



Review

# The Potential of Using Chitosan on Cereal Crops in the Face of Climate Change

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**Abstract:** This review presents the main findings from measurements carried out on cereals using chitosan, its derivatives, and nanoparticles. Research into the use of chitosan in agriculture is growing in popularity. Since 2000, 188 original scientific articles indexed in Web of Science, Scopus, and Google Scholar databases have been published on this topic. These have focused mainly on wheat (34.3%), maize (26.3%), and rice (24.2%). It was shown that research on other cereals such as millets and sorghum is scarce and should be expanded to better understand the impact of chitosan use. This review demonstrates that this chitosan is highly effective against the most dangerous diseases and pathogens for cereals. Furthermore, it also contributes to improving yield and chlorophyll content, as well as some plant growth parameters. Additionally, it induces excellent resistance to drought, salt, and low temperature stress and reduces their negative impact on cereals. However, further studies are needed to demonstrate the full field efficacy of chitosan.

**Keywords:** chitosan; chitooligosaccharides; nanoparticles; maize; wheat; rice; millets; barley; cereal



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## 1. Introduction

Cereals are one of the most important crops on Earth. They are responsible for feeding the human population of the world. Cereal grains account for more than half of the world's daily caloric intake [1]. It is therefore not surprising that cereals account for as much as half of the global cultivated area [2]. Nowadays, the biggest challenge for cultivation is climate change. Increased CO<sub>2</sub> concentrations, extreme weather phenomena, rising temperatures, and droughts can be stress factors for many crops. Consequently, climate change also directly affects cereal production. One of the factors reducing yields is air temperature increase. It has been shown that global wheat production decreases by 6% for every 1 °C increase in air temperature [3]. Researchers emphasize that plant tolerance to higher temperatures may be a key trait for wheat yields in the future. Furthermore, it is extremely important to achieve drought tolerance [4,5]. This is particularly important for water-limited areas. It should be noted here that the production of and demand for cereals is constantly increasing, while the water resources required for cultivation are not rising. Another problem is the constantly increasing demand for water, for purposes other than agriculture. This phenomenon will be the main reason for water shortages for agriculture in the coming decades in China [6]. It is therefore extremely important to take actions in agriculture to help plants survive and adapt to climate change to guarantee food security. There are various methods to reduce the impact of climate change on plant physiology and the yield losses associated with its deterioration. These include improved irrigation, appropriate use of fertilizers, and increased emphasis on breeding varieties that will be more resistant to these changes [7]. Furthermore, another solution is to develop varieties with superior genetic yield potential and stress adaptation [8]. It may also be beneficial to use special antitranspirant formulations to allow cereals to better use and accumulate water to survive a drought period. Antitranspirants are chemicals that reduce transpiration rate. Limiting transpiration through their use on plants is beneficial in the context of

increasing demand for limited water resources. The application of antitranspirants is a great opportunity for the proper development especially of those crops that require irrigation [9]. One of the compounds included in the broad group of antitranspirants is chitosan.

Chitosan is a derivative of chitin and is considered the second most common polymer in the world after cellulose [10]. Chitosan, as well as chitin, are classified as polysaccharides containing randomly distributed  $\beta$ -(1-4)-linked D-glucosamine and N-acetylglucosamine units. Chitosan is mainly obtained from leftovers obtained from seafood processing such as crab and shrimp shells, as well as fish scales. Furthermore, the potential to receive it from waste fungal mycelium is also indicated [11,12]. In agriculture, chitosan is used through foliar application to plants, seed treatment, or as a direct soil fertilizer.

During studies involving the use of this agent on plants, its antitranspirant properties have been repeatedly confirmed. Research on peppers has shown that chitosan decreases transpiration through partial or full closure of stomata [9]. Reduction of transpiration by the application of chitosan was also observed in the case of *Phaseolus vulgaris* L. [13] and after spraying coffee leaves through chitosan oligomers [14]. Moreover, chitosan has been identified as a growth promoter [15–17]. Furthermore, this product exhibits properties helping to control diseases and prevent crop pathogens. It affects the elicitation of defense-related enzymes [18]. It also has fungicidal or fungistatic potential, which is confirmed by the effect of chitosan on the morphology of microorganisms [19]. Due to its high efficacy in disease control, and the fact that it is biodegradable and environmentally friendly, it ought to perform well, not only in conventional farming but also in organic farming [20]. Worldwide research is increasingly considering the use of chitosan derivatives, besides chitosan alone, as well as nanoparticles. Moreover, the combination of chitosan nanoparticles with other elements such as copper (Cu), zinc (Zn), selenium (Se), as well as silver (Ag) is becoming widely used [21–23]. Researchers suggest that chitosan based metallic nanoparticles may be even more effective than bulk chitosan in anti-pathogenic and plant growth-promoting activities [24]. Also in the research, the potential for the use of chitosan and its derivatives in agriculture and the need to systematize the current state of knowledge is repeatedly highlighted. This manuscript aims to review published research findings on the impact of chitosan on cereal production. Moreover, it focuses on the role of chitosan as a management tool. This paper presents how the application of this product affects plant parameters and indices. Consolidating knowledge in this area will allow a comprehensive presentation of the role of chitosan in cereal cultivation.

## 2. Methodological Framework

The aim of this review is to present, systematize and evaluate the current state of knowledge concerning the effects of chitosan on the most important plant group in the world, namely cereals. In the article, significant plant parameters and traits influenced by chitosan were selected. These are presented in subsections such as yields, growth parameters, chlorophyll content, gas exchange, water-use efficiency (WUE), relative water content (RWC), pathogen and disease control. This paper presents the results of research conducted since 2000 with their synthesis and evaluation. Original scientific articles registered in Web of Science, Scopus, and also Google Scholar were taken into consideration for this analysis. The search included the phrase: chitosan AND the name of the cereal. Cereals were defined as wheat, rice, maize, barley, oats, rye, sorghum, and millets. For this review, studies involving chitosan derivatives and nanoparticles were also eligible. To synthesize the current state of research, one of the last chapters presents the number of articles found and current research trends in the application of chitosan on cereals. The number of papers specified in this review is the final score obtained after filtering the search results in the Web of Science, Scopus and Google Scholar databases and excluding articles that did not match the research topic.

### 3. Effects of Chitosan on Cereal Yields

The parameters that are of most interest from the point of view of grain production are yield and its indicators. Regardless of its other positive properties, chitosan has no chance of becoming widely used on cereals if it does not have a positive effect on yield. Many studies have been carried out in this context. In the case of wheat, the application of chitosan resulted in a 13.6% increase in yield per hectare in comparison with a control crop. Furthermore, it had a positive effect on tillers per plant, spikes per plant, and 1000 grain weight [25]. It was also shown that exogenous use of chitosan on this plant improves other yield parameters such as a number of grain/spikes, grain index as well as grain yield. Their increase was also recorded under moderate and severe drought conditions [26]. Moreover, under reduced irrigation conditions, a beneficial effect of chitosan was observed concerning economical yield. It was also noted that the use of chitosan together with hydrogel enhances this result [27]. For wheat, the application of chitosan under limited irrigation conditions slightly improved the biological yield and grain yield, and improved it significantly for 1000 grain weight. The result for plants without stress could not be reached [28]. Moreover, research on maize has shown that the application of chitosan under low-temperature conditions increases the germination index. Furthermore, it also reduces the average germination time [29]. Similar positive results were obtained in a study on barley (*Hordeum vulgare* L.) under semi-arid conditions. A significant improvement of grain yield per plant, number of spikes per plant and number of grains per spike, and 100-grain weight compared to samples without chitosan was observed [30]. Also after the application of chitosan with DAP fertilizer (Diammonium phosphate 46% P<sub>2</sub>O<sub>5</sub>), an increase of the same parameters was achieved [31]. Another cereal on which research was conducted was maize. Tests on this plant also demonstrated that an enhanced grain yield was obtained after the use of chitosan [32]. Moreover, measurements carried out on this cereal after application of chitosan and its derivatives: N-succinyl chitosan and N, O-dicarboxymethylated chitosan (each separately and a mixture of two together) showed that all these substances increased grain yield and harvest index. However, it was the highest for the mixture of derivatives [33]. Studies have also been carried out on the effects of the use of chitosan with plant growth promoting rhizobacteria (PGPR). It was found that this combination can improve maize production [34]. Application of Cu-chitosan nanoparticles significantly increased grain yield and 100 grain weight of maize [35]. A positive effect on grain yield was also observed after using chitosan-silicon nano-fertilizer on maize (*Zea mays* L.) [36]. In the case of Zn-chitosan nanoparticles application on maize, an increase in grain yield from 20.5 to 39.8% was achieved [37]. Studies carried out on wheat also showed that the foliar application of nano chitosan nitrogen, phosphorus, and potassium fertilizer enhances yields [38]. The harvest index as well as the crop index also improved after this treatment compared to the control sample [39]. Additionally, research has been conducted into the use of chitosan oligosaccharides on wheat. They showed that the tillering stage and returning-green stage of plants were the most sensitive to this application. It was also proven that treatment with chitosan oligosaccharides has the potential to increase yield components, such as spike number and grains per spike [40]. Moreover, the multifunctional complex 'Vitaplan CL + 0.1% Chitosan' was also applied in wheat experiments. After its use, yields were increased by 24.4% compared with the control [41]. Furthermore, other multifunctional biologics with chitosan have also been shown to positively affect grain yield and quality [42]. The research was also conducted under salinity stress conditions on two wheat varieties. It was found that plants treated with chitosan had better results regarding 1000 grain weight, straw yield, and biological yield as well as grain yield [43]. Furthermore, a positive effect of chitosan nanoparticles as well as chitosan nanoparticles loaded with *N*-acetylcysteine under ozone stress conditions, was also observed. This treatment was shown to increase the weight of 1000 durum wheat seeds [44]. In studies on the application of nanochitosan particles to finger millet, an improvement in yields was noted compared to the control sample [45]. This is in agreement

with subsequent research, where an increase in grain weight as well as grain yield, was obtained. However, no significant effect was noticed on the number of inflorescences [46].

Studies on cereal treatment with chitosan have considered not only different varieties of this antitranspirant, but also various concentrations and application methods. One such study was the application of varying concentrations (0, 50, 75, 100, and 125 ppm) of chitosan on maize in the early stages of growth. It was found that the greatest seed yields are obtained at the two highest concentrations [47]. Measurements were also conducted concerning the application of chitosan with different molecular weights (monomer, oligomer, polymer) and three different methods of application (seed soaking, seed soaking + foliar spraying, foliar spraying). The potential to obtain higher yields was found after soaking the seeds before planting rice and then spraying foliar polymeric chitosan four times in a dose of 20 ppm [48]. Later measurements of the application of different variants of chitosan on rice confirmed that the maximum yield was achieved after seed soaking and soil application. The authors indicate that this is because, in soil, chitosan is available to plants longer than in foliar spray. An increase in seed numbers per panicle was also noted, but it was not significant [49]. Studies carried out on rice plants in Vietnam also point to promising yield increases after chitosan [50]. The use of chitosan nanoparticles on wheat increased grain yield. Interestingly, foliar application had a better effect than applying chitosan to the soil. This is not fully consistent with the results described above. An increase in biomass, spike weight, number of grains per spike, and grain yield was also noted. According to the authors, this improvement is due to several factors such as changes in transpiration and improvements in the rate of photosynthesis and water status in wheat. Also, modifications to the leaf organelle ultrastructure and the maintenance of the nutrient supply have an impact [51]. Moreover, the application of chitosan nanoparticles on barley (*Hordeum vulgare* L.) resulted in an improvement of the number of grains per spike, the grain yield as well as the harvest index. Additionally, the highest 1000-grain weight value was obtained with the highest nanoparticle dose of 90 ppm [52].

From the above review, it is clear that chitosan has a strong effect on improving cereal yield. Furthermore, it is effective both as chitosan itself and as its derivatives and nanoparticles. A trend towards more beneficial results at higher concentrations is noticeable. However, no clear conclusions can be drawn as to which application method is the most effective. Certainly, chitosan has a positive effect on yield and yield indices regardless of the type of grain. The conclusions of the above review are based on a large number of field studies [25–28,30,31,38,40,42–44,47,50,51]. Moreover, they have also been verified by experiments conducted under laboratory [36,37], and greenhouse conditions [33–35,45,48]. Furthermore, this review has shown that, chitosan has the potential to reduce the effects of drought stress, salt stress, and low temperatures, thus improving the yield. The widespread use of chitosan on cereals, especially in regions of the world particularly exposed to the negative effects of various types of stressors, would make it possible to mitigate the yield loss caused by environmental changes. It should be noted that studies have shown that chitosan can cope with a wide range of conditions. This indicates the potential of chitosan as a universal tool that can be used worldwide, regardless of climate to improve yields.

#### 4. Growth Parameters

Besides yield, growth parameters are also an important aspect from the point of view of global grain cultivation. More than half of the articles considered in this review took into account the effect of chitosan on this group of parameters. For a clearer presentation, it has been decided to divide this chapter into subchapters on different plants.

##### 4.1. Wheat and Barley

One of the experiments conducted was the application of chitoooligomers (COS) on wheat. An increase in root fresh weight and also in shoot fresh weight of wheat (*Triticum aestivum* L. cv. Jimai 22) was observed. Depending on the type of COS, an increase in root fresh weight of 21.8% to as much as 53.2%, compared to the control sample, was

achieved [53]. Also, tests on wheat have shown that chitosan hexamers with different degrees of acetylation improve growth parameters [54]. Moreover, research has been carried out on a water-soluble form of chitosan, namely chitosan hydrochloride. It has been shown that this substance stimulates growth and affects germination rate and root development of durum wheat [55]. Comparative studies were also conducted on the effect of different concentrations of chitosan as well as chitosan nanoparticles on wheat. It was shown that the best growth effects occur at 50 µg/mL for chitosan and 5 µg/mL in the case of nanoparticles. This includes parameters such as seedling length, number of adventitious roots, seed germination percentage, germination index, vitality index, fresh weight, the ratio of root/shoot and seedling index. A better effect has been shown with a lower concentration of nanoparticles than chitosan. This is due to higher adsorption on the surface of the wheat seeds [56]. Moreover, the studies undertaken on wheat also showed an increase in root length, shoot length, fresh weight, dry weight after foliar application of chitosan nanoparticles loaded with nitrogen, phosphorus and potassium [39]. In a study of the use of chitosan nanoparticles on barley (*Hordeum vulgare* cv. Reyhan) and wheat (*Triticum aestivum* cv. Pishtaz), two application methods of seed priming and direct exposure were also compared. Positive effects on seedling, root and shoot lengths were observed, with seeds priming but only at low chitosan nanoparticle concentrations of 30 ppm. At high values like 90 ppm this treatment had negative effects on growth characteristics in both application methods [57]. In barley studies, the application of 1, 3, and 6 g/L of chitosan resulted in a significant improvement in plant height, but not in spike length [30].

Based on research over the last 20 years, it can be concluded that in the case of wheat, chitosan has a positive effect on growth parameters. This concerns both germination and root parameters. Nanoparticles, especially in low concentrations, also contribute to the improvement of many parameters. The number of publications on barley is not as high as for wheat. However, in papers the positive effect of chitosan on growth parameters has been noted a few times also for barley.

#### 4.2. Millets

Another cereal type analysed in the context of chitosan application was millet. Tests carried out using an Alexa preparation containing chitosan for pearl millet demonstrated improvements of plant height at the vegetative phase, number of tillers, and 1000 seed weight [58]. A positive effect was also achieved in subsequent studies using chitosan nanoparticles, increasing seed germination percentage and seedling vigor [59]. Also, in the case of finger millet, the application of chitosan nanoparticles was shown to increase the number of leaves, leaf length, and shoot length. Furthermore, an improvement in dry weight of up to 52% compared with the control sample was observed [46]. In other studies on the use of nano-chitosan particles on this same plant, no major influence on the means of leaf length and number was found. However, a significant impact on dry weight was observed [45]. Also, the effect of the copper-chitosan nanoparticle (CuChNp) in two different methods of application, as a foliar spray as well as combined application (involving seed coat and foliar spray), on finger millet (*Eleusine coracana* Gaertn.) was studied. In both treatments, an increase in several parameters such as the number of leaves, leaf length, shoot height, as well as fresh and wet plant weight, was observed. The highest increase was recorded in the case of dry weight, where it reached 297% in the combined application and 152% in the foliar treatment [60]. Despite the relatively small number of studies in relation to other cereals, measurements conducted on millets show that chitosan nanoparticles contribute to the improvement of many growth parameters. Nevertheless, more research is desirable, to strengthen the hypothesis of the favourable impact on this cereal's growth indices. These results could be extremely valuable, considering that this cereal is a source of food in many poor countries.

