Advances in chitosan biopolymer composite materials: from bioengineering, wastewater treatment to agricultural applications

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Keywords: chitosan, carbon nanocomposites, bio-engineering, wastewater treatment, agricultural applications

Abstract
Chitosan has become the most known and second abundantly available recyclable, non-hazardous and eco-friendly biopolymer after cellulose with several advantageous biomedical, agriculture, and wastewater treatment applications. As nanotechnology has progressed, researchers have begun incorporating chitosan-based carbon compounds into various compounds, elements, and carbonaceous materials to increase their efficiency and biocompatibility. Chitosan carbon compounds have also been used directly in many applications due to their inherent chelating and antibacterial features and the presence of customizable functional groups. This review widely discusses the properties and synthesis of chitosan and chitosan composite. It also discusses the modification of chitosan with different compounds, metals, carbonaceous materials, and agriculture residues to allow their use on an industrial scale. Recent advances in the use of chitosan in biomedical, agro-waste management, agriculture, wastewater treatment, and a few other applications (such as food packaging, cosmetics, and the textile and paper sector) are briefly discussed. Furthermore, this analysis reveals that chitosan and its composite materials are potential, low-cost products for environmental clean-up that can be made with basic manufacturing procedures.

1. Introduction
For the past two decades, the need for natural, sustainable, and renewable materials has increased to reduce the impact on the environment due to the industrial revolution and modern industries. It has encouraged scientists to look for more eco-friendly materials and chemicals. Biomass has garnered much attention due to its low cost
Chitosan is an example of such an environmentally favorable resource. Chitosan, also called deacetylated chitin, can be classified as a naturally occurring polycationic linear polysaccharide formed by fragmentary chitin deacetylation. Widely known as one of the most copious natural polysaccharides that are only second to cellulose, chitin is present inside the exoskeletons of insects or crustaceans, including crabs or shrimp fungus cell walls, as discussed further in this paper. Chitosan is made from chitin that has been deacetylated. Chitosan is made up of 14 linked 2-acetamido-2-deoxy-D-glucose molecules of N-acetylglucosamine. Chitin is structurally identical to cellulose, except for the C2-portion containing acetamide groups (\(\text{NHCOCH}_3\)). Chitin has shown similarities to other materials, unlike Chitosan, a linear polymer generated using (14)-linked 2-amino-2-deoxy—D-glucopyranose and is generated using N-deacetylation is a copolymer of the compounds N-acetylglucosamine and glucosamine and is characterized by the amount of deacetylation \([1]\). At each measure of distance between 10 and 10.5 Å, a turn is present along the chain. Chitosan is divided into three types: alpha chitosan, beta chitosan, and gamma chitosan. Alpha-chitosan is the most prevalent of them. Chitosan’s reactive functional group is likewise divided into three distinct categories of C2, C3, and C6 \([2]\). Figure 1 represents the basic structure of the chitosan bio-polymer.

Chitosan is an indigestible fiber that can electrostatically attract and bond with negatively charged dietary lipids, preventing them from being absorbed. Chitosan’s hemostatic effect is based on an ionic contact between the cationic chitosan polymer and the anionic membranes of red blood cells; it even acts when fibrin is present. Positive zeta potentials are formed as a direct consequence of the widespread existence of amino groups on the exterior of chitosan. Due to a pKa of nearly 6.5, chitosan’s amino groups generally tend to be present in a protonated form at neutral or acidic pH and thereby help stabilize the nanoparticles \([1]\). On the contrary, the physiochemical features of chitosan can tend to change based on factors such as the amount of deacetylation, molecular masses, and pH. Multifarious derivative forms of chitosan derivatives have been created to derive or control the physicochemical features of chitosan polysaccharides. Chitosan can be classified based on its inherent features such as viscosity, quality, shape, molar weight, purity, and amount of acetylation \([3]\). The amount of acetylation and the molar weight are the most important features of all for characterization owing to their strong influence over the performance, manufacture, characterization, and resultant application of chitosan.

Chitosan has also emerged as one of the most widely used materials across industries such as the cosmetics industry, textile industry, food industry, paper industry, biotechnological applications, pharmaceutical industry, medicine, and agricultural applications due to its promising biological and physicochemical qualities \([4]\). Chitosan is used in water treatment because of its good flocculant properties, and for COD of organic substances, metal ions, solids, and dangling solids, it has qualities including quick deposition speeds and a larger withdrawal efficiency \([5]\). Chitosan is used in agriculture as a means of preventing plant diseases. The toxicity of these compounds was discovered and their ability to suppress the germination and spread of fungi. Further, they have shown promise in fighting viruses, germs, and other microorganisms. Nontoxic, mucous, hemocompatible, biodegradable, anticancer, antioxidant, and antibacterial characteristics are only some of the chitosan’s biological features. These characteristics make chitosan an extremely exciting biomaterial for different types of biological utilization. Because of their antioxidant, cleaning, protective, humectant, and antioxidant properties, chitosan, and its derivatives are frequently utilized in cosmetics \([6]\). It can also function as a cross-linking instrument between fibers inside the paper. Increasing the chitosan dose will help improve the physical attributes of paper, including its tensile strength and water absorption, but will not affect the brightness of the paper.

A key indication of the wide presence and consequent significance of both Chitin and Chitosan is their abundant presence across multifarious organisms in nature. Chitin and Chitosan are widely present in Marine...
Animals such as Annelids, Molluscs, Coelcentrates, Lobsters, Crabs, Shrimps, Prawns, or other Crustaceans. They are also present in microorganisms such as Green Algae, Mycelia Penicillium, on Fungi, Spores, Yeast, Chytridiaceae’s cell walls Ascomyces, and Blastocladiaceae [7].

2. Understanding chitosan-based carbon nanomaterials

Chitin is considered the most commonly found natural polysaccharide, only second to cellulose. It is a fairly inexpensive and readily available substance. Chitin, also known as poly-(1→4)-N-acetyl-glucosamine, is prevalent in three major structures classified into α, β, and γ and possesses organized crystalline microfibrils that give birth to the structural features present inside yeast and fungi cells. It could be termed the most crucial derivative of chitin [8, 9]. Chitin and chitosan are widely prevalent in natural sources or organisms such as annelids, crustaceans, Mollusca, spiders, ants, and fungi. On the same lines, CT and CS can be classified as linear polysaccharides, which contain two monomeric units, one in the form of N-acetylated groups or N-acetyl-2-amino-2-deoxy-d-glucose and one with N-deacetylated groups with amino acids or 2-amino-2-deoxy-d-glucose residues. Further, as CT substances can accommodate lower amounts of the latter compound, they show low solubility in acidic solvents, whereas the samples of CS accommodate lesser quantities of the former compound which means it possesses less solubility inside acidic solvents. Most authors consider CT and CS as polymers possessing the quantity of 2-amino-2-deoxy-d-glucose units lesser and more than 60%, respectively [10].

As indicated earlier, chitosan is mostly used in the health and food industries, as indicated earlier, amongst other polysaccharides. It could be called a copolymer connected to (1→4)-amino-2-deoxy-D-glucan and 2-acetamido-deoxy-D-glucan [8]. The availability of amino and hydroxyl groups, which are known to be the most suitable compounds for supporting tonnes of multiple organic metal complexes, takes the credit for making chitosan a suitable nominee to be used in the form of a precursor in heterogeneous and molecular catalysts [11, 12]. Also, these amino and hydroxyl groups in chitosan play a vital role in making chemical modifications possible and fetching for hybrid material preparation [13].

Moreover, chitosan is acquired through the alkaline deacetylation of chitin. It has features including biodegradability and biocompatibility, non-toxicity, antimicrobial as a polymer with the ability to form film and counter heat.

Chitosan has a positive charge and good solubility in solutions with a pKa value between 6.2 and 7, or the acid-to-neutral range. By endeavor of its bio-adhesive properties, CS with diverged metals in solution [14, 15]. The Chelation of CS depends on -NH2 groups in the C-2 position and the reaction deftly executed here by the quaternization of the -NH2 groups [16]. According to the opinions of various researchers, chitosan, owing to its excellent physical, biological, and chemical properties, has shown great promise for being used in applications across multiple fields.

2.1. Properties of chitosan-based carbon nanomaterials

Being used in applications across multiple fields, the unique properties of chitosan, such as adsorption, flocculation, and coagulation abilities, have enabled it to replace other materials which are not as compatible and cost a lot. This motivates many researchers to study chitosan. The chemical structure of chitosan, as opposed to other polysaccharides (cellulose or starch), allows for particular alterations to build polymers for specialized uses. It has a great electrostatic attraction mechanism. It is natural, low-cost, biodegradable, and the second-most abundant biopolymer [17].

As it is formed due to the deacetylation of chitin, the amount of deacetylation decides its variety of properties like solubility, relative molar mass, pKa, and viscosity. The degree of acetylation is linearly linked to biodegradability and inversely linked to biocompatibility, solubility, and viscosity. Water, bases, and other organic solvents are solvents in which this natural polymer is not soluble; nevertheless, it is soluble in acetic, citric, or formic acids, as well as phosphoric, perchloric, or hydrochloric acid solutions [3]. It has some interesting properties that help it be used in pharmaceuticals and the medical sector, such as high antibacterial effects, being very biodegradable and biocompatible, and non-toxicity. It is antitumor, hemostatic, analgesic, antimicrobial, hypocholesterolemic, and antioxidant. Different factors also directly influence the biodegradation kinetics of chitosan and chitin, such as the dimensions of the polymer chain and the spread of acetyl groups [18]. Chitosans are modified by using additives, reagents, elements, or compounds to enhance their adsorption capacity, electrochemical performance, and mechanical properties, as reported by several researchers [3]. To enhance the properties of chitosan, chitosan composites are being formed as shown in table 1.

On the one hand, their reactive groups can create composites with a variety of compounds that have been shown to have a higher potential to absorb wastewater contaminants and to withstand an acidic environment.
Table 1. Enhancement in properties and applications as a result of chitosan Composite formation.

| Chitosan based nanomaterial | Properties enhanced                                                                 | Possible applications                                                                 | References |
|----------------------------|------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|------------|
| Chitosan with clay (Montmorillonite) | Improved mechanical strength, provided bioactivity                                    | Regeneration of bones, Delivery of Drugs, Healing Wounds, and healing biosensing.     | [19]       |
| Chitosan coated with coconut husk | Increases adsorption capacity of chitosan                                          | Wastewater treatment (removing heavy metals like Cr, Pb, etc)                         | [20]       |
| Chitosan coated on Fe₃O₄ | Protect oxidation to hematite, and colloidal stability reduces contact effect        | Antitumor                                                                            | [21]       |
| Chitosan intercalated with Ag | Improved antimicrobial efficacy, high antibacterial activity                         | Biomedical                                                                           | [21]       |
| Chitosan with PVA and TiO₂ (TCP) | Mechanical integrity (TCP 3%, elastic modulus achieved 0.2–3 GPa), cell viability increases (TCP 0.5% achieved 100% viability) | Biomedical                                                                           | [22]       |
| Chitosan/PLGA-PEG | Hydrophilic surface, flexibility, increases cell survival rate, mechanical properties (Chitosan/PLGA-PEG with 7:3 ratio achieved tensile strength of 12.63 MPa), flexibility increases cell survival rate, cell adhesion (OD value in 3 days −1.7) | Biomedical                                                                           | [23]       |
| Chitosan/alginate | Adsorption capacity (2.5 times more at 0 °C, electrical conductivity)               | CO₂ capture                                                                          | [24]       |
| Chitosan/carbon-dots (CD) | UV-visible blocking (20% transmittance reduced), thermal stability (at 250 °C, CD increases weight loss decreases by 29%) mechanical stability (tensile stress increased by 12.3 MPa with 0.3% wt CD) improves wettability (contact angle −78.02°) | Medical and industrial uses                                                           | [25]       |
| Chitosan/helical carbon/PAF/sodium dodecyl sulphate | Smooth surface, separation efficiency (98.5% dyes rejected), antifouling (hydrophilicity increases as contact angle achieved is 44.4°) | Selective separation and waste water treatment                                         | [26]       |
| RGO/chitosan/Ag | Photocatalytic performances (degradation efficiency ~100% for methylene blue in 70 min and ~90% for Rhodamine B in 80–100 min) | Dyes removal                                                                         | [27]       |
| Chitosan/zeolite | Adsorption capacity (for 0.5 g adsorbent at dosage, COD reduced by 45% in 60 min) | Wastewater treatment                                                                | [5]        |
| CaCO₃/Ca(PO₄)₂/chitosan | Increases mechanical properties, biodegradable                                     | Orthopaedics implants                                                                | [28]       |
| Chitosan/HNTs-NH₂/EGDE | Thermal stability (weight loss at 800 °C reduced by 20%), WVTR (for HNTs-NH₂ 10 wt% and EGDE 20 wt% 2440 ± 110 g m⁻² day⁻¹ WVTR achieved), and mechanical features (tensile strength for HNTs-NH₂ 10 wt% and EGDE 20 wt% 24 ± 23.52 ± 0.51 MPa) | Biomedical                                                                           | [29]       |
Numerous processes, such as the degree of electrostatic attraction and the amount of complexation, microprecipitation, and the exchange of ions, are a part of the reactions among the metallic ions and chitosan functional groups [19].

Chitosan can be combined with gelatin, which affects its physicochemical and mechanical features. Such crosslinkers can be used to produce scaffolds that can be used to engineer tissues, as gelatin is biodegradable, biocompatible, and antigenic. Due to this, it increases the swelling behavior and wettability of chitosan [30]. According to its uses, this biomaterial could be conveniently transformed into substances including gels, nano and micromolecules, nanofibers, sponges, and membranes. Biological or physicochemical features of chitin and chitosan membranes or scaffolds have been seen to be greatly affected by the amount of N-acetylation, crystallinity, degradation, along with molecular mass, which depends on the origin of the extracted chitin [3].

Chitin enters in three different types. Chitosan exhibits crystallinity and polymorphism depending on the polymer’s origin and treatment during the extraction process. Chitin, or 0% deacetylated and completely deacetylated chitosan, or 100% deacetylated, had the highest crystallinity. In acidic settings, chitosan’s straight, unbranched morphology and increased molecular content improve its effectiveness as a viscosity enhancer. It also acts as a pseudoplastic material, reducing viscosity as shear rate increases [31].

With increasing chitosan content, decreasing temperature, and increasing DD, the viscosity of the chitosan solution increases [32]. Chitosan can be combined with fillers to make carbon-based nanocomposites that can be used in the regeneration of bones, the delivery of drugs, the healing of wounds, and the applications of biosensing. Polymer-clay nano-composites have been researched as they improve the features of the compound in comparison to macro or micro composites. Montmorillonite is an aluminosilicate clay intercalated with chitosan, a layered silicate that constitutes silicon, aluminum, oxygen, hydroxyl, or magnesium groups.

