioxidant, antibacterial and anti-inflammatory properties are well documented (Hewlings & Kalman, 2017), it has been combined with metal nanoparticles to impart antimicrobial and antioxidant behavior (Alves et al., 2017), and it can act as a natural inhibitor of nanoparticle oxidation (Patra & El Kurdi, 2021). Incorporating curcumin alongside chitosan is therefore of interest for extending the functional life of ZVI-based materials and adding value for both water treatment and biomedical use. The studies on materials that has combined ZVI nanoparticle, chitosan and curcumin in bead form are of high interest for environmental remediation, where controlled removal of contaminants is important, and adopting the biocompatibility of the two materials, for drug delivery and antibacterial applications. The need for effective and sustainable cleanup technologies is growing as environmental contamination increases, and naturally derived polymer-based nanomaterials align with global trends in green nanotechnology. This review therefore aims to examine the stabilization mechanisms, synthesis strategies, characterization techniques and potential applications of nanoscale zero-valent iron encapsulated in chitosan curcumin.

Review Methodology

This work is a narrative review, aiming at reviewing the scientific evidence, the stabilization, the synthesis techniques, the characterization strategies, the applications, and the future scope of zero-valent iron (ZVI) nanoparticles stabilized or encapsulated using chitosan and curcumin-based matrices. A literature search was performed via Google, Google Scholar, and Scopus for the retrieval of all relevant peer reviewed articles published between 2010 and 2026. The search keywords used were ("zero-valent iron" or "nanoscale zero-valent iron" or nZVI) AND (chitosan or encapsulation or stabilization), ("curcumin" or "curcumin-mediated nanoparticles") AND (iron nanoparticles or ZVI), and ("chitosan and curcumin") AND ("nanocomposite or beads or encapsulation"). Search words were coupled with Boolean operators (AND, OR). Moreover, through screening of the reference list, additional publications were collected where possible.

Challenges of ZVI Nanoparticles

Despite these advantages, ZVI nanoparticles suffer from intrinsic limitations that reduce long-term efficiency and durability. The most prominent is rapid oxidation on contact with air or aqueous media (Jiang et al., 2015). Surface oxidation in the presence of water and oxygen produces iron oxide species containing Fe (II) and Fe (III), and the resulting passivation layer greatly reduces the ability of the particles to degrade pollutants or take part in other reactions (Jiang et al., 2015).

A second problem is the strong tendency of ZVI nanoparticles to aggregate. Their very small size and high surface energy give rise to strong interparticle attractive forces, and the resulting agglomeration decreases surface area, reactivity and reaction efficiency (Kouhiyan Afzal et al., 2017). Uncontrolled agglomeration also produces inhomogeneous dispersions, which complicates industrial and environmental use (Kouhiyan Afzal et al., 2017).

Zerovalent Iron

Overview of Zerovalent Iron

ZVI has attracted considerable research attention because of its wide use in environmental research, materials science and catalysis (Plessl et al., 2023). As a reactive material and an effective electron donor in redox reactions, it is well suited to chemical transformation, pollutant degradation and contaminant removal. Its ready availability, low cost and low toxicity further support its potential for broad industrial and environmental use (Zeng et al., 2024).

Applications of ZVI

The best-known application of ZVI is environmental decontamination, where it is used to treat wastewater, detoxify soil and clean up contaminated groundwater (Plessl et al., 2023). Its efficiency stems from its ability to drive redox reactions: Fe^0 donates electrons to contaminants, which are reduced to less harmful or insoluble forms (Crane & Scott, 2012; Calderon & Fullana, 2015). This is particularly effective for toxic heavy metals such as Manganese, lead, chromium and arsenic. ZVI has also been used to reduce nitrate in agricultural runoff and to dechlorinate chlorinated hydrocarbons such as trichloroethylene (TCE) and polychlorinated biphenyls (PCBs) (Han, 2016), and nanoscale ZVI and its composites have been applied to the removal of organic compounds more broadly (Li et al., 2021).