### 4.3. Maize

Research has also been conducted on maize. It was shown that the use of chitosan in the early stages of development improved plant height, leaf number, leaf length and breadth, and leaf area [47]. In addition to improving plant height and leaf surface, the effect of the substance on the growth of shoot and root dry weight has also been reported [61]. Furthermore, in the case of maize, chitosan improved root length, root surface, and root volume also under cadmium stress conditions [62]. Positive results were also obtained in later studies with foliar application of different concentrations of chitosan nano-fertilizer (0.01, 0.04, 0.08, 0.12, and 0.16%) on the same plant. Improvement of parameters such as plant height, root length, root number, and stem diameter was shown. The highest values were observed at a concentration of 0.16% [63]. It was also found that the application of an adequate dose of chitosan-based nanoparticle fertilizer increased the fresh and dry biomass of maize [64]. Moreover, research has been conducted using a nutrient-water carrier prepared with N, O-carboxymethyl chitosan, among others. Its application had a positive effect on the root length and seedling height of maize [65]. Also after the use of nanochitosan on this plant, a growth-promoting effect on plant height and leaf area was observed [66]. Other studies on rice have also confirmed that chitosan nanoparticles (ChNP) affect growth parameters. This treatment resulted in a higher number of leaves and plant length compared to the control sample [67]. It also confirmed that the combination of moringa and chitosan had a beneficial effect on the index-seed germination and growth parameters of maize [68]. Furthermore, it has been proven that coating the seeds with chitosan increases not only the height of maize plants but also of sorghum. An increase in seed germination was also found for these crops [69].

However, there are also some articles with opposite results [70]. In one of them, no effect on plant height, root length, leaf surface, shoot and root area and total dry matter was observed 10 days after chitosan application to maize. Further studies have reported a positive reaction of chitosan on maize hybrids (DKB 390 and DKB 390 VTPRO) increasing the percentage of germination. There was no impact on root length, nevertheless, its anatomy changed [71]. Other measurements show that a chitosan coating on maize did not affect the rate of seed emergence in comparison with the control sample. Moreover, it did not contribute to higher seedling germination rates [72]. However, these are not the only studies showing a reduction in growth parameters. Other measurements showed negative effects of chitosan on maize (*Zea mays* L.) seed emergence. This result may be due to the high concentration of the polymer applied and the simultaneous use of fertilizers and salicylic acid [73]. Moreover, when using high concentrations of polymeric chitosan/tripolyphosphate on maize, germination inhibition was reported [74]. Therefore, the results obtained for chitosan applied on maize are contradictory.

Research involving the use of Cu-chitosan nanoparticles on maize seedlings showed an increase in germination percent, shoot and root length, root number, seedling length, fresh and dry weight, and seed vigor index, but only at concentrations of 0.01 to 0.12%. At a concentration of 0.16%, inhibition of seedling growth was observed. The authors explain that this is due to excessive Cu content, and thus a decrease in metabolic enzymes [75]. The growth of plant height, stem diameter, root length, and root number after application of Cu-chitosan nanoparticle on maize at concentrations of 0.01 to 0.12% was also observed in later studies [35]. The positive effect of this treatment was also noted for shoot length, fresh as well as dry weight [76]. The research was also carried out on seed treatment of maize with salicylic acid-chitosan nanoparticles (SA-CS NPs). These showed an enhancement in germination percent, shoot-root length, fresh weight, and seedling vigor index with this use. Interestingly SA-CS NPs showed much better results than bulk chitosan alone [77]. A positive effect was also demonstrated for Zn-chitosan nanoparticles. It has been proven that its use increases maize parameters, such as plant height, stem diameter, as well as root length [37]. Studies were also conducted on the application of chitosan-silicon nano-fertilizer on maize (*Zea mays* L.). They showed a significant increase in leaf area, shoot length, root length as well as root number compared to an untreated control sample [36].

On the basis of the review carried out, it can be concluded that the results with regard to maize are not conclusive. There are many studies showing that chitosan or chitosan varieties have a positive effect on growth parameters, in particular plant height and root characteristics. However, there are also several articles that show negative or no influence of this substances on growth parameters. It can therefore be concluded that more research should be carried out on maize, with close monitoring of the experimental conditions. In this way, it will be possible to analyse them in detail in relation to the individual factors influencing the results.

#### 4.4. Rice

In relation to growth parameters, a number of studies have also been carried out on rice (*Oryza sativa* L.). In one of these, no effect of chitosan on seedling growth was observed. The authors believe, the concentration of the substance may justify this result [78]. Measurements were also carried out to cover the application of chitosan with different molecular weights (monomer, oligomer, polymer) and three different methods of application (seed soaking, seed soaking + foil spraying, foil spray). No significant changes in the height of rice plants were noticed. However, it has been shown that the application of the polymer by seed soaking before planting and then four foliar sprayings with chitosan significantly increases dry matter accumulation. Therefore, it was concluded that this form of application stimulates growth [48,49]. The increase in dry matter is also confirmed by subsequent studies on the use of chitosan (both oligomeric and polymeric). Moreover, an improvement in plant height, leaf, and fresh root weight was also obtained. Interestingly, the best results were obtained for oligomer with an 80% degree of deacetylation at 40 mg/L [79]. Also, the application of oligochitosan was shown to enhance rice growth [80]. Other studies showed that chitosan oligosaccharides stimulated the growth of rice roots and stems. Furthermore, it stimulated metabolic processes and photosynthesis at the seedling stage [81]. Research has also been conducted into the use of lanthanum-modified chitosan oligosaccharide nanoparticles (Cos-La) on rice (*Oryza sativa* L). It has been shown that Cos-La enhances plant height and fresh weight [82].

As we can see, the results concerning the influence of chitosan, and also its varieties and nanoparticles on cereal growth parameters are not unequivocal. Many studies report improvements for each of the cereals considered. However, there are also some reports emphasizing no effect, or even a negative effect of chitosan, specifically for maize. Researchers emphasize that the differences obtained in plant reactions (concerning growth parameters) to chitosan application may result from the physicochemical properties of chitosan (deacetylation degree, molecular weight, and viscosity), as well as plant type [79,83]. Moreover, it is suggested that various seed germination reactions with chitosan may result from the concentration of the substance used, the experimental conditions, and the specific seed and crop features [72]. To understand the exact influence of chitosan, its derivatives, and nanoparticles on growth parameters, a more detailed analysis is needed. Such an analysis would consider each parameter separately, the type of application, its concentration, and individual factors during the experiment. This topic could be an interesting development of this review.

#### 4.5. Different Stress Conditions

Studies were also carried out on the use of chitosan under different types of stress (e.g., drought, salt, temperature). It was decided to describe their results, irrespective of the type of cereal, in a separate section, as they are a valuable source of knowledge in the face of climate change.

Under drought conditions, chitosan also promoted improvements in fresh and dry root weight. Furthermore, it was shown that lower concentrations of chitosan had a higher efficacy [84]. Also, studies under these conditions on barley indicated that chitosan improved plant height, number of leaves, and leaf area [85]. Exogenous application of chitosan on wheat was proven to have a positive effect on plant growth parameters. As

a result, an increase in flag leaf area and also shoot dry weight was observed. Moreover, the improvement of these parameters was also observed under conditions of limited irrigation [26]. This indicates the potential of using chitosan during drought conditions. Measurements were carried out in rice (*Oryza sativa* L. 'Leung Pratew123') exposed to osmotic stress. After its rehydration, crops treated with chitosan showed higher fresh and dry weight [86]. Furthermore, chitosan showed a positive influence on leaf area and biomass in rice also under difficult conditions of elevated ozone concentration [87]. A positive effect of chitooligomers (COS) with different degrees of polymerization on wheat (*Triticum aestivum* L. Jimai 22) under chilling stress was also observed. The results obtained indicate that this treatment improved growth parameters such as shoot and root length as well as fresh and dry weight under stress conditions [88]. Similar results were obtained in maize where a significant increase in shoot height, dry weight, root dry was recorded under low temperature conditions [29]. Also under cold stress conditions, chitooligosaccharide (COS) improved fresh root and shoot weight, as well as rice root vigor [89]. Thus, it can be concluded that chitosan has potential not only in plant adaptation to drought, but also to cold. Improvements in growth parameters were also noted after the use of chitooligosaccharide and also sulfated chitooligosaccharide (SCOS) under salt stress conditions. An increase in shoot length, root length, wet weight, and dry weight of wheat (*Triticum aestivum* L. Jimai 22) was observed [90]. Improvement of growth parameters under salt stress conditions was also noticed when chitosan was used on the varieties Sakha 94 and Gemmieza 9 [43]. In the case of maize, a reduction in the negative effects of salt stress on shoot dry weight was also observed after chitosan application [61]. Furthermore, maize treated with chitosan under this stress condition showed an improvement in parameters such as root length and plant height [91].

All of these results indicate that chitosan does an excellent job of mitigating the effects of stress cereal growth parameters. It had beneficial effects under drought, cold, salt stress, and elevated ozone concentration conditions. This is particularly important, given that many areas of the world are currently facing increasing stress phenomena. The results of this review highlight the considerable potential of chitosan for cereal adaptation to climate and environmental change.

## 5. Chlorophyll Content

In worldwide research, chlorophyll a, chlorophyll b, as well as total chlorophyll are among the most frequently determined content of photosynthetic pigments. Chlorophyll is responsible for the green color of plants. Moreover, chlorophyll content has also been shown to be an indicator of photosynthetic capacity [92]. Further, it can be used to better predict biomass and crop productivity [93]. Also, a relationship between midday gross primary production (GPP) and total crop chlorophyll content has been discovered [94]. In measurements involving the application of chitosan to cereals, parameters determining chlorophyll have not been ignored. An attempt has been made to determine how this product affects the chlorophyll content of plants.

Studies carried out on wheat showed that chitosan improved chlorophyll content. This had a positive effect on plant growth under drought stress [25]. Also, research conducted under moderate and severe drought conditions showed that wheat treated with chitosan achieved higher values of total chlorophyll as well as total carotenoid concentration [26]. In studies on rice under drought conditions, an improvement in chlorophyll a and b were obtained for plants with chitosan [84]. Moreover, after the application of chitosan at concentrations of 0.01 to 0.12%, an increase in chlorophyll a and b content was recorded in maize [35]. Similar results were obtained in subsequent studies using different concentrations of chitosan nano-fertilizer (0.01, 0.04, 0.08, 0.12, and 0.16%) on the same plant. In all cases, the substance caused an increase in total chlorophyll with the highest concentration of 0.04% [63]. It has also been shown that the application of chitosan has a positive effect on increasing the greenness of maize leaves [95]. On the other hand, in the case of rice, no significant changes were observed in leaf greenness as measured by



chlorophyll meter [49]. Other measurements carried out on rice (*Oryza sativa* L. 'Leung Pratew123') immediately before exposure to osmotic stress, noted an increase in Chl a content. An increase in chlorophyll b and carotenoids was also observed, but was not significant. After osmotic stress, the results were variable. The cultivar LPT123 maintains elevated pigment levels but its salt tolerant mutant line (LPT123-TC171) does not [86]. In the case of wheat (*Triticum aestivum* L. Jimai 22), treatment with chitooligosaccharide and also with sulfated chitooligosaccharide improved chlorophyll a and b content under salt stress conditions [90]. An increase in photosynthetic pigments was also recorded in two other wheat varieties Sakha 94 and Gemmieza 9 under salt stress. Chitosan-treated plants recorded higher chlorophyll a, chlorophyll b, as well as carotenoids, compared to the control [43]. Studies on rice noted a slight increase in chlorophyll b/a, which has the potential to maximize yields. Also, this research suggests that chloroplast is a target organelle for chitosan action [79]. Furthermore, chitosan reduced the negative effect of elevated ozone concentrations on chlorophyll in the case of rice. After 7 days of ozone exposure, the chlorophyll values of plants treated with chitosan were similar to the unstressed control [87].

In addition to chitosan, studies have also been carried out using its derivatives and nanoparticles. The chlorophyll aspect was not omitted in these either. The impact of chitosan and its derivatives (*N*-succinylchitosan and *N*, *O*-dicarboxymethylated chitosan) on maize under water stress conditions was also analysed. The results indicate that the above treatments affect photosystem II activity. Moreover, after the application of these substances, the content of chlorophyll, a, and a+b was higher in comparison with the control sample also subjected to water stress [96]. An increase in chlorophyll content was also observed after the application of chitosan nanoparticles on wheat. The highest result was obtained, with the highest tested substance concentration of 90 ppm [51]. Other studies on wheat have shown that 5 µg/mL chitosan nanoparticles have a positive effect on chlorophyll and photosynthetic capacity [56]. After the application of copper-chitosan nanoparticles (CuChNp) on finger millet, the chlorophyll content increased. Foliar application increased it by 32%, and combined application (involving seed coat and foliar spray) by 84% [60]. An increase in chlorophyll content was also demonstrated after the application of Zn-chitosan nanoparticles on maize [37]. Treatment of maize seeds with salicylic acid-chitosan nanoparticles (SA-CS NPs) also improved total chlorophyll [77]. Studies have also been conducted on the effect of chitooligomers (COS) with different degrees of polymerization on wheat (*Triticum aestivum* L. Jimai 22) under chill stress. COS was shown to mitigate the stress-induced decrease in chlorophyll content [88]. Furthermore, also under water stress conditions, barley treated with chitosan showed an increase in chlorophyll a and b [85]. The effect of increasing total chlorophyll content was also found during tests using Chitosan-silicon nano-fertilizer on maize (*Zea mays* L.) [36]. Studies were also conducted using chitosan nanoparticles containing the NO donor *S*-nitroso-mercaptosuccinic acid. This agent applied to maize was shown to prevent salt-induced changes in chlorophyll content and maximum quantum yield of photosystem II [97].

In general, in studies involving both the use of chitosan and its derivatives or nanoparticles, it is possible to observe a beneficial effect on chlorophyll. The impact of antitranspirant on this parameter was investigated under both field [25,26,43] and pot conditions [49,63,84]. The results of scientific research show that, regardless of the type of cereal, chitosan increases chlorophyll content. Furthermore, chitosan also copes well with drought and salt stress, as well as low temperatures. These results are particularly promising in the context of ongoing climate change. Perhaps chitosan will be an effective tool for maintaining, and even improving chlorophyll content regardless of adverse plant conditions.

## 6. Gas Exchange

This chapter considers the parameters directly related to gas exchange. These include photosynthetic rate ( $P_N$ ), stomatal conductance ( $g_s$ ), and intercellular  $CO_2$  concentration ( $C_i$ ). The effects of chitosan on all of these components have been reviewed. An experiment

carried out on maize showed that the net photosynthetic rate ( $P_N$ ) decreased on the first day after chitosan application. However, on the following days, it increased, but only on the third day was it statistically significant. Then  $P_N$  was higher than in the control fields by 10 and 18% depending on CH5 pentamer concentrations ( $10^{-5}$  and  $10^{-7}$  M) [70]. Similar results were obtained in subsequent studies, where not only chitosan but also its derivatives: N-succinyl chitosan and N, O-dicarboxymethylated chitosan were used on maize. Research conducted under water scarcity conditions has shown that on the first day of stress the photosynthetic rate ( $P_N$ ) in both the treatment of chitosan and derivatives decreased. After 15 days of the experiment,  $P_N$  increased, while after rehydration, it reached the value of a non-stress (irrigated) control sample [96]. This was also confirmed by later tests, where after 15 days the chitosan derivatives (each separately), and also their mix, contributed to an increase in the photosynthetic rate [33]. Pearl millet also showed a decrease in photosynthesis rate under drought stress. Initially, it was even greater in chitosan-treated plants than in control plants. However, after 7 days, plants with chitosan had a much higher photosynthetic rate [98]. Studies carried out on two maize hybrids, one tolerant of (DKB 390) and the other sensitive to (BRS 1030) drought, showed that after foliar application of chitosan, higher photosynthesis was present in DKB 390 [99]. Moreover, research conducted on wheat (*Triticum aestivum* L. Jimai 22) also showed that the application of chito oligomers can improve photosynthesis [53]. It was also found that chitosan hexamers with different degrees of acetylation increase the photosynthetic rate and stomatal conductance of wheat seedlings [54]. Furthermore, chitosan showed a positive effect on photosynthesis in rice also under difficult conditions of elevated ozone concentration [87].

Under water deficit conditions on maize, studies were carried out on the effects of chitosan and two of its derivatives (N-succinylchitosan and N, O-dicarboxymethylated chitosan). Measurements conducted on leaves showed, on the first day after application, a decrease in carboxylation efficiency ( $P_N/C_i$ ) in comparison to control tests (both irrigated and stressed). However, after rehydration, the values in all treatments increased and were higher than the irrigated sample, in contrast to stomatal conductance ( $g_s$ ) and intercellular  $CO_2$  concentration ( $C_i$ ), whose values decreased [96]. Scientists highlight the importance of chitosan in regulating the carbon and nitrogen metabolism in wheat [100]. Also, the potential of chitosan to regulate the carbon metabolism in rice was noted [79]. In a study on maize, foliar application of chitosan  $140 \text{ mg L}^{-1}$  was found to cause a decrease in  $g_s$ . Thus it acts as an antiperspirant, without negatively affecting the  $P_N$  and the  $C_i$  [101].

## 7. Water-Use Efficiency (WUE)

There are two definitions of water-use efficiency (WUE). The first says that it is the ratio of photosynthesis to transpiration, also referred to in the literature as transpiration efficiency. The second describes it as the amount of carbon assimilated as biomass, or grain produced per unit of water consumed by the crop. For now, one of the key questions is how climate change (precipitation, temperature, and carbon dioxide) will affect plants and their WUE [102–105]. Therefore, the effect of antitranspirant use on this parameter is also important and of interest.