Incorporating inorganic particles like bioactive ceramics and glass and metal nanomaterials into the chitosan matrix improved its mechanical properties and can provide bioactivity to an inert material [19].

Even though chitosan possesses excellent adsorption characteristics, its low degree of solubility at lower pH levels means that binding sites are not available. Therefore, chitosan is coated with cocoa husk char. These materials are used for removing heavy metals like chromium and lead from aqueous solutions [20]. Inorganic metal nanoparticles incorporated in chitosan by simple cross-linking reaction increase its mechanical properties and zeta potential. Chitosan coating on magnetic improves oxidation to hematite and colloidal stability. This improved stability of modified chitosan with nanoparticles is due to the creation of positive charges on the surface of magnetite. This coating enhances biocompatibility and reduces cytotoxicity effects.

Surface modification of nanoparticles promotes cell invasion, binding of fibroblast growth factor, activation of macrophages, and the development of anti-tumor immunity. Silver intercalation into the chitosan structure can boost antimicrobial efficacy and antibacterial recreation, opposing all types of bacteria. The photocatalytic action, mechanical power, compound opposition under UV, biocompatibility, dissolvability in basic or acidic conditions, and antibacterial conduct of chitosan created with titanium oxide are all outstanding. Chitosan with zinc oxides shows properties of disinfection and bactericidal. Hence the mixed composites can be appropriate for the medical and food industries. Pt and quantum dots exhibit optical and luminescent properties with chitosan, introducing photothermal effects to tumors while simultaneously imaging cells [21].

High biocompatibility was also seen from polymer composites prepared using nanotube powder of TiO2 and PVA. Titanium oxide enhances the structural, physical, and chemical properties and the mechanical integrity of the fabricated composite materials [22]. Carbon nanomaterials that are blue-green and fluorescent and made from chitosan can be used as heavy metal indicators and treat wastewater. This material has the features of easy preparatory techniques and can be used conveniently [23].

Chitosan is combined with RGD (arginine-glycine-aspartic acid) peptides and PLGA-PEG (Poly(L-lactide-co-glycolide), Poly(ethylene glycol)) to create composites with good mechanical properties, hydrophilic surfaces, and flexibility. The chitosan-based scaffolds were achieved by PLGA-PEG, a compound that offers steady conditioning to help link cells to the scaffold. The combination of PLGA-PEG and chitosan increases chitosan’s cell adherence. Adding RGD improves the composite membrane’s cell adherence and survivability even more [24]. Graphitic carbons produced using cheap alginate and chitosan has outstanding features, making them ideal for reversible CO2 adsorption and exceeding the CO2-adsorption limit in most ACs reported. These characteristics stems from the graphitic carbon morphology, which combines sufficient interface area and ultra-microporosity, the existence of N molecules that are organically prevalent inside chitosan, the beads’ spherical micrometric shape, high density, and electrical conductivity [33].

Normal thermogelling polymers have poor mechanical features and less gel stability when faced with physiological environments. Thus, a thermogelling polymer that mainly constitutes chitosan has the potential to be crosslinked and construct an elastic and sturdy hydrogel. These gels have great application in biomedical fields, including an injectable conveyance framework and 3-dimensional cell environments [34]. Chitosan-carbon nanocomposites hydrogel is fabricated, and this composite has interesting properties. The electrostatic connection amongst the cationic and anionic charges on carbon dots assisted this hydrogel in
having amazing predominant features such as UV–visible impedance, thermal solidity, and physical sturdiness in contrast with chitosan hydrogel films. Here, the carbon dots are prepared from green source ‘tea’ [25].

Acylation of chitosan can be done by using L-arginine in the presence of sulfuric and hydrochloric acid as crosslinkers and solubility agents, respectively. Chitosan-Arg has a lesser adsorption capacity than Chitosan virgin, but it has stronger chemical stability and crystallinity, which may allow it to be used in acidic and alkaline solvents, along with subsequent cycles of desorption and adsorption [35]. For wastewater treatment, nanofiber was created utilizing a helical carbon film primarily composed of chitin, deposited onto PSF platforms, and cross-linked with sodium dodecyl sulfate. Compared to fibers lacking helical carbon, this fiber exhibits improved pure water permeability and a smooth surface. Testing over large periods with the help of the feed solvent or the simulated wastewater exhibited continuous flow without reducing the efficiency in separating the solutes, suggesting the membranes possess robust detachment and antifouling capabilities [26].

Another hydrogel is prepared from reduced graphene oxide, chitosan, or silver nanomaterial composites for removing dye degradation for wastewater treatment. Different experiments show excellent efficiency in removing methylene blue from single or mixed solutions and exhibit good photocatalytic performances [27]. Chitosan-zeolite composites can also be used to remove COD from water as their absorption capacity increases compared to only zeolite and chitosan [5]. Chitosan’s strong functionality, which includes a single amine and two hydroxyl groups capable of donating an available combo of electrons, makes it soluble within less concentrated and aqueous solutions of acetic acid and allows the creation of coordination bonds, allowing for significant chemical modification. Because of this property, we can graft fatty acids (carboxylic acids, which are hydrophobic) into chitosan chains (hydrophilic), and the resultant product is amphiphilic.

Chitosan degrades at temperatures having fewer melting points, preventing it from being used for various purposes. Plasticization of polysaccharides is one technique to get around this problem. Sucrose, sorbitol, sucrose, polyethylene glycol, and glycerol were researched as plasticizers, with chitosan being the plasticizing specialist. The crystallinity of the plasticized chitosan dropped as the plasticizer concentration increased, from 63.7% of the initial powder of chitosan to 43.0% for the sample plasticized with extra water, and then to virtually entirely amorphous form in the sample that had been plasticized with the additional use of water. Thermo-mechanical plasticization has the potential to be a promising method for large-scale chitosan plasticization [36].

Chitosan is one of the polymers that gained popularity due to its osteoconductive properties. However, the polymer’s lack of mechanical strength makes it challenging to use as an implant. Calcium phosphate and calcium carbonate are combined with chitosan to form particle-filled bioresorbable composites for orthopedic implants to improve mechanical strength. The production of multipurpose scaffolds is one of the more advanced applications of these composites. The controlled release of medicinal or bioactive substances from these scaffolds is a relatively new contribution to this fascinating science [28]. Raw halloysite nanotubes were functionalized using (3-aminopropyl)triethoxysilane, followed by which new films of chitosan biofilms were created using amino-edited halloysite nanotubes functioning as strengthening substances and ethylene glycol diglycicyd ether being used as the agent for cross-linking. In a chitosan membrane matrix, HNTs-NH2 had a greater homogenous dispersion, and the microstructure of the films improved. The injection of EDGE and HNTs-NH2 into chitosan enhanced the material’s physical and mechanical qualities, such as its water resistance, thermal sturdiness, and WVTR [29].

Chitosan can create much more metal than chitin due to the availability of free amino groups present inside it. It is not easily soluble at lower pH, and its functional binding locations are unavailable to facilitate absorption. Physical support with better metal binding locations must be made available for the processing and use of chitosan. Its features could be modified according to its applications. It is biocompatible, easily metabolized, and is used to enhance penetration. These properties make them useful for various medical applications and are bio-degradable. The presence of positive charges also acts as a bioadhesive. It is utilized for medical purposes owing to its wound-healing qualities. It is abundant in nature, cost-effective, and environmentally friendly. Hydrogels prepared from chitosan lack mechanical strength and have low solubility. The ability to control efficient drug delivery through its parameters is also limited. Crosslinked chitosan is used to immobilize enzymes [37]. Chitosan also acts as a structure-directing agent when used as an additive in carbon structures. It increases the volume of the pores and the surface area of the biomolecules. It improves the performance of supercapacitors through its high specific capacitance and good performance. A hybrid porous carbon structure can be developed by mixing chitosan with other complexes.

An example of this is chitosan blended with gelatin inside an acidic solution. The hybrid structure formed has an increased energy density of 34 Wh kg⁻¹ and an increased power density of 900 W kg⁻¹ [38]. The properties of chitosan, especially its antimicrobial activity, greatly depend on its molecular mass and deacetylation. The chemical morphology of chitosan is very similar to that of cellulose. The amino acid content of chitosan dictates its subdivision into three types, and the different functional groups form hydrogen bonds both inside and with other molecules, particularly at the C-3, C-2, and C-6 locations.
Chitosan has certain limitations due to its poor solubility, high viscosity, and easy coagulation with proteins. The amount of deacetylation is controlled using the concentration of NaOH molecules in its chain, proportional to chitin’s transformation to chitosan. The amount of deacetylation is critical in determining the properties of chitosan. Properties like matrix swelling behavior and the release of proteins are all dependent on the amount of deacetylation. 85% deacetylation is considered good as it allows maximum solubility of chitosan in water and a higher positive charge density. Chitosan is also an efficient bioabsorbent due to its intrinsic mucoadhesive property. The binding of chitosan with mucus helps in developing delivery systems. Its functionality depends on its physicochemical properties. Composites are analyzed based on

(i) the identification of their main component, and

(ii) their ability to meet the required properties. Chitosan has the property to penetrate tight junctions and can be utilized for clinical medical conveyance systems. The existence of amine groups inside its chains makes it soluble in highly acidic solutions. In biomedical applications, chitosan can be cross-linked by dissolving it in non-soluble mediums or increasing its pH [39].

Chitosan acts as a carbon precursor. When electrolytes like KOH are combined with chitosan, the pores' volume, and surface area increase [40]. The amount of hydrogen absorbed depends on the pore volume [41]. Chitosan is also used to absorb pollutants from water bodies. Its low cost and polymeric nature make it a good absorbent. Other properties of chitosan include biocompatibility and biodegradability. The hydroxyl and amino groups in its chain give it chromatographic uses. The chemical and physical features of chitosan can be enhanced by injecting other substances [42].

Crosslinking reactions produce major differences in the chemical morphology of chitosan. To counter the drawbacks of chitosan and sharpen its properties, we can combine chitosan with other biomaterials to form composites. Chitosan composites can be formed by grafting, cross-linking, and functionalization. Composites formed by mixing clay with chitosan showed good regeneration ability. Cross-linking to form hydrogels could be better by injecting reagents like formaldehyde and glutaraldehyde [43]. Chitosan is generally taken out of crab shells and crustaceans. It can also be obtained from insects and microorganisms. Recently, the properties of chitosan extracted from fungus have been studied. It is obtained using two methods: chemical or biological. Through chemical methods, it is extracted using strong acids and alkaline treatments. In biological methods, it is extracted from microorganisms [44].

Chitosan from fungal sources possesses greater solubility and an amount of deacetylation. The chemical properties of chitosan could be studied with the help of scanning electron microscopy and cyclic voltammetry [45]. During deacetylation, chitosan loses about 25% of its acetyl content, thereby converting to chitosan. Chitosan can be modified into different forms according to its modification. It can be modified physically to form powders, gels, nanoparticles, and sponges. Chemical modification is usually carried out by cross-linking its chains [46].

The properties of chitosan and its significance in applications could be realized in a greater depth. Key properties of chitosan include its biocompatibility, the ease with which it could be used safely, its biodegradability, and its ability to chelate with metallic ions. These wide-ranging properties make it a unique material and increase its adaptability across multiple fields and industries. Further, chitosan is found to be immunoadjuvant, fungistatic, hemostatic, non-toxic, spermicidal, and is a drug delivery agent adding to its special array of properties.

Compared to many other polymers, chitosan is also a linear and a natural polymer with anti-tumor and anti-cholesteremic, making it a highly interesting material to study [47]. Its properties make it suitable for membrane filtration of toxic metal ions. Heparin, histidine, and succinic anhydride can be used as grafting materials for chitosan. Chitosan could also be dissolved into formic or acetic acid to prepare membranes.

2.2 Microstructural behaviour & material characterization
Chitosan is modified to enhance the properties of its polymer, including microstructural properties like specific surface area, mesoporous and microporous areas. To strengthen properties, many elements (nitrogen and phosphorus) and groups (−NH2 and OH−) are incorporated into chitosan, as shown in table 2.

Chitosan doped with nitrogen and carbonized at 850 °C has a large surface area and a high mesoporous ratio that will help better adsorption capacity. Further temperature increases cause chitosan degradation. It was seen from XPS analysis that ‘O’ content kept decreasing with increasing carbonized temperature. ‘N’ content shows similar behavior. It has good conductivity and less resistance. The electrode formed from this chitosan-based material had the optimum capacitance features due to pore morphology and relevant N content changes. Also, it is found that this electrode has an excellent adsorption rate and capacitive deionization adsorption stability. It can effectively work in a different solution environment [48].
Table 2. Chitosan-based carbon materials and their resultant changes in properties of chitosan.