Beyond environmental science, ZVI is studied in catalysis, nanotechnology and materials synthesis. Its high surface reactivity makes it an active catalyst in organic synthesis and hydrogenation reactions (Zhu et al., 2023). ZVI can also generate reactive oxygen species (ROS) that break down organic pollutants, which has drawn interest in Fenton-like reactions (Yamaguchi et al., 2017) and makes ZVI relevant to advanced oxidation processes (AOPs) in wastewater treatment.

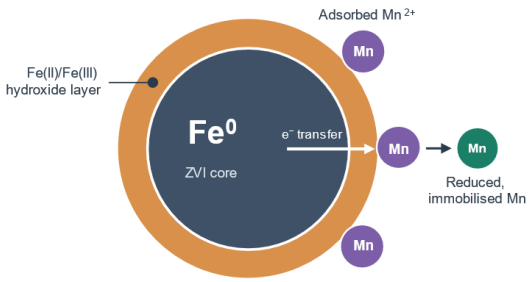


Figure 1: The Zerovalent Iron Nanoparticle Core Shell Redox Reaction with the Contaminant (Mn)

Encapsulation

Encapsulation is the production of micro- or nano-scale systems in which active molecules are enclosed within a biodegradable matrix or wall material. It is used widely in the food, pharmaceutical, cosmetic and agricultural sectors. Encapsulation protects labile bioactive compounds from

harsh conditions such as heat and oxygen, and it preserves the potency of volatile substances such as essential oils over time (Detsi et al., 2020). It can also provide targeted delivery and controlled release, improve handling by converting liquids into solids, mask unpleasant odors or flavors, and increase the aqueous solubility of bioactive compounds (Nedovic et al., 2011; Munin & Edwards-Lévy, 2011).

Many encapsulation methods have been developed for natural products such as extracts, pure bioactive compounds and essential oils, using a variety of matrices. Nanoencapsulation approaches are broadly divided into top-down and bottom-up methods. Top-down methods include emulsification and emulsification–solvent evaporation, whereas bottom-up methods include supercritical fluid processes, inclusion complexation, coacervation and nanoprecipitation (Detsi et al., 2020). The two strategies are often combined, and both hydrophilic and lipophilic bioactive compounds have been nanoencapsulated (Jafari, 2017). Microencapsulation, which covers particle sizes from about 1 μm to 1 mm, can be used to target active substances to specific sites. Its methods are commonly grouped as chemical, physico-chemical or physico-mechanical, and they include spray drying, spray congealing, emulsification, fluid-bed coating, ionic gelation, coacervation, centrifugal extrusion, melt extrusion, pan coating, solvent evaporation, polymerization and liposome entrapment (Jyothi et al., 2010). Emulsification, coacervation and supercritical fluid processing have been used for both hydrophilic and lipophilic molecules, whereas inclusion complexation, emulsification–solvent evaporation and nanoprecipitation have mainly been applied to lipophilic molecules (Detsi et al., 2020).

Encapsulation Techniques

Among the many available approaches, the most common are spray drying, ionic gelation, emulsification and simple or complex coacervation (Table 1). In spray drying, the bioactive compound is mixed with a matrix material and atomized into fine droplets by a nozzle or spinning wheel; hot air then evaporates the water and the dried particles are collected. The method is inexpensive, quick and simple, and it can convert liquid feeds into powders, improve stability, allow continuous large-scale production and lower storage and transport costs (Assadpour & Jafari, 2019).

Ionic gelation is a mild, simple and solvent-free way of producing stable nanoparticles. It relies on the interaction between oppositely charged macromolecules and a non-toxic multivalent species. Despite good loading capacity, its limitations include high polydispersity, pH sensitivity and relatively large particle size (Shetta et al., 2019).