Studies carried out on wheat have shown that, after exogenous use of chitosan, WUE values improve. Furthermore, for plants treated with chitosan under moderate and severe drought stress, an increase in WUE was observed compared to untreated wheat and under normal conditions [26]. Also under salt stress conditions, it was shown that WUE was higher for wheat treated with chitosan compared to a control sample [43]. The influence of chitosan and its derivatives (N-succinylchitosan and N, O-dicarboxymethylated chitosan) under water stress conditions on maize was measured. Results showed that the WUE is higher for N, O-dicarboxymethyl and chitosan on both the first day of stress and after rehydration compared to two control samples (one irrigated and one stressed), in contrast to the values measured in the middle of the study duration, i.e., 15 days of stress, where results were lower [96].

Water-use efficiency was not a frequently analysed parameter in research on the chitosan effect on cereals. It is therefore difficult to draw universal conclusions. There are only a few studies that have taken this parameter into account. This should be changed, as WUE has a significant role in the adaptation and productivity of plants in water-limited areas. This concerns both the present as well as future climate change [106].

## 8. Relative Water Content (RWC)

The monitoring of water levels in plants is extremely important due to climate change and the intensification of droughts. One of the parameters used for this purpose is relative water content (RWC). It is responsible for biological water activity in plant tissues. In the assessment of the water balance of plants, RWC is one of the most important indices. Furthermore, RWC is a simple tool for farmers to monitor the water status of a plant to improve production [107]. Studies on the application of chitosan nanoparticles loaded with nitrogen, phosphorus, and potassium (NPK) on wheat showed an increased water content [39]. Also, foliar application of different concentrations of chitosan nanoparticles contributed to an increase in RWC for wheat. This is most likely due to a lower transpiration rate. The highest result of RWC was achieved at a level of 90 ppm of the substance [51]. Similar results, and the greatest improvement for the 90 ppm dose were also achieved with foliar application to barley (*Hordeum vulgare* L.) [52]. Furthermore, under reduced irrigation conditions for this plant, chitosan caused an increase in RWC [85]. In measurements on maize, RWC in plants treated with chitosan 140 mg L<sup>-1</sup> for 15 days of drought conditions remained at the same level as in irrigated plants. At lower chitosan concentrations, a reduction in RWC during drought was recorded compared to well-watered plants [101]. The positive effect of chitosan on increasing RWC under drought conditions was also observed in experiments on rice [84]. Higher RWC values after chitosan treatment under drought stress were also observed in pearl millet [98]. Therefore it can be concluded that this treatment mitigated the impact of drought on the decrease in relative water content. In general, the application of chitosan and nanoparticles had a positive effect on RWC. More importantly, it also improved this parameter under drought conditions for major cereals such as wheat, maize, and rice. This is extremely important from the point of view of climate change, the increasing frequency of drought periods, and maintaining global food security.

## 9. Pathogen and Disease Control

The research carried out concerning the effect of chitosan on cereal diseases has been extensive. In this review, many papers were found on the impact of this product on different types of *Fusarium*. Studies on wheat and durum wheat (*Triticum durum*) have shown that chitosan is an effective tool to reduce the damage caused by the fungal pathogen *Fusarium graminearum* [108,109]. Scientists observed a decrease in the growth of *F. graminearum* at the lowest tested dose of chitosan 0.5 mg/g [110]. Research has also been conducted on durum wheat on the effect of hydrochloride chitosan. The results showed a decrease in the growth of *F. graminearum* [55]. Furthermore, it has been proven that in the case of wheat and barley, chitosan and isolates of *Pseudomonas* spp. cause a decrease in Fusarium seedling blight [111]. Also, promising effects were obtained when chlorophyllin-chitosan complex (Chl-CHS) was applied to wheat. Furthermore, in the case of this compound, no simultaneous reduction in growth and chlorophyll parameters was observed [112]. Also, research was conducted using a combination of chitosan and a plant biostimulant (liquid seaweed extract) prepared from a brown macroalga *Ascophyllum nodosum*. After using this combination, measurements on wheat leaves showed a significant decrease in the area infected by the *F. graminearum* pathogen [113]. The fact that chitosan as well as chitosan nanoparticles can control the disease *Fusarium* head blight, caused by fungi from the genus *Fusarium*, is also confirmed by other studies [114–116]. These results are very important, because *Fusarium* head blight disease is one of the important challenges for wheat cultivation.

The impact of chitosan on other diseases has also been studied. In other research on wheat, it was found that this substance suppresses *Septoria* leaf blotch disease [117]. Beneficial results were also obtained with chitosan hydrolyzate, which contained low-molecular-weight chitosan and its oligomer. It has been shown that a hydrolyzate concentration of 200 µg/mL causes total inhibition of *Septoria* leaf blotch of wheat [118]. Furthermore, measurements were also carried out on wheat using chitosan and its derivatives (Chit-V) as well as vanillin-modified chitosan. All these treatments decreased the leaf area infected by the phytopathogen *Cochliobolus sativus*. These substances were therefore found to induce resistance in wheat to *C. sativus*, which causes dark-brown blotch disease [119]. Moreover, the multifunctional complex 'Vitaplan CL + 0.1% Chitosan' proved to be even more effective in the fight against wheat diseases. The study showed that its use decreased plant damage caused by brown rust by 20.6%. Also, it reduced the development of root rot, spots with powdery mildew, and the number of yellow rust strips. It is therefore an effective tool for decreasing disease incidence [41]. In the case of root rot, powdery mildew and leaf rust, studies have shown that other multifunctional biologics with chitosan also have the potential to defend wheat against this disease [42,120]. However, the results obtained with the application of ChitoPlant (Chitosan 99.9%) on the Edvins winter wheat variety are not conclusive. In one year of the study, this treatment was not effective against yellow rust, while in the following year an increase in effectiveness was observed. The authors state that this may be due to the different application timing and stress the need for further research [121]. It was also noted that chitosan reduced the percentage of wheat leaves infected by dark brown spot and also brown rust. In the control sample, leaf infection was 100%, while with chitosan it was only 25%. Even better results were obtained after treatment with chitosan in combination with salicylic acid. Leaf infection by dark brown spot was reduced to 20% and in the case of brown rust to 10% [122].

Furthermore, studies on maize showed that foliar application of chitosan reduced not only leaf spot disease, but also gray leaf blight, late wilt, and ear rot [123]. It was also found that chitosan had a positive effect on reducing leaf blight disease in this plant [32]. In addition, the potential of chitosan in fumonisin production by *Fusarium verticillioides* and *Fusarium proliferatum* has been investigated on maize samples. A decrease in growth of these *Fusarium* species was observed, using chitosan and water activity (aW) [124]. It also points to the huge potential of non-toxic chitosan to replace conventional antifungal agents [55]. A study on maize also found that chitosan in combination with *Cuscuta pedicellata* extract has the potential to be protective against *Fusarium oxysporum* [125]. The potential to increase resistance to *Fusarium oxysporum* was also observed in studies on rice. Chitosan oligosaccharide treatment was shown to reduce the incidence of seedling blight [126].

Studies also have been carried out on the effect of chitosan on rice crops (*Oryza sativa* L.) and their defensive reactions to stress and on the production of anti-fungal phytoalexins [127]. It has been proven that if rice leaves contain high levels of fibre, soaking the seeds in chitosan increases the potential for disease control and insect infection [49]. Measurements were also carried out on rice after the application of lanthanum-modified chitosan oligosaccharide nanoparticles (Cos-La). It was demonstrated that Cos-La induced resistance to rice blast [82]. Also, the use of chitosan guar nanoparticles may be effective in controlling rice blast, as well as blight disease [128]. Moreover, it has been observed that the percentage of rice attacked by brown planthopper after application of chitosan is reduced. This is very important, because this insect is one of the causes of crop losses in rice yields [50]. Also, chitosan-magnesium (CS-Mg) nanocomposite have proved to be effective in inhibiting the growth of two rice pathogens *Acidovorax oryzae* and *Rhizoctonia solani* [129]. For *Rhizoctonia solani*, chitosan nanoparticles without additives were also successful in suppressing this pathogen [130]. Also, after the use of chitosan, inhibition of mycelium development, as well as the occurrence of the disease caused by this pathogen was observed [131]. These results suggest the potential of chitosan and its derivatives in combating rice sheath blight. One study even says that chitosan reduced the severity

of this disease by up to 89% [132]. Moreover, chitosan applied to rice was found to enhance defense responses against other pathogens. The potential of 0.25% chitosan to control *Aphelenchoides besseyi*, the rice pathogen that causes white tip disease, has also been noted [133]. Moreover, the effectiveness of defense against rice blast pathogen *Magnaporthe grisea* has been proven. It has been observed that chitosan with low molecular weight contributes to higher resistance than with high molecular weight [134]. Studies have also been conducted on the effect of chitosan-silver nanoparticles combined with trihexad on rice blast caused by fungus *Pyricularia oryzae*. The antifungal potential of this chemical combination has been indicated [135]. It has also been found that *N,O*-acylchitosan has the potential to control *Botrytis cinerea* gray mold and *Pyricularia oryza* blast mould on rice. Furthermore, this derivative has shown better results than chitosan treatment alone [136]. The potential to control *Pyricularia oryzae* has also been demonstrated with the treatment of chitosan nanoparticles loaded with protocatechuic acid [137]. All these results suggest that chitosan and its variants can help to effectively combat rice blast. This is extremely important, as this disease contributes to significant crop damage. Other diseases that reduce the yield of rice are bacterial leaf blight and leaf streak. Studies have shown that chitosan has an antibacterial effect and is capable of preventing this disease, too [138]. Furthermore, biosynthesised chitosan nanoparticles have also shown inhibitory effects on the growth of *Xanthomonas oryzae* pv. *oryzae* (Xoo), a pathogen that causes bacterial leaf blight of rice [139]. Research has also been conducted on the use of COS-OGA, which are formulations of chitosan oligomers (COS) and pectin-derived oligogalacturonides (OGA). It was shown that COS-OGA can control root-knot nematode caused by *Meloidogyne graminicola* on rice [140].

Tests carried out in both greenhouse and field conditions on pearl millet showed that chitosan seed priming protects crops from downy mildew. Furthermore, the effect of chitosan on the regulation of resistance gene analogue RGPM213 to infection by downy mildew pathogen was also investigated in pearl millet [141]. The use of this substance causes systemic and durable resistance to this type of infection [58,142,143]. This has also been confirmed by later studies of seed treatment with nanochitosan particles [59]. The results of these research works are extremely significant, because this is the most devastating disease with pearl millet. This plant is resistant to drought and heat, and is grown mainly in Asia and Sub-Saharan Africa, where it is one of the basic foods for poor people [144,145]. The second plant in this group, on which the influence of nanochitosan particles was studied, was finger millet. The measurements showed that they inhibit the development of *Pyricularia grisea*, which causes blast disease. Moreover, the use of this substance resulted in a lower frequency of the disease [45]. It has also been shown that the application of copper-chitosan nanoparticles (CuChNp) on finger millet causes protection against blast disease [60]. The same conclusions were obtained for the treatment of oligochitosan on rice [80]. Moreover, the potential after treating seeds with chitosan and hydrolyzed chitosan for defense reactions to *Pyricularia grisea* (Cooke) Sacc. was also shown by research on the same plant [146]. Similar conclusions were reached for chitosan nanoparticles [147]. All of the above-mentioned results indicate that both chitosan and its varieties are effective tools in the fight against blast disease in cereal crops.

The potential of this product to control powdery mildew on barley (*Hordeum vulgare* L.) plants was also analysed and it was noted that it could slow the spread of the fungus [148]. Experiments with the use of chitosan on winter wheat (*Triticum aestivum* L.) indicate that there is a need for further research into the impact of this measure on pink snow mould (*Microdochium nivale*) [149]. Also, it has been shown that under the abiotic stress of maize, the use of chitosan reduces the development of the fungi *A. flavus* and *F. moniliforme* [150]. Subsequent studies on maize and sorghum confirmed that the application of chitosan had a fungistatic effect against *A. flavus* and a fungicidal effect against *Rhizopus* spp. [69]. In studies involving the use of Cu-chitosan nanoparticles on maize, it has been shown that this substance can act as an antifungal preparation for *Curvularia* leaf spot (CLS) disease [35]. It has been proven that Zn-chitosan nanoparticles (NPs) also have such properties and cause higher mycelial growth inhibition [37]. Furthermore, it has been shown that Cu-chitosan

nanocomposites are an effective antifungal agent against post-flowering stalk rot disease on maize [151]. Research on the same plant using salicylic acid-chitosan nanoparticles (SA-CS NPs) has also shown positive results for controlling this disease [77]. Scientists also note the need to consider chitooligosaccharides with different degrees of acetylation in the context of the use of protective preparations containing chitosan and the regulations for their use [152]. Therefore, research has also been carried out into the effect of chitooligosaccharides as well as chitooligosaccharides with different degrees of acetylation on reducing root rot in wheat and changes in the level of gene expression of pathogens [153,154]. It has been shown that the use of this derivative of chitosan stimulates defensive reactions to the necrotrophic fungus *Bipolaris sorokiniana*, which is responsible for the rot [153]. It has also been proven that this treatment strengthens the resistance of wheat calli to the bunt fungal pathogen *Tilletia caries* (DC) Tul. [155]. However, the researchers still stress the need for further studies on chitosan to increase data on its impact on crop diseases [156].

Based on the above overview, chitosan is highly effective in reducing the spread of cereal diseases. Its application is very broad. It has a beneficial influence, regardless of the crop type. This is particularly important for cereals, which are largely responsible for feeding the world's population. Chitosan and its nanoparticles have proven to be effective against rice diseases such as blast and sheath blight. These diseases are the main factors preventing stable rice production in the world [157]. However, the researchers also emphasise that despite promising results in disease control, chitosan nanoparticles have not yet found widespread application in rice cultivation [130]. In the case of finger millet, chitosan showed effective protection against not only blast disease but also downy mildew. It also affected many other pathogens occurring in barley or maize crops. Moreover, it reduces the most important wheat diseases such as rusts, blotches, and head blight. This is particularly significant considering that fungal diseases can cause yield losses of 15–20% per year [158]. Furthermore, cereal diseases also affect harvest quality and safety in terms of toxins [159]. Based on this review, it can be concluded that cereal disease damage can be reduced by the widespread application of chitosan during cultivation.

## 10. State of Knowledge and Research Trends

Since 2000, 188 original scientific articles on the use of chitosan, its derivatives, nanoparticles, or chitosan fertilizers on cereals have been published. All papers considered for this article were found in the Web of Science, Scopus, or Google Scholar databases. This review includes not only articles describing the field application of chitosan on cereals but also laboratory studies covering the effects of the antitranspirant on plant traits and disease reduction. All the papers found in the databases during this review are listed in Table 1. Most of the studies focused on the use of chitosan, chitooligosaccharides (COS), or nanoparticles. Among nanoparticles, Zn-chitosan nanoparticles, Cu-chitosan nanoparticles, chitosan-silver nanoparticles, and also chitosan-La nanoparticles were found. Applications also included irradiated chitosan, chitosan hydrochloride, chitosan nanoemulsion, or chitosan fertilizers.

**Table 1.** Summary of papers on chitosan, its derivatives and cereals published since 2000.

Chitosan Type	Cereal	References
Chitosan	Barley	[30,31,85,111,114,148,160–163]
	Maize	[29,32,33,47,61,62,69–74,91,95,96,99,101,110,123–125,150,164–167]
	Pearl millet	[141–143,168]
	Rice	[48–50,78,79,84,86,87,127,129,131–134,138,146,161,169–178]
	Sorghum	[69,179]
	Wheat	[25–28,43,100,108–111,113–117,119,121,122,149,161,167,169,180–186]
Chitooligosaccharide (COS)/ chitosan oligomer/ chitooligomer	Barley	[187,188]
	Rice	[80,81,89,126,189–191]
	Wheat	[40,53,88,90,100,152–155,185,192–194]

Table 1. Cont.