| Chitosan based carbon nanomaterial | The additives used and environment provided | Microstructural Properties | Improvement in properties for application | References |
|-----------------------------------|---------------------------------------------|---------------------------|------------------------------------------|------------|
| Nitrogen-doped chitosan           | N\textsubscript{2} atmosphere carbonized at 850 °C, pyrolysis with KOH | SSA-2334 m\textsuperscript{2} g\textsuperscript{-1}, Pore volume-1.23 cm\textsuperscript{3} g\textsuperscript{-1}, mesopores-94% | Increases adsorption rate, used to make | [48] |
| Nitrogen phosphorus co-doped chitosan | N\textsubscript{2} atmosphere carbonized at 700 °C, in H\textsubscript{3}PO\textsubscript{4} and NaNH\textsubscript{2} solution, hydrothermal carbonization | Diameter-3.86 nm, SSA-3646 m\textsuperscript{2} g\textsuperscript{-1}, pore volume-2.87 cm\textsuperscript{3} g\textsuperscript{-1}, micropores-1253 m\textsuperscript{2} g\textsuperscript{-1}, mesopores-2393 m\textsuperscript{2} g\textsuperscript{-1} | Increase electrochemical performance for supercapacitors. | [49] |
| Hydroxyapatite/chitosan nanocomposite | Chitosan mixed in Ca(NO\textsubscript{3})\textsubscript{2}.4H\textsubscript{2}O and (NH\textsubscript{4})\textsubscript{2}HPO\textsubscript{4} at 25 °C by hybridization | The crystalline structure of less than 50 nm | Mechanical strength increases for biodegradable composite | [50] |
| Nitrogen oxygen Co-doped chitosan | Mixed with KNO\textsubscript{3} and Mg(NO\textsubscript{3})\textsubscript{2}.6H\textsubscript{2}O, exothermic pyrolysis at 600 °C | SSA-922 m\textsuperscript{2} g\textsuperscript{-1}, with pore volume 0.49 cm\textsuperscript{3} g\textsuperscript{-1}, I\textsubscript{D}/I\textsubscript{G}—0.93 | Specific capacitance increases, good material for electrodes of supercapacitors. | [51] |
| Chitosan/cellulose nanocrystal bio composite | Chitosan mixed with cellulose nanocrystal of 10 wt% in PEG 4000, carbonized at 1200 °C | SSA-251 m\textsuperscript{2} g\textsuperscript{-1}, pore volume-0.159 cm\textsuperscript{3} g\textsuperscript{-1}, | Increase instability, specific capacity, in anode making | [52] |
| Cellulose/chitosan carbon mats | Chitosan and cellulose mixed in a ratio of 5:5 with polyacrylonitrile, prepared by single nozzle electrospinning and carbonized at 900 °C | Diameter-316 nm, SSA-374 m\textsuperscript{2} g\textsuperscript{-1}, pore volume-0.135 cm\textsuperscript{3} g\textsuperscript{-1} | Increases electrochemical performance for making anode | [53] |
| n-doped graphitic carbon | Chitosan to carbon nanoparticle by hydrothermal and pyrolysis process at 900 °C | Diameter-20–30 nm, SSA-533.41 m\textsuperscript{2} g\textsuperscript{-1}, pore volume-0.65 cm\textsuperscript{3} g\textsuperscript{-1} | Increases in electrocatalytic performance for oxygen reduction reaction | [54] |
| Chitosan/carbon black fibre supported bimetallic | CB-CS fiber mixed with Co(NO\textsubscript{3})\textsubscript{2} and CuSO\textsubscript{4} and then with NaBH\textsubscript{4} | Diameter-190 nm | Improvement in the removal of dyes and pathogenic bacteria in water | [55] |
| Chitosan derived N/NiO\textsubscript{x} co-doped nanosheets of carbon | Chitosan mixed with H\textsubscript{2}O\textsubscript{2} and NH\textsubscript{3} then with Ni(NO\textsubscript{3})\textsubscript{2}, carbonized at 800°C in N\textsubscript{2} atmosphere | SSA-12574 m\textsuperscript{2} g\textsuperscript{-1}, average pore-5.91 size/nm, I\textsubscript{D}/I\textsubscript{G}—0.96 | Increases specific capacitance and stability for making supercapacitors | [56] |
| Magnetic chitosan biopolymer | Chitosan cross-linked with Fe\textsubscript{3}O\textsubscript{4} magnetic nanoparticles using glutaraldehyde | Diameter-200–500 nm, spherical | Increased in sorption ability, excellent reusability in handling dyeing effluent containing cationic and anionic dyes | [57] |
| Nanocomposite film consisting of a Chitosan Matrix and essential oils | The essential oil Cinnamodendron dinisii Schwanke was nano encapsulated in a Chitosan wall with the aid of zein being used as a wall substance producing an active nanocomposite film | The particle size of NP-oil nanoparticles: 68.84 ± 2.48 nm | An improvement was observed against thermal degradation and in antioxidant and antimicrobial activity, indicating the potential of being used in film packaging and meat conservation | [58] |

Zeta Potential of NP-oil nanoparticles: 33.0 ± 0.78 mV
Chitosan is used in making electrodes based on N,P-doped chitosan. This doping can help change the electrochemical characteristics of electrodes made from this chitosan. Heteroatoms are doped using a carbonization strategy, i.e., a mixture of chitosan H₃PO₄, CH₃COOH, and NaNH₂ at different carbonization temperatures of 600 °C, 700 °C, or 800 °C. Chitosan carbonized at 700 °C has the highest specific surface area, ultra-high capacitance, and excellent stability. It also has macropores and mesopores that provide sufficient capacity for storing electrolytes while efficiently speeding up ion transport, resulting in a high rate capability. Furthermore, if P is not doped, it will only have a vermicular morphology, indicating that H₃PO₄ can operate as a pore widening agent, allowing the formation of many macropores or mesopores.

This doped material is primarily composed of an amorphous carbon morphology, although a narrow array of structured graphitic areas may also be seen in SEM and HRTEM pictures. It has a lower degree of graphitization, which indicates the largest defect content, attributed to the right carbonization temperature and heteroatom doping. Without the addition of H₃PO₄, the degree of graphitization is higher. Applying that H₃PO₄ is important in forming amorphous structures, which could be attributed to the catalytic impact of H₃PO₄ during this process. According to XPS tests, multiple oxygen molecules verifiable inside the material might offer a rise in capacitance. Because of the extremely large N content and medium P content and the synergistic influences of their functional groups might have good electrochemical performance. After using this electrode over 10,000 cycles, there is no significant change in its initial pore structure, and the pore also does not collapse, but there is a decrease in P content due to oxidation. For the above reasons [49], this doping results in high pseudocapacitance and upgrades carbon substances' wettability and electric conductivity.

Chitosan-based materials were used to make electrodes doped with nitrogen by combining chitosan, acetic acid, polyvinylpyrrolidone (PVP), KNO₃, and Mg(NO₃)₂·6H₂O into a solution, which was then transformed into aerogel and carbonized at three different temperatures: 500 °C, 6000 °C, and 700 °C. The material formed has abundant pores with multiple sizes at the 600 °C activation process, while at 500 °C, unformed pores were seen, and at 700 °C, the temperature is too high for this material process. At 600 °C, it has a high partial pressure that implies it has numerous mesopores of 3.5 nm and nitrogen intake also increases, which shows it has micropores of 0.5 nm. With a further increase in temperature, the degree of graphitization decreases, resulting in more disordered structures. N content decreases with an increase in carbonization temperature as it starts decomposing.

Some groups of N, like pyridinic N, pyrrolic N, and graphitic N, could facilitate extra free electrons that provide good pseudocapacitance. Graphitic N helps to increase the conductivity of carbon materials. The outstanding performance of material carbonized at 600 °C has a high capacitance, which can be attributed to the synergism effect of additional pseudocapacitance as a result of the heteroatoms of nitrogen and oxygen and the sturdy structures of their pores, with the help of compounds such as KNO₃ and Mg(NO₃)₂·6H₂O. This material shows less resistance to equivalent series and less resistance to the transfer of charges. It also shows excellent stability with a high efficiency of 88% at the end of 10,000 charging and discharging cycles. The high capacitance is attributed to its large specific surface area, co-doping between nitrogen and oxygen molecules, and the excellent hierarchical pore morphology that could show higher activated locations for adsorption of electrolyte ions [51].

Chitosan can be combined with biocomposites (cellulose nanocrystals), i.e., having self-doped nitrogen to form a potential anode material for lithium-ion batteries. They mix chitosan (CS) with cellulose nanocrystals (CNC, i.e., mostly made from rice straw) in different suspension ratios and polyethylene glycol 4000 as pore-expanding agents to form a membrane after this membrane is carbonized at high temperatures of 800 °C, 1000 °C, 1200 °C, and 1500 °C to obtain different samples to find further the suitable ratio of composite that can be mixed and the appropriate carbonization temperature.

Most amorphous zones were found below the carbonization temperature of 1200 °C. Further, using XRD, it was noted that the distance between graphite-like microcrystalline layers decreases. These materials reach stability after a temperature of 1200 °C. The degree of graphitization decreases from 800 °C to 1200 °C, but increases from 1200 °C to 1500 °C, indicating a faster rate of development of disordered graphitic morphology. It was seen that the first degree of graphitization increases and then decreases by adding different ratios of CNC, from 0 wt% to 5 wt%, and 10 wt% to 15 wt%, which shows great interfacial interactions between CS and CNC that are good for graphite structure. N content decreases with increased temperature and an increase in CNC ratios. Micropores, mesopores, and macropores coexisted in the samples. Different results suggest that composites with a 1200 °C carbonization temperature and a 10% CNC ratio have a reasonable pore distribution of micropores, mesopores, and macropores that produce a high surface area that contributes to the fast transport of electrolyte ions. CS without CNC at 1000 °C has a high specific surface area and high N content but poor stability [52].

Chitosan can also be transformed into graphitic structures doped with nitrogen and carbon electrocatalysts by a two-step hydrothermal process. Firstly, chitosan was converted into N-doped carbon nanoparticles through hydrothermal reactions, followed by high-performance graphitic carbon nanoparticles doped with
nitrogen-oxygen reduction reaction electrocatalyst with the help of a pyrolysis reaction at 900 °C. The carbon material is sized at 30–40 nm. XPS confirms the presence of N and its groups like pyridinic-N, pyrrolic-N, and graphitic-N. This analysis also observed that a rise in the ORR catalytically active pyridinic nitrogen-doped constituents occurs while there is a decrementing in the ORR catalytically inactive pyrrolic nitrogen content. The size of the particles decreased to 20–30 nm after pyrolysis, as observed by SEM, and the specific surface area increased. Pyrolysis Treatment of chitosan helps increase pyridinic nitrogen content further, increase pore volume and surface area, and create good connections between the particles that can help improve mass and electron transport.

Chitosan can also be co-doped with nitrogen and sulfur by a hydrothermal process, i.e., sized between 20 and 30 nm. This shows an unfavorable two-electron ORR process and bad catalytic activity. After pyrolysis treatment of this material, it surpasses both nitrogen-doped material and Pt/c catalysts in ORR activity. So this data confirms that the chitosan property can be further enhanced by co-doping than single atoms doped for ORR performance [54].

2.3. Synthesis technologies
2.3.1. Electrospraying technique
For medical conveyance, imaging, coverings on implants, and engineering tissues, electrospraying, a solvent atomization-based technique, is utilized to manufacture microparticle and nanoparticle cargo conveyors. It is also known as electrohydrodynamic atomization or electrodynamic spraying. The typical electrospraying setup for polymeric particle generation includes an increased voltage power source, a plastic or glass syringe closed by a capillary made of metals to store solutions of polymers, a pump syringe for monitoring solution transport, along with a collector that is grounded, as shown in figure 2. With increased electric fields supplied for the needle, the charged liquid spray can split into smaller drops and construct microscopic molecules with a small size spread on the collector [59].

The nature of the solvent used, the degree of conductivity, the amount of surface tension, viscosity, the molecular weight, the amount of flow, the degree of used electric charge, and the physical length between the needle tip and collector can all affect the structures and dimensions of the electrospray molecules. Electrospraying entails applying an electric charge to the polymer solution, and increased electric voltages can deconstruct the droplet’s surface, resulting in droplets with dimensions of a few nanometers, depending on the reaction factors. Various methodologies can be used for electrospraying, such as plate electrospraying, solution electrospraying, coaxial electrospraying, and deposition electrospraying. However, plate and solution electrospraying are the most commonly used methods. Plate electrospraying is also known as conventional electrospraying. In plate electrospraying, we collect the charged particles in the plate as singular droplets or in the
form of an agglomerate of droplets. In solution electrospraying, CaCl₂ is used to collect charged droplets, facilitating the precipitation of polymer drops as nano and microspheres. Coaxial electrospraying uses two polymer solutions having two different syringes, one within the other. In this way, it creates a core-shell structure. In the deposition technique, particles accumulate directly on a substrate plated with electrospraying substances instead of a plate [61].

Vincenzo Guarino et al combined chitosan with polycaprolactone (PCL) and processed it through simultaneous or sequential electrospraying and electrospraying. Due to the concentration of treated solutions that impact the construction of entanglements in chains or evaporation, PCL microparticles having a spherical shape or flattened particles were formed. The particle size of chitosan nanoparticles and their distribution can also be controlled by controlling voltage and flow rate. Electrospraying techniques can efficiently load chitosan nanoparticles with pharmaceuticals like antibiotics, making them potentially useful as drug delivery vehicles for medical agents’ aimed and sustained conveyance [62].

Moreno et al researched chitosan polymer from electrospraying technique with various molecular masses, amount of decacytlation, and amount of polymerization of chitosan, and with the impact of solvent constituents. Chitosan particles that are stable in water were obtained using EtOH and acetic acid as a solvent, and chitosan particles were obtained using EtOH and acetic acid as a solvent. The solution’s conductivity required for forming chitosan molecules decreased when the amount of acetic acid in the solution was increased. EtOH addition to the chitosan solutions was shown to reduce conductivity and viscosity, allowing for easier electrospraying and creating more homogeneous chitosan particles. Stable chitosan was obtained by dissolving 3% w/v of decreased atomic mass chitosan, having a degree of polymerization of 177–292, inside the combinatory solution of ethanol and acetic acid at 50/50% v/v [61].

2.3.2. Ionotropic gelation method

The ionotropic gelation method is a technique that utilizes the electrostatic reactions between two ionic components and produces microparticles and nanoparticles under specific conditions. This method produces stable, non-toxic chitosan nanoparticles free of organic solvents. It is quite basic, and it relies on contrastingly charged polyanion chains to bind to oppositely charged amino groups inside chitosan. Tripolyphosphate, or TPP, is a commonly used ionic cross-linker that relies on electrostatic reactions rather than chemical cross-linking, preventing agent toxicity and other undesirable effects, as shown in figure 3. TPP is used due to its non-toxicity, multivalency, and ability to form gels via ionic interaction. The charge density of both chitosan and TPP, which is affected by the acidity of the mixture, can govern the interaction [59].

Ahmad Abolhasani et al observed the effects of two key parameters, the TPP mass proportions and the concentration of its solution, on the synthesis of chitosan nanomaterials with the help of the ion-gelation technique, followed by the production and characterization of nanomaterials that are based on chitosan and are biodegradable and drug-loaded, for encapsulating novel medicines. 3′-4′-(methylsulfonyl) phenyl)-4′-4′-[4′-(methylsulfonyl) phenyl]-4′-4′-[4′-(methylsulfonyl) phenyl]-4′-4′-(4′-4′-(4′-4′-(4′-4′-(4′-4′-H-spiro[indene-2,5′-isoxazol]))-[1,2-b]pyridine]-4′-4′-(4′-4′-4′-4′-4′-4′-H-spiro[indene-2,5′-isoxazol]). The results showed that as the chitosan or TPP amounts grew, the dimension of the molecules increased as well, whereas the ratio of the mass ratio was not as impactful at the time of the cross-linking process. CNPs containing MTS had particle diameters and zeta potentials within the range of 256–350 nm and 24.08–38.70 mV, respectively. The capture order rose gradually as the polymer concentration in formulations was raised [65].

