Research Journal of Agricultural Science, 58 (3), 2026; ISSN: 2668-926X;

http://doi.org/10.59463/RJAS.2026.3.15

CHITOSAN-BASED BIOPREPARATIONS FOR SUSTAINABLE AGRICULTURE: FROM FUNCTIONAL PROPERTIES TO FORMULATION AND PLANT GROWTH APPLICATIONS

Valentina Elena GORGAN[1] (ORCID: 0009-0008-7559-1489);
Petronela NECHITA[2] (ORCID: 0000-0001-7846-0451)
[1] "Dunărea de Jos" University of Galați, Doctoral School of Fundamental and Engineering Sciences, 47 Domnească Street, RO-800008, Galați, Romania
[2] Faculty of Engineering and Agronomy of Brăila, "Dunărea de Jos" University of Galați, 29 Calea Călărașilor, RO-810017, Brăila, Romania
Corresponding author: *valentina.gorgan@ugal.ro*

Abstract. *Chitosan is a biodegradable biopolymer with valuable functional properties and significant potential for the development of biopreparations intended for sustainable agriculture. Due to its physicochemical and biological characteristics, it can contribute to stimulating seed germination, plant growth, and development, as well as to the producing of formulation systems that facilitate the application and enhance the efficacy of active substances. This paper aims to highlight relevant and significant data from the specialized literature regarding the use of chitosan in the production of agricultural biopreparations, focusing on its functional properties, formulation methods, and potential for combination with other biopolymers. Published information concerning various application areas is utilized, alongside findings that underscore chitosan's potential to support plant physiological processes and contribute to the development of formulations tailored to the requirements of modern agriculture. By synthesizing and correlating available data, this paper provides an overview of the progress made in this field, highlighting both reported advantages and areas that require further research. An analysis of existing scientific contributions can help identify promising pathways for optimizing formulations, improving the efficacy of biopreparations, and expanding the potential uses of chitosan in agriculture. Furthermore, an understanding of the results obtained from reported research serves as an important starting point for establishing new experimental approaches and designing innovative solutions based on biopolymers. In this context, harnessing the potential of chitosan can contribute to the development of effective biopreparations and the promotion of more environmentally friendly agricultural practices, in line with the goals of sustainable agriculture.*

Keywords*: chitosan, biopreparations, sustainable agriculture, biodegradable formulation, plant growth-promption*

INTRODUCTION

The growing demand for marine resources creates challenges regarding the management of fishery waste; however, the valorization of this waste allows for the recovery of valuable compounds—such as chitin, chitosan, proteins, lipids, and minerals—which have applications in various fields, including agriculture. (COPPOLA et al., 2021; SINGH et al., 2022)

The excessive use of fertilizers and agrochemicals contributes to soil degradation, water pollution, the impairment of beneficial microorganisms, and a decline in soil fertility. (ZHANG et al., 2020; HAYASHI et al., 2010; KALIA et al., 2011) Furthermore, reliance on pesticides can promote the development of pathogen resistance and lead to environmental pollution. (STALEY et al., 2015) These impacts underscore the need for sustainable alternatives that can protect agricultural ecosystems without compromising productivity.

In this context, natural biopolymers offer potential for the development of biodegradable formulations used to create biofertilizers, biopesticides, and biostimulants. (CHAKRABORTY et al., 2023; MARWAL et al., 2022; NARWADE et al., 2023; PARAJULI et al.,

http://doi.org/10.59463/RJAS.2026.3.15

2022) Such products can support the functioning of agroecosystems and enhance plant stress resistance by leveraging beneficial microorganisms and biologically active substances. (BRUSSAARD et al., 2007; AHMADI, 2010; HOLTZE et al., 2008) Nevertheless, their efficacy depends on the stability, viability, and performance of their active components under actual conditions of use.

Due to its physicochemical and biological properties, chitosan is a promising material for the development of agricultural biopreparations—both through its own intrinsic activity and as a matrix for the controlled release of active substances or beneficial microorganisms. Its versatility—existing in forms such as solutions, films, and hydrogels—allows for the adaptation of formulations to a wide range of applications. This study aims to critically analyze the specialized literature regarding the properties of chitosan and its use in formulations designed to support plant growth and development, highlighting its potential for sustainable agriculture.

MATERIAL AND METHODS

The study is based on a critical analysis of specialized literature identified in the ScienceDirect Freedom Collection database and in open-access scientific publications. Both review articles and experimental studies were analyzed, covering the properties of chitosan, the preparation and characterization of chitosan-based formulations, and their application in agriculture. The selected literature was examined comparatively, focusing on the types of formulations, application strategies, and key reported results regarding effects on plant growth and development, with an emphasis on the potential for use in protected-cultivation horticulture.