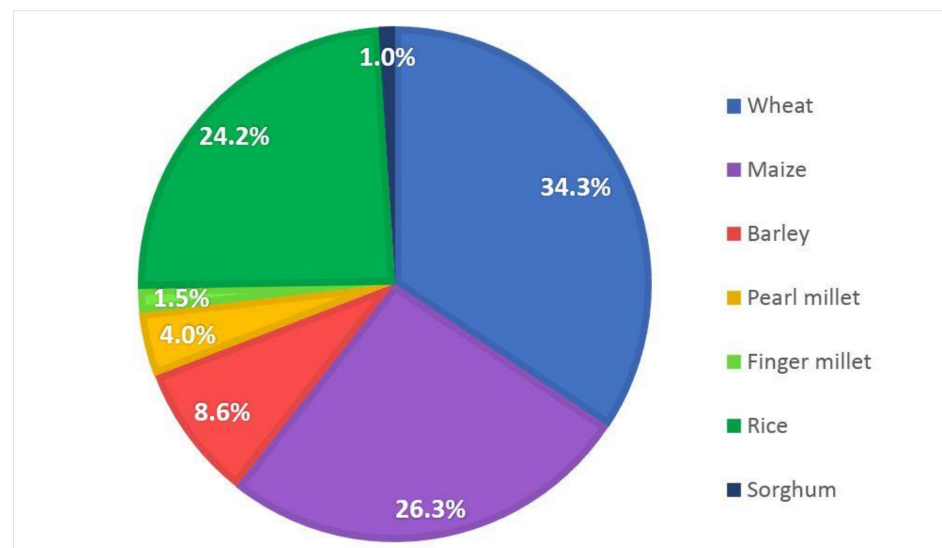
Chitosan Type	Cereal	References
Chitooligosaccharide (COS)/ chitosan oligomer/ chitooligomer	Barley Rice Wheat	[187,188] [80,81,89,126,189–191] [40,53,88,90,100,152–155,185,192–194]
Chitosan nanoparticles	Barley Finger millet Pearl millet Rice Wheat	[52,57] [46] [45,59] [67,130,139] [51,56,116]
Cu-chitosan nanoparticles	Finger millet Maize	[60] [35,75,76,151]
Zn-chitosan nanoparticles	Maize Wheat	[37] [195–198]
Chitosan nanoparticles loaded with nitrogen, phosphorus and potassium (NPK)	Wheat	[38,39]
Irradiated chitosan	Barley	[199,200]
<i>N</i> -succinylchitosan and <i>N,O</i> -dicarboxy-methylated chitosan	Maize	[33,96]
<i>N,O</i> -acylchitosan (NOAC)	Rice	[136]
Oligochitosan	Wheat	[201]
Deacetylated chitosan	Wheat	[202]
Vanillin-modified chitosan	Wheat	[119]
Chitosan nanoemulsion	Pearl millet Wheat	[98] [203]
Chitosan hydrochloride	Wheat	[55,204]
Chitosan-La nanoparticles, lanthanum-modified chitosan oligosaccharide nanoparticles (Cos-La)	Rice	[82]
Chitosan silver-nanoparticles	Rice	[135]
Moringa with chitosan and iron (MHCFE) nanoparticles	Maize	[68]
Chitosan nanoparticles containing <i>S</i> -nitrosomercaptosuccinic acid ( <i>S</i> -nitroso-MSA)	Maize	[97]
Salicylic acid-chitosan nanoparticles	Maize	[77]
Sepiolite-chitosan nanocomposites	Maize	[205]
Chitosan nanoparticles loaded with <i>N</i> -acetylcysteine	Wheat	[44]
Chitosan nanoparticles loaded with protocatechuic acid (PCA)	Rice	[137]
Chitosan guar nanoparticle	Rice	[128]
Chitosan nanoparticles encapsulated with <i>Cymbopogon martinii</i> essential oil	Maize	[206]

Table 1. Cont.

Chitosan Type	Cereal	References
Aqueous commercial formulation containing 4% chitosan name Alexa	Pearl millet	[58]
Chitosan and PUSA hydrogel	Wheat	[28,186]
Chitosan and plant biostimulant made from <i>A. nodosum</i> (liquid seaweed extract or LSE)	Wheat	[113]
Chitosan and hydrogel	Wheat	[27]
Chlorophyllin-chitosan complex (Chl-CHS)	Wheat	[112]
Chitin and chitosan hexamers, homogeneous chitosan hexamers [(GlcN) <sub>6</sub> ]	Wheat	[54]
Vitaplan, CL + chitosan	Wheat	[41,42,120]
Chitosan hydrolyzate	Wheat	[118]
Formulations of chitosan oligomers (COS) and pectin-derived oligogalacturonides (OGA), COS-OGA	Rice	[140]
Modified chitosan (MCTS), gibberellin, glutamic acid, sodium	Rice	[207]
Modified chitosan (MCTS), gibberellin, glutamic acid, sodium $\alpha$ -naphthalene acetic acid, sodium bentonite, polyvinyl acetate (PVAc), potato dextrose agar (PDA), emulsifier (OP-10), ethylene glycol (EG), polyethylene glycol 1000 (PEG-1000)	Maize, Barley, Wheat	[208]
Chitosan/sodium alginate hydrogel rings loaded with chlorantraniliprole (CLAP)	Maize	[209]
Chitosan/tripolyphosphate nanoparticles loaded with paraquat herbicide	Maize	[210]
Gel of chitosan and ZnO nanoparticles, CH-ZnO4 chitosan-ZnO nanoparticles	Maize	[211]
Paraquat-loaded pectin/chitosan/tripolyphosphate nanoparticles	Maize	[212]
Carboxylated graphene oxide-chitosan spheres	Wheat	[213]
Chitosan/nanochitosan with plant growth-promoting rhizobacteria (PGPR)	Pearl millet Maize Rice	[214] [34,66] [215]
Fertilizer/nanofertilizer with chitosan	Maize Wheat	[36,63–65,216] [217]
Quitomax <sup>®</sup> bioproduct based on chitosan	Rice	[218]



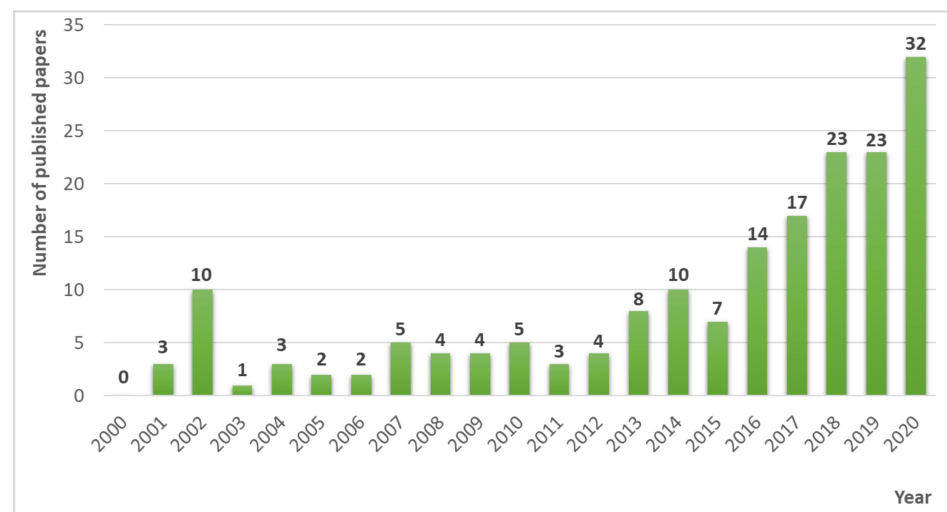
This review showed that wheat is the most popular cereal in the study, which accounts for 34.3% of all measurements (Figure 1). The second most frequent cereal in published papers is maize (26.3%) and the third is rice (24.2%). The percentage of research on barley is 8.6% and pearl millet only 4.0%. Studies on the use of chitosan on sorghum or finger millet are very rare. Their percentage contribution to the total is 1.0% and 1.5% respectively. This review indicates the need for more measurements on these crops to better understand the impact of chitosan on cereals. Furthermore, excluding studies on grain storage and further food processing, no publications on the use of chitosan on either oats or rye as plants have been found since 2000. This indicates a clear tendency for researchers to consider the most popular cereals and omit from their studies those with smaller cultivated areas worldwide. However, it should not be forgotten that to better identify the effect of chitosan, less common plants belonging to the cereal group should be considered.



**Figure 1.** Share of each cereal in original scientific papers on the use of chitosan.

This does not change the fact that the enormous potential of the application of chitosan, its derivatives, or nanoparticles on cereals is being increasingly recognized worldwide. Consequently, the application of chitosan-based products in agriculture is growing in popularity. In China alone, there are more than 50 different chitosan-based bioproducts with officially issued certificates [100]. Scientific research is also increasingly taking into account the use of this product. This has been particularly evident in recent years. Since 2016, the number of research papers focusing on the use of chitosan and its derivatives or nanoparticles on cereals has increased dramatically (Figure 2).

In 2020, a total of 32 articles were published, which is four times more than in 2013. Moreover, in 2000 there was not a single paper on this topic. The noticeable increasing trend of interest in this topic is very positive, because antitranspirants including chitosan can be an excellent tool for adaptation of cereals to climate change due to their high-stress tolerance. Also, the measurements and cell analyses carried out indicate that chitosan is not toxic.



**Figure 2.** Number of original scientific articles on the use of chitosan and its derivatives and nanoparticles on cereals published between 2000 and 2020.

It should be emphasised that this also includes high concentrations of this substance [71]. It has also been noted that the application of chitosan is environmentally friendly and reduces production costs [50]. The significant increase in scientific research in this area allows valid and accurate conclusions to be drawn and will contribute to a faster implementation of the widespread use of chitosan on cereals.

## 11. Conclusions

Based on this review, a marked increase in interest regarding the use of chitosan on cereals has been noted in recent years. Since 2000, 188 papers have been published on the use of chitosan and its derivatives and nanoparticles on cereals. The most popular were articles on wheat, maize, and rice. The need to expand the number of measurements on less popular cereals such as finger millet, pearl millet rye, oats, and sorghum has also been noted. Thanks to increased research activity in recent years, the state of knowledge on the effects of antitranspirants has improved considerably. It is clear from the review that chitosan, as well as its derivatives and nanoparticles, are non-toxic and have positive effects on cereals. Their application contributes to increased yields, not only under normal conditions but also during drought stress, salt, or low temperatures. Most studies also show positive effects on certain growth parameters. However, a more detailed analysis, taking into account the application method, concentration, and individual factors during the measurements is needed to formulate specific conclusions on cereal. Moreover, there is a tendency to alleviate the effects of stress and to improve growth parameters under unfavourable conditions. Regardless of the type of cereal, this antitranspirant also has a positive impact on chlorophyll content. Furthermore, this review has shown that chitosan is highly effective against pathogens and cereal diseases such as fusarium seedling blight, blast disease, septoria leaf blotch, downy mildew, and many others. It significantly reduces damage caused by the most threatening diseases to maize, wheat, rice, barley, and millet. Its application is effective regardless of the type of cereal and, more importantly, it covers a very wide range of pathogens. This demonstrates the enormous application value of chitosan in agriculture. Effective control of diseases, which is currently one of the biggest challenges in cereal cultivation, will significantly limit harvest losses. Chitosan, with its environmentally friendly composition and high effectiveness, can be an excellent alternative to synthetic fertilizers, pesticides and chemicals for disease control. Also, treating cereals with this product will reduce the negative effects of drought, salt, and low temperature stress on crops and contribute to higher yields. This shows the enormous potential of chitosan as a universal product for improving cereal yields regardless of environmental conditions.

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## References

- Awika, J.M. Major Cereal Grains Production and Use Around the World. *ACS Symp. Ser.* **2011**, *1089*, 1–13. [[CrossRef](#)]
- FAO. *World Food and Agriculture—Statistical Yearbook*; FAO: Rome, Italy, 2020. [[CrossRef](#)]
- Asseng, S.; Ewert, F.; Martre, P.; Rötter, R.P.; Lobell, D.B.; Cammarano, D.; Kimball, B.A.; Ottman, M.J.; Wall, G.W.; White, J.W.; et al. Rising Temperatures Reduce Global Wheat Production. *Nat. Clim. Chang.* **2015**, *5*, 143–147. [[CrossRef](#)]
- Barnabás, B.; Jäger, K.; Fehér, A. The Effect of Drought and Heat Stress on Reproductive Processes in Cereals. *Plant Cell Environ.* **2008**, *31*, 11–38. [[CrossRef](#)] [[PubMed](#)]
- Stratonovitch, P.; Semenov, M.A. Heat Tolerance Around Flowering in Wheat Identified as a Key Trait for Increased Yield Potential in Europe Under Climate Change. *J. Exp. Bot.* **2015**, *66*, 3599–3609. [[CrossRef](#)] [[PubMed](#)]
- Xiong, W.; Holman, I.; Lin, E.; Conway, D.; Jiang, J.; Xu, Y.; Li, Y. Climate Change, Water Availability and Future Cereal Production in China. *Agric. Ecosyst. Environ.* **2010**, *135*, 58–69. [[CrossRef](#)]
- Wang, J.; Vanga, S.K.; Saxena, R.; Orsat, V.; Raghavan, V. Effect of Climate Change on the Yield of Cereal Crops: A Review. *Climate* **2018**, *6*, 41. [[CrossRef](#)]
- Reynolds, M.P.; Quilligan, E.; Aggarwal, P.K.; Bansal, K.C.; Cavalieri, A.J.; Chapman, S.C.; Chapotin, S.M.; Datta, S.K.; Duveiller, E.; Gill, K.S.; et al. An Integrated Approach to Maintaining Cereal Productivity under Climate Change. *Glob. Food Sec.* **2016**, *8*, 9–18. [[CrossRef](#)]
- Bittelli, M.; Flury, M.; Campbell, G.S.; Nichols, E.J. Reduction of Transpiration Through Foliar Application of Chitosan. *Agric. For. Meteorol.* **2001**, *107*, 167–175. [[CrossRef](#)]
- Pandey, P.; Verma, M.K.; De, N. Chitosan in Agricultural Context—A Review. *Bull. Environ. Pharmacol. Life Sci.* **2018**, *7*, 87–96.
- Kaur, S.; Dhillon, G.S. The Versatile Biopolymer Chitosan: Potential Sources, Evaluation of Extraction Methods and Applications. *Crit. Rev. Microbiol.* **2013**, *40*, 155–175. [[CrossRef](#)] [[PubMed](#)]
- Kumari, S.; Kumar Annamareddy, S.H.; Abanti, S.; Kumar Rath, P. Physicochemical Properties and Characterization of Chitosan Synthesized from Fish Scales, Crab and Shrimp Shells. *Int. J. Biol. Macromol.* **2017**, *104*, 1697–1705. [[CrossRef](#)]
- Iriti, M.; Picchi, V.; Rossoni, M.; Gomasasca, S.; Ludwig, N.; Gargano, M.; Faoro, F. Chitosan Antitranspirant Activity Is Due to Abscisic Acid-Dependent Stomatal Closure. *Environ. Exp. Bot.* **2009**, *66*, 493–500. [[CrossRef](#)]
- Dzung, N.A.; Khanh, V.T.P.; Dzung, T.T. Research on Impact of Chitosan Oligomers on Biophysical Characteristics, Growth, Development and Drought Resistance of Coffee. *Carbohydr. Polym.* **2011**, *84*, 751–755. [[CrossRef](#)]
- Anusuya, S.; Sathiyabama, M. Effect of Chitosan on Growth, Yield and Curcumin Content in Turmeric under Field Condition. *Biocatal. Agric. Biotechnol.* **2016**, *6*, 102–106. [[CrossRef](#)]
- Chakraborty, M.; Hasanuzzaman, M.; Rahman, M.; Khan, M.A.R.; Bhowmik, P.; Mahmud, N.U.; Tanveer, M.; Islam, T. Mechanism of Plant Growth Promotion and Disease Suppression by Chitosan Biopolymer. *Agriculture* **2020**, *10*, 624. [[CrossRef](#)]
- Mondal, M.M.A.; Malek, M.A.; Puteh, A.B.; Ismail, M.R.; Ashrafuzzaman, M.; Naher, L. Effect of Foliar Application of Chitosan on Growth and Yield in Okra. *Aust. J. Crop Sci.* **2012**, *6*, 918–921.
- Badawy, M.E.I.; Rabea, E.I. Chitosan and Its Derivatives as Active Ingredients against Plant Pests and Diseases. In *Chitosan in the Preservation of Agricultural Commodities*; Elsevier Inc.: Amsterdam, The Netherlands, 2016; pp. 179–219, ISBN 9780128027356. [[CrossRef](#)]
- Bautista-Baños, S.; Hernandez-Lauzardo, A.N.; Velazquez-del Valle, M.G.; Hernández-López, M.; Barka, E.A.; Bosquez-Molina, E.; Wilson, C.L. Chitosan as a Potential Natural Compound to Control Pre and Postharvest Diseases of Horticultural Commodities. *Crop Prot.* **2006**, *25*, 108–118. [[CrossRef](#)]
- Orzali, L.; Corsi, B.; Forni, C.; Riccioni, L. Chitosan in Agriculture: A New Challenge for Managing Plant Disease. In *Biological Activities and Application of Marine Polysaccharides*; InTech: London, UK, 2017. [[CrossRef](#)]
- Yu, J.; Wang, D.; Geetha, N.; Khawar, K.M.; Jogaiah, S.; Mujtaba, M. Current Trends and Challenges in the Synthesis and Applications of Chitosan-Based Nanocomposites for Plants: A Review. *Carbohydr. Polym.* **2021**, *261*, 117904. [[CrossRef](#)]