2.3.3. Reverse micelle method

With this method, very small polymeric nanoparticles can be prepared. As shown in figure 4, a surfactant was used to dissolve within an organic solvent to generate reverse micelles. To avoid turbidity, an aqueous chitosan solution was added while continuously stirring. Under steady stirring, a crosslinking agent was added to this translucent solution [66]. Previous research employing Na 1,4-bis-2-ethylhexyl sulfo succinate reverse micelles as very small reactors showed that the final molecule dimension could be affected by adjusting the reagent concentration and reverse micelles water amount. The influence of the micellar surface in producing chitosan nanomaterials was investigated by M. Soledad Orellano et al to acquire insight into this approach. The findings indicated that the reverse micellar approach could be used to produce chitosan nanoparticles from Na 1,4-bis-2-ethylhexyl sulfo su ccinate and benzyl-n-hexadecyl dimethyl ammonium chloride reverse micelles. In Na 1,4-bis-2-ethylhexyl sulfo su ccinate reverse micelle, the crosslinking process occurs at the micellar interface, which is more effective [67].

Mortezakafshgari et al made alginate and chitosan nanoparticles with the help of a reverse micelle method that consists of cetyltrimethyl ammonium bromide in the form of a surfactant, isooctane in the form of a solvent, and 1-hexanol in the form of a co-solvent. The results were quite fascinating. There is an increment in the nanomaterial dimensions proportionally to any change in alginate or chitosan concentrations. Typically,
dimensions vary between 220–490 nm for alginate and 210–1050 nm for chitosan. Further, the reduction in size with an increment in the volumetric proportions of co-solvent or solvents could be seen [68].

2.3.4. Electrospinning method
Chitosan nanofibers are made using electrospinning techniques. The viscosity, the voltage needed for operating it, and the flow, pressure, velocity, and temperature can all influence electrospinning. Furthermore, as it is connected to the degree of the entanglement of the polymer molecule chain inside the solution, viscosity is an important characteristic in electrospinning. It utilizes electric force and uses it for drawing threads from solutions of polymers that are charged, or the polymer can melt and then have fiber widths in the range of a few hundred nanometers. This is done with the help of a polymer jet that can be inserted via a charged needle, following which the solvent that the polymer has dissolved in undergoes evaporation, and solid polymer fibers can be deposited on the collects, as shown in figure 5.

Electrospinning has features similar to both electrospraying and traditional solution dry fiber spinning. To manufacture solid threads from solution, the procedure does not need to utilize higher temperatures or coagulation chemistry. As a result, the method is well adapted to manufacturing fibers containing big and complicated compounds. There are different electrospinning methods, such as co-axial electrospinning, emulsion electrospinning, and melt electrospinning. A dual-solution feed system is used in a coaxial configuration, allowing the addition of a particular solution onto the other at the tip of the spinneret. A core-shell structure is frequently found when the solutions are immiscible.

On the other hand, miscible solutions can cause porosity or the creation of fiber having separate phases due to the separation of phases at the time of the solidification of the fibers. Emulsions could also be employed to

Figure 3. The ionotropic gelation method set up using TPP [64]. Reprinted with permission from [64].
make core-shell or composite fibers without modifying the spinneret. However, owing to the increased quantity of variables for consideration in manufacturing the emulsion, these fibers are often more complex to make than coaxial spinning. In contrast to solution electrospinning, electrospinning of polymer melts does not require volatile solvents. The fiber diameters obtained from solution electrospinning are usually slightly bigger than those formed from polymer melts due to their high viscosity. Fiber homogeneity is usually rather good after obtaining steady flow rates and thermal equilibrium. Several studies were conducted where chitosan is synthesized with polymers like polyethylene oxide, polyvinyl alcohol, and PLA, as well as renewable polymers like gelatin, alginate, and silk fibroin, as well as nanomaterials by electrospun method for wound dressing, to help better the physical robustness, antibacterial reactivity, and antiadhesive qualities of its nanofibers [69].

Sang Jin Lee et al made a composite of chitosan with Ag nanoparticles by the electrospinning method for wound dressing and tested their antibacterial responsiveness against Pseudomonas aeruginosa and Methicillin-resistant Staphylococcus aureus, which are gram-negative and gram-positive, respectively. The findings obtained were quite efficient as this composite is effective for antibacterial treatment in wound care [16].

Satyajeet S. Ojha et al used polyethylene oxide as a foundation to make chitosan nanofiber using electrospinning inside a core-sheath geometry. Using SEM, it can be seen that an approximate diameter of 125 nm radius has a
visible geometry of core-sheath geometry prior to removing the sheath and chitosan nanofibers of nearly 100 nm in diameter following the washing of polyethylene oxide with deionized water [70].

2.3.5. Spray drying method
Spray drying involves quickly making a slurry or a liquid dry and transforming it into a dry powder with the help of hot gas. Many heat-sensitive products, such as foods and pharmaceuticals, or materials that require an extremely uniform, tiny particle size, favor this drying method. The heated drying medium is air. However, N2 is utilized when a flammable solvent such as ethanol is used, and the resultant product is sensitive to oxygen. As shown in figure 6, the atomization and combination of small drops using gas streams, followed by the separation and collection of powder that has been dried, are all performed in three steps. Gulenmelike et al process chitosan with water and glacial acetic acid in a nanospray dryer to determine the parameters of the nanospray dryer on particle features and operation load. Oriifice leads that are small in size cause smaller particles to form for end-products with low operation potential according to particle characteristics and operation capacity data. Contrarily, the sprayed volume indicated a linear relationship with operating potential even though it had no major impact on the dimension of the particle. A rise in the concentration of polymers and enhanced dry powder production revealed an increased rise in positive zeta potential, but it had a lower operating capacity [71]. The comparative study of advantages and disadvantages of synthesis technologies is shown in table 3.

2.4. Chitosan-carbonaceous materials
Chitosan nanocomposites with activated carbon (AC), graphene (G), biochar (BC), carbon-nanotube (CNTs), and graphene oxide (GO) have superior properties. Through different studies, it was found that chitosan has low mechanical properties and has lower amounts of surface area and volume of the pores, which is disadvantageous for different kinds of applications, but after combining it with other carbonaceous materials, properties are enhanced. This type of chitosan-carbonaceous material mostly finds its uses in making electrodes, supercapacitors, and wastewater treatment by adsorption. According to various studies, graphene oxide (45%) and activated carbon (25%) are the most commonly used carbonaceous materials, followed by CNTs (18%), biochar (7%), and graphene (5%). The qualities of both materials are enhanced as a result of the formation of chitosan and its composites with carbonaceous materials, as shown in table 4.

2.4.1. Activated carbon (AC) and chitosan composite
An AC is an adsorbent made from carbonaceous raw material with most of the volatile non-carbon elements and a portion of the original carbon content removed by thermal or chemical processes, resulting in a structure with a large surface area. AC is mostly made from coconut shells or other nut shells, coal, wood, and petroleum coke. Pyrolysis or carbonization is the main method of preparing AC, which is not economical. Therefore, after combining it with chitosan, the process becomes cost-effective, and it also increases the specific surface area of
Table 3. Comparative study of advantages and disadvantages of synthesis technologies.

| Synthesis technologies | Advantages | Disadvantages |
|------------------------|------------|---------------|
| Electro spraying       | High encapsulation capacity; simple process; rapid | Use of organic solvent; low production rate. |
| Inotropic gelation     | Economic and simple; less time; no organic solvent; reversible physical cross-linking through electrostatic reactions; safe. | Produce nanomaterial of poor mechanical strength. |
| Reverse micelle        | Produce small size of nanoparticles with desired shape and morphology; production is continuous and high; solvent recovery. | 
| Electrospinning        | Relatively less expensive technique; magnify mechanical properties; can draw fibers with few microns to nanometers. | Utilization of organic solvents; due to increased voltage, it is difficult to make scaffolds. |
| Spray drying           | Rapidly; easily modify product quality according to needs; low number of operators, and high efficiency. | Complex equipment; thermal efficiency is not good therefore uses a lot of heat; expensive device. |

Table 4. Enhancement in properties of both chitosan and carbonaceous materials due to formation of their composites.

| Chitosan composites with | Changes in chitosan | Changes in carbonaceous material |
|-------------------------|---------------------|---------------------------------|
| Activated carbon        | Increases specific surface area | Economic and eco-friendly |
| Graphene/graphene oxide | Enhances adsorption capacity | Minimize dispersibility and agglomeration tendency |
| Biochar                 | Provide support and high surface area | Provide more chelating sites to biochar |
| Carbon nanotubes        | Enhances mechanical properties | Reduces its agglomeration tendency and poor structural group |

Chitosan. Mohammad Malakootian et al made a bio-nano composite of CoFe2O4/activated carbon-chitosan for ciprofloxacin adsorption, a biologically resistant pollutant. The specific surface area of the nanocomposite is 474.36 m² g⁻¹, and the resultant volume of pores is 0.3745 cm³ g⁻¹. At pH 5, the highest removal is obtained. Results indicate that this nanocomposite adsorbs about 93.59% of ciprofloxacin from an aqueous solution and can also be recycled effectively [72].

FerdaCivan Cavusoglu et al composed a nanocomposite with AC/chitosan/Fe3O4 to adsorb crystal violet. The maximum theoretical adsorption potential was 505.87 mg g⁻¹ at 298 K. The desorption rate was 64.63% during the primary cycle and 27.38% during the tertiary cycle [73]. HakimehSharififard et al synthesized a bio-nano composite composed of chitosan, Fe, and GO by sonolysis synthesis to remove cadmium from the adsorption technique. The contentful reactions amongst functional groups of AC, oxygen, iron ions, and amine groups of chitosan were revealed by characterization analysis. The results of continuous adsorption trials indicate that this bio-nano composite could be an excellent option for removing heavy metals from industrial wastewaters [74]. In the adsorbing Congo red dye, S R Sowmya et al made a composite material from chitosan, AC, and nano-zerovalent iron. These results were quite optimistic. It absorbs 100% dye in 70 min at room temperature at neutral pH. A rise in adsorption efficacy was found, with a rise in temperature and a reduction in pH. The pH of 1, at 50 °C with a starting dye concentration of 50 mg l⁻¹ and adsorbent amount of 1500 mg l⁻¹, was found to have the best adsorption [75].

Hassan Rezaei et al developed a chitosan-AC nanocomposite to remove nitrate, ammonia, and phosphate from aquaculture wastewater. At optimum conditions, the removal and adsorption potential for nitrate, phosphate, and ammonia pollutants were 99.98 percent, 99.77 percent, and 65.65 percent, respectively, and 6.65, 6.14, and 7.32 mg g⁻¹. Owing to an increased clearance rate of chitosan and activated carbon nano-composites, 99.98% removal was achieved [76].

2.4.2. Graphene oxide (GO)/Graphene (G) and chitosan composite

Graphene is a novel variety of carbonaceous materials that promise mechanical, electrical, and thermal features. It also possesses a huge specific surface area of 2630 m² g⁻¹, making it effective in adsorption. However, graphene is easily agglomerated in an aqueous solution, reducing its surface area [77]. Previously, graphene was made through the chemical vapor deposition method, which is costly and complicated. This approach involves the exposition of Pt, Ni, or Titanium Carbide to benzene or ethylene at increased temperatures to generate graphene as a monolayer. No other options for imposing crystalline epitaxy onto any non-metal substrates were found. However, research published in 2012 demonstrated analysis of graphene’s interfacial adhesion energy and indicated that the removal of graphene from a metallic board could be done effectively on which it is created while also hypothetically reusing the board an endless number of times for future applications.
Hummer’s approach is commonly used to prepare GO from graphite. Although GO contains numerous active structural groups, its increased levels of dispersion, inclination to agglomerate, and limited recovery lower its potential to be used for adsorption. Therefore, combining GO/G with chitosan can improve its characteristics. Jiazh Duan et al made a chitosan-GO nanocomposite hydrogel that was used to suggest a simple technique for the light-stimulus actuator. The produced CS/GO hydrogel films have very sensitive reactions to light irradiation and increased temperature rise due to increased efficacy in photothermally converting GO nanosheets. The deformation is aided by the gradient water distribution generated by the photothermal process. The amount of GO in the nanocomposite film could affect the deformation property [78]. Figueroa T et al designed a nanocomposite of GO-chitosan with N-(3-dimethyl aminopropyl)-N-ethyl carbodiimide) hydrochloride and N-hydroxysuccinimide for the delivery of proanthocyanidins. The resultant nanocomposite was stable and, on average, had a diameter of 480 nm [79].

Mohamadreza Tavoli et al incorporated chitosan/GO nanocomposite into polymethylmethacrylate (PMMA) bone cement. According to the findings, adding 25 weight percent of CS/GO nanocomposite powder to PMMA bone cement increased the compressive modulus by 69.1%, the compressive strength by 16.2%, and the bending robustness by 24.0 percent. It also shows that MG-63 cell culture revealed that 25 wt percent PMMA-Cs/GO composite bone cement helped improve cell survival, proliferation, and cell adhesion [80]. Alexa Maria Croitoru et al made a film of GO/chitosan/EDTA for eliminating Pb\(^{2+}\) ions mainly from aqueous solutions. The injection of EDTA into a chitosan solution can aid in the adsorption process. GO, and EDTA includes MnO\(_2\), Al\(_2\)O\(_3\), and SiO\(_2\) has an adsorption potential of 78.2 mg g\(^{-1}\), 77.8 mg g\(^{-1}\), and 75.9 mg g\(^{-1}\) each. The obtained GO nanocomposite powder had a high affinity towards Pb\(^{2+}\) ions and the highest adsorption value of 889 mg g\(^{-1}\) [81].

Xiaoming Yang et al made a chitosan-GO nanocomposite by straightforward self-assembly of each material in the aqueous medium. On a molecular scale, graphene oxide is disseminated throughout the chitosan matrix, and certain reactions between the matrix of chitosan and graphene oxide layers could be seen. By adding 1 wt percent graphene oxide, the tensile robustness and Young’s modulus of each of the materials mainly made of graphene increased by roughly 122 and 64 percent, respectively, compared to pure chitosan. Simultaneously, the elasticity during the break moment rises dramatically [82]. Monica Cobos et al evaluated the impact of glycerol plasticizer on GO-chitosan nanocomposites. Due to the uniform spread of GO nanosheets within the chitosan matrix and excellent interfacial contacts among them, the insertion of GO nanosheets inside unplasticized and glycerol plasticized chitosan resulted in GO/chitosan nanocomposites having improved physical properties and stability across temperatures. In the glycerol plasticized nanocomposites, the improvements in Young’s modulus and tensile robustness were much larger. Glycerol improved the interaction of GO nanosheets with the chitosan matrix. As a result, the chitosan/GO/glycerol nanocomposite can be used in medical applications that demand highly improved mechanical properties [83].