Emulsification creates a heterogeneous system of two immiscible liquid phases, oil-in-water (O/W) or water-in-oil (W/O), in which one liquid is dispersed as droplets in the other. Because emulsions are inherently unstable, surfactants or other stabilizers are added (Lohith Kumar & Sarkar, 2018). O/W emulsions, in which oil droplets are dispersed in an aqueous phase and stabilized by biopolymers or food-grade surfactants, are used to encapsulate essential oils, and nanoemulsions have been widely applied to bioactive compounds in food processing (Lohith Kumar & Sarkar, 2018). Coacervation is among the oldest and most popular encapsulation methods in the food, cosmetic and pesticide industries. It involves the separation of two liquid phases from a colloidal solution and can be simple or complex depending on the number of polymers used; it is particularly suited to heat-labile components. Complex coacervates, however, can be unstable, and the process can be costly and involve hazardous chemicals (Detsi et al., 2020).

Much of this literature concerns food and pharmaceutical bioactives. Its principles, namely protection of the core, control of release and improved handling, are nonetheless directly relevant to the stabilization of reactive inorganic nanoparticles such as ZVI.

Table 1: Common Encapsulation Techniques Discussed in the Reviewed Literature

	Principle	Reported advantages	Reported limitations
Spray drying	Bioactive and matrix are atomized into hot air; water evaporates to give a dry powder	Inexpensive, quick, simple; continuous large-scale production; converts liquids to powders; lower storage and transport costs	Not specified in the sources reviewed
Ionic gelation	Interaction of oppositely charged macromolecules with a non-toxic multivalent species	Mild, simple, solvent-free; good loading capacity	High polydispersity, pH sensitivity, relatively large particle size
Emulsification	Dispersion of one liquid as droplets in an immiscible liquid (O/W or W/O), stabilized by surfactants or biopolymers	Widely used for essential oils and bioactive compounds (nanoemulsions)	Emulsions are inherently unstable and need stabilizers
Coacervation	Separation of two liquid phases from a colloidal solution (simple or complex)	Long established; suited to heat-labile components	Complex coacervates can be unstable, costly and involve hazardous chemicals

Curcumin in Nanotechnology

Chemical Properties of Curcumin

Curcumin is a diarylheptanoid polyphenol in which a β-diketone methane unit carries two feruloyl groups; it occurs naturally in the roots of Curcuma longa and is chemically related to ferulic acid (National Center for Biotechnology Information [NCBI], 2025). It is classed as a polyphenol, β-diketone, enone and aromatic ether. PubChem records a broad set of roles for the compound, including anti-inflammatory, antineoplastic, hepatoprotective, neuroprotective and immunomodulatory activity, as well as roles as a coloring agent, an iron-chelating agent and an inhibitor of several enzymes such as histone deacetylase (NCBI, 2025). The ability of curcumin to participate in metal-containing systems has also been demonstrated through the synthesis and characterisation of curcumin-based metal complexes, highlighting its potential relevance in the development of functional metal-containing material (Olusola et al. 2025). Its iron-chelating and antioxidant character is of particular relevance to iron-based nanomaterials.

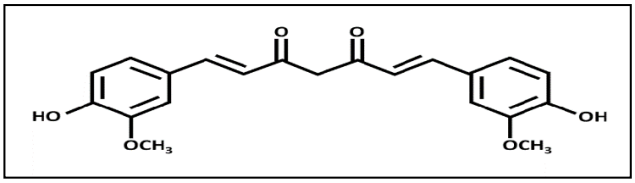


Figure 2: Chemical Structure of Curcumin (Akinremi et al., 2018)

Role of Curcumin in Nanotechnology

Metal nanoparticles such as gold, silver and ZVI are prone to aggregation and oxidation because of their chemical reactivity and high surface energy. On exposure to air or water, surface oxidation can diminish their performance in biomedical applications, contaminant degradation and catalysis (Patra & El Kurdi, 2021). One of the main roles of curcumin in nanotechnology is to mitigate this problem: it can act as a natural inhibitor of oxidation, slowing the process and helping to preserve the reactivity and structural integrity of nanoparticles over time. Curcumin can also interact with nanoparticle surfaces and form a protective layer that hinders agglomeration and promotes uniform dispersion in solution. This is especially relevant to ZVI, which tends to form iron oxide shells that reduce its effectiveness in environmental cleanup.