22. Sheikhalipour, M.; Esmailpour, B.; Behnamian, M.; Gohari, G.; Giglou, M.T.; Vachova, P.; Rastogi, A.; Brestic, M.; Skalicky, M. Chitosan–Selenium Nanoparticle (Cs–Se NP) Foliar Spray Alleviates Salt Stress in Bitter Melon. *Nanomaterials* **2021**, *11*, 684. [[CrossRef](#)]
23. Anusuya, S.; Banu, K.N. Silver-Chitosan Nanoparticles Induced Biochemical Variations of Chickpea (*Cicer arietinum* L.). *Biocatal. Agric. Biotechnol.* **2016**, *8*, 39–44. [[CrossRef](#)]
24. Chouhan, D.; Mandal, P. Applications of Chitosan and Chitosan Based Metallic Nanoparticles in Agrosociences—A Review. *Int. J. Biol. Macromol.* **2021**, *166*, 1554–1569. [[CrossRef](#)] [[PubMed](#)]
25. Zeng, D.; Luo, X. Physiological Effects of Chitosan Coating on Wheat Growth and Activities of Protective Enzyme with Drought Tolerance. *Open. J. Soil Sci.* **2012**, *2*, 282–288. [[CrossRef](#)]
26. Farouk, S.; EL-Metwally, I.M. Synergistic Responses of Drip-Irrigated Wheat Crop to Chitosan and/or Silicon under Different Irrigation Regimes. *Agric. Water Manag.* **2019**, *226*, 105807. [[CrossRef](#)]
27. Babu, T.V.K.; Sharma, R.; Pallekonda, V.K. Efficacy of Hydrogel and Chitosan on Wheat (*Triticum Aestivum* L.) Physio-Biochemical and Economical Yield Parameters under Deficit Irrigation Level. *J. Pharmacogn. Phytochem.* **2018**, *7*, 2244–2247.
28. Burondkar, S.S.; Sharma, R.; Singh, A.S.; Akshay, S.M. Efficacy of Pusa Hydrogel and Chitosan on Wheat (*Triticum aestivum* L.) Growth and Yield under Water Deficit Condition. *J. Pharmacogn. Phytochem.* **2018**, *7*, 501–505.
29. Guan, Y.J.; Hu, J.; Wang, X.J.; Shao, C.X. Seed Priming with Chitosan Improves Maize Germination and Seedling Growth in Relation to Physiological Changes under Low Temperature Stress. *J. Zhejiang Univ. Sci. B.* **2009**, *10*, 427–433. [[CrossRef](#)] [[PubMed](#)]
30. Al-Tawaha, A.M.; Al-Ghzawi, A. Response of Barley Cultivars to Chitosan Application under Semi-Arid Conditions. *Res. Crop.* **2013**, *14*, 427–430.
31. Al-Tawaha, A.R.M.; Jahan, N.; Odat, N.; Al-Ramamneh, E.A.; Al-Tawaha, A.R.; Abu-Zaitoon, Y.; Alhawatem, M.; Amanullah, A.; Abdur Rauf, A.R.; Wedyan, M. Growth, Yield and Biochemical Responses in Barley to DAP and Chitosan Application under Water Stress. *J. Ecol. Eng.* **2020**, *21*, 86–93. [[CrossRef](#)]
32. Monjane, J.; Dimande, P.; Zimba, A.; Nhachengo, E.; Teles, E.; Helio, N.; Uamusse, A. Antifungal Activity of Biopesticides and Their Effects on the Growth Parameters and Yield of Maize and Pigeon Pea. *Trop. J. Nat. Prod. Res.* **2020**, *4*, 512–515. [[CrossRef](#)]
33. Rabêlo, V.M.; Magalhães, P.C.; Bressanin, L.A.; Carvalho, D.T.; Reis, C.O.; Karam, D.; Doriguetto, A.C.; Santos, M.H.; Filho, P.P.S.S.; Souza, T.C. The Foliar Application of a Mixture of Semisynthetic Chitosan Derivatives Induces Tolerance to Water Deficit in Maize, Improving the Antioxidant System and Increasing Photosynthesis and Grain Yield. *Sci. Rep.* **2019**, *9*, 8164. [[CrossRef](#)]
34. Agbodjato, N.A.; Noumavo, P.A.; Adjanohoun, A.; Agbessi, L.; Baba-Moussa, L. Synergistic Effects of Plant Growth Promoting Rhizobacteria and Chitosan on In Vitro Seeds Germination, Greenhouse Growth, and Nutrient Uptake of Maize (*Zea mays* L.). *Biotechnol. Res. Int.* **2016**. [[CrossRef](#)] [[PubMed](#)]
35. Choudhary, R.C.; Kumaraswamy, R.V.; Kumari, S.; Sharma, S.S.; Pel, A.; Raliya, R.; Biswas, P.; Saharan, V. Cu-Chitosan Nanoparticle Boost Defense Responses and Plant Growth in Maize (*Zea mays* L.). *Sci. Rep.* **2017**, *7*, 9754. [[CrossRef](#)]
36. Kumaraswamy, R.V.; Saharan, V.; Kumari, S.; Choudhary, R.C.; Pal, A.; Sharma, S.S.; Rakshit, S.; Raliya, R.; Biswas, P. Chitosan-Silicon Nanofertilizer to Enhance Plant Growth and Yield in Maize (*Zea mays* L.). *Plant Physiol. Biochem.* **2021**, *159*, 53–66. [[CrossRef](#)]
37. Choudhary, R.C.; Kumaraswamy, R.V.; Kumari, S.; Sharma, S.S.; Pal, A.; Raliya, R.; Biswas, P.; Saharan, V. Zinc Encapsulated Chitosan Nanoparticle to Promote Maize Crop Yield. *Int. J. Biol. Macromol.* **2019**, *127*, 126–135. [[CrossRef](#)] [[PubMed](#)]
38. Abdel-Aziz, H.M.M.; Hasaneen, M.N.A.G.; Omer, A.M. Foliar Application of Nano Chitosan NPK Fertilizer Improves the Yield of Wheat Plants Grown on Two Different Soils. *Egypt. J. Exp. Biol.* **2018**, *14*, 63–72.
39. Abdel-Aziz, H.M.M.; Hasaneen, M.N.; Omer, A.M. Nano Chitosan-NPK Fertilizer Enhances the Growth and Productivity of Wheat Plants Grown in Sandy Soil. *Span. J. Agric. Res.* **2016**, *14*, 17. [[CrossRef](#)]
40. Wang, M.; Chen, Y.; Zhang, R.; Wang, W.; Zhao, X.; Du, Y.; Yin, H. Effects of chitosan Oligosaccharides on the Yield Components and Production Quality of Different Wheat Cultivars (*Triticum aestivum* L.) in Northwest China. *Field Crops Res.* **2015**, *172*, 11–20. [[CrossRef](#)]
41. Kolesnikov, L.E.; Priyatkin, N.S.; Popova, E.V.; Kolesnikova, Y.R.; Zuev, E.V.; Solodyannikov, M.D.; Novikova, I.I. The Effectiveness of Biopreparations in Soft Wheat Cultivation and the Quality Assessment of the Grain by the Digital X-Ray Imaging. *Agron. Res.* **2020**, *18*, 2436–2448. [[CrossRef](#)]
42. Kolesnikov, L.E.; Popova, E.V.; Novikova, I.I.; Priyatkin, N.S.; Arkhipov, M.V.; Kolesnikova, Y.R.; Potrakhov, N.N.; van Duijn, B.; Gusarenko, A.S. Multifunctional Biologics Which Combine Microbial Anti-Fungal Strains with Chitosan Improve Soft Wheat (*Triticum aestivum* L.) Yield and Grain Quality. *Agric. Biol.* **2019**, *54*, 1024–1040. [[CrossRef](#)]
43. Abdallah, M.M.S.; Ramadan, A.A.E.-M.; El-Bassiouny, H.M.S.; Bakry, B.A. Regulation of Antioxidant System in Wheat Cultivars by Using Chitosan or Salicylic Acid to Improve Growth and Yield Under Salinity Stress. *Asian J. Plant Sci.* **2020**, *19*, 114–126. [[CrossRef](#)]
44. Picchi, V.; Gobbi, S.; Fattizzo, M.; Zefelippo, M.; Faoro, F. Chitosan Nanoparticles Loaded with N-Acetyl Cysteine to Mitigate Ozone and Other Possible Oxidative Stresses in Durum Wheat. *Plants* **2021**, *10*, 691. [[CrossRef](#)] [[PubMed](#)]
45. Sathiyabama, M.; Manikandan, A. Chitosan Nanoparticle Induced Defense Responses in Fingermillet Plants against Blast Disease Caused by *Pyricularia grisea* (Cke.) Sacc. *Carbohydr. Polym.* **2016**, *154*, 241–246. [[CrossRef](#)]
46. Sathiyabama, M.; Manikandan, A. Foliar Application of Chitosan Nanoparticle Improves Yield, Mineral Content and Boost Innate Immunity in Finger Millet Plants. *Carbohydr. Polym.* **2021**, *258*, 117691. [[CrossRef](#)]

47. Mondal, M.M.A.; Puteh, A.B.; Dafader, N.C.; Rafii, M.Y.; Malek, M.A. Foliar Application of Chitosan Improves Growth and Yield in Maize. *J. Food Agric. Environ.* **2013**, *11*, 520–523.
48. Boonlertnirun, S.; Sarobol, E.; Sooksathan, I. Effects of Molecular Weight of Chitosan on Yield Potential of Rice Cultivar Suphan Buri 1. *Agric. Nat. Resour.* **2006**, *40*, 854–861.
49. Boonlertnirun, S.; Boonraung, C.; Suvanasara, R. Application of Chitosan in Rice Production. *J. Met. Mater. Miner.* **2008**, *18*, 47–52.
50. Van Toan, N.; Hanh, T.T. Application of Chitosan Solutions for Rice Production in Vietnam. *Afr. J. Biotechnol.* **2013**, *12*, 382–384. [[CrossRef](#)]
51. Behboudi, F.; Tahmasebi-Sarvestani, Z.; Kassae, M.Z.; Modarres-Sanavy, S.A.M.; Sorooshzadeh, A.; Mokhtassi-Bidgoli, A. Evaluation of Chitosan Nanoparticles Effects with Two Application Methods on Wheat Under Drought Stress. *J. Plant. Nutr.* **2019**, *42*, 1439–1451. [[CrossRef](#)]
52. Behboudi, F.; Tahmasebi Sarvestani, Z.; Zaman Kassae, M.; Modares Sanavi, S.A.M.; Sorooshzadeh, A.; Ahmadi, S.B. Evaluation of Chitosan Nanoparticles Effects on Yield and Yield Components of Barley (*Hordeum vulgare* L.) under Late Season Drought Stress. *J. Water Environ. Nanotechnol.* **2018**, *3*, 22–39. [[CrossRef](#)]
53. Zhang, X.; Li, K.; Liu, S.; Xing, R.; Yu, H.; Chen, X.; Li, P. Size Effects of Chitoooligomers on the Growth and Photosynthetic Characteristics of Wheat Seedlings. *Carbohydr. Polym.* **2016**, *138*, 27–33. [[CrossRef](#)]
54. Li, K.C.; Zhang, X.Q.; Yu, Y.; Xing, R.E.; Liu, S.; Li, P.C. Effect of Chitin and Chitosan Hexamers on Growth and Photosynthetic Characteristics of Wheat Seedlings. *Photosynthetica* **2020**, *58*, 819–826. [[CrossRef](#)]
55. Francesconi, S.; Steiner, B.; Buerstmayr, H.; Lemmens, M.; Sulyok, M.; Balestra, G.M. Chitosan Hydrochloride Decreases *Fusarium graminearum* Growth and Virulence and Boosts Growth, Development and Systemic Acquired Resistance in Two Durum Wheat Genotypes. *Molecules* **2020**, *25*, 4752. [[CrossRef](#)] [[PubMed](#)]
56. Li, R.; He, J.; Xie, H.; Wang, W.; Bose, S.K.; Sun, Y.; Hu, J.; Yin, H. Effects of Chitosan Nanoparticles on Seed Germination and Seedling Growth of Wheat (*Triticum aestivum* L.). *Int. J. Biol. Macromol.* **2019**, *126*, 91–100. [[CrossRef](#)] [[PubMed](#)]
57. Behboudi, F.; Tahmasebi Sarvestani, Z.; Zaman Kassae, M.; Modares Sanavi, S.A.M.; Sorooshzadeh, A. Phytotoxicity of Chitosan and SiO<sub>2</sub> Nanoparticles to Seed Germination of Wheat (*Triticum aestivum* L.) and Barley (*Hordeum vulgare* L.) Plants. *Not. Sci. Biol.* **2017**, *9*, 242–249. [[CrossRef](#)]
58. Sharathchandra, R.G.; Raj, S.N.; Shetty, N.P.; Amruthesh, K.N.; Shetty, H.S. A Chitosan Formulation Elexa Induces Downy Mildew Disease Resistance and Growth Promotion in Pearl Millet. *Crop Prot.* **2004**, *23*, 881–888. [[CrossRef](#)]
59. Siddaiah, C.N.; Prasanth, K.; Satyanarayana, N.R.; Mudili, V.; Gupta, V.K.; Kalagatur, N.K.; Satyavati, T.; Dai, X.F.; Chen, J.Y.; Mocan, A.; et al. Chitosan Nanoparticles Having Higher Degree of Acetylation Induce Resistance against Pearl Millet Downy Mildew Through Nitric Oxide Generation. *Sci. Rep.* **2018**, *8*, 2485. [[CrossRef](#)] [[PubMed](#)]
60. Sathiyabama, M.; Manikandan, A. Application of Copper-Chitosan Nanoparticles Stimulate Growth and Induce Resistance in Finger Millet (*Eleusine coracana* Gaertn.) Plants against Blast Disease. *J. Agric. Food Chem.* **2018**, *66*, 1784–1790. [[CrossRef](#)]
61. Al-Tawaha, A.R.; Turk, M.A.; Al-Tawaha, A.R.M.; Alu'datt, M.H.; Wedyan, M.; Al-Ramamneh, E.; Hoang, A.T. Using Chitosan to Improve Growth of Maize Cultivars under Salinity Conditions. *Bulg. J. Agric. Sci.* **2018**, *24*, 437–442.
62. Qu, D.Y.; Gu, W.R.; Zhang, L.G.; Li, C.F.; Chen, X.C.; Li, L.J.; Xie, T.L.; Wei, S. Role of Chitosan in the Regulation of the Growth, Antioxidant System and Photosynthetic Characteristics of Maize Seedlings under Cadmium Stress. *Russ. J. Plant Physiol.* **2019**, *66*, 140–151. [[CrossRef](#)]
63. Sharma, G.; Kumar, A.; Devi, K.A.; Prajapati, D.; Bhagat, D.; Pal, A.; Raliya, R.; Biswas, P.; Saharan, V. Chitosan Nanofertilizer to Foster Source Activity in Maize. *Int. J. Biol. Macromol.* **2020**, *145*, 226–234. [[CrossRef](#)]
64. Kubavat, D.; Trivedi, K.; Vaghela, P.; Prasad, K.; Anand, K.V.; Trivedi, H.; Patidar, R.; Chaudhari, J.; Andhariya, B.; Ghosh, A. Characterization of Chitosan Based Sustained Release Nano-Fertilizer Formulation as a Soil Conditioner Whilst Improving Biomass Production of *Zea mays* L. *Land Degrad. Dev.* **2020**, *31*, 2734–2746. [[CrossRef](#)]
65. Wang, J.; Chen, H.; Ma, R.; Shao, J.; Huang, S.; Liu, Y.; Jiang, Y.; Cheng, D. Novel Water-and Fertilizer-Management Strategy: Nutrient-Water Carrier. *J. Clean. Prod.* **2021**, 125961. [[CrossRef](#)]
66. Khati, P.; Chaudhary, P.; Gangola, S.; Bhatt, P.; Sharma, A. Nanochitosan Supports Growth of *Zea mays* and Also Maintains Soil Health Following Growth. *3 Biotech.* **2017**, *7*, 81. [[CrossRef](#)] [[PubMed](#)]
67. Divya, K.; Vijayan, S.; Nair, S.J.; Jisha, M.S. Optimization of Chitosan Nanoparticle Synthesis and Its Potential Application as Germination Elicitor of *Oryza sativa* L. *Int. J. Biol. Macromol.* **2019**, *124*, 1053–1059. [[CrossRef](#)]
68. Tovar, G.I.; Briceño, S.; Suarez, J.; Flores, S.; González, G. Biogenic Synthesis of Iron Oxide Nanoparticles Using *Moringa oleifera* and Chitosan and Its Evaluation on Corn Germination. *Environ. Nanotechnol. Monit. Manag.* **2020**, *14*, 100350. [[CrossRef](#)]
69. Mohamed, C.; Amoin, N.E.; Etienne, T.V.; Yannick, K.N. Use of Bioactive Chitosan and *Lippia Multiflora* Essential Oil as Coatings for Maize and Sorghum Seeds Protection. *EurAsian J. Biosci.* **2020**, *14*, 27–34.
70. Khan, W.; Prithviraj, B.; Smith, D. Effect of Foliar Application of Chitin and Chitosan Oligosaccharides on Photosynthesis of Maize and Soybean. *Photosynthetica* **2002**, *40*, 621–624. [[CrossRef](#)]
71. Martins, M.; Veroneze-Junior, V.; Carvalho, M.; Carvalho, D.T.; Barbosa, S.; Doriguetto, A.C.; Magalhaes, P.C.; Riberio, C.; dos Santos, M.H.; de Sousa, T.C. Physicochemical Characterization of Chitosan and Its Effects on Early Growth, Cell Cycle and Root Anatomy of Transgenic and Non-Transgenic Maize Hybrids. *Aust. J. Crop Sci.* **2018**, *12*, 56. [[CrossRef](#)]