Chrisanne Naicker et al create nanocomposite beads from magnetic chitosan chloride, GO, and metal oxides (MnO\(_2\), AlO\(_3\), and SiO\(_2\)) to remove wastewater’s Cr(VI) ions. Chitosan/GO composite with MnO\(_2\), AlO\(_3\), and SiO\(_2\) has an adsorption potential of 78.2 mg g\(^{-1}\), 77.8 mg g\(^{-1}\), and 75.9 mg g\(^{-1}\) each. The obtained composites have a spherical bead shape. The highest adsorption-desorption cycle was obtained with MnO\(_2\). All composites are resistant to severe pH and are appropriate for contaminated water treatment, including loaded reactors in columns and immersion in river water when inside porous mediums [84]. Figure 7 shows the mechanism of grafting chitosan on graphene oxide.

### 2.4.3. Carbon nanotubes (CNTs)

Carbon materials, including ACS, CNTS, and graphene, have been utilized electrochemically for storing energy and treating water. Carbon nanotubes have sparked much research effort due to their use in electrical double-layer capacitors. Single-walled nanotubes (SWNTs) and multi-walled nanotubes (MWNTs) are two types of nanostructured materials (MWNTs). They have high electrical conductivity and good physical and thermal stability, all desirable characteristics for electrochemical capacitors with high power and stability [85]. The limited energy density is due to the accessible tubular connections, high intrinsic conductivity, and lower active surface area (500 m\(^2\) g\(^{-1}\)), and additional production procedures are required to combat agglomeration. 2014. It was demonstrated that CNTs joined with PVA yielded a permeable surface with a high wettability and an enormous particle available surface region, prompting further development of the electrosorption limit. Shrewd materials are strong state transducers with identifying and activating abilities, such as piezoelectric, pyroelectric, electrostrictive, magnetoelectric, piezoresistive, electroactive, etc. Brilliant materials, like piezoelectric earthenware production, electroactive polymers, and shape memory compounds, have multiple drawbacks that keep them from being utilized in pragmatic applications [86].

Furthermore, because CNTs possess great strength and increased thermal and electrical conductivities, they could concurrently facilitate morphological and functional demands, such as actuation, sensing, and power generation. Carbon nanotubes have gained traction in the research field due to their one-of-a-kind structures,
multiple possible utilisations, and excellent physical features. Elastic and thermal Carbon nanotubes show remarkable mechanical properties, such as flexibility and a seamless hexagonal configuration, for a C-C covalent bond. Compared to carbon reinforcing fibers, the ratio of robustness to the mass of nanotubes inside the axial way is more than four times. Thermal conductivity is also high along the CNT axis, nearly 1750–5800 W m$^{-1}$K$^{-1}$\cite{87}.

The direction of polarisation of the ferromagnetic anodes used to contact the nanotube decides the twisting course of charge transporters entering and leaving the nanotube, just like adjusting the nanotube’s resistivity. The high conductivity and magnetoresistance impacts, where the nanotube-metallic intersection seems to affect the subordinate twist vehicle majorly, can theoretically be used to build spintronic nanoscale devices.

Absorption: Because of their vast surface area and empty and sheeted molecules, they are shown to have great adsorption capability in removing contaminants in wastewater. CNTs could be useful adsorbents for removing ions like Cu$^{2+}$, Cr$^{3+}$, Zn$^{2+}$, Pb$^{2+}$, and Cr$^{6+}$ from wastewater. Due to intense reactions between dioxins and CNTs, they have also been more absorbent than ACs in removing dioxins, and CNTs have lately been employed to remove color molecules\cite{88}. CNTs also have special qualities such as optical, electrical, magnetic, chemical, and physical capabilities\cite{89}. CNT and chitosan composites are used in biomedical, as shown in figure 8.

Electroconductivity: CNTs could either be semiconducting or metallic depending on the level of chirality. These nanotubes can conduct electricity without the dissipation of heat. The conductance of SWNTs is predicted to be not be impacted by the diameter and length and is defined as $G_0 = 2e^2 lh = 1/12.9$ K$\Omega$, defined as a unit of the conductance quantum.
2.4.4. Biochar

Biochar is pyrogenic dark carbon acquired by pyrolyzing biomass like wood and grass under nitrogen-or oxygen-restricted conditions. It is a strong carbonaceous substance made by thermally treating biomass in an oxygen-exhausted climate. It has exceptional surface characteristics and is proposed as a minimal expense adsorbent for remediating soil and water filtration. With the far-reaching creation of sugars, their use is being augmented commonly when contrasted with the usage in the previous decade.

Every year, approximately 300 million tons of coking wastewater is produced in China, accounting for 1.59% of the global industrial chemical oxygen demand emissions. Traditional biological treatments are common treatment technologies for coking wastewater [90]. Many types of non-biodegradable dissolved organic matter still exist in biotreated coking wastewater, including phenolic compounds, polycyclic aromatic HCs, and N, O, and S-containing heterocyclic materials.

Studies have demonstrated that biochar can effectively adsorb DOM in wastewater; however, the hydrophobicity of biochar hinders the adsorption efficiency of hydrophilic DOM removal, as hydrophilic substances account for a large proportion (25%–60%) of DOM in BTCW. Chitosan, a deacetylated derivative of chitin, has proven to be efficient for DOM, such as amino and hydroxyl groups, and when grafted on the surface of biochar, it will make it more hydrophilic. Many sites in the chitosan molecular chain become absorption sites. Chitosan modification could improve the potential of adsorption of attapulgite and activated carbon for DOM in an aqueous solution.

Results replicated the hypothesis that biochar (45 min) reached adsorption equilibrium faster than CB (60 min), but the adsorption rate and equilibrium adsorption capacity of CB for DOM were significantly improved, hence confirming that modifications in chitosan could improve the affinity of biochar to DOM [47].

3. Discussions

Chitosan has been applied and used in multiple fields, including biomedical, wastewater treatment, supercapacitor, electrode, packaging industry, food industry, as shown in figure 9. Chitosan has some drawbacks, but those can be overcome by using fillers, nanoparticles, additives, reagents, as we discussed above. Water treatment is mostly done by the adsorption technique using modified chitosan [91]. As a consequence of their special features such as being non-toxic, cationicity, biodegradability, and high absorption capacity, chitosan, and its derivatives have gotten much attention as suitable adsorbents for dyes, including azo dyes, oil spills, heavy metals like cobalt and copper, and multiple endocrine-disrupting materials and pharma substances. Physical and chemical differences inside the raw form of chitosan, such as cross-linking and grafting more functional groups onto the backbone of chitosan to absorb the dye, have yielded a variety of chitosan derivatives.

Chitosan doped with different kinds of elements like nitrogen, phosphorus, nickel oxide, sulfur, and nitrogen-oxygen co-doped is used to make supercapacitors with high specific surface area, the electrode for microbial fuel cells, and the anode for lithium-ion electrode [92]. Chitosan-based materials are the focus of food packaging research. Furthermore, chitosan-based materials contain food-preserving antioxidant activity and the capacity to form films, allowing for the creation of transparent foils and bags. It can also be found in various
cosmetic formulations and goods, including dental enamel, nail and tooth lacquer, lipsticks, mouthwash, washing products, breath fresheners, chewing gums, and deodorants. As a result of being nontoxic and having other features such as being biocompatible, biodegradable, and very adaptable polymers, chitosan, and its forms have shown to be practical to be used in a wide range of biomedical uses, some of which have been included in therapeutic techniques by the pharma industry. Chitosan can be employed as a non-natural kidney membrane owing to its inherent mechanical strength and urea and creatinine permeability. To develop dialysis capabilities, it could be changed by mixing with polymers that are soluble in water and using graft copolymerization. It can also work as a wound-healing accelerator. Chitosan has been extensively researched to engineer tissues since its capacity to stimulate development and the decomposition of the mineral-rich matrix. Because chitosan has a structure similar to numerous glycosaminoglycans prevalent in articular cartilages, it can be an excellent scaffolding substance to engineer articular cartilages. Because chitosan is a good biomaterial, it could engineer liver tissues. A key factor why chitosan was chosen to be a scaffold for hepatocyte culture is the similarity in morphology to glycosaminoglycans found in the extracellular matrix of the liver.

Chitosan can also be used in agro-waste management. Different researchers showed the use of chitosan in different agriculture fields. Chitosan boosted pathogen control efficacy, raised germination rate, stimulated defense replies opposing the rice blast pathogens, accelerated rice growth and yield while reinforcing the defense response, and reduced water use in the pepper plant when used as an antibacterial agent. Chitosan nanoparticle applications include pesticide conveyance for protecting crops, fertilizer conveyance for sustained and
well-balanced nutrition, herbicide conveyance to eradicate weeds, micronutrient conveyance for promoting the development of crops, improving soil health, and the conveyance of genetic substances to transform plants [94].

3.1. Role in agriculture applications
Developing technologies that increase food yield while minimizing negative effects on the environment is urgently needed. In this situation, controlled delivery methods for the delayed release of genetic or agrochemical elements are essential. For reasons that have been deliberated upon in this paper earlier, Chitosan has come up as a potential conveyer for the regulated conveyance of agrochemicals. In the realm of drug conveyance, chitosan is extensively utilized. Its appeal stems from its beneficial structural and biological features, including cationic, aqueous acidic solubility, and biodegradability. Chitosan research has progressed from starting as a general agent for treating sewage to regulating the growth of plants, as a soil conditioner, as an agent for antistaling in fruits and vegetables, and as an agent for covering seeds with applications in managing diseases in crops in particular. In tomatoes, cucumber, and other such seeds, chitosan triggers the defense of plants. It also affects their rate of germination. In pearl millet, priming seeds with chitosan improves their germination and vigor. Furthermore, solutions related to the priming of seeds using acidic chitosan solutions were found to boost maize vigor.

Chitosan also increased rice production and growth while enhancing the defense response. Other surveys have also indicated that chitosan is useful in modifying plant responses to abiotic conditions such as salt and water stress. Water use was reduced by 26–43 percent in pepper plants treated with chitosan, but there was no discernible difference in biomass output. The same results indicate that chitosan could be used as an antitranspirant in agriculture, where water loss is an issue. Chitosan coverings are being developed as a viable option for insecticides. They have been shown to slow the progression of degradation and generate resistance to rising in the host’s tissue. Its products can be used in several ways, such as reducing disease levels, minimizing water requirements, and enhancing crop productivity in an environmentally sustainable manner. The shape, size, density, and extent of an active component’s release from molecules based on chitosan are all factors [94].

Chitosan nanocomposites could be created in various methods, such as emulsion cross-connecting, emulsion-bond combination, precipitation, ionotropic gelation, switch micelles, and sieving, utilizing nano-scaled controlled delivery gadgets. By presenting a 3D organization morphology in the nano-emulsion, cross-connecting works on the mechanical strength of the last molecule. Chitosan created by ionotropic gelation is steady, non-poisonous, and naturally dissolvable [94]. We use chitosan nanomaterials as a drug conveyance framework in various kinds of uses, as visible in figure 10.

3.1.1. Pesticide delivery system
Pest management challenges and concerns about the excessive utilization of pesticides in agriculture have sparked heated debate and discussion. For solid wood preservation, polyvinyl pyridine and polyvinyl pyridine-co-styrene nanomaterials are used in regulating the release of fungicides such as chlorothalonil and tebuconazole. The active component was nearly quantitatively incorporated using this approach. Pesticide carriers are inorganic nanoparticles like TiO₂, Fe₂O₃, SiO₂, or Al₂O₃ for greater bioactivity and lower residues. The amount of fertilizer and water used determines the extent and quality of plant development.
3.1.2. Macronutrient and micronutrient delivery system

Accordingly, better harvest yields require better water assets and manure supplement usage. According to gauges, applied manures contain between 40%–70% nitrogen, 80%–90% phosphorus, and 50%–70% potassium, which plants cannot consume. Not only can the right blend of slow-discharge manures and superabsorbent polymers help plant nourishment and yields, but it can also keep water losses from disappearing and reduce water system recurrence. An NPK complex compost having both monitored delivery and water-maintenance characteristics was made by utilizing an inside covering of chitosan and an external covering of poly (corrosive acrylic co-acrylamide) [P( AA-co-AM)], a superabsorbent polymer. The product was found to deliver nutrients in a controlled, delayed manner.

Micronutrients like Mg, B, Cu, Fe, Cl, Mb, and Zn are critical in plant development. Agricultural methods like liming acid soils lead to micronutrient deficits in crops by reducing the presence of these nutrients [95]. Chitosan is changed to maintain plant growth using 1-naphthyl acetic acid, an essential plant growth hormone [96]. Chitosan induced significant variations in organic acids, amino acids, and sugars in wheat seedling leaf according to metabolite profiling. There was a significant increase in sucrose after chitosan treatment and an increase in the activities of sucrose phosphate synthase and fructose 1,6-2 phosphatase, and an increase in the relative articulation of sucrose phosphate synthase and fructose 1,6-2 phosphatase. A few Krebs cycle metabolites, like oxaloacetate and malate, were likewise upgraded, similar to the activities of phosphoenolpyruvate carboxylase and pyruvate dehydrogenase. Chitosan, then again, may assist with N decline and digestion. Glutamate, aspartate, and a couple of other amino acids were more noteworthy in chitosan-affected plants, joined by the actuation of basic N decrease and glutamine synthetase/glutamate synthetase cycle chemicals. These discoveries recommended a pleiotropic regulation of C and N digestion inside wheat seedlings instigated using chitosan, giving a critical understanding of the metabolic instruments of plants because of chitosan and giving an establishment for future chitosan application in farming [97].

3.1.3. Herbicides delivery system

Several studies show that 10%–15% of the crop is lost every year due to weed growth, which steals essential nutrients from plants or crops, causing plants or crops to die due to a lack of available nutrients and water. However, the widespread usage of herbicides to control weeds has resulted in major environmental and public health issues. The substance stability, dissolvability, bioavailability, photodegradation, and soil sorption of the utilized herbicides are totally to blame for the issues they cause. In this context, herbicide formulations with controlled release have become a requirement, as they often boost herbicide efficacy at lower dosages. Use alginate or chitosan nanoparticles as a transporter. They showed that combining paraquat with alginate/chitosan nanomaterials modifies the herbicide’s outbreak characteristics and soil reactions, suggesting this combination could be a useful tool for minimizing paraquat’s harmful effects [98]. Chitosan and clay (montmorillonite) were adsorbents in the herbicide clopyralid in an aqueous soil and water mixture. The bi-nano composites exhibited excellent herbicide adsorption capability at pH values where the anionic avatar of functional principles with the positive ionic avatar of chitosan dominated. When the bio-nano composite contained a higher percentage of chitosan, it was more effective at removing the herbicide from the aqueous solution. The composites successfully absorbed clopyralid from the soil at a slightly acidic pH. Using such a formulation can assist in restricting the anionic transfer of pesticide mobility within the conditions, lowering the danger of intoxication of surface and underground water bodies [99].