RESULTS AND DISCUSSIONS

Chitosan is a biopolymer of natural origin, obtained through the deacetylation of chitin; it is a structural polysaccharide that serves as a component of the exoskeleton of crustaceans. (ALEMU et al., 2023)

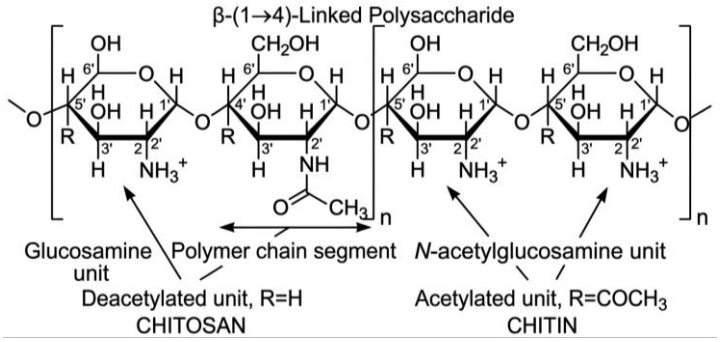


Figure 1. Chitin and chitosan

Chemically, chitin and chitosan are linear polysaccharides composed of varying proportions of N-acetyl-2-amino-2-deoxy-D-glucose (N-acetylglucosamine, GlcNAc) and 2-amino-2-deoxy-D-glucose (glucosamine, GlcN) units, linked by β-(1→4) glycosidic bonds. Their chemical structures are shown in Figure 1. The primary structural difference between the two polymers lies in the proportion of acetyl groups: their removal via deacetylation converts chitin into chitosan,

resulting in the formation of free amino groups. The physicochemical properties of chitosan—including its solubility and behavior in solution—are influenced primarily by its molecular weight, degree of acetylation, and the pH of the medium. In an acidic environment, the protonation of amino groups facilitates the solubilization of chitosan in aqueous acidic solutions, whereas chitin generally remains insoluble under such conditions. (GHORMADE et al., 2017; ARANAZ et al., 2009)

Chitin can exist in three main crystalline forms—α-chitin, β-chitin, and γ-chitin—which differ in the orientation of their polymer chains. In α-chitin, the chains are arranged antiparallel; in β-chitin, they are parallel; and in γ-chitin, a combination of these arrangements is present. α-Chitin, found in sources such as the exoskeletons of crustaceans and the cell walls of fungi, is the most widespread form and serves as the primary raw material for the production of chitosan. (NAMBOODIRi et al., 2020; SINGH et al., 2017)

The production of chitosan from crustaceans generally involves three main stages: demineralization, deproteinization, and deacetylation. Demineralization is carried out by treating the material with hydrochloric acid (HCl), which removes mineral compounds—primarily calcium carbonate—by converting them into soluble calcium chloride. In the next stage, treatment with sodium hydroxide (NaOH) facilitates the removal of proteins and other organic components associated with the chitin. Finally, the chitin undergoes deacetylation through treatment with a concentrated NaOH solution (typically 40–50% by weight) at high temperatures. This process reduces the proportion of acetyl groups, resulting in the formation of chitosan. The characteristics of the final product depend on the processing conditions and the degree of deacetylation achieved. (JIMÉNEZ-GÓMEZ et al., 2020)

Interest in chitosan stems from its biological and technological properties; these include reported antioxidant, antimicrobial, and antifungal activities, as well as its potential for use in various formulation systems. (WAYS et al., 2018; SIZÍLIO et al., 2018 ; AZUMA et al., 2015; AVELELAS et al., 2019; KE et al., 2021; SHIH et al., 2019; SARKAR et al., 2020; AMIRANI et al., 2020) However, these properties are closely linked to the physical and chemical characteristics of the biopolymer—specifically its molecular weight and degree of acetylation—underscoring the importance of characterizing the material prior to use. (ARANAZ et al., 2009; JIANG et al., 2017) In agriculture, chitosan is used as an active agent or carrier in formulations such as solutions, nanoparticles, hydrogels, and biodegradable films—either alone or in combination with polymers, nutrients, and beneficial microorganisms—to stimulate plant growth, enhance water retention, and facilitate the controlled release of active substances.

Solutions and suspensions for foliar application

One of the simplest ways to use chitosan in agriculture involves preparing aqueous solutions, which are then applied via foliar spraying or—in certain experimental setups—by watering the cultivation substrate.

EL AMERANY et al. (2022) evaluated the effect of chitosan solutions on the growth, physiology, and fruit quality of tomatoes (*Solanum lycopersicum*). Chitosan derived from shrimp shell waste was dissolved in 0.05% (v/v) acetic acid to create a 1 mg/mL stock solution, from which concentrations of 0.25, 0.50, 0.75, and 1 mg/mL were prepared. Foliar treatments were applied at two-week intervals, and their effects were assessed in terms of vegetative biomass, yield, and fruit characteristics. A concentration of 0.75 mg/mL increased leaf area by approximately 11% and the fresh weight of the above-ground biomass by 16%, while a dose of 0.50 mg/mL resulted in a roughly 57% increase in total fruit weight compared to the control. Conversely, a concentration of 1 mg/mL reduced both fruit size and water content, highlighting the importance of optimizing the dosage based on the specific agronomic objective.