Curcumin is widely applied in biomedicine through nanoparticle-mediated delivery, especially for anti-inflammatory, anticancer and antibacterial therapy (Olusola et al. 2025; Saberian et al., 2025). Its pharmacological potential is limited by its hydrophobic character and rapid metabolism, which result in poor bioavailability. To address this, curcumin has been entrapped in nanocarriers such as liposomes, polymeric nanoparticles and metallic nanocomposites, which improves its solubility and stability and can increase absorption and circulation time (Saberian et al., 2025).

Because curcumin can regulate inflammatory pathways at the molecular level, it has also been incorporated into nanomedicine formulations for chronic inflammatory diseases. Curcumin-functionalized nanoparticles show antimicrobial and anti-inflammatory activity and have been used in infection prevention, wound healing and tissue engineering (Kumari et al., 2022). In oncology, curcumin-loaded nanoparticles have shown improved targeting of tumor tissue and suppression of tumor growth with less damage to surrounding healthy tissue (Hafez Ghoran et al., 2022).

Chitosan as an Encapsulation Matrix

Properties of Chitosan

Chitosan is a natural biopolymer obtained by deacetylation of chitin, the second most abundant natural polymer after cellulose, which is derived mainly from the exoskeletons of crustaceans such as prawns, crabs and lobsters. Chitosan is used in pharmaceuticals, biotechnology and environmental science because it is non-toxic, biodegradable and biocompatible (Detsi et al., 2020). Its amino groups make it cationic, so it can interact with negatively charged species such as metal ions, proteins and cell membranes. Together with its high adsorption capacity, this makes chitosan well suited to metal chelation, pollutant removal and drug encapsulation (Detsi et al., 2020).

Chitosan is also highly hydrophilic and has a high affinity for metals, which supports its gelation and its formation into membranes and films (Hsu et al., 2024). It has intrinsic antioxidant and antibacterial activity, which is useful in wound healing, food preservation and pharmaceutical products (Vinsová & Vavríková, 2011). In nanotechnology, chitosan serves as an encapsulant and stabilizer that can protect nanoparticles against oxidation and agglomeration, and it can improve dispersion, functionality and structural quality when combined with functional materials such as curcumin and ZVI (Detsi et al., 2020; Kpomah et al., 2025; Raza et al., 2020).

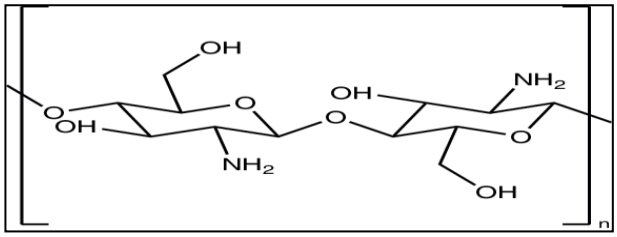


Figure 3: Chemical Structure of Chitosan [Akinremi et al., 2018]

Applications of Chitosan in Nanotechnology

The chemical structure of chitosan makes it applicable to stabilization, controlled release and encapsulation of nanoparticles. Its most promising uses are in biomedical nanotechnology, including tissue engineering, wound healing and drug delivery (Frigaard et al., 2022; Yanat & Schroën, 2021). Chitosan nanoparticles can encapsulate and protect drugs and bioactive compounds and release them under controlled conditions. They increase the solubility and bioavailability of hydrophobic drugs such as curcumin, which is valuable in cancer therapy (Yanat & Schroën, 2021). Owing to its mucoadhesion and biocompatibility, chitosan has been used to make nanocarriers for oral, nasal and transdermal drug delivery (Frigaard et al., 2022).

Outside medicine, chitosan is important in water purification and contaminant removal (Bhatt et al., 2023). Its ability to chelate metal ions makes it suitable for removing heavy metals such as lead, mercury and arsenic from wastewater, and chitosan nanocomposites have adsorbed organic pollutants such as dyes, pesticides and pharmaceuticals. Combining chitosan with other nanomaterials, including activated carbon and ZVI, has produced improved filtration systems that adsorb and neutralize pollutants effectively (Bhatt et al., 2023). Chitosan has also been used in food preservation and packaging: its antibacterial nature extends shelf life, and chitosan nanocoatings can protect fresh vegetables, meat and dairy products from oxidative degradation and microbial growth (Mihai & Popa, 2015; Kpomah et al., 2025).