3.1.4. Soil health improvement

Soil health improvement is also a concerning factor, as sometimes, after continuous farming, the soil becomes insufficient in nutrients or has inadequate water quantity. In this context, nano-sensors can aid in expanding practices in farming with precision via the detection and correction of agronomic problems in less time. It has been observed that nanoparticles such as zeolites and hydrogels can help improve soil water-holding capacity [100]. The biosensor is made up of chitosan that has been crosslinked with glutaraldehyde and then changed using paramagnetic Fe₃O₄. The Fe₃O₄/CS nano composite film, which is simple to make, has a high accumulation ability for determining and removing heavy metals, and it also ‘reports’ the reaction through an electrical reaction.

3.1.5. Generic materials

Nanotechnology has demonstrated its utility in modifying plants’ genes by introducing new genes that result in agricultural enhancement. When compared to conventional gene transformation techniques, this approach offers substantial benefits. Plant cell walls are the greatest obstacle to gene delivery in crops. Coacervation between the strongly charged amine bunches on chitosan and the negatively charged phosphate bunches on DNA can undoubtedly result in chitosan/DNA nanoparticles [101]. Chitosan, contrarily, has less efficacy in transfection. The efficacy of transfection is dependent on the molecular mass of chitosan, the amount of
deacetylation, the acidity of the transfecting medium, and the cell type [102]. The use of chitosan in formulations containing short interfering RNA has generated a lot of interest (siRNA). Chitosan can manufacture nanoparticles by forming a combination with siRNA due to its cationic tendencies. Several studies have suggested that siRNA trapped in Chitosan nanoparticles can be used as a carrier for siRNA conveyance [103].

Nanochitosan is also used to regulate abiotic stress inside plants [104]. Salinity is a major stressor that affects plant growth throughout the world. More than 20% of all agricultural fields are required to possess increased salinity at a level that could significantly affect plant development [105]. By enhancing the bioavailability of nitrogen oxide (NO), chitosan increased leaf S-nitrosothiol and chlorophyll levels in treated plants. NO is a signaling molecule that helps plants respond to various abiotic stressors [106]. When applied to tomato plants under salt stress, chitosan-polyvinyl alcohol hydrogels with and sans copper nanomaterials encouraged plant growth and the gene expression in producing jasmonic acid and superoxide dismutase, both of which could be required in detoxifying compounds [107]. As reported in several studies, drought stress can also be maintained by using chitosan nanoparticles. The chloroplasts are destroyed by drought stress, lowering the quantity of chlorophyll and using the photosynthetic enzymes that are part of the Calvin cycle.

3.2. Role in agro-waste management

Horticulture refers to the cultivation of food and related products. Like other activities such as industrialization, agriculture is the most extreme source of waste age. Farming waste is one of the principal issues that influence biodiversity in various districts worldwide. Rural effluents are caused by the abundance of water utilized in water system frameworks. Rural wastes refer to squander delivered due to multiple horticultural tasks. It includes excrement with various waste extracted from ranches, poultry houses, and slaughterhouses; collected waste; compost run-off from fields; pesticides released into soils, air, or water; and salt and residue released from fields.

Studies have been conducted to indicate how chitosan can be extracted from prawn shells and become efficient for various uses. Understanding scientific strategies FTIR and SEM alongside the gel arrangement property of the pre-arranged chitosan approves the case. In this study, Pandharipande, S L et al Biosilms shaped of chitosan-lignin, for example, CL1 and CL2, have almost comparative elastic qualities as detailed in the past papers. These biosilms have potential applications in the bundling field of touchy materials. Chitosan being of greater expense, its biocomposite with lignin, which is a minimal expense regular item, would drop down the expense of biocomposite films shaped. An additional benefit is that the byproducts like scavenger shells and mixing it with one more side-effect lignin is a legitimate use of such materials into valuable applications. These biosilms have been examined for utilitarian gathering presence, surface morphology, and mechanical property utilizing FTIR, SEM, and elasticity separately [108].

Safa, Y et al concentrated on how chitosan-cushioned rice and wheat husk can be utilized to dispose of receptive colour from fluid solution. In a few studies for colour removal [109], horticultural waste rice husk was used as an adsorbent. The receptive red 195 colours evacuation utilized chitosan-cushioned wheat husk and rice husk adsorbents. They were washed with refined water to eliminate contamination from the air and ground. The cushioned rice and wheat husk were ready with chitosan in the proportion of 6:1 w/w. It was disintegrated in a 2% acidic corrosive arrangement with persistent mixing for 12 h. Then, at that point, the substance was sifted, and the stove dried to get a cushioned type of rice and wheat husk and put in an electric broiler (J-FM 3, JISICO) at 65 °C for 3 h for enactment to remove the physisorbed species. Rice and wheat husk cushioning with chitosan increases the adsorption limit of husk materials. Using the adsorption technique, around 80% of receptive colour was expelled. Responsive colours are the principal poisons of material ef

3.3. Role in biomedical application

Chitosan is being used in various bio-engineering applications, as shown in figure 11. It can be covalently and ionically crosslinked with hydrogels to absorb bioactive compounds. The ionically crosslinked hydrogels have
excellent biocompatibility allowing them application potential in various pharmaceutical utilizations. They can form implants, bandages, and thermogelling systems and be the gel base for orally administered medicines [37]. The polyelectrolyte nature of chitosan and its pH flexibility has been designed for controlling its interaction with anionic nanomaterials. The positive charge of chitosan gives it anti-bacterial properties. Silver (Ag) loaded chitosan nanoparticles exhibit better antimicrobial activity and structure [39]. Chitosan-based hydrogels also promise to be used in medicine conveyance and tissue engineering. The use of chitosan for developing smart devices that reduce drug side effects is yet to be explored [40]. Chitosan is also used in the development of aerogel for anticancer drugs. Chitosan-based biomaterials can be utilized for regenerating the central nervous network by crossing the hurdle between the brain and blood. Neural regeneration can be obtained through their ability to form scaffolds that are porous and can hold both biomolecules and cells [110].

Chitosan–polymer materials display amphiphilic behavior that disperses in organic solvents and could be utilized in multiple medical applications like engineering tissues and bone reconstruction [111]. Peptide chitosan hybrids have biointeracting properties and cell adhesion properties that could be utilized for drug delivery, cell therapy, and engineering tissues. The addition of amines and alcohol groups to chitosan improves its conjugation to other biomolecules, enhancing the site-specific delivery of various drugs [112].

Chitosan–polyester materials have also been designed through the chemical transformation of polymers subjected to plastic flow. The polymer blends were amphiphilic and easily dissolved in organic solvents. This method is employed to manufacture microfibres and microbeads that have high bioactivity. It preserves the purity of the finished matrix as no catalyst or initiators are added to the solid-state reactive blend. These polymeric materials find multiple applications in the biomedical field [111].

3.3.1. Modifications and uses of chitosan scaffold
Bioimmitic calcium phosphate mineralized GO or chitosan scaffolds show high cell adhesion and growth potential. They possess better mechanical strength because of the electrostatic bonds formed among the functional groups of GO with CS amine groups. It exhibits a hierarchical microporous structure with good absorption of nanoparticles. Nanoparticles were added to improve their osteoinductivity and antibacterial properties. They are effective against the strains of Escherichia coli and Staphylococcus epidermidis. These scaffolds with large micropores show great biocompatibility, bone marrow stromal cells, and regeneration of tissues. It can be effectively used in bone marrow tissue engineering [113]. Intermolecular forces modified Chitosan with an organic–inorganic molecule, polyhedral oligomeric silsesquioxane, and CNTs. The
introduction of CNTs efficiently improved the adsorption capacity of the POSS-CS compound after POSS was put on the CS molecule to the CS molecule’s stability. The enhanced adsorption capacity was shown for the MO and CR solutions by the made POSS-CNTs-CS compound, and this excellent property makes the composite show promise for utilization in food, wastewater therapy, and clinical treatment, just as giving groundbreaking plans to the planning of CS-based multi-composites [114].

Its well-being and critical natural and substance properties are described by its well-being, including biodegradability, biocompatibility, bioactivity, and polycationicity. Moreover, the NH2 and hydroxyl [OH-] bunches give chitosan numerous unusual qualities, making it relevant in numerous spaces and exceptionally appropriate for substance responses.

3.3.2. Nanocomposites and their applications
Notwithstanding organisms, chitosan and its nanoparticles possess few antimicrobial features, even opposing the anti-infection safe Gram-negative and Gram-positive microbes, requiring further examinations of major bacterial and parasitic fish microorganisms. In addition, practical examinations are required to clarify their activity component. Chitosan nanocomposites are exceptionally urgent in their applications in the material business, food bundling, medication, and water sterilization of fish ranches. Particles that have negative charges on their surface can be effectively bound with CSNPs, making them pertinent for a wide scope of purposes.

Fish collagen and chitosan films could be utilized for controlled, confined medication conveyance and chemotherapy. Bioadhesive chitosan nanoparticles have been utilized as carriers, encapsulators, or immobilizers of bioactive fixings, including catechins, chlorogenic corrosive (from soil products), and food additive ‘Thyme’ fundamental oil. Without a doubt, the utilization of chitosan nanoparticles in antimicrobial immunomodulation action has acquired the most extreme significance because of the high effect on further developing hydroponics creation. This survey article also features their advantages in the strength of amphibian organic entities’ strength of amphibian organic entities’ natural and clinical utilization of chitosan-put-together buildings concerning fish and scavengers [115].

3.3.3. Biofoam - structure, and uses
The development of biofoam primarily made using chitosan showed the concentration of chitosan played an important role in its microstructure and hence its physical properties, whereas the lack of chitosan in its structures gave a filament filled with voids, leading to lower values of thermal conductivity than glass wool. One of these bio-foam structure applications was for inserting ceramic slurry. Using a replica technique, a successful preparation of a porous ceramic morphology inside alumina was 70% free porosity, which seems most relevant for the mentioned application due to being better environmentally than conventional polyurethane foams when pyrolyzed. Nonetheless, further activity depends on monitoring sample homogeneity for elaborating extremely monitored porosity of ceramic substances using chitosan-based bio-foams [116].

With the utilization of radiation corrupted chitosan readiness of hybrid polymers, organization of chitosan with polyvinyl liquor was done, which upon illumination, the synthetic design of chitosan advanced a chain scission response, changing its hydrophilic equilibrium and bringing down its atomic weight. Its impact prompted biocompatible HPNs, after which IR and XRD results showed improved responses among CS and PVA and diminished crystallinity with expanded retained portions individually. Moreover, cell feasibility experiments accompanied by human dermal fibroblast cells revealed that the HPN could be practical and not harmful, demonstrating its potential for use in biomedical and tissue designing applications [117].

3.3.4. Extraction of chitosan for use as biomaterials
Using two protocols in two stages, the acquisition of chitosan from a mushroom G. lucidum. Protocol two was for obtaining the desirable characteristics for the biomaterial in the cases of DRX, FTIR deacetylation percentage, and a Thermogravimetric study. Moreover, the chitosan powder fulfilled bio reactivity in vitro requirements, indicating the material’s biocompatibility. These properties show promise and are essential to chitosan’s use in various fields, including cosmetics, pharmaceuticals, biomedicine, and food, to name a few [6].

Utilizing a characteristic polymer, gelatin, as the center format, the creation of chitosan nanofibers utilizing a dissolvable watery acidic corrosive improvement was seen utilizing normally inferred cross-linkers, particularly oxidized dextran and sucrose in the water-safe capacity of the nanofiber. Moreover, being regular polymers, chitosan and gelatin show superb biocompatibility and reasonable bioreactivity. The cell grip completed affirmation of their biocompatibility and cell development of these cross-connected center shell gelatin/chitosan nanofibers, which showed that the present observed chitosan nanofibers with gelatin as their core after cross-linking with the cross-linkers as mentioned earlier, show immense potential for various types of tissue regeneration in the biomedical field [118].
3.3.5. Applications of chitosan in wound dressing
A medical application of chitin and chitin-derived chitosan with high promise is its use in wound dressing using their adhesive nature and antifungal and bactericidal characteristics. Permeability to oxygen is a crucial property with high importance in association with wound dressing and treatment of burns. Chitin and chitosan are amazing substances for dressing wounds and healing, using their excellent properties. The chitin-derivative membrane can be utilized to speed the healing of wounds. The temperature-sensitive material Polypropylene-NIPAAm-collagen-chitosan membrane has the potential to be used as a default release of dressing materials after the wound has healed. Further improvement of these membranes is being done using numerous polymers that give the desired wound healing applications. Substantial advances towards this application can be seen and testified by understanding these polysaccharides, which gives us a valid basis for these membranes to be ideal candidates for wound dressing applications shortly [119].

3.3.6. Study of chitosan structure and biocompatibility
A straightforward, economical, and functional interface enhanced Raman scattering, or SERS substrate was put forward in this study for biomedical applications with a simple one-step method to fabricate a hybrid 3D porous structure using nanomaterials made of silver chitosan. Chitosan over here was utilized as a template for decomposing Silver NPs. Although the betterment factor is much lower than the rest of the SERS substrates, this particular substrate can be suitable in SERS pharma utilisations due to this compromise being adequate with excellent biocompatibility. This fabrication with biocompatibility put forward using the chitosan template makes it appealing for transporting bioactive compounds for genetic markers of DNA with one strand, drug screening, and even gene expression profiling [120].

3.3.7. Recent studies on the use of chitosan
Modern advancements in the medical utilization of environmentally preferred chitosan and its blended electrospun nanofibers have contributed to a novel medicine conveyance system and improved stage in regenerative medicine, a rapidly developing field in life sciences. Due to its many advantageous properties, this biopolymer is widely applied for biomedical applications, which are given in detail in this study. For chitosan nanofiber fabrication, a pioneering technique includes electrospinning, due to which these nanofibers can widely be utilized in unique biomedical applications using their high porosity and surface area. As a result, electrospun fibers of this polysaccharide are of great interest, as they have great value in various biomedical and pharmaceutical applications such as drug conveyance, wound dressing, and the engineering of tissues medical and body implant interphases [121].

Diabetes, bedsores, and extensive burns are among the many health problems associated with impaired wound healing. This leads to a longer healing time, putting the patient at risk of other complications. Improved wound healing was investigated, which led to the use of CNTs, chitosan–SWCNTs, and chitosan–MWCNTs, showing promising potential. Followings up on the potential hydrotherapeutic activities of these hydrogels [(C-MWCNTs) and (C-SWCNTs)] and confirming the same requires research in non–mice animal species to eliminate potential side effects [122].