72. Lizárraga-Paulín, E.G.; Miranda-Castro, S.P.; Moreno-Martínez, E.; Lara-Sagahón, A.V.; Torres-Pacheco, I. Maize Seed Coatings and Seedling Sprayings with Chitosan and Hydrogen Peroxide: Their Influence on Some Phenological and Biochemical Behaviors. *J. Zhejiang Univ. Sci. B* **2013**, *14*, 87–96. [[CrossRef](#)] [[PubMed](#)]
73. Peña-Datoli, M.; Hidalgo-Moreno, C.M.I.; González-Hernández, V.A.; Alcántar-González, E.G.; Etchevers-Barra, J.D. Maize (*Zea mays* L.) Seed Coating with Chitosan and Sodium Alginate and Its Effect on Root Development. *Agrociencia* **2016**, *50*, 1091–1106.
74. Nakasato, D.Y.; Pereira, A.E.; Oliveira, J.L.; Oliveira, H.C.; Fraceto, L.F. Evaluation of the Effects of Polymeric Chitosan/Tripolyphosphate and Solid Lipid Nanoparticles on Germination of *Zea mays*, *Brassica rapa* and *Pisum sativum*. *Ecotoxicol. Environ. Saf.* **2017**, *142*, 369–374. [[CrossRef](#)] [[PubMed](#)]
75. Saharan, V.; Kumaraswamy, R.V.; Choudhary, R.C.; Kumari, S.; Pal, A.; Raliya, R.; Biswas, P. Cu-Chitosan Nanoparticle Mediated Sustainable Approach to Enhance Seedling Growth in Maize by Mobilizing Reserved Food. *J. Agric. Food Chem.* **2016**, *64*, 6148–6155. [[CrossRef](#)]
76. Choudhary, R.C.; Joshi, A.; Kumari, S.; Kumaraswamy, R.V.; Saharan, V. Preparation of Cu-Chitosan Nanoparticle and Its Effect on Growth and Enzyme Activity During Seed Germination in Maize. *J. Pharmacogn. Phytochem.* **2017**, *6*, 669–673.
77. Kumaraswamy, R.V.; Kumari, S.; Choudhary, R.C.; Sharma, S.S.; Pal, A.; Raliya, R.; Biswas, P.; Saharan, V. Salicylic Acid Functionalized Chitosan Nanoparticle: A Sustainable Biostimulant for Plant. *Int. J. Biol. Macromol.* **2019**, *123*, 59–69. [[CrossRef](#)] [[PubMed](#)]
78. Martínez-González, L.; Reyes Guerrero, Y.; Falcón Rodríguez, A.; Núñez Vázquez, M. Effect of Seed Treatment with Chitosan on the Growth of Rice (*Oryza sativa* L.) Seedlings Cv. INCA LP-5 in Saline Medium. *Cult. Trop.* **2015**, *36*, 143–150.
79. Chamnanmanoontham, N.; Pongprayoon, W.; Pichayangkura, R.; Roytrakul, S.; Chadchawan, S. Chitosan Enhances Rice Seedling Growth Via Gene Expression Network between Nucleus and Chloroplast. *Plant Growth Regul.* **2015**, *75*, 101–114. [[CrossRef](#)]
80. Yacob, N.; Mahmud, M.; Talip, N.; Hashim, K.; Harun, A.R.; Zaman, K. Degradation of Chitosan for Rice Crops Application. *Nucl. Sci. Tech.* **2013**, *24*, 1–5.
81. Xie, X.; Yan, Y.; Liu, T.; Chen, J.; Huang, M.; Wang, L.; Chen, M.; Li, X. Data-Independent Acquisition Proteomic Analysis of Biochemical Factors in Rice Seedlings Following Treatment with Chitosan Oligosaccharides. *Pestic Biochem. Physiol.* **2020**, *170*, 104681. [[CrossRef](#)] [[PubMed](#)]
82. Liang, W.; Yu, A.; Wang, G.; Zheng, F.; Hu, P.; Jia, J.; Xu, H. A Novel Water-Based Chitosan-La Pesticide Nanocarrier Enhancing Defense Responses in Rice (*Oryza sativa* L.) Growth. *Carbohydr. Polym.* **2018**, *199*, 437–444. [[CrossRef](#)] [[PubMed](#)]
83. Iriti, M.; Faoro, F. Chitosan as a MAMP, Searching for a PRR. *Plant Signal. Behav.* **2009**, *4*, 66–68. [[CrossRef](#)] [[PubMed](#)]
84. Moolphuerk, N.; Pattanagul, W. Pretreatment with Different Molecular Weight Chitosans Encourages Drought Tolerance in Rice (*Oryza sativa* L.) Seedling. *Not. Bot. Horti. Agrobot. Cluj Napoca* **2020**, *48*, 2072–2084. [[CrossRef](#)]
85. Hafez, Y.; Attia, K.; Alamery, S.; Ghazy, A.; Al-Doss, A.; Ibrahim, E.; Rashwan, E.; El-Maghraby, L.; Awad, A.; Abdelaal, K. Beneficial Effects of Biochar and Chitosan on Antioxidative Capacity, Osmolytes Accumulation, and Anatomical Characters of Water-Stressed Barley Plants. *Agronomy* **2020**, *10*, 630. [[CrossRef](#)]
86. Pongprayoon, W.; Roytrakul, S.; Pichayangkura, R.; Chadchawan, S. The Role of Hydrogen Peroxide in Chitosan-Induced Resistance to Osmotic Stress in Rice (*Oryza Sativa* L.). *Plant Growth Regul.* **2013**, *70*, 159–173. [[CrossRef](#)]
87. Phothis, R.; Theerakarunwong, C.D. Effect of Chitosan on Physiology, Photosynthesis and Biomass of Rice (*Oryza sativa* L.) under Elevated Ozone. *Aust. J. Crop Sci.* **2017**, *11*, 624–630. [[CrossRef](#)]
88. Zou, P.; Tian, X.; Dong, B.; Zhang, C. Size Effects of Chitooligomers with Certain Degrees of Polymerization on the Chilling Tolerance of Wheat Seedlings. *Carbohydr. Polym.* **2017**, *160*, 194–202. [[CrossRef](#)] [[PubMed](#)]
89. Zhang, Y.; Fan, L.; Zhao, M.; Chen, Q.; Qin, Z.; Feng, Z.; Fujiwara, T.; Zhao, Z. Chitooligosaccharide Plays Essential Roles in Regulating Proline Metabolism and Cold Stress Tolerance in Rice Seedlings. *Acta Physiol. Plant* **2019**, *41*, 77. [[CrossRef](#)]
90. Zou, P.; Li, K.; Liu, S.; He, X.; Zhang, X.; Xing, R.; Li, P. Effect of Sulfated Chitooligosaccharides on Wheat Seedlings (*Triticum aestivum* L.) under Salt Stress. *J. Agric. Food Chem.* **2016**, *64*, 2815–2821. [[CrossRef](#)]
91. Turk, H. Chitosan-Induced Enhanced Expression and Activation of Alternative Oxidase Confer Tolerance to Salt Stress in Maize Seedlings. *Plant Physiol. Biochem.* **2019**, *141*, 415–422. [[CrossRef](#)]
92. Croft, H.; Chen, J.M.; Luo, X.; Bartlett, P.; Chen, B.; Staebler, R.M. Leaf Chlorophyll Content as a Proxy for Leaf Photosynthetic Capacity. *Glob. Chang. Biol.* **2017**, *23*, 3513–3524. [[CrossRef](#)] [[PubMed](#)]
93. Liu, C.; Liu, Y.; Lu, Y.; Liao, Y.; Nie, J.; Yuan, X.; Chen, F. Use of a Leaf Chlorophyll Content Index to Improve the Prediction of Above-Ground Biomass and Productivity. *PeerJ* **2019**, *6*, e6240. [[CrossRef](#)] [[PubMed](#)]
94. Gitelson, A.A.; Viña, A.; Verma, S.B.; Rundquist, D.C.; Arkebauer, T.J.; Keydan, G.; Leavitt, B.; Ciganda, V.; Burba, G.G.; Suyker, A.E. Relationship between Gross Primary Production and Chlorophyll Content in Crops: Implications for the Synoptic Monitoring of Vegetation Productivity. *J. Geophys. Res.* **2006**, *111*, D08S11. [[CrossRef](#)]
95. Boonlertnirun, S.; Meechoui, S.; Sarobol, E. Physiological and Morphological Responses of Field Corn Seedlings to Chitosan under Hypoxic Conditions. *Scienceasia* **2010**, *36*, 89–93. [[CrossRef](#)]
96. dos Reis, C.O.; Magalhães, P.C.; Avila, R.G.; Almeida, L.G.; Rebelo, V.M.; Carvalho, D.T.; Cabral, D.F.; Karam, D.; Correa de Souza, T. Action of N-Succinyl and N,O-Dicarboxymethyl Chitosan Derivatives on Chlorophyll Photosynthesis and Fluorescence in Drought-Sensitive Maize. *J. Plant Growth Regul.* **2019**, *38*, 619–630. [[CrossRef](#)]
97. Oliveira, H.C.; Gomes, B.C.; Pelegrino, M.T.; Seabra, A.B. Nitric Oxide-Releasing Chitosan Nanoparticles Alleviate the Effects of Salt Stress in Maize Plants. *Nitric Oxide* **2016**, *61*, 10–19. [[CrossRef](#)] [[PubMed](#)]

98. Priyaadharshini, M.; Sritharan, N.; Senthil, A.; Marimuthu, S. Physiological Studies on Effect of Chitosan Nanoemulsion in Pearl Millet under Drought Condition. *J. Pharmacogn. Phytochem.* **2019**, *8*, 3304–3307.
99. Veroneze-Júnior, V.; Martins, M.; Mc Leod, L.; Souza, K.R.D.; Santos-Filho, P.R.; Magalhães, P.C.; Carvalho, D.T.; Santos, M.H.; Souza, T.C. Leaf Application of Chitosan and Physiological Evaluation of Maize Hybrids Contrasting for Drought Tolerance under Water Restriction. *Braz. J. Biol. Sci.* **2020**, *80*, 631–640. [[CrossRef](#)]
100. Zhang, X.; Li, K.; Xing, R.; Liu, S.; Li, P. Metabolite Profiling of Wheat Seedlings Induced by Chitosan: Revelation of the Enhanced Carbon and Nitrogen Metabolism. *Front. Plant Sci.* **2017**, *8*. [[CrossRef](#)]
101. Almeida, L.G.; Magalhães, P.C.; Karam, D.; Silva, E.M.D.; Alvarenga, A.A. Chitosan Application in the Induction of Water Deficit Tolerance in Maize Plants. *Acta Sci. Agron.* **2020**, *42*. [[CrossRef](#)]
102. Hatfield, J.L.; Dold, C. Water-Use Efficiency: Advances and Challenges in a Changing Climate. *Front. Plant Sci.* **2019**, *10*, 103. [[CrossRef](#)]
103. Yu, L.; Gao, X.; Zhao, X. Global Synthesis of the Impact of Droughts on Crops' Water-Use Efficiency (WUE): Towards Both High WUE and Productivity. *Agric. Syst.* **2020**, *177*, 102723. [[CrossRef](#)]
104. Niu, S.; Xing, X.; Zhang, Z.; Xia, J.; Zhou, X.; Song, B.; Li, L.; Wan, S. Water-Use Efficiency in Response to Climate Change: From Leaf to Ecosystem in a Temperate Steppe. *Glob. Chang. Biol.* **2011**, *17*, 1073–1082. [[CrossRef](#)]
105. Umair, M.; Kim, D.; Choi, M. Impact of Climate, Rising Atmospheric Carbon Dioxide, and Other Environmental Factors on Water-Use Efficiency at Multiple Land Cover Types. *Sci. Rep.* **2020**, *10*, 11644. [[CrossRef](#)]
106. Xu, L.K.; Hsiao, T.C. Predicted Versus Measured Photosynthetic Water-Use Efficiency of Crop Stands under Dynamically Changing Field Environments. *J. Exp. Bot.* **2004**, *55*, 2395–2411. [[CrossRef](#)]
107. Wanjiku, J.G.; Kamuhia, O.; Rono, O.; Kavere, M. Effectiveness of Relative Water Content as a Simple Farmer's Tool to Determine Plant Water Deficit. *Afr. J. Hort. Sci.* **2019**, *16*, 21–28.
108. Ghazimohseni, V.; Sabbagh, S. Effect of Chitosan on Gene Expression and Activity of Enzymes Involved in Resistant Induction to Fusarium of Wheat. *Iran J. Plant Prot. Sci.* **2015**, *46*, 363–371. [[CrossRef](#)]
109. Orzali, L.; Forni, C.; Riccioni, L. Effect of Chitosan Seed Treatment as Elicitor of Resistance to *Fusarium graminearum* in Wheat. *Seed Sci. Technol.* **2014**, *42*, 132–149. [[CrossRef](#)]
110. Zchetti, V.; Cendoya, E.; Nichea, M.J.; Chulze, S.N.; Ramirez, M.L. Preliminary Study on the Use of Chitosan as an Eco-Friendly Alternative to Control *Fusarium* Growth and Mycotoxin Production on Maize and Wheat. *Pathogens* **2019**, *8*, 29. [[CrossRef](#)]
111. Khan, M.R.; Fischer, S.; Egan, D.; Doohan, F.M. Biological Control of *Fusarium* Seedling Blight Disease of Wheat and Barley. *Phytopathology* **2006**, *96*, 386–394. [[CrossRef](#)] [[PubMed](#)]
112. Lukseviciute, V.; Luksiene, Z. Inactivation of Molds on the Surface of Wheat Sprouts by Chlorophyllin-Chitosan Coating in the Presence of Visible LED-Based Light. *J. Photochem. Photobiol. B Biol.* **2020**, *202*, 111721. [[CrossRef](#)] [[PubMed](#)]
113. Gunupuru, L.R.; Patel, J.S.; Sumarah, M.W.; Renaud, J.B.; Martin, E.G.; Prithiviraj, B. A Plant Biostimulant Made from the Marine Brown Algae *Ascophyllum nodosum* and Chitosan Reduce *Fusarium* Head Blight and Mycotoxin Contamination in Wheat. *PLoS ONE* **2019**, *14*, e0220562. [[CrossRef](#)] [[PubMed](#)]
114. Khan, M.R.; Doohan, F.M. Comparison of the Efficacy of Chitosan with that of a Fluorescent Pseudomonad for the Control of *Fusarium* Head Blight Disease of Cereals and Associated Mycotoxin Contamination of Grain. *Biol. Control* **2009**, *48*, 48–54. [[CrossRef](#)]
115. Kheiri, A.; Jorf, S.A.; Malhipour, A.; Saremi, H.; Nikkhah, M. Application of Chitosan and Chitosan Nanoparticles for the Control of *Fusarium* Head Blight of Wheat (*Fusarium graminearum*) In Vitro and Greenhouse. *Int. J. Biol. Macromol.* **2016**, *93*, 1261–1272. [[CrossRef](#)] [[PubMed](#)]
116. Kheiri, A.; Moosawi Jorf, S.A.; Malhipour, A.; Saremi, H.; Nikkhah, M. Synthesis and Characterization of Chitosan Nanoparticles and Their Effect on *Fusarium* Head Blight and Oxidative Activity in Wheat. *Int. J. Biol. Macromol.* **2017**, *102*, 526–538. [[CrossRef](#)] [[PubMed](#)]
117. El-Gamal, N.G.; El-Mougy, N.S.; Abdel-Kader, M.M.; Ali Khalil, M.S. Influence of Inorganic Salts and Chitosan as Foliar Spray on Wheat Septoria Leaf Blotch Disease Severity under Field Conditions. *Arch. Phytopathol. Plant Protect.* **2020**, 1–13. [[CrossRef](#)]
118. Shagdarova, B.T.; Ilyina, A.V.; Lopatin, S.A.; Kartashov, M.I.; Arslanova, L.R.; Dzhavakhiya, V.G.; Varlamov, V.P. Study of the Protective Activity of Chitosan Hydrolyzate against Septoria Leaf Blotch of Wheat and Brown Spot of Tobacco. *Appl. Biochem. Microbiol.* **2018**, *54*, 71–75. [[CrossRef](#)]
119. Popova, E.V.; Domnina, N.S.; Kovalenko, N.M.; Sokornova, S.V.; Tyuterev, S.L. Effect of Chitosan and Vanillin-Modified Chitosan on Wheat Resistance to Spot Blotch. *Appl. Biochem. Microbiol.* **2016**, *52*, 537–540. [[CrossRef](#)]
120. Kolesnikov, L.E.; Novikova, I.I.; Surin, V.G.; Popova, E.V.; Priyatkin, N.S.; Kolesnikova, Y.R. Estimation of the Efficiency of the Combined Application of Chitosan and Microbial Antagonists for the Protection of Spring Soft Wheat from Diseases by Spectrometric Analysis. *Appl. Biochem. Microbiol.* **2018**, *54*, 540–546. [[CrossRef](#)]
121. Feodorova-Fedotova, L.; Bankina, B.; Strazdina, V. Possibilities for the Biological Control of Yellow Rust (*Puccinia Striiformis* F. Sp. Tritici) in Winter Wheat in Latvia in 2017–2018. *Agron. Res.* **2019**, *17*, 716–724. [[CrossRef](#)]
122. Popova, E.V.; Domnina, N.S.; Kovalenko, N.M.; Sokornova, S.V.; Tyuterev, S.L. Influence of Chitosan Hybrid Derivatives on Induced Wheat Resistance to Pathogens with Different Nutrition Strategies. *Appl. Biochem. Microbiol.* **2018**, *54*, 535–539. [[CrossRef](#)]
123. El-Mougy, N.S.; Abouelnaser, H.M.; Abdel-Kader, M.M. Seed Dressing and Foliar Spray with Different Fungicide Alternatives for Controlling Maize Diseases under Natural Field Conditions. *Plant Arch.* **2020**, *20*, 2755–2759.