In regenerative medicine and tissue engineering, chitosan scaffolds support bone and cartilage regeneration and wound healing by providing an environment conducive to cell proliferation, differentiation and tissue regeneration. These scaffolds can be functionalized with growth factors or other bioactive molecules to promote healing (Rajinikanth et al., 2024). Biodegradability, tunable functionality and the ability to stabilize nanostructures underlie the versatility of chitosan across materials science, environmental remediation and medicine.

Advantages of Chitosan Encapsulation

Encapsulating ZVI nanoparticles in chitosan offers several advantages. The most significant is stabilization: chitosan forms a barrier around the nanoparticles that protects them from rapid oxidation and clumping, which allows them to keep their reactivity for longer and improves their performance in pollutant removal and water purification (Huang et al., 2021). Chitosan also supports controlled reactivity through slow and sustained availability of ZVI (Fan et al., 2020), which benefits long-term systems such as slow-release remediation technologies. In addition, chitosan is reported to improve the biocompatibility of the nanocomposite, which supports its use in environmental and biomedical settings such as drug delivery and antibacterial treatment.

Nanocomposite beads: Synthesis and Applications

Overview of Nanocomposite Beads

Nanocomposite beads are materials designed to encapsulate nanoparticles within a polymer matrix, thereby improving their stability and functionality in different applications (Darwish et al., 2022). They are useful in catalysis, water purification and medicine because they improve the dispersibility and functionality of the embedded nanoparticles. By enclosing the particles in a polymer matrix, beads avoid the aggregation and rapid degradation that limit free nanoparticles. A further strength is the ability to regulate the release and functionality of embedded nanoparticles, which favors long-term reactivity applications such as controlled drug release and pollutant degradation in wastewater treatment. Beads also offer greater structural stability and mechanical strength, allowing them to withstand varied environmental conditions (Darwish et al., 2022).

Methods of Synthesis

Several techniques are used to prepare nanocomposite beads, each aimed at properties such as good dispersion of nanoparticles, improved stability and controlled porosity. Chitosan beads production methods include crosslinking and co-precipitation (Pu et al., 2017). Co-precipitation is widely used because of its efficiency and ease in producing stable nanocomposite structures; nanoparticles and polymer precursors are precipitated together in solution to achieve uniform encapsulation (Bayat et al., 2018). It is especially effective for metal-based nanocomposites used in environmental and catalytic applications. The sol–gel process makes stable, highly porous materials through condensation and hydrolysis reactions that build three-dimensional networks with high surface area and controlled porosity (Budnyak et al., 2015). Such materials are useful in biomedical fields, catalysis and other applications in which surface interactions are critical.

Electrospinning, in which a polymer solution containing nanoparticles is subjected to a high-voltage electric field, is mainly used to produce nanofibrous materials with high surface-to-volume ratios and high mechanical strength. These are applied in tissue engineering, filtration membranes and drug delivery (Çamlik et al., 2025). To improve functionality and durability, crosslinking is also routinely applied (Narayanan & Han, 2017). By chemically linking polymer chains, crosslinking increases mechanical stability and water resistance and helps control the release of encapsulated nanoparticles. It is especially important in drug delivery, where slow release sustains therapeutic activity and reduces side effects (Narayanan & Han, 2017).

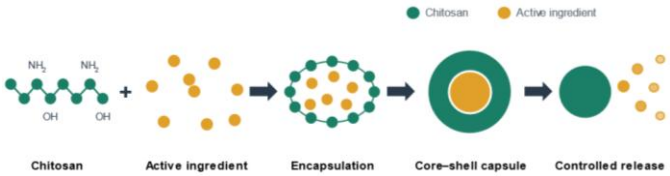


Figure 4: Encapsulation of Chitosan with Various Active Ingredients

Table 2: Comparative Studies of Magnetic Polymeric Based Fabrication Mechanism and Their Applications