3.3.8. Methods of dissolution
Removing the limitation of the biomedical application of chitosan materials requires overcoming the simple but tough challenge of dissolving chitosan in plain water. An environmentally-friendly dissolution method is proposed that includes dissolving chitosan in ionic liquids after which it is frozen for a night. This approach makes it appealing for transporting bioactive compounds for genetic markers of DNA with one strand, drug screening, and even gene expression profiling [123]. Carbon nanotubes show vast potential for transporting biomolecules, being a variation of inorganic conveyance frameworks. Carboxylated MWCNT (multi-walled) and MWCNT chitosan–folic acid particle hybrids were studied, synthesized, and characterized, and the results that were observed pointed out that two major determinators were determining the efficacy in transportation and the cytotoxicity of carriers that were mainly composed using MWCNTs, which were the MWCNT length and surface functionalization. Furthermore, it is helpful in this biomedical application to effectively synthesize gene conveyance systems mainly composed of CNST [124].

A problem arises when pure silk fibroin is applied to engineer tissues for their excellent biocompatibility, which causes bacterial infection problems. To cancel out this confrontation, introducing CS and PDA in electrospun nanofibrous silk fibroin via LBL assembly enhances the natural polymers’ antibacterial property and cytocompatibility. Using the LBL technique, the fabrication of the electrospun SF biomaterial was successfully carried out with CS and PDA depositions, the indication being a rougher surface morphology from SEM images. A remarkable antibacterial ability was also seen after coating more than 5 bilayers of CS/PDA. After the
observations, the conclusion derived from the studies showed that CS and PDA polished SF mats could be an inventive multifunctional biomaterial, especially in the medical field [125].

3.3.9. Composite materials
A mixture of biodegradable ceramic substances and biocompatible polymers mimics the natural function. Therefore, composite CTS-based materials have recently played a major role in engineering bone tissues. CTS with hydroxyapatite composite has excellent osteoconductive, osteoinductive, and osteogenic features, making it a promising material for bone implants. The various morphological, chemical and physical reactions along with \textit{in vitro} studies have been carried out for CNT, CTS/HAp, and the composite substances too, which are synthesized with only issues persisting in the mechanical aspect of the mentioned materials, but the addition of CNT to the composite would most definitely improve the support and help in the functioning of the natural bone. Much research is underway to address the shortcomings in the synthesis of physical features and the cytotoxicity of CNT. Surely, the progress of research in the efficiency of CNT can pave the way towards numerous advantages for the futuristic applications of engineering bone tissues [14].

Using the freeze-drying method, the antibacterial property of prepared chitosan-carbon nanotube hydrogels was examined with variations in the concentration of CNT in the chitosan, which was later chemically characterized using Optical Microscopy, SEM, and Fourier Transforms-Infrared Spectroscopy. The end product during the synthesis of Chitosan-based CNTs hydrogel showed a clear morphology of pores with the uptake of water and the capacity to retain, besides, a solid antimicrobial action against \textit{S. aureus}, \textit{E. coli}, and \textit{C. tropicalis}, making CNT in a chitosan grid a promising up-and-coming substance in medical as well as food science utilization [89].

A half-and-half arrangement of multi-walled CNTs covered by chitosan was uncovered as a pH-sensitive transporter for methotrexate vectorization to a cellular breakdown in the lungs. The successful covering of the carbon nanostructure by Cs was measured by thermogravimetric investigation and later surveyed by SEM, TEM, and X-ray photoelectron spectroscopy, separately, after which the use of Raman Spectroscopy was carried out for the characterization of interactions between porphyrins-carbo and carbon counterparts. This novel structure had the potential to act as a nanocarrier in a certain specific conveyance of methotrexate to the cancerous lungs cells (H1299), having much less toxicity than functional MRC-5 cells. The conclusion brought on by the study is of extreme relevance if estimating the possibility of medical utilization of this tool, even though for confirmation of the therapeutic performance and related properties and abilities, further experiments and research need to be conducted to rule out any negative results and allow for the use of the cells for clinic use and against one of the most common types of cancer: lung cancer [125].

The synthesis of GO-chitosan composite layers with loaded layers structure was done using exfoliated chemically GO sheets, which were utilized as an adaptable nanostructured template and antibacterial for synthesizing stem cells. The strength and elastic modulus were adjusted for an advantageous increase by increasing the GO content. Significant antibacterial ability was seen from the GO–chitosan composite, similar to the chitosan layers, against the \textit{Staphylococcus aureus} bacteria. Considering the fluorescent figures of the cytoskeleton fibers of actin of hMSCs and the mechanical strength of the GO sheets and chitosan layer’s stem cell proliferation, the mentioned composite could be a promising platform for hMSC culture [128].

Various proportions of a chitosan-gelatin-ferulic corrosive mix were utilized to prepare unique movies of methotrexate vectorization to a cellular breakdown in the lungs. The successful covering of the carbon nanostructure by Cs was measured by thermogravimetric investigation and later surveyed by SEM, TEM, and X-ray photoelectron spectroscopy, separately, after which the use of Raman Spectroscopy was carried out for the characterization of interactions between porphyrins-carbo and carbon counterparts. This novel structure had the potential to act as a nanocarrier in a certain specific conveyance of methotrexate to the cancerous lungs cells (H1299), having much less toxicity than functional MRC-5 cells. The conclusion brought on by the study is of extreme relevance if estimating the possibility of medical utilization of this tool, even though for confirmation of the therapeutic performance and related properties and abilities, further experiments and research need to be conducted to rule out any negative results and allow for the use of the cells for clinic use and against one of the most common types of cancer: lung cancer [125].

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3.3.10. Use of biomaterials
New original biomaterials with enhanced required features, including photoluminescence, biocompatibility, and high stability, are in dire need of utilization in the medical area. The preparation of a novel type of nanomaterial for such applications was carried out using only biocompatible components. This attempt was successful in the research, and the obtainment of chitosan–based carbon dots (chitosan QCDs) was achieved according to the principles of Green Chemistry in a fast and efficient manner. The use of amino acids to prepare the CsQCDs with simultaneous functionalization under conditions assisted by microwaves led to prepared carbon nanodots with exceptional photoluminescence, which led to crosslinking chitosans and carbonizing them. The best modifying agent was lysine, enabling N-doping processes, resulting in the large quantum material formation of nanomaterials that were observed to have a spherical shape typical for QCDs. The perfumed XTT test and morphological analysis on human dermal fibroblasts were used to confirm the low
amount of cytotoxicity in the synthesized biomaterials. Concluding the research, it was found that chitosan-based quantum dots showed high potential in the application and use in medical areas such as cell labeling, diagnostics, theragnostic, and controlled drug delivery systems [130]. Chitosan’s primary amine group is responsible for its cationic nature, controlled drug release, mucoadhesion, in situ gelation, antibacterial, permeation enhancement, and other qualities [131].

Chitosan is a polymer with no toxicity and more than one helpful utilization in the medical field and the agriculture sector, but chitosan has shown more promising applications as further studies are carried out. With the evolution of nanotechnology showing potential, incorporating chitosan-based nanomaterial has been done in various products to improve efficiency and biocompatibility. Moreover, direct use of these nanomaterials has also been done in many applications because of their inborn antimicrobial and chelating properties, including the accessibility of the utilitarian gatherings to be changed. The utilization of such chitosan-heavy nanoparticles in the agrarian and biomedical areas identified with the administration of abiotic stress in plants, water accessibility for crops, controlling foodborne microorganisms, and malignant growth photothermal treatment was studied in detail, along with insights given for the next steps of action to be taken.

3.3.11. Use of chitosan in cancer therapy

Apart from the popular uses of these nanomaterials in bone tissue engineering, wound healing, wound dressing, bio-sensing, and gene delivery, nano chitosan-based materials can be used in cancer photothermal therapy, an emerging study that is not broadly discussed. Drug delivery systems (DDSs) with controlled pharmacological substances must be designed and synthesized to improve cancer patient treatment. Chitosan and chitosan-modified polymers are the most widely used natural biomaterials [131]. In cancer photothermal therapy and monitoring foodborne pathogens, the utilization of materials made using nano chitosan and their derivatives show potential. Furthermore, the use of chitosan in conjunction with folic acid to create ZnS quantum dots loaded onto nanocarriers shows promise in the therapy for suicidal genes; the synthesis of chitosan-ZnS-FA nanomaterials as an anticancer medical framework; and highly useful applications of chitosan-based nanomaterials. Chitosan nanoparticles mixed with essential plant oils are tested instead of FBPs; these CSNPs exhibit better performance than chitosan nanocapsules regardless of the presence of lime essential oils. When CSNPs are formulated with many essential oils, an observed increase in antimicrobial impact is due to various FBPs having a high ratio of retained vital oils. Another potential application of CSNP that was mentioned above relating to controlling food pathogens was studied in detail, and the observation that was drawn showed that chitosan-based materials with or without plant extract had an antiviral impact, opposing viruses resulting from food, including the MS2 phage, Marine Norovirus, and Feline calicivirus. Furthermore, the use of chitosan-based materials to treat the primary viral food-originating germ human norovirus has been attempted, indicating prospects for further research against this and other viruses [104].

3.3.12. Chitosan nanofibrils

To get into detail about the pros of this scaffold would be ultrafine, continuous fibers with increased porosity that is permeable to oxygen, changeable distribution of pore dimensions, increased values of the surface to volume proportion, and mainly, structural identity to natural extracellular matrices in the skin that encourage cell movement, synthesis, and adhesion. Recent studies have made it possible to synthesize chitin and chitosan nanofibrils with higher flexibility and resourcefulness. An example of chitin nanofibril material is Dibutyrylchloritohydroxypropyl (DBCP), a soluble derivative in water that has been shown to have resourceful biological characteristics. This chitin derivative was prepared by butyric anhydride and shrimp chitin, which were utilized under unique conditions, with the catalyst being perchloric acid. Presently, DBCP fibrous substances are being widely used to heal wounds; and more studies into this widen the understanding by using even applications to multiple real-life patients with different indications.

This demonstration demonstrated that the results of wound relief were generally satisfactory, focusing on examples of burn-inflicted injuries, traumatic wounds following operations, and even different situations resulting in the removal of the epidermis. DBCP fibrous materials were studied for their effects on repair reactions and techniques of action, along with multiple other tests that guaranteed the efficiency of chitin nanofibril/chitosan glycolate-based results for the restoration of the subcutaneous structure. When it comes to chitosan-based fibrous materials, electrospinning technology has proven to be the best, inexpensive, rapid, and highly efficient method because of its simplicity for the production of nanofibers with the use of high voltage electrically charged liquid.

In recent times, biocompatible carboxyethyl chitosan and polyvinyl alcohol, or CECS/PVA nanofibers, were conjugated through the electrospinning of water-heavy solution to be utilized in the form of a promising substance for utilization in dressing wounds. The cytotoxicity assessment of this fiber mat showed non-toxicity towards specific L929 cells; cell culture findings exhibited that they were great promoters of the L929 cell synthesis and
spread, leading to the conclusion that this newfound electrospun matrix would be a highly promising skin regeneration application in wound dressing.

Also, as a result of the verifiable truth, chitosan subordinates with quaternary ammonium bunches contain high viability, opposing microscopic organisms and growths, making it broadly adequate that the objective location of these polymers is the cytoplasmic layer of bacterial cells. The photograph cross-connecting of electrospun mats featuring quaternary chitosan was extraordinarily productive in hindering the development of gram-negative and gram-positive microbes. The outcomes and further corroborative tests were completed proposing a likely material for wound dressing applications [119].

Chitosan, a copolymer of β-(1→4)-linked 2-acetamido–2-deoxy-D-glucopyranose and 2-amino–2-deoxy-D-glucopyranose. It is generally taken from basic deacetylation of chitin, the most important constituent of the exoskeletons of crustaceans, which has several uses, including in macromolecular connections swollen in aqueous or biological solvents, called in simple terms, hydrogels. The amount of deacetylation and the molecular mass are two major factors that influence chitosan features. Due to its highly interesting intrinsic properties, the biomedical and pharmaceutical fields have focused attention on it, proving to benefit both sectors immensely.

3.3.13. Structure of hydrogels
Three types of divisions can be made for covalently crosslinked chitosan hydrogels concerning their structure, which are the following: crosslinking chitosan with itself, hybrid polymer connections, and semi-or full-interpenetrating polymer connections. The most straightforward is chitosan crosslinking with itself, which includes two underlying units related to a similar polymeric chain. The end design of such hydrogels might be viewed as crosslinked gel connections disintegrating within moments of an ensnared network framed by chitosan chains of limited versatility. Regarding HPNs, the response is passed through between an underlying unit of a chitosan chain and that unit of a polymeric chain of another kind. Finally, semi-or full-IPNs have a non-responding polymer added to the chitosan arrangement prior to crosslinking, prompting the development of a crosslinked chitosan network where the non-responding polymer is caught. Further crosslinking of one extra polymer to have two snared crosslinked networks shaping a full IPN is likewise conceivable, albeit the microstructure and properties can be unique about its compared semi-IPN.

The use of this three covalent chitosan crosslinking leads to a non-changeable connection formation, facilitating free diffusion of water and enhanced physical features of the hydrogel, causing intriguing derived features. Two main applications of the covalently crosslinked hydrogels were proven useful in drug delivery systems as bioactive material release through diffusion and permanent connections utilized as a scaffold in cell cultures. Assessment of the biocompatibility is yet to be done, and a noticeable drawback of a problem arising from the administration of such systems into the human body due to observed findings of potential poisonous extra crosslinkers or compounds [37].

3.3.14. Use in drugs
Chitosan nanoparticles can be an important carrier system for drugs [133]. When taken into consideration, drugs and other medical substances derived from plants are less poisonous, showing unintended null effects against diabetes mellitus, a critical non-treatable metabolic condition. In drug delivery, chitosan nanoparticles are immensely important as carriers and supplementation of anti-diabetic drugs, being such attractive carrier systems for research to be used effectively in other anti-diabetic drugs. A demonstration of biomolecule-stacked chitosan nanomaterials with the help of Gymnemaysia nerved aqueous leaf extracts by ionically gelating chitosan with tripolyphosphate negative ions was fabricated, which showed that such active biomolecules cross-linked with nanoparticles show a physiological property of significant antibacterial activity.