In another study, ULLAH et al. (2020) investigated the use of chitosan to mitigate the effects of salinity on tomatoes (*Solanum lycopersicum* cv. *Rio Grande*). Concentrations of 50, 100, and 150 mg/L were tested under salinity conditions induced by the application of NaCl solutions at 0, 50, 100, and 150 mM. Chitosan was applied foliarly three times during the experiment, starting 14 days after transplanting. The evaluation included morphological parameters, fruit yield and quality, as well as chlorophyll content. Among the concentrations tested, 150 mg/L generally yielded the most favorable effects, being associated with improved growth and certain fruit quality indicators, along with an average yield of up to 1.38 kg per plant. The results support the potential of chitosan solutions for mitigating the negative effects of salt stress on tomatoes.

Solutions for seed treatment and priming

Treating seeds with chitosan solutions is a pre-sowing application method aimed at improving germination, seedling vigor, and tolerance to abiotic stress.

GUAN et al. (2009) studied the effects of chitosan priming on maize (*Zea mays* L.) seeds, using two lines with varying degrees of tolerance to low temperatures. The seeds were treated with 0.25%, 0.50%, and 0.75% (w/v) chitosan solutions—with the pH adjusted to 5.1—by placing them on layers of absorbent paper moistened with the solution; they were kept at 15 °C in the dark for 48–64 hours. Following treatment, the seeds were dried until they reached their initial moisture content. Although the treatments did not significantly increase the final germination percentage, they improved the germination index, reduced the mean germination time, and stimulated root and shoot development. Furthermore, a reduction in certain indicators of cellular damage was observed, alongside favorable changes in the content of soluble sugars and proline, as well as in the activity of antioxidant enzymes. The 0.50% concentration generally yielded the best results, highlighting the potential of chitosan priming to stimulate early maize development under low-temperature conditions.

Application of chitosan in culture media and to the soil

Chitosan can be incorporated directly into nutrient media used for *in vitro* cultivation, or it can be applied to the soil—either alone or in combination with other organic materials and biological inputs—to stimulate plant development and improve growing conditions.

ASGHARI-ZAKARIA et al. (2009) evaluated the *in vitro* application of chitosan on seedling development and minituber production in potatoes (*Solanum tuberosum* L., *'Agria'* cultivar). Commercial chitosan, with a stated purity of 99.9%, was incorporated into a Murashige–Skoog nutrient medium supplemented with thiamine HCl (1 mg/L), sucrose (30 g/L), and agar (6 g/L), at a pH of 5.7–5.8. Concentrations of 5, 15, 50, 150, and 500 mg/L were tested; nodal cuttings were cultured *in vitro* for 21 days before being transferred to peat-filled pots in a greenhouse. Concentrations of 5–15 mg/L promoted root development, while a dose of 500 mg/L stimulated the growth of the aerial parts and the production of minitubers. At this concentration, the number of minitubers increased from 2.44 to 3.33 per plant, and their total mass increased from 13.82 to 15.56 g per plant, compared to the control. However, higher doses had adverse effects on root development, confirming that the plant response is concentration-dependent.

EL AMERANY et al. (2020) also analyzed the effects of chitosan—applied both individually and in combination with arbuscular mycorrhizal fungi and compost—on the growth and nutrition of tomato plants. The experiment involved compost proportions of 0%, 5%, 10%, and 20%, with assessments covering root and shoot biomass, leaf area, photosynthetic parameters, sugar and protein content, and the anatomical characteristics of the stems. The best results were achieved by combining chitosan with mycorrhizae and 10% compost—a treatment that promoted plant development and nutrient uptake. These findings highlight the potential for the integrated use of

chitosan with organic amendments and beneficial microorganisms, although the observed effects cannot be attributed solely to the polymer itself.

ISABEL et al. (2024) demonstrated that encapsulating *Pseudomonas fluorescens* in 3% chitosan enhances the stability of the biofertilizer and maintains bacterial viability (7×10^{10} CFU/mL) for ten months. When applied to tomato plants, this formulation promoted plant growth and fruit development, underscoring the potential of chitosan as a carrier for microbial biofertilizer formulations.

Another area of application involves using nanochitosan as an amendment to improve soil properties. SHANMUGAVEL and SOLORZA-FERIA (2026) prepared nanochitosan from blue crab (*Callinectes sapidus*) exoskeletons via ionic gelation, using sodium tripolyphosphate (TPP) as a cross-linking agent. For the preparation, 50 mg of chitosan was dissolved in 100 mL of 1% acetic acid; subsequently, 75 mg of TPP dissolved in 100 mL of water was added gradually under stirring, yielding nanoparticles with an average size of approximately 38.8 nm. The suspension was applied via irrigation—at a dosage of 5 mg of nanochitosan per 15 kg of soil—for the cultivation of tomatoes. The treatment increased soil moisture from 22% to 39%, water-holding capacity from 70% to 84%, and total nitrogen content from 1.4 to 3.8 g/kg. Furthermore, favorable effects were observed regarding root and shoot development, flowering, and certain fruit quality indicators. The results suggest that nanochitosan may contribute to improved water and nutrient retention in the soil; however, validation of these effects under field conditions remains necessary.