Primary mechanism	Applications	**References**
Zerovalent Iron chitosan beads	Entrapment of hexavalent chromium	Liu et al.,2010
Magnetic Chitosan Beads of Fast Kinetics and high capacity	Copper removal	Jiang et al.,2014
Magnetic hydrogel beads of chitosan with sodium citrate	Heavy metal removal	Pu et al., 2017
Metal NPs supported chitosan coated carboxymethyl cellulose bead	Removal of 4-Nitrophenol	Nujud et al.,2022
Magnetic chitosan coated Iron based	Curcumin nanocarrier	Parso et al., 2025
Iron Cassava Peel nanoparticles	Degradation of pharmaceutical wastewater	Akoji et al., 2026

Characterization Techniques for Nanocomposites

Several complementary techniques are used to establish the structure, composition and functionality of synthesized nanocomposite beads (Arora et al., 2021; Gobena & Woldeyonnes, 2024; Kpomah et al., 2025). The combined use of spectroscopic, structural and morphological techniques has also been demonstrated in curcumin-based metal systems, where techniques such as FTIR, UV–Vis spectroscopy, XRD and electron microscopy were used alongside biological and in-silico assessments to characterize the synthesized complexes (Olusola et al., 2025). Together they describe the morphological, chemical and physical characteristics of the composite and help confirm that chitosan, curcumin and ZVI have been incorporated into the matrix (Table 2).

Fourier transform infrared spectroscopy (FTIR) is the primary method for identifying functional groups. Characteristic peaks for hydroxyl (–OH), amine (–NH_2) and carbonyl (–C=O) groups make FTIR especially useful in verifying encapsulation of ZVI in a chitosan–curcumin matrix (Gobena & Woldeyonnes, 2024). Changes in these peaks indicate interaction between the biopolymer matrix and the iron nanoparticles, which is consistent with integration and stabilization (Arora et al., 2021).

Scanning electron microscopy (SEM) is used to examine surface morphology. High-resolution imaging gives information on the size, shape and distribution of nanoparticles within the polymer matrix (Gobena & Woldeyonnes, 2024), together with surface roughness, porosity and structural homogeneity, all of which influence reactivity and performance (Arora et al., 2021). The microstructure also shows whether nanoparticles are dispersed or aggregated. X-ray diffraction (XRD) provides structural analysis and information on crystallinity (Arora et al., 2021; Gobena & Woldeyonnes, 2024). Phase composition, crystallite size and degree of crystallinity can be inferred from the patterns: peaks attributable to zerovalent iron support its presence in the composite, whereas additional peaks may indicate iron oxides or other phases (Arora et al., 2021; Gobena & Woldeyonnes, 2024). Knowledge of the crystalline state matters because it bears on the chemical stability and reactivity of the material (Arora et al., 2021).

Transmission electron microscopy (TEM) gives very high-resolution images at the nanoscale and allows individual nanoparticles in the chitosan–curcumin matrix to be visualized. Whereas SEM shows the surface, TEM reveals the interior of the sample, including particle size and entrapment (Gobena & Woldeyonnes, 2024). TEM is therefore important for confirming that ZVI nanoparticles are evenly dispersed and properly enclosed in the biopolymer, since encapsulation success directly affects performance in catalysis, controlled drug release and pollutant degradation (Gobena & Woldeyonnes, 2024).

Dynamic light scattering (DLS) and thermogravimetric analysis (TGA) measure particle size distribution and thermal stability, respectively (Arora et al., 2021; Gobena & Woldeyonnes, 2024). TGA gives the decomposition profile of the composite and thus its thermal resistance, which matters for applications under diverse environmental conditions. DLS gives the hydrodynamic size of nanoparticles in solution, which is informative about dispersibility and tendency to agglomerate. Combining these platforms allows the physicochemical characteristics of the beads to be assessed against the structural and functional demands of their intended use, whether catalysis, biomedical work or environmental purification.