124. Ferrochio, L.V.; Cendoya, E.; Zanchetti, V.G.L.; Farnochi, M.C.; Massad, W.; Ramirez, M.L. Combined Effect of Chitosan and Water Activity on Growth and Fumonisin Production by *Fusarium verticillioides* and *Fusarium proliferatum* on Maize-Based Media. *Int. J. Food Microbiol.* **2014**, *185*, 51–56. [[CrossRef](#)] [[PubMed](#)]
125. Butt, U.R.; Naz, R.; Nosheen, A.; Yasmin, H.; Keyani, R.; Hussain, I.; Hassan, M.N. Changes in Pathogenesis-Related Gene Expression in Response to Bioformulations in the Apoplast of Maize Leaves against *Fusarium oxysporum*. *J. Plant Interact.* **2019**, *14*, 61–72. [[CrossRef](#)]
126. Ma, B.; Wang, J.; Liu, C.; Hu, J.; Tan, K.; Zhao, F.; Yuan, M.; Zhang, J.; Gai, Z. Preventive Effects of Fluoro-Substituted Benzothiadiazole Derivatives and Chitosan Oligosaccharide against the Rice Seedling Blight Induced by *Fusarium oxysporum*. *Plants* **2019**, *8*, 538. [[CrossRef](#)]
127. Agrawal, G.K.; Rakwal, R.; Tamogami, S.; Yonekura, M.; Kubo, A.; Saji, H. Chitosan Activates Defense/Stress Response (S) in the Leaves of *Oryza sativa* Seedlings. *Plant Physiol. Biochem.* **2002**, *40*, 1061–1069. [[CrossRef](#)]
128. Sathiyabama, M.; Muthukumar, S. Chitosan Guar Nanoparticle Preparation and Its In Vitro Antimicrobial Activity Towards Phytopathogens of Rice. *Int. J. Biol. Macromol.* **2020**, *153*, 297–304. [[CrossRef](#)]
129. Ahmed, T.; Noman, M.; Luo, J.; Muhammad, S.; Shahid, M.; Ali, M.A.; Zhang, M.; Li, B. Bioengineered Chitosan-Magnesium Nanocomposite: A Novel Agricultural Antimicrobial Agent against *Acidovorax oryzae* and *Rhizoctonia solani* for Sustainable Rice Production. *Int. J. Biol. Macromol.* **2021**, *168*, 834–845. [[CrossRef](#)] [[PubMed](#)]
130. Divya, K.; Vijayan, S.; Thampi, M.; Varghese, S.; Jisha, M.S. Induction of Defence Response in *Oryza Sativa* L. against *Rhizoctonia Solani* (Kuhn) by Chitosan Nanoparticles. *Microb. Pathog.* **2020**, *149*, 104525. [[CrossRef](#)]
131. Liu, H.; Tian, W.; Li, B.; Wu, G.; Ibrahim, M.; Tao, Z.; Wang, Y.; Xie, G.; Li, H.; Sun, G. Antifungal Effect and Mechanism of Chitosan against the Rice Sheath Blight Pathogen, *Rhizoctonia solani*. *Biotechnol. Lett.* **2012**, *34*, 2291–2298. [[CrossRef](#)]
132. Wong, M.Y.; Surendran, A.; Saad, N.M.; Burhanudin, F. Chitosan as a Biopesticide Against Rice (*Oryza Sativa*) Fungal Pathogens, *Pyricularia Oryzae* and *Rhizoctonia Solani*. *Pertanika. J. Trop. Agric. Sci.* **2020**, *43*, 275–287.
133. Ibrahim, A.Y.; Kurniawati, F. The Efficacy of Chitosan to Control Nematode *Aphelenchoides besseyi* Christie through Seed Treatment. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *468*, 012025. [[CrossRef](#)]
134. Lin, W.; Hu, X.; Zhang, W.; Rogers, W.J.; Cai, W. Hydrogen Peroxide Mediates Defence Responses Induced by Chitosans of Different Molecular Weights in Rice. *J. Plant Physiol.* **2005**, *162*, 937–944. [[CrossRef](#)]
135. Pham, D.C.; Nguyen, T.H.; Ngoc, U.T.P.; Le, N.T.T.; Tran, T.V.; Nguyen, D.H. Preparation, Characterization and Antifungal Properties of Chitosan-Silver Nanoparticles Synergize Fungicide against *Pyricularia oryzae*. *J. Nanosci. Nanotechnol.* **2018**, *18*, 5299–5305. [[CrossRef](#)]
136. Badawy, M.E.I.; Rabea, E.I.; Rogge, T.M.; Stevens, C.V.; Smagghe, G.; Steurbaut, W.; Höfte, M. Synthesis and Fungicidal Activity of New N,O-Acyl Chitosan Derivatives. *Biomacromolecules* **2004**, *5*, 589–595. [[CrossRef](#)]
137. Pham, T.T.; Nguyen, T.H.; Thi, T.V.; Nguyen, T.-T.; Le, T.D.; Vo, D.M.H.; Nguyen, D.H.; Nguyen, C.K.; Nguyen, D.C.; Nguyen, T.T.; et al. Investigation of Chitosan Nanoparticles Loaded with Protocatechuic Acid (PCA) for the Resistance of *Pyricularia oryzae* Fungus against Rice Blast. *Polymers* **2019**, *11*, 177. [[CrossRef](#)]
138. Li, B.; Liu, B.; Shan, C.; Ibrahim, M.; Lou, Y.; Wang, Y.; Xie, G.; Li, H.; Sun, G. Antibacterial Activity of Two Chitosan Solutions and Their Effect on Rice Bacterial Leaf Blight and Leaf Streak. *Pest. Manag. Sci.* **2013**, *69*, 312–320. [[CrossRef](#)]
139. Abdallah, Y.; Liu, M.; Ogunyemi, S.O.; Ahmed, T.; Fouad, H.; Abdelazez, A.; Yan, C.; Yang, Y.; Chen, J.; Li, B. Bioinspired Green Synthesis of Chitosan and Zinc Oxide Nanoparticles with Strong Antibacterial Activity against Rice Pathogen *Xanthomonas oryzae* Pv. *Oryzae. Mol.* **2020**, *25*, 4795. [[CrossRef](#)]
140. Singh, R.R.; Chinnasri, B.; De Smet, L.; Haeck, A.; Demeestere, K.; Van Cutsem, P.; Van Aabel, G.; Gheysen, G.; Kyndt, T. Systemic Defense Activation by COS-OGA in Rice Against Root-Knot Nematodes Depends on Stimulation of the Phenylpropanoid Pathway. *Plant Physiol. Biochem.* **2019**, *142*, 202–210. [[CrossRef](#)]
141. Ranjini, P.; Prasad, M.; Kumar, J.S.; Sekhar, S.; Kesagodu, D.; Shetty, H.S.; Kini, K.R. Chitosan and B-Amino Butyric Acid Up-Regulates Transcripts of Resistance Gene Analog RGPM213 in Pearl Millet to Infection by Downy Mildew Pathogen. *J. Appl. Biol. Biotechnol.* **2016**, *4*, 1–6. [[CrossRef](#)]
142. Manjunatha, G.; Roopa, K.S.; Prashanth, G.N.; Shetty, H.S. Chitosan Enhances Disease Resistance in Pearl Millet against Downy Mildew Caused by *Sclerospora graminicola* and Defence-Related Enzyme Activation. *Pest Manag. Sci.* **2008**, *64*, 1250–1257. [[CrossRef](#)] [[PubMed](#)]
143. Manjunatha, G.; Niranjana-Raj, S.; Prashanth, G.N.; Deepak, S.; Amruthesh, K.N.; Shetty, H.S. Nitric Oxide Is Involved in Chitosan-Induced Systemic Resistance in Pearl Millet against Downy Mildew Disease. *Pest. Manag. Sci.* **2009**, *65*, 737–743. [[CrossRef](#)] [[PubMed](#)]
144. Passot, S.; Gnacko, F.; Moukouanga, D.; Lucas, M.; Guyomarc'h, S.; Ortega, B.M.; Atkinson, J.A.; Belko, M.N.; Bennett, M.J.; Gantet, P.; et al. Characterization of Pearl Millet Root Architecture and Anatomy Reveals Three Types of Lateral Roots. *Front. Plant Sci.* **2016**, *7*, 829. [[CrossRef](#)] [[PubMed](#)]
145. Saxena, R.; Vanga, S.; Wang, J.; Orsat, V.; Raghavan, V.; Saxena, R.; Vanga, S.K.; Wang, J.; Orsat, V.; Raghavan, V. Millets for Food Security in the Context of Climate Change: A Review. *Sustainability* **2018**, *10*, 2228. [[CrossRef](#)]
146. Rodríguez, A.T.; Ramírez, M.A.; Cárdenas, R.M.; Hernández, A.N.; Velázquez, M.G.; Bautista, S. Induction of Defense Response of *Oryza sativa* L. against *Pyricularia Grisea* (Cooke) Sacc. by Treating Seeds with Chitosan and Hydrolyzed Chitosan. *Pestic. Biochem. Physiol.* **2007**, *89*, 206–215. [[CrossRef](#)]



147. Manikandan, A.; Sathiyabama, M. Preparation of Chitosan Nanoparticles and Its Effect on Detached Rice Leaves Infected with *Pyricularia Grisea*. *Int. J. Biol. Macromol.* **2016**, *84*, 58–61. [[CrossRef](#)] [[PubMed](#)]
148. Faoro, F.; Maffi, D.; Cantu, D.; Iriti, M. Chemical-Induced Resistance Against Powdery Mildew in Barley: The Effects of Chitosan and Benzothiadiazole. *BioControl* **2008**, *53*, 387–401. [[CrossRef](#)]
149. Hofgaard, I.S.; Ergon, Å.; Wanner, L.A.; Tronsmo, A.M. The Effect of Chitosan and Bion on Resistance to Pink Snow Mould in Perennial Ryegrass and Winter Wheat. *J. Phytopathol.* **2005**, *153*, 108–119. [[CrossRef](#)]
150. Lizárraga-Paulín, E.G.; Torres-Pacheco, I.; Moreno Martínez, E.; Miranda-Castro, S.P. Chitosan Application in Maize (*Zea mays*) to Counteract the Effects of Abiotic Stress at Seedling Level. *Afr. J. Biotechnol.* **2011**, *10*, 6439–6446.
151. Choudhary, M.K.; Joshi, A.; Sharma, S.S.; Saharan, V. Effect of laboratory Synthesized Cu-Chitosan Nanocomposites on Control of PFSR Disease of Maize Caused by *Fusarium verticillioides*. *Int. J. Curr. Microbiol. Appl. Sci.* **2017**, *6*, 1656–1664. [[CrossRef](#)]
152. Maksimov, I.V.; Valeev, A.S.; Cherepanova, E.A.; Burkhanova, G.F. Effect of Chitooligosaccharides with Different Degrees of Acetylation on the Activity of Wheat Pathogen-Inducible Anionic Peroxidase. *Appl. Biochem. Microbiol.* **2014**, *50*, 82–87. [[CrossRef](#)]
153. Burkhanova, G.F.; Yarullina, L.G.; Maksimov, I.V. The Control of Wheat Defense Responses During Infection with *Bipolaris sorokiniana* by Chitooligosaccharides. *Russ. J. Plant Physiol.* **2007**, *54*, 104. [[CrossRef](#)]
154. Yarullina, L.G.; Kasimova, R.I.; Akhatova, A.R. Activity of Protective Proteins in Wheat Plants Treated with Chitooligosaccharides with Different Degrees of Acetylation and Infection with *Bipolaris sorokiniana*. *Appl. Biochem. Microbiol.* **2014**, *50*, 524–530. [[CrossRef](#)]
155. Maksimov, I.V.; Cherepanova, E.A.; Surina, O.B. Effect of Chitooligosaccharides on Peroxidase Isoenzyme Composition in Wheat Calli Cocultured with Bunt Causal Agent. *Russ. J. Plant Physiol.* **2010**, *57*, 124–130. [[CrossRef](#)]
156. Maluin, F.N.; Hussein, M.Z. Chitosan-Based Agronanochemicals as a Sustainable Alternative in Crop Protection. *Molecules* **2020**, *25*, 1611. [[CrossRef](#)]
157. Jia, Y.; Jia, M.H.; Wang, X.; Zhao, H. A Toolbox for Managing Blast and Sheath Blight Diseases of Rice in the United States of America. In *Protecting Rice Grains in the Post-Genomic Era*; Jia, Y., Ed.; IntechOpen: London, UK, 2019; pp. 35–52. [[CrossRef](#)]
158. Figueroa, M.; Hammond-Kosack, K.E.; Solomon, P.S. A Review of Wheat Diseases—A Field Perspective. *Mol. Plant Pathol.* **2018**, *19*, 1523–1536. [[CrossRef](#)] [[PubMed](#)]
159. Savary, S.; Ficke, A.; Aubertot, J.N.; Hollier, C. Crop Losses Due to Diseases and Their Implications for Global Food Production Losses and Food Security. *Food Sec.* **2012**, *4*, 519–537. [[CrossRef](#)]
160. Ibrahim, H.; Arafa, S. Effect of Chitosan on Growth, Yield and Certain Salinity Stress-Related Metabolites in Two Barley Cultivars Contrasting in Salt Tolerance. *J. Plant Prod.* **2020**, *11*, 899–906. [[CrossRef](#)]
161. Tham, L.X.; Nagasawa, N.; Matsushashi, S.; Ishioka, N.S.; Ito, T.; Kume, T. Effect of Radiation-Degraded Chitosan on Plants Stressed with Vanadium. *Radiat. Phys. Chem.* **2001**, *61*, 171–175. [[CrossRef](#)]
162. Loreti, E.; Bellincampi, D.; Millet, C.; Alpi, A.; Perata, P. Elicitors of Defence Responses Repress a Gibberellin Signalling Pathway in Barley Embryos. *J. Plant Physiol.* **2002**, *159*, 1383–1386. [[CrossRef](#)]
163. Dragičević, V.; Nikolić, B.; Radosavljević, M.M.; Đurić, N.A.; Dodig, D.; Stoiljković, M.M.; Kravić, N. Barley Grain Enrichment with Essential Elements by Agronomic Biofortification. *Acta Period. Technol.* **2016**, *47*, 1–9. [[CrossRef](#)]
164. Qu, D.Y.; Zhang, L.G.; Gu, W.R.; Cao, X.B.; Fan, H.C.; Meng, Y.; Chen, X.C.; Wei, S. Effects of Chitosan on Root Growth and Leaf Photosynthesis of Maize Seedlings under Cadmium Stress. *Chin. J. Plant Ecol.* **2017**, *36*, 1300. [[CrossRef](#)]
165. Otie, V.; Ping, A.; John, N.M.; Eneji, A.E. Interactive Effects of Plant Growth Regulators and Nitrogen on Corn Growth and Nitrogen Use Efficiency. *J. Plant Nutr.* **2016**, *39*, 1597–1609. [[CrossRef](#)]
166. Younas, H.S.; Abid, M.; Shaaban, M.; Ashraf, M. Influence of Silicon and Chitosan on Growth and Physiological Attributes of Maize in a Saline Field. *Physiol. Mol. Biol. Plants* **2021**, *27*, 387–397. [[CrossRef](#)] [[PubMed](#)]
167. Peykani, L.S.; Sepehr, M.F. Effect of Chitosan on Antioxidant Enzyme Activity, Proline and Malondialdehyde Content in *Triticum aestivum* L. and *Zea Mays* L. under Salt Stress Condition. *Iran. J. Plant Physiol.* **2018**, *9*, 2661–2670.
168. Sujeeth, N.; Deepak, S.; Shailasree, S.; Kini, R.K.; Shetty, S.H.; Hille, J. Hydroxyproline-Rich Glycoproteins Accumulate in Pearl Millet after Seed Treatment with Elicitors of Defense Responses against *Sclerospora graminicola*. *Physiol. Mol. Plant Pathol.* **2010**, *74*, 230–237. [[CrossRef](#)]
169. Paulert, R.; Ebbinghaus, D.; Urlass, C.; Moerschbacher, B.M. Priming of the Oxidative Burst in Rice and Wheat Cell Cultures By Ulvan, a Polysaccharide from Green Macroalgae, and Enhanced Resistance against Powdery Mildew in Wheat and Barley Plants. *Plant Pathol.* **2010**, *59*, 634–642. [[CrossRef](#)]
170. Ohnishi, M. Effects of Application of Chitosan Solutions on the Growth of Rice (*Oryza Sativa*) Seedlings. *Jpn. J. Crop Sci.* **2008**, *77*, 259–265. [[CrossRef](#)]
171. Chibu, H.; Shibayama, H.; Mitsutomi, M.; Arima, S. Effects of Chitosan Application on Chitinase Activity in Shoots of Rice and Soybean. *Jpn. J. Crop Sci.* **2002**, *71*, 212–219. [[CrossRef](#)]
172. Chibu, H.; Shibayama, H.; Arima, S. Effects of Chitosan Application on the Shoot Growth of Rice and Soybean. *Jpn. J. Crop Sci.* **2002**, *71*, 206–211. [[CrossRef](#)]
173. Ko, J.A.; Kim, K.O.; Park, H.J. Effects of Molecular Weight and Chitosan Concentration on GABA Contents of Germinated Brown Rice. *Korean J. Food Sci. Technol.* **2010**, *42*, 688–692.