Seed coatings and films

Coating seeds with chitosan forms polymeric films that can influence germination and seedling development. GODÍNEZ-GARRIDO et al. (2022) tested 0.1%, 0.5%, and 1% chitosan solutions—as well as coatings consisting of chitosan flakes and acrylic resin—on sesame (*Sesamum indicum* L.) and common bean (*Phaseolus vulgaris* L.). Microscopy revealed continuous, uniform films, and the results showed increases in germination (up to 26% for beans and 16% for sesame), germination rates (62% and 58%, respectively), and root length (up to 77% for beans and a fourfold increase for sesame) compared to the control. These findings support the potential of chitosan-based coatings to enhance germination and seedling vigor.

In addition to seed coating, chitosan-based nanoparticles can facilitate the delivery of growth regulators. PEREIRA et al. (2017) developed two systems for the encapsulation of gibberellic acid (GA_3): alginate/chitosan (ALG/CS) and chitosan/sodium tripolyphosphate (CS/TPP), both with a final GA_3 concentration of 50 µg/mL. After one hour of treating bean seeds, the encapsulation efficiency was 100% for ALG/CS and 90% for CS/TPP. The ALG/CS system increased leaf surface area by approximately 78% compared to the control, while CS/TPP promoted root elongation under certain conditions. The results highlight the potential of these formulations for the delivery of bioactive compounds, with effects depending on the composition of the nanoparticles and the encapsulated substance.

Another example of a nanostructured formulation involves chitosan nanoparticles for the delivery of fulvic acid, as evaluated by Huy et al. (2025) in soybean (*Glycine max* L.). These were produced via ionic gelation, using chitosan dissolved in 1% acetic acid, with fulvic acid as the active substance. Concentrations of 0.05, 0.1, 0.2, and 0.5 mM were tested, with the 0.1 mM variant selected for subsequent experiments. The preparation was administered by watering the soil—at a dose of 200 mL/plant, daily, for five days—starting at the V3 growth stage; subsequently, the plants were subjected to salt stress through the application of a 150 mM NaCl solution. The treatment stimulated the development of both roots and aerial parts, increased chlorophyll content, contributed to maintaining ionic balance, and reduced certain indicators of oxidative stress. These results

highlight the potential of this formulation to enhance salinity tolerance in soybeans, although the observed effects cannot be attributed solely to the chitosan.

Hydrogels and Controlled-Release Systems

Chitosan-based hydrogels facilitate water retention, the incorporation of nutrients, and the controlled release of active substances; their properties can be optimized through cross-linking and by combining them with other polymers.

IQBAL et al. (2024) developed composite hydrogels based on starch and chitosan, cross-linked with citric acid and reinforced by the incorporation of nanocellulose, wood ash, or NPK fertilizer. The base hydrogel was prepared by dissolving 2 g of starch and 2 g of chitosan in 100 mL of a 6% (w/v) citric acid solution, followed by stirring for one hour at 80 °C and heating for six hours at 100 °C. For the composite formulations, various fillers were added, depending on the experimental variant. The hydrogels absorbed between 200% and 420% of their own mass in distilled water and between 104% and 220% in a saline medium, while also undergoing biodegradation within approximately 110 days. In experiments involving peas (*Pisum sativum* L.), the formulation containing NPK promoted plant growth, highlighting the potential of these materials for water retention and nutrient supply. However, the observed effects reflect the properties of the composites and cannot be attributed solely to the chitosan.

LIU et al. (2024) developed a chitosan-based hydrogel designed for the controlled release of iron, with the aim of improving the availability of this micronutrient to plants. Various cross-linking systems were evaluated, and the formulation containing 1% genipin—designated as GE-CSG@Fe—exhibited an iron-loading capacity of 326.15 mg/g. Iron release was pH-dependent, occurring more rapidly in an acidic environment and more slowly at a neutral pH. Biological assays, which included wheat seed germination and the cultivation of tomatoes in pots, indicated favorable effects on germination, plant growth, and nutrient uptake. This system highlights the potential for using chitosan-based hydrogels as biodegradable carriers for micronutrient fertilization and for regulating the availability of these nutrients within the growth medium.

Another type of chitosan-based formulation involves encapsulation—a process that entails incorporating an active substance into a polymeric delivery system, with the aim of protecting it from degradation factors and controlling its release. (AKPO et al., 2024) In this context, chitosan-based particles can be produced via the ionic gelation method, which employs sodium tripolyphosphate (TPP) as a cross-linking agent. Particle formation relies on electrostatic interactions between the protonated amino groups of the chitosan and the negatively charged phosphate groups of the TPP (ABDELHADY et al., 2023).