Table 3: Characterization Techniques of Chitosan Curcumin-based ZVI Nanocomposite Matrices

Technique	Information Obtained	Relevance to encapsulated ZVI beads
FTIR	Functional groups (–OH, –NH_2, C=O); peak shifts	Indicates interaction between the biopolymer matrix and iron nanoparticles
SEM	Surface morphology, size, shape, distribution, roughness, porosity	Shows whether nanoparticles are dispersed or aggregated and whether the matrix is homogeneous
XRD	Crystalline structure, phase composition, crystallite size, crystallinity	Peaks for Fe^0 support its presence; extra peaks may indicate iron oxides or other phases
TEM	Internal structure at the nanoscale; particle size; entrapment	Confirms even dispersion and proper enclosure of ZVI in the matrix
DLS	Hydrodynamic size and size distribution in solution	Informs dispersibility and tendency to agglomerate
TGA	Decomposition profile and thermal stability	Indicates thermal resistance under varied conditions

Applications of Nanocomposite Beads

The stability, reactivity and versatility of nanocomposite beads make them useful across many sectors. In water purification they serve as key removal agents for pollutants, adsorbing organic contaminants such as pesticides and dyes as well as metals such as lead, arsenic and mercury; their porosity maximizes contact between reactive nanoparticles and contaminants (Tesh & Scott, 2014). In pharmacy, beads have been studied extensively as controlled-release systems, in which targeted and sustained release from a polymer–nanoparticle matrix can optimize therapy and reduce adverse effects. This is especially helpful in chronic diseases such as cancer, diabetes and cardiovascular disease, where prolonged drug activity is needed (Mishra et al., 2019).

Beads also serve as high-surface-area, stable supports for catalytic nanoparticles, providing a controlled environment for oxidation, reduction and degradation reactions in chemical synthesis, fuel development and decontamination (Liao et al., 2019). In biomedical engineering they have been used in wound healing and tissue repair, and, being biocompatible and biodegradable at controlled rates, they can support tissue growth and protect against infection in implanted devices; they are also used in antimicrobial coatings that reduce bacterial colonization of surfaces and medical devices (Liu et al., 2022). In food packaging, nanocomposite materials with antimicrobial properties limit bacterial growth and spoilage, extending shelf life and improving food safety while reducing waste in the supply chain (Gupta et al., 2023).

CONCLUSION

The zerovalent iron (ZVI) nanoparticles provide considerable potentials for the environmental remediation due to their high reactivity and reducing ability. Even though literature reveals that the oxidation, passivation and agglomeration have the capacity to limit their practical performance. The nanoparticle stability, dispersion, handling and controlled reactivity might be improved by the encapsulation of chitosan-based matrices potentially incorporated with curcumin via the complementary properties of chitosan and curcumin functional groups.

However, the literature reports on the combination of ZVI-curcumin encapsulated with chitosan remains limited, and the anticipated benefits of this approach have not been established sufficiently via direct comparative experimental studies. The systematic studies of comparing chitosan separately, curcumin separately and in combined matrices are therefore required, which should be supported by complementary structural and physicochemical characterization, quantitative evaluation of oxidation resistance including treatment performance under realistic conditions and assessment of environmental safety. The validation would reveal whether the naturally derived matrices would provide practical

advantages for developing a stable and sustainable ZVI-based polymeric materials for waste water treatment and other relevant applications. The future study should be focused on ZVI strong tendency to aggregate including experimental approach to the nZVI curcumin chitosan bead

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper**.**

CREDIT AUTHOR STATEMENT

M.A.O: Conceptualization, data curation, formal analysis, investigation, methodology, resources, software, writing – original draft.
O. S. O.: Data curation, Investigation, Methodology, Validation, Software, Writing – original draft, Writing – review & editing.
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M.A.D: Formal analysis, Methodology, Resources, Validation, Visualization, Writing – review & editing.
T. A. A.: Data curation, Investigation, Methodology, Validation, Software, Writing – original draft, Writing – review & editing.

FUNDING ACKNOWLEDGEMENT

No funding was received for this study.

ETHICAL APPROVAL

Not applicable

CONSENT TO PARTICIPATE AND CONSENT TO PUBLISH DECLARATIONS

Not applicable

DATA AVAILABILITY STATEMENT

The datasets generated and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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