Additionally, chitosan nanoparticles (CNPs) that were filled with Stevia rebaudiana leaf extract bioactive compounds were observed to be either polygonal or spherical, exhibiting highly efficient agents against diabetes. For anticancer therapy, using nanotechnology incorporated biomaterials is undertaken, bringing to the spotlight chitosan nanomaterials showing their high potential in treating cancer, biosensing, demonstrative imaging, and designated drug conveyance. Cytosolic or intracellular ROS in the nano complex treats harmful cells towards ROS-intervened pressure, which causes the malignancy cell demise. Examination of the adequacy of 5-fluorouracil and curcumin stacked N, O-carboxymethyl chitosan nanomaterials towards the hindrance of colon disease cells was done and considered, and later showed that exemplification of a mix of medications, for instance, CUR and 5-FU alongside chitosan/palladium, worked on the anti-cancer movement. One more vital exhibition of biomolecule stacked chitosan nanoparticles in the SiHa cervical disease cell line showed the promising anticancer capability of the equivalent. In the cytotoxic action, the surface charge of polymer cationic chitosan was the fundamental factor because of electrostatic communication among adversely and emphatically charged gatherings of growth cells and amino charged gatherings of chitosan individually. The chitosan-Cu nanoparticle against the A549 cancer cells [39].
3.3.15. Use of chitosan with other antimicrobials

Vast studies and research have been carried out using nano chitosan with other naturally occurring antimicrobials. For strawberry preservation, the utilization of Chitosan Nanoparticles (CSNPs) into edible films was prepared, mixed with a percent of chitosan, glycerol, and ethanolic extracts from propolis, resulting in inhibitory effect impacts opposing FBPs depending on the concentration. CSNPs combined with AgNPs synthesized using L. salicaria or purple loosestrife extracts from medicinal plants demonstrated precise and effective control of AgNP proliferation and inhibition of bacterial growth. The second application of CSNPs is in reducing the development of microbes in orange juice by utilizing the effectiveness of CSNPs and CS-nisin nanoparticles with the analysis done using four foodborne pathogens.

Here, a reduced microbial growth was seen after using each pathogen with the orange juice, with the finding being drawn to be a synergistic antimicrobial effect between the nisin and chitosan nanoparticles. Incorporating nisin into chitosan or chitosan–monomethyl fumaric corrosive nanoparticle has also demonstrated enhanced antibacterial effects of nisin against some foodborne microorganisms. Moreover, CS–covered liposome nanoparticles stacked with nisin were viewed as successful against three normal foodborne microorganisms, and chitosan and nisin could be synergized by diminishing microbial supplement take-up and teaching pore development in the cell membrane. Another study showed that CSNPs stacked with the sans cell supernatants of lactic corrosive bacterial societies were utilized to test the antimicrobial impact of foodborne bacterial and parasitic strains, out of which Lactobacillus helveticus showed the most elevated antimicrobial movement and was later on used to dissect the least inhibitory fixation along with CSNPs [142].

3.4. Role in wastewater treatment applications

It is a very serious issue for water pollutants; organic or inorganic contaminants, biologically or chemically, have increased relevance for scientists and authorities globally. Pollutants include dyes, pesticides, toxicants, heavy metals, and heavy metals, primarily from medical factories. When these effluents meet rivers and lakes, one of the five elements, i.e., water, is polluted [134]. Thus, such contamination must be constructively extracted to meet progressively uncompromising environmental top-tier standards. Thus, after many studies and experiments, it has come to light that the non-toxic and biodegradable biopolymer chitosan can be used in wastewater treatment [135].

A very large number of industries, including textile, cosmetics, paper, and pulp, make use of large amounts of organic dyes. The effluent of these industries encompasses unwanted aggregates of organic dyes, and they are required to be taken care of [136]. Dyes are often venomous and precarious for the environment. In past years, numerous techniques for dye elimination from wastewater have been seen [137]. The process of removing dyes out of the wastewater bodies is being asked for explosively. As mentioned above, dyes are typically disaffiliated and are often poisonous [138]. These techniques involve chemical coagulation, oxidation, ozonation, irradiation, precipitation, and adsorption [139]. Adsorption has proved to be the most productive, resourceful, and economical technique in the efacing of dyes. AC is a broadly used adsorbent for effacing most dyes due to its high potentiality for adsorption of different dyes. Also, its utilization is quite low owing to increased value [140].

Adsorption done by chitosan is become a striking de mixing procedure due to the material’s copiousness naturally, non-toxicity, ability to exchange ions, and investigations in a study have shown that adsorbents made from chitosan have very high adsorption potentials apropos multiple types of dyes [138]. Chitosan shows increased adsorption limits toward colours [141], metal particles, and other ionic atoms due to chitosan’s assorted functional groups. To further develop the adsorption limit of the chitosan dots, a few substance change techniques (for example, cross-connecting [142], the expansion of ionic particles, and the addition of new utilitarian gatherings) have been utilized [143]. Furthermore, chitosan in the acidic fluid arrangement can be a cationic polymer, which collaborates with the anionic toxin in the wastewater and builds the expulsion efficiency of the colour [142]. In any case, there are still difficulties in chitosan in the acidic arrangement in the generous wastewater stream because of the end of the acidic arrangement and the poisonousness and gear misfortune caused by standard acids like HCl or H2SO4 [143].

Chitosan can efficiently eliminate Direct Blue-86 (DB-86) from industries’ effluvium. Chitosan is easily available, reasonable, and reusable. This natural polymer is an efficient adsorbent for eliminating large amounts of DB-86 up to 300 mg l⁻¹ in most operating conditions. The most prominent parameter in the adsorption procedure of DB-86 by chitosan is pH. The robust electrostatic movement is established between protonated amino acids in chitosan and anionic dye in an acidic solution. Hence, the maximum elimination of DB-86 was acquired at pH ≈ 2. Alternatively, a more acidic solution, more R-NH₃⁺ on the facet of chitosan is generated, and more attractiveness is endured by the positively charged facet of anionic dye DB-86 and chitosan. Similar findings are shown by Mahmoodi et al and Chiou et al in an alkaline medium. Positively charged chitosan was deprotonated in an alkaline medium so that the desirability between chitosan and anionic dye became much
more delicate. As a result, anionic dye decreased from the active site of chitosan [144]. In alkaline medium (pH = 13.5), DB-86 is desorbed (72%) from chitosan. Consequently, chitosan is reused and reformed numerous times. Eventually, chitosan was tremendously used to eliminate DB-86 out of spiked Karoon River example and the effluent of Pars Paper industry sample, a localized pulp, and paper industry at Ahvaz.

The equilibrium data using the batch system correlated well with the model of Langmuir adsorption. The maximum potential of chitosan was calculated at nearly 60 mg g\(^{-1}\). Based on this study, it could be concluded that chitosan, as an environmentally friendly adsorbent, can be useful for dye elimination from the wastewater of different industries such as paper and pulp. Leaning on your work’s particular directive and demand, it could be needed to substantiate that the handled chemicals are not ejected in the emitted water. Chitosan-based flocculants in the water treatment solutions permit examining the residuals on-site within 10 min. This examining of residuals warrants to substantiate the catalog that no residual chemistry is let out back into nature—certifying that if following government rules and directives, ongoing process to keep up the procurement time, and abolishing the cost and annoyance of using other labs that would be requisite for synthetic treatment chemicals. As above, we have already achieved the liberty of mentioning that adsorption is the most trustable and easily accessible substitute for effacing the adulterants from the wastewater and parallely employing chitosan in the form of an adsorbent in heavy metal atoms is shown in numerous research [145].

During biosorption, the bond between chitosan and metallic functional groups incorporates differentiating wonders such as complexation, electrostatic attraction, micro-precipitation, and ions trade. It has come to pass that complicated development among chitosan, and metal particles throughout adsorption interaction can be advised in two distinct methods: the Bridge model and the Pendant model.

Shalaby, Emad A (2017) inspected the adsorption of the chitosan potential in weighty metal particles from material wastewaters such as Cu (II) and Pb (II) and watery arrangements of Zn (II) and Fe (III). The destroying productivity noticed was 91.67 % for Pb particles and 54.15 % for Cu particles, and affected due to pH notation that is so helpful outline that in examinations of residuals warrants to substantiate the catalog that no residual chemistry is let out back into nature—certifying that if following government rules and directives, ongoing process to keep up the procurement time, and abolishing the cost and annoyance of using other labs that would be requisite for synthetic treatment chemicals. As above, we have already achieved the liberty of mentioning that adsorption is the most trustable and easily accessible substitute for effacing the adulterants from the wastewater and parallely employing chitosan in the form of an adsorbent in heavy metal atoms is shown in numerous research [145].

Maintenance of Fe(III) particles on chitosan is impacted by elements, for example, contact duration, the focus stages proportions, pH, and blending speed. Fe(III) particles’ maintenance on chitosan is firmly subject to pH modifications. Chitosan is broken up when the pH is less than 3, and a colloid arrangement is obtained with more than 4.5. The balance in the chitosan adsorption is set up moderately rapidly, after 60 min, and the adsorption limit concerning holding the Fe(III) particles is more than 80 % (mg/g). Checking electron magnifying instrument pictures indicates the framed buildings and the compound change of chitosan relies upon the particle focus. Primary examination by SEM gives a sign that the component of adsorption of Fe(III) particles on chitosan is an intricate wonder, including the development of nodosities on chitosan’s morphology. The system of maintenance of Fe(III) particles on chitosan is a mind-boggling wonder and includes the development of bumps on the design of chitosan via surface adsorption of metal particles and solid networking with functional gatherings.

Chitosan flocculants are utilized in dynamic water treatment frameworks for versatile water treatment, and explanation, to semi-detached, siphoned water-absorbing coarse filtration and geotextile packs, and altogether uninvolved water treatment models, for example, bio-filtration and check dams. Though polyacrylamides are utilized with passive and semi-passive systems, it is hard to employ them with active treatment systems as they need compact commands on a loose dose rate. Alternatively, they produce a ropy congregation that will tie up to filtration media and leads it to the difficult task of keeping up the efficiency and system uptime.

Chitosan can be further modified with grafting and cross-linking agents (such as glutaraldehyde, epichlorohydrin, and others) to improve pollutant adsorption effectiveness (metal ion, dyes, and pharmaceuticals). Cross-linking is frequently used to improve the chemical and mechanical stability of chitosan. However, it often reduces the adsorption capacity of chitosan/modified chitosan for pollutant adsorption. Before cross-linking, however, grafting, insertion of solid adsorbents (e.g., metals, clays, and activated carbon), or a combination of both improves the adsorption capacity of cross-linked chitosan-based materials [146].

The ethylenediaminetetraacetic acid (EDTA) functionalization of a magnetic chitosan/Al\(_2\)O\(_3\)/Fe\(_3\)O\(_4\) (M-CS) nanocomposite was used to improve its adsorption behavior for the removal of Cd (II), Cu (II), and Zn (II) metal ions from aqueous solution. M-CS’ EDTA functionalization improved its adsorption capacity by 9.1, 5.6, and 14.3 times toward Cu, Cd, and Zn ions, respectively. Cd(II) > Cu(II) > Zn(II) had the highest adsorption capacity, and the highest adsorption efficiency was attained at pH 5.3, with removal percentages of 99.98, 93.69, and 83.81% for Cu, Cd, and Zn ions, respectively [147].
3.5. Miscellaneous applications
Chitin was a characteristic polysaccharide vital first recognized in 1884. Many living things use this biopolymer; in terms of the amount of chitin produced each year on the planet, it is the second most abundant polymer after cellulose. When the chitin deacetylation levels come to nearly half (contingent upon the beginning of the polymer), it becomes dissolvable in low pH solvents termed chitosan. Chitosan and its subordinates have pragmatic applications as arrangements, suspensions, particles, for example, dabs, tars, circles, nanoparticles, and wipes, gels and hydrogels, froths, layers and movies, strands, infinitesimal strings, and frameworks in many areas: medicament and medicine, drug stores, cosmetology, cleanliness, and individual consideration, food and nourishment, agribusiness and agrochemistry, material and paper ventures, palatable entertainment world and bundling, biotechnology, science, and drink fields, ecology, photography, and such arising areas as nutraceuticals, practical materials and cosmetic-materials, cosmeceuticals, nanotechnology, and hydroponics [148–155].

3.5.1. Food industry
Because of its bioactive properties and cationic person, chitosan is utilized as healthful fixing, and chitosan is supported by the US Food and Drug Administration as a, for the most part, perceived as protected food added substance, dietary fiber (hypocholesterolemic impact), and practical elements for the shopper. Chitosan has additionally been supported as a food additive in Japan and Korea since the 1990s [4].

3.5.2. Cosmetics
The flexibility of Chitosan is that it can be produced in various chain lengths and with distinct properties that can be used in the cosmetic, personal care, and sanitary industries. The sub-atomic load of most chitosan items is high that they cannot infiltrate the skin, which is a significant benefit that makes it reasonable for healthy skin. The particular properties in beauty care products utilized are: cationic (chitosan and hair convey inverse electrical charges), bacteriostatic, fungistatic, antistatic, film-forming, dampness holding (chitosan holds dampness in low moisture and keeps up with hand in high mugginess), and controlled arrival of bioactive specialists. It is compatible with other ingredients such as starch, glucose, saccharose, polyols, oils, fats, waxes, acids, non-ionic emulsifiers, and non-ionic water-soluble gums easily be used in cosmetic formulations.

3.5.3. Textiles and paper industry
The many properties of chitosan include cost-effectiveness, non-toxic, biocompatible, biodegradable, antimicrobial activity, antistatic activity, chelating property, deodorizing property, film-forming ability, chemical reactivity, dyeing improvement ability, thickening property, and also wound healing activity. This makes it an interesting prospect to use chitosan in the textile industry. There are many possibilities for developing new textile and cosmetic products containing chitosan-based nanoparticles with advanced properties (UV-blocking, water repellent, self-cleaning). The first use of chitosan in the papermaking industry was reported in 1936 (Struszcz 2002). The main use was to improve the wet strength of paper. Chitosan as a functional material can also interact with cellulose pulp during paper formation and be film-forming to offer cohesive resistance to rupture [4].

4. Conclusion
According to various research, Chitosan has multiple natural advantages, including high porosity, biodegradability, structural integrity, and non-toxicity. Chitosan can be found in abundance in nature. It is inexpensive to manufacture and modify. It can be used in various situations due to its many qualities. It was evident that it may easily create composites with various metals (N₂, O₂, Si, etc), compounds (Al₂O₃, Fe₃O₄, etc), carbonaceous materials (biochar, carbon nanotubes, graphene, graphene oxide, activated carbon, etc), and agro-waste (coconut husk, tea, etc). Chitosan’s thermal and mechanical stability can be increased by utilizing grafting and cross-linking agents and various biopolymers such as cellulose [147, 154–159]. Chitosan derived from chitin can be modified using a variety of synthesis techniques (electrospraying, electrospinning, ionotropic gelation, reverse micelle, and spray drying), allowing it to be used in a variety of fields, including agriculture, biomedical, agro-waste management, water treatment, microbial fuel cells, cosmetics, textiles, paper, and pulp. Depending on the use, chitosan is changed or synthesized. Chitosan is a great research subject since it is inexpensive, readily available, and has the highest solubility of any biopolymer, and many academics are now working on chitosan [63, 93, 160–162].
Data availability statement

No new data were created or analysed in this study.

Conflict of interest

The authors declare no conflict of interest.

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