To prepare the chitosan-based particles, Tahereh Tayebi and colleagues (2025) utilized a method based on ionic gelation. Thus, chitosan was dissolved in 0.5% (w/v) acetic acid to a concentration of 0.9 mg/mL, under magnetic stirring for 24 hours. Subsequently, the pH of the solution was adjusted to 5.5 using 1 M NaOH, and the solution was filtered through a 0.45 μm pore-size filter. Separately, a TPP solution with a concentration of 0.25 mg/mL was prepared and filtered through a 0.22 μm pore-size filter. To form the particles, 2 mL of the TPP solution was added gradually, drop by drop, to 5 mL of the chitosan solution under continuous stirring. The resulting suspension was centrifuged at 27,670 × g for 60 minutes; the supernatant was removed, and the recovered particles were lyophilized for 48 hours.

This type of formulation can be used for the protection and delivery of beneficial microorganisms. Feng et al. developed a composite hydrogel consisting of carboxymethyl-chitosan, sodium alginate, and calcium chloride, designed for the encapsulation of the plant growth-promoting bacterium *Ensifer* C5. The formulation was obtained by combining a 1.4% (w/v) sodium alginate solution—prepared in 0.15 mol/L NaCl—with a 0.6% (w/v) carboxymethyl-chitosan

http://doi.org/10.59463/RJAS.2026.3.15

solution, followed by the addition of a 0.07 mol/L $CaCl_2$ solution. The hydrogel was tested on rapeseed (*Brassica napus*), pak choi (*Brassica rapa* subsp. *chinensis*), and *Arabidopsis thaliana*. Application of the formulation improved bacterial survival and root colonization, and promoted plant growth. In field experiments with rapeseed, the combination of the hydrogel and bacterium C5 resulted in an approximately 30% increase in yield compared to the control. The study highlights the role of carboxymethyl-chitosan as a carrier material for microbial biofertilizers, with the observed effects being attributed to the composite system and the encapsulated microorganism, rather than to the polymer used in isolation.

Biodegradable films and coatings for mulching

Chitosan-based films and coatings can be applied to the surface of the substrate or soil to form a physical barrier, control weeds, and reduce the use of conventional plastic materials. The performance of these formulations depends on their mechanical properties, adhesion, and rate of biodegradation.

GIACCONE et al. (2018) evaluated a sprayable, biodegradable mulch for weed control in the cultivation of ornamental shrubs (*Viburnum lucidum*). The formulation consisted of 1.5% chitosan, 3% acetic acid, polyglycerol, cellulose fibers, and carbon black. The solution was applied by spraying onto the substrate surface at a rate of 2 L/m², forming a protective film. The treatment suppressed weed emergence for over two months and caused no apparent phytotoxic effects on the cultivated plants. However, as the film degraded, weeds reappeared, highlighting the importance of the stability and functional lifespan of the protective layer. In this instance, the primary effect was physical—preventing weed emergence—rather than a direct biostimulatory effect on the crop.

PITTARELLO et al. (2025) investigated the use of a biodegradable mulch film—composed of carboxymethyl cellulose, chitosan, and sodium alginate—for the cultivation of lettuce (*Lactuca sativa*) under Mediterranean conditions. The film was tested both independently and in combination with monoammonium phosphate (MAP), and was compared against a commercial biodegradable mulch and a polyethylene film. Although the experimental film began to degrade after approximately three weeks, lettuce yield, pigment content, and the level of bioactive compounds were comparable to those obtained using conventional films. The results support the potential of chitosan-based composite materials for developing mulching solutions with a low environmental impact, while also highlighting the need to optimize their durability in relation to the duration of the crop cycle.

Overall, chitosan-based formulations have diverse applications in agriculture, ranging from stimulating plant growth to soil amendment and the controlled release of nutrients. Their efficacy depends on their composition, concentration, and application conditions, and the effects of composite formulations should be attributed to all the components involved.

CONCLUSIONS

Chitosan is a highly versatile, biodegradable biopolymer with significant potential for enhancing stress tolerance, thereby promoting plant growth and development.

The diversity of available chitosan formulations—and their combination with nutrients or beneficial microorganisms—supports the producing of sustainable biopreparations, the efficacy of which depends on their composition and the conditions under which they are applied.

BIBLIOGRAPHY

ABDELHADY, M. M., et al., 2023 – A Review of the Preparation, Characterization, and Applications of Chitosan Nanoparticles in Nanomedicine. *Molecules*, 28 (9): 3898. Basel: MDPI, Switzerland.

AHMADI, M., 2010 – Effect of Zinc and Nitrogen Fertilizer Rates on Yield and Yield Components of Oilseed Rape (*Brassica napus* L.). *American-Eurasian Journal of Agriculture and Environmental Science*, 7 (3): 259–264. Faisalabad: IDOSI Publications, Pakistan.