174. Rakwal, R.; Tamogami, S.; Agrawal, G.K.; Iwahashi, H. Octadecanoid Signaling Component “Burst” in Rice (*Oryza sativa* L.) Seedling Leaves Upon Wounding by Cut and Treatment with Fungal Elicitor Chitosan. *Biochem. Biophys. Res. Commun.* **2002**, *295*, 1041–1045. [[CrossRef](#)]
175. Kananont, N.; Kositsup, B.; Pichyangkura, R.; Chadchawan, S. Effects of chitosan and associated solvents on the growth of ‘Pathumthani1’ rice (*Oryza sativa* L. ‘Pathumthani1’) seedlings. *J. Chitin Chitosan Sci.* **2014**, *2*, 99–105. [[CrossRef](#)]
176. Yang, C.; Li, B.; Ge, M.; Zhou, K.; Wang, Y.; Luo, J.; Ibrahim, M.; Xie, G.; Sun, G. Inhibitory Effect and Mode of Action of Chitosan Solution against Rice Bacterial Brown Stripe Pathogen *Acidovorax Avenae* Subsp. *Avenae* RS-1. *Carbohydr. Res.* **2014**, *391*, 48–54. [[CrossRef](#)]
177. Boonlertnirun, S.; Sarobol, E.D.; Meechoui, S.; Sooksathan, I. Drought Recovery and Grain Yield Potential of Rice after Chitosan Application. *Agric. Nat. Resour.* **2007**, *41*, 1–6.
178. Seang-Ngam, S.; Limruengroj, K.; Pichyangkura, R.; Chadchawan, S.; Buaboocha, T. Chitosan Potentially Induces Drought Resistance in Rice *Oryza Sativa* L. Via Calmodulin. *J. Chitin Chitosan Sci.* **2014**, *2*, 117–122. [[CrossRef](#)]
179. Holguin-Peña, R.J.; Vargas-López, J.M.; López-Ahumada, G.A.; Rodríguez-Félix, F.; Borbón-Morales, C.G.; Rueda-Puente, E.O. Effect of Chitosan and *Bacillus amilolyquefasciens* on Sorghum Yield in the Indigenous Area “Mayos” in Sonora. *Terra Latinoamericana* **2020**, *38*, 705–714. [[CrossRef](#)]
180. Rahneshan, M.; Taliei, F.; Ahangar, L.; Sabouri, H.; Kia, S. Effect of Chitosan on the Expression Pattern of Some Pathogenicity Related Genes in Wheat Infected with Powdery Mildew. *J. Crop Breed.* **2020**, *11*, 124–132. [[CrossRef](#)]
181. Masjedi, M.H.; Roozbahani, A.; Baghi, M. Assessment Effect of Chitosan Foliar Application on Total Chlorophyll and Seed Yield of Wheat (*Triticum aestivum* L.) under Water Stress Conditions. *J. Crop Nutr. Sci.* **2017**, *3*, 14–26.
182. Kuwabara, C.; Takezawa, D.; Shimada, T.; Hamada, T.; Fujikawa, S.; Arakawa, K. Abscisic Acid- and Cold-Induced Thaumatin-Like Protein in Winter Wheat Has an Antifungal Activity Against Snow Mould, *Microdochium nivale*. *Physiol. Plant.* **2002**, *115*, 101–110. [[CrossRef](#)]
183. Haggag Wafaa, M.; Tawfik, M.M.; Abouzienna, H.F.; Abd El Wahed, M.S.A.; Ali, R.R. Enhancing Wheat Production under Arid Climate Stresses Using Bio-Elicitors. *Gesunde Pflanz.* **2017**, *69*, 149–158. [[CrossRef](#)]
184. Hameed, A.; Sheikh, M.A.; Hameed, A.; Farooq, T.; Basra, S.M.A.; Jamil, A. Chitosan Priming Enhances the Seed Germination, Antioxidants, Hydrolytic Enzymes, Soluble Proteins and Sugars in Wheat Seeds. *Agrochimica* **2013**, *57*, 97–110.
185. Díaz-Martínez, J.M.; Aispuro-Hernández, E.; Vargas-Arispuro, I.; Falcón-Rodríguez, A.B.; Martínez-Téllez, M.Á. Chitosan Derivatives Induce Local and Distal Expression of Defence-Related Genes in Wheat (*Triticum aestivum* L.) Seedlings. *Agrociencia* **2018**, *52*, 497–509.
186. Singh, A.S.; Sharma, R.; Dubey, S.; Kumar, V. Efficacy of Pusa Hydrogel and Chitosan on Wheat (*Triticum aestivum* L.) Physiological and Biochemical Parameters Under Water Deficit Condition. *J. Pharmacogn. Phytochem.* **2018**, *7*, 1589–1591.
187. Ramakrishna, R.; Sarkar, D.; Manduri, A.; Iyer, S.G.; Shetty, K. Improving Phenolic Bioactive-Linked Anti-Hyperglycemic Functions of Dark Germinated Barley Sprouts (*Hordeum vulgare* L.) Using Seed Elicitation Strategy. *J. Food Sci. Technol.* **2017**, *54*, 3666–3678. [[CrossRef](#)] [[PubMed](#)]
188. Ramakrishna, R.; Sarkar, D.; Shetty, K. Metabolic Stimulation of Phenolic Biosynthesis and Antioxidant Enzyme Response in Dark Germinated Barley (*Hordeum vulgare* L.) Sprouts Using Bioprocessed Elicitors. *Food Sci. Biotechnol.* **2019**, *28*, 1093–1106. [[CrossRef](#)] [[PubMed](#)]
189. Zhou, J.; Chen, Q.; Zhang, Y.; Fan, L.; Qin, Z.; Chen, Q.; Qiu, Y.; Jiang, L.; Zhao, L. Chitoooligosaccharides Enhance Cold Tolerance by Repairing Photodamaged PS II in Rice. *J. Agric. Sci.* **2018**, *156*, 888. [[CrossRef](#)]
190. Yang, A.; Yu, L.; Chen, Z.; Zhang, S.; Shi, J.; Zhao, X.; Yang, Y.; Hu, D.; Song, B. Label-Free Quantitative Proteomic Analysis of Chitosan Oligosaccharide-Treated Rice Infected with Southern Rice Black-Streaked Dwarf Virus. *Viruses* **2017**, *9*, 115. [[CrossRef](#)]
191. Kim, S.W.; Park, J.K.; Lee, C.H.; Hahn, B.S.; Koo, J.C. Comparison of the Antimicrobial Properties of Chitosan Oligosaccharides (COS) and EDTA Against *Fusarium fujikuroi* Causing Rice Bakanae Disease. *Curr. Microbiol.* **2016**, *72*, 496–502. [[CrossRef](#)]
192. Zou, P.; Li, K.; Liu, S.; Xing, R.; Qin, Y.; Yu, H.; Zhou, M.; Li, P. Effect of Chitoooligosaccharides with Different Degrees of Acetylation on Wheat Seedlings Under Salt Stress. *Carbohydr. Polym.* **2015**, *126*, 62–69. [[CrossRef](#)]
193. Khairullin, R.M.; Akhmetova, I.E.; Yusupova, Z.R. Inhibition of IAA-Induced Growth of Wheat Coleoptile Fragments by Chitin-Chitosan Oligomers. *Biol. Bull.* **2002**, *29*, 135–138. [[CrossRef](#)]
194. Liu, D.; Jiao, S.; Cheng, G.; Li, X.; Pei, Z.; Pei, Y.; Yin, H.; Du, Y. Identification of Chitosan Oligosaccharides Binding Proteins from the Plasma Membrane of Wheat Leaf Cell. *Int. J. Biol. Macromol.* **2018**, *111*, 1083–1090. [[CrossRef](#)]
195. Deshpande, P.; Dapkekar, A.; Oak, M.D.; Paknikar, K.M.; Rajwade, J.M. Zinc Complexed Chitosan/TPP Nanoparticles: A Promising Micronutrient Nanocarrier Suited for Foliar Application. *Carbohydr. Polym.* **2017**, *165*, 394–401. [[CrossRef](#)] [[PubMed](#)]
196. Dapkekar, A.; Deshpande, P.; Oak, M.D.; Paknikar, K.M.; Rajwade, J. M Zinc Use Efficiency Is Enhanced in Wheat Through Nanofertilization. *Sci. Rep.* **2018**, *8*, 6832. [[CrossRef](#)] [[PubMed](#)]
197. Deshpande, P.; Dapkekar, A.; Oak, M.; Paknikar, K.; Rajwade, J. Nanocarrier-Mediated Foliar Zinc Fertilization Influences Expression of Metal Homeostasis Related Genes in Flag Leaves and Enhances Gluten Content in Durum Wheat. *PLoS ONE* **2018**, *13*, e0191035. [[CrossRef](#)] [[PubMed](#)]
198. Hameed, A.; Khalid, A.; Ahmed, T.; Farooq, T. Nano-Priming with Zn-Chitosan Nanoparticles Regulates Biochemical Attributes and Boost Antioxidant Defence in Wheat Seeds. *Agrochimica* **2020**, *64*, 207–221. [[CrossRef](#)]

199. Nagasawa, N.; Mitomo, H.; Ha, P.T.; Watanabe, S.; Ito, T.; Takeshita, H.; Yoshii, F.; Kume, T. Suppression of Zn Stress on Barley by Irradiated Chitosan. In Proceedings of the Takasaki Symposium on Radiation Processing of Natural Polymers, Gunma, Japan, 23–24 November 2000; pp. 27–34. Available online: <https://www.osti.gov/etdeweb/servlets/purl/20226898#page=42> (accessed on 3 June 2021).
200. Luan, L.Q.; Nagasawa, N.; Tamada, M.; Nakanishi, T.M. Enhancement of Plant Growth Activity of Irradiated Chitosan by Molecular Weight Fractionation. *Radioisotopes* **2006**, *55*, 21. [[CrossRef](#)]
201. Ma, L.; Li, Y.; Yu, C.; Wang, Y.; Li, X.; Li, N.; Chen, Q.; Bu, N. Alleviation of Exogenous Oligochitosan on Wheat Seedlings Growth under Salt Stress. *Protoplasma* **2012**, *249*, 393–399. [[CrossRef](#)]
202. Cruz, M.F.A.D.; Diniz, A.P.C.; Rodrigues, F.A.; Barros, E.G.D. Foliar Application of Products on the Reduction of Blast Severity on Wheat. *Trop. Plant Pathol.* **2011**, *36*, 424–428. [[CrossRef](#)]
203. Mirbolook, A.; Rasouli-Sadaghiani, M.; Sepehr, E.; Lakzian, A.; Hakimi, M. Fortification of Bread Wheat with Iron Through Soil and Foliar Application of Iron-Organic-Complexes. *J. Plant Nutr.* **2021**, *44*, 1386–1403. [[CrossRef](#)]
204. Žabka, M. Calcium Disodium Ethylenediaminetetraacetate as a Safe Compound for Crop Protection with the Potential to Extend the Basic Substances Group. *Plant Protect. Sci.* **2020**, *56*, 123–131. [[CrossRef](#)]
205. Mohammadi, N.; Shariatmadari, H. Effect of Magnesium Silicate Nanocomposites Coating of Phosphate Fertilizer on the Availability and Plant Uptake of Phosphorus. *Commun. Soil Sci. Plant Anal.* **2020**, *51*, 2581–2591. [[CrossRef](#)]
206. Kalagatur, N.K.; Nirmal Ghosh, O.S.; Sundararaj, N.; Mudili, V. Antifungal Activity of Chitosan Nanoparticles Encapsulated with *Cymbopogon martinii* Essential Oil on Plant Pathogenic Fungi *Fusarium graminearum*. *Front. Pharmacol.* **2018**, *9*, 610. [[CrossRef](#)]
207. Zeng, D.; Shi, Y. Preparation and Application of a Novel Environmentally Friendly Organic Seed Coating for Rice. *J. Sci. Food Agric.* **2009**, *89*, 2181–2185. [[CrossRef](#)]
208. Kudasova, D.; Mutaliyeva, B.; Vlahoviček-Kahlina, K.; Jurić, S.; Marijan, M.; Khalus, S.V.; Prosyanič, A.V.; Šegota, S.; Španić, N.; Vinčeković, M. Encapsulation of Synthesized Plant Growth Regulator Based on Copper(II) Complex in Chitosan/Alginate Microcapsules. *Int. J. Mol. Sci.* **2021**, *22*, 2663. [[CrossRef](#)]
209. Yang, L.; Song, Z.; Li, C.; Huang, S.; Cheng, D.; Zhang, Z. Fabricated Chlorantraniliprole Loaded Chitosan/Alginate Hydrogel Rings Effectively Control *Spodoptera frugiperda* in Maize Ears. *Crop Prot.* **2021**, *143*, 105539. [[CrossRef](#)]
210. Grillo, R.; Pereira, A.E.S.; Nishisaka, C.S.; de Lima, R.; Oehlke, K.; Greiner, R.; Fraceto, L.F. Chitosan/Tripolyphosphate Nanoparticles Loaded with Paraquat Herbicide: An Environmentally Safer Alternative for Weed Control. *J. Hazard. Mater.* **2014**, *278*, 163–171. [[CrossRef](#)]
211. Martins, N.C.T.; Avellan, A.; Rodrigues, S.; Salvador, D.; Rodrigues, S.M.; Trindade, T. Composites of Biopolymers and Zn Nps for Controlled Release of Zinc in Agricultural Soils and Timed Delivery for Maize. *ACS Appl. Nano Mater.* **2020**, *3*, 2134–2148. [[CrossRef](#)]
212. Rashidipour, M.; Maleki, A.; Kordi, S.; Birjandi, M.; Pajouhi, N.; Mohammadi, E.; Heydari, R.; Rezaee, R.; Rasoulian, B.; Davari, B. Pectin/Chitosan/Tripolyphosphate Nanoparticles: Efficient Carriers for Reducing Soil Sorption, Cytotoxicity, and Mutagenicity of Paraquat and Enhancing Its Herbicide Activity. *J. Agric. Food Chem.* **2019**, *67*, 5736–5745. [[CrossRef](#)]
213. Zhao, L.; Guan, X.; Yu, B.; Ding, N.; Liu, X.; Ma, Q.; Yang, S.; Yilihamu, A.; Yang, S.T. Carboxylated Graphene Oxide-Chitosan Spheres Immobilize Cu<sup>2+</sup> in Soil and Reduce Its Bioaccumulation in Wheat Plants. *Environ. Int.* **2019**, *133*, 105208. [[CrossRef](#)] [[PubMed](#)]
214. Raj, S.N.; Deepak, S.A.; Basavaraju, P.; Shetty, H.S.; Reddy, M.S.; Kloepper, J.W. Comparative Performance of Formulations of Plant Growth Promoting Rhizobacteria in Growth Promotion and Suppression of Downy Mildew in Pearl Millet. *Crop Prot.* **2003**, *22*, 579–588. [[CrossRef](#)]
215. Vasudevan, P.; Reddy, M.S.; Kavitha, S.; Velusamy, P.; Paulraj, R.S.; Purushothaman, S.M.; Gnanamanickam, S.S. Role of Biological Preparations in Enhancement of Rice Seedling Growth and Grain Yield. *Curr. Sci.* **2002**, *83*, 1140–1143.
216. Dhlamini, B.; Paumo, H.K.; Katata-Seru, L.; Kutu, F.R. Sulphate-Supplemented NPK Nanofertilizer and Its Effect on Maize Growth. *Mater. Res. Express* **2020**, *7*, 095011. [[CrossRef](#)]
217. Abdel-Aziz, H.; Hasaneen, M.N.; Omar, A. Effect of Foliar Application of Nano Chitosan Npk Fertilizer on the Chemical Composition of Wheat Grains. *Egypt. J. Bot.* **2018**, *58*, 87–95. [[CrossRef](#)]
218. Rodríguez-Pedroso, A.T.; Reyes-Pérez, J.J.; Méndez-Martínez, Y.; Ramírez-Arrebató, M.A.; Falcón-Rodríguez, A.; Valle-Fernández, Y.; Hernández-Montiel, L.G. Effect of the Quitomax<sup>®</sup> on Yield of Rice Cultivo (*Oryza sativa*, L.) Var. J-104. *Rev. Fac. Agron. (LUZ)* **2019**, *36*, 98–110.