AKPO, E., COLIN, C., PERRIN, A., CAMBEDOUZOU, J., CORNU, D., 2024 – Encapsulation of Active Substances in Natural Polymer Coatings. *Materials*, 17 (11): 2774. Basel: MDPI, Switzerland.

ALEMU, D., GETACHEW, E., MONDAL, A. K., 2023 – Study on the Physicochemical Properties of Chitosan and Their Applications in the Biomedical Sector. *International Journal of Polymer Science*, 2023: 5025341. London: Hindawi/Wiley, United Kingdom.

AMIRANI, E., HALLAJZADEH, J., ASEMI, Z., MANSOURNIA, M. A., YOUSEFI, B., 2020 – Effects of Chitosan and Oligochitosans on the Phosphatidylinositol 3-Kinase-AKT Pathway in Cancer Therapy. *International Journal of Biological Macromolecules*, 164: 456–467. Amsterdam: Elsevier, The Netherlands.

ARANAZ, I., MENGÍBAR, M., HARRIS, R., PAÑÓS, I., MIRALLES, B., ACOSTA, N., GALED, G., HERAS, A., 2009 – Functional Characterization of Chitin and Chitosan. *Current Chemical Biology*, 3 (2): 203–230. Sharjah: Bentham Science Publishers, United Arab Emirates.

ASGHARI-ZAKARIA, R., MALEKI-ZANJANI, B., SEDGHI, E., 2009 – Effect of In Vitro Chitosan Application on Growth and Minituber Yield of *Solanum tuberosum* L. Plant, Soil and Environment, 55 (6): 252–256. Prague: Czech Academy of Agricultural Sciences, Czech Republic.

AVELELAS, F., HORTA, A., PINTO, L. F. V., MARQUES, S. C., NUNES, P. M., PEDROSA, R., LEANDRO, S. M., 2019 – Antifungal and Antioxidant Properties of Chitosan Polymers Obtained from Nontraditional Polybius henslowii Sources. *Marine Drugs*, 17: 239. Basel: MDPI, Switzerland.

AZUMA, K., OSAKI, T., MINAMI, S., OKAMOTO, Y., 2015 – Anticancer and Anti-Inflammatory Properties of Chitin and Chitosan Oligosaccharides. *Journal of Functional Biomaterials*, 6: 33–49. Basel: MDPI, Switzerland.

BRUSSAARD, L., DE RUITER, P. C., BROWN, G. G., 2007 – Soil Biodiversity for Agricultural Sustainability. *Agriculture, Ecosystems & Environment*, 121 (3): 233–244. Amsterdam: Elsevier, The Netherlands.

CHAKRABORTY, N., MITRA, R., PAL, S., GANGULY, R., ACHARYA, K., MINKINA, T., et al., 2023 – Biopesticide Consumption in India: Insights into the Current Trends. *Agriculture*, 13 (3): 557. Basel: MDPI, Switzerland.

COPPOLA, D., LAURITANO, C., PALMA ESPOSITO, F., RICCIO, G., RIZZO, C., DE PASCALE, D., 2021 – Fish Waste: From Problem to Valuable Resource. *Marine Drugs*, 19 (2): 116. Basel: MDPI, Switzerland.

EL AMERANY, F., RHAZI, M., BALCKE, G., WAHBI, S., MEDDICH, A., TAOURIRTE, M., HAUSE, B., 2022 – The Effect of Chitosan on Plant Physiology, Wound Response, and Fruit Quality of Tomato. *Polymers*, 14: 5006. Basel: MDPI, Switzerland.

EL AMERANY, F., RHAZI, M., WAHBI, S., TAOURIRTE, M., MEDDICH, A., 2020 – The Effect of Chitosan, Arbuscular Mycorrhizal Fungi, and Compost Applied Individually or in Combination on Growth, Nutrient Uptake, and Stem Anatomy of Tomato. *Scientia Horticulturae*, 261: 109015. Amsterdam: Elsevier, The Netherlands.

GHORMADE, V., PATHAN, E. K., DESHPANDE, M. V., 2017 – Can Fungi Compete with Marine Sources for Chitosan Production? *International Journal of Biological Macromolecules*, 104 (Part B): 1415–1421. Amsterdam: Elsevier, The Netherlands.

GIACCONE, M., CIRILLO, C., SCOGNAMIGLIO, P., TEOBALDELLI, M., MATAFFO, A., STINCA, A., PANNICO, A., IMMIRZI, B., SANTAGATA, G., MALINCONICO, M., BASILE, B., 2018 – Biodegradable

Mulching Spray for Weed Control in the Cultivation of Containerized Ornamental Shrubs. Chemical and Biological Technologies in Agriculture, 5: 21. London: *Springer Nature*, United Kingdom.

GODÍNEZ-GARRIDO, N. A., TORRES-CASTILLO, J. A., RAMÍREZ-PIMENTEL, J. G., COVARRUBIAS-PRIETO, J., CERVANTES-ORTIZ, F., AGUIRRE-MANCILLA, C. L., 2022 – Effects on Germination and Plantlet Development of Sesame (*Sesamum indicum* L.) and Bean (*Phaseolus vulgaris* L.) Seeds with Chitosan Coatings. *Agronomy*, 12 (3): 666. Basel: MDPI, Switzerland.

GUAN, Y. J., HU, J., WANG, X. J., SHAO, C. X., 2009 – Seed Priming with Chitosan Improves Maize Germination and Seedling Growth in Relation to Physiological Changes under Low Temperature Stress. *Journal of Zhejiang University-SCIENCE B*, 10 (6): 427–433. Hangzhou: Zhejiang University Press, China.

HAYASHI, K., YAN, X., 2010 – Airborne Nitrogen Load in Japanese and Chinese Agroecosystems. *Soil Science and Plant Nutrition*, 56 (1): 2–18. Abingdon: Taylor & Francis, United Kingdom.

HOLTZE, M. S., SØRENSEN, S. R., SØRENSEN, J., AAMAND, J., 2008 – Microbial Degradation of the Benzonitrile Herbicides Dichlobenil, Bromoxynil and Ioxynil in Soil and Subsurface Environments—Insights into Degradation Pathways, Persistent Metabolites and Involved Degrader Organisms. *Environmental Pollution*, 154 (2): 155–168. Amsterdam: Elsevier, The Netherlands.

HUY, V. N., METHELA, N. J., AL-AZAWI, T. N. I., KHAN, M., FALUKU, M., BROWN, A., LEE, D.-S., DAS, A. K., AMIR, R., LAY, L., MUN, B.-G., KIM, Y., HUSSIAN, A., YUN, B.-W., 2025 – Fulvic Acid-Releasing Chitosan Nanoparticles Promote the Growth and Salt Stress Tolerance of Soybean Plants. *Physiologia Plantarum*, 177 (3): e70254. Hoboken, NJ: Wiley, United States.

IQBAL, D. N., TARIQ, Z., PHILIPS, B., SADIQA, A., AHMAD, M., AL-AHMARY, K. M., ALI, I., AHMED, M., 2024 – Nanocellulose/Wood Ash-Reinforced Starch–Chitosan Hydrogel Composites for Soil Conditioning and Their Impact on Pea Plant Growth. *RSC Advances*, 14 (13): 8652–8664. Cambridge: Royal Society of Chemistry, United Kingdom.

JIANG, Y., FU, C., WU, S., LIU, G., GUO, J., SU, Z., 2017 – Determination of the Deacetylation Degree of Chitooligosaccharides. *Marine Drugs*, 15: 332. Basel: MDPI, Switzerland.

JIMÉNEZ-GÓMEZ, C. P., CECILIA, J. A., 2020 – Chitosan: A Natural Biopolymer with a Wide and Varied Range of Applications. *Molecules*, 25 (17): 3981. Basel: MDPI, Switzerland.

KALIA, A., GOSAL, S. K., 2011 – Effect of Pesticide Application on Soil Microorganisms. *Archives of Agronomy and Soil Science*, 57 (6): 569–596. Abingdon: Taylor & Francis, United Kingdom.

KE, C. L., DENG, F. S., CHUANG, C. Y., LIN, C. H., 2021 – Antimicrobial Actions and Applications of Chitosan. *Polymers*, 13: 904. Basel: MDPI, Switzerland.

LIU, H., HUANG, Z., SHI, Y., CAI, T., MIAO, Q., GAO, Z., CUI, Z., 2024 – Lightweight pH-Responsive Chitosan Hydrogel Iron Fertilizer: Efficient Performance, Controlled Release, and Tomato Application. *Journal of Environmental Chemical Engineering*, 12 (5): 113428. Amsterdam: Elsevier, The Netherlands.

MARWAL, A., SRIVASTAVA, A. K., GAUR, R. K., 2022 – Plant Viruses as Biopesticides. In: *New and Future Developments in Microbial Biotechnology and Bioengineering: Sustainable Agriculture: Advances in Microbe-based Biostimulants*, pp. 181–194. Amsterdam: Elsevier, The Netherlands.

NAMBOODIRI, M. M. T., PAKSHIRAJAN, K., 2020 – Valorization of Waste Biomass for Chitin and Chitosan Production. In: *Bhaskar*, T., Pandey, A., Rene, E. R. and Tsang, D. C. W. (eds.), Waste Biorefinery, pp. 241–266. Amsterdam: Elsevier, The Netherlands.

NARWADE, J. D., ODANETH, A. A., LELE, S. S., 2023 – Solid-State Fermentation in an Earthen Vessel: Trichoderma viride Spore-Based Biopesticide Production Using Corn Cobs. *Fungal Biology*, 127 (7–8): 1146–1156. Amsterdam: Elsevier, The Netherlands.

PARAJULI, S., SHRESTHA, J., SUBEDI, S., PANDEY, M., 2022 – Biopesticides: A Sustainable Approach for Pest Management. *SAARC Journal of Agriculture*, 20 (1): 1–13. Dhaka: SAARC Agriculture Centre, Bangladesh.

PEREIRA, A. E. S., SILVA, P. M., OLIVEIRA, J. L., OLIVEIRA, H. C., FRACETO, L. F., 2017 – Chitosan Nanoparticles as Carrier Systems for the Plant Growth Hormone Gibberellic Acid. *Colloids and Surfaces B: Biointerfaces*, 150: 141–152. Amsterdam: Elsevier, The Netherlands.

PITTARELLO, M., RODINÒ, M. T., SIDARI, R., PANUCCIO, M. R., COZZI, F., BRANCA, V., PETROVIČOVÁ, B., GELSOMINO, A., 2025 – Employment of Biodegradable, Short-Life Mulching Film on High-Density Cropping Lettuce in a Mediterranean Environment: Potentials and Prospects. *Agriculture*, 15 (11): 1219. Basel: MDPI, Switzerland.

SARKAR, S., DAS, D., DUTTA, P., KALITA, J., WANN, S. B., MANNA, P., 2020 – Chitosan: A Promising Therapeutic Agent and Effective Drug Delivery System in Managing Diabetes Mellitus. *Carbohydrate Polymers*, 247: 116594. Amsterdam: Elsevier, The Netherlands.

SHANMUGAVEL, D., SOLORZA-FERIA, O., 2026 – Application of Sustainable Crab-Waste-Derived Nanochitosan as a Soil Amendment for Tomato Cultivation in Loam Soil. *Sustainability*, 18 (3): 1213. Basel: MDPI, Switzerland.

SHIH, P. Y., LIAO, Y. T., TSENG, Y. K., DENG, F. S., LIN, C. H., 2019 – A Potential Antifungal Effect of Chitosan against Candida albicans Is Mediated via the Inhibition of SAGA Complex Component Expression and the Subsequent Alteration of Cell Surface Integrity. *Frontiers in Microbiology*, 10: 602. Lausanne: Frontiers Media SA, Switzerland.

SINGH, R., SHITIZ, K., SINGH, A., 2017 – Chitin and Chitosan: Biopolymers for Wound Management. *International Wound Journal*, 14 (6): 1276–1289. Oxford: Wiley, United Kingdom.

SINGH, S., NEGI, T., SAGAR, N. A., KUMAR, Y., TARAFDAR, A., SIROHI, R., SINDHU, R., PANDEY, A., 2022 – Sustainable Processes for Treatment and Management of Seafood Solid Waste. *Science of the Total Environment*, 817: 152951. Amsterdam: Elsevier, The Netherlands.

SIZÍLIO, R. H., GALVÃO, J. G., TRINDADE, G. G. G., PINA, L. T. S., ANDRADE, L. N., GONSALVES, J. K. M. C., LIRA, A. A. M., CHAUD, M. V., ALVES, T. F. R., ARGUELHO, M. L. P. M., et al., 2018 – Chitosan/PVP-Based Mucoadhesive Membranes as a Promising Delivery System of Betamethasone-17-Valerate for Aphthous Stomatitis. *Carbohydrate Polymers*, 190: 339–345. Amsterdam: Elsevier, The Netherlands.

STALEY, Z. R., HARWOOD, V. J., ROHR, J. R., 2015 – A Synthesis of the Effects of Pesticides on Microbial Persistence in Aquatic Ecosystems. *Critical Reviews in Toxicology*, 45 (10): 813–836. Abingdon: Taylor & Francis, United Kingdom.

TAYEBI, T., BARADARAN-RAFII, A., HAJIFATHALI, A., RAHIMPOUR, A., ZALI, H., SHAABANI, A., NIKNEJAD, H., 2021 – Biofabrication of chitosan/chitosan nanoparticles/polycaprolactone transparent membrane for corneal endothelial tissue engineering. *Scientific Reports*, 11: 7060. London: Springer Nature, United Kingdom.

ULLAH, N., BASIT, A., AHMAD, I., ULLAH, I., SHAH, S. T., MOHAMED, H. I., JAVED, S., 2020 – Mitigation the Adverse Effect of Salinity Stress on the Performance of the Tomato Crop by Exogenous Application of Chitosan. *Bulletin of the National Research Centre*, 44: 181. London: Springer Nature, United Kingdom.

WAYS, T. M. M., LAU, W. M., KHUTORYANSKIY, V. V., 2018 – Chitosan and Its Derivatives for Application in Mucoadhesive Drug Delivery Systems. *Polymers*, 10: 267. Basel: MDPI, Switzerland.

ZHANG, X., GUO, J., VOGT, R. D., MULDER, J., WANG, Y., QIAN, C., WANG, J. G., ZHANG, X. S., 2020 – Soil Acidification as an Additional Driver to Organic Carbon Accumulation in Major Chinese Croplands. *Geoderma*, 366: 114234. Amsterdam: Elsevier, The Netherlands.