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Application of Microalgae and their Nanocomposites for Food Biopreservation

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ABSTRACT

The present review indicates the increasing significance of natural bioactive compounds and nanomaterials in food bio preservation, in which Spirulina platensis, chitosan, and selenium nanoparticles (SeNPs) are emphasized. These include powerful antimicrobial and antioxidant properties that such agents have which render them as viable substitutes to the traditional chemical preservatives. Their personal properties, biological functions, and actions as well as the novel developments of nanotechnology, which improve their stability, functionality, and topography in food systems are reviewed. Particular emphasis is directed to integrated applications in which natural compounds and nanomaterials have a synergetic effect on microbial control and food quality. Despite the promising prospects of these bio preservative strategies, there are aspects of safety, toxicity testing, migration, and regulatory policies. In general, the presented work underlines that combining natural bioactive compounds with nanotechnology may provide real sustainable methods of shelf life extension and food safety, and those additional studies are necessary to guarantee safe large-scale use.

Keywords: Spirulina, Chitosan, Selenium nanoparticles, Natural food preservatives, Nanotechnology

Introduction

Food spoilage is of great concern because it causes both economic losses and health hazards to the consumers (Onyibe *et al*., 2021). Figure 1 illustrates that the spoilage of food may be due to many factors such as microbial contamination, chemical reactions, enzymatic activity and physical changes (Mafe *et al*., 2024).

One of the most common types of food spoilage is associated with microbial contamination, which is mostly caused by bacteria, yeasts, and molds (Karanth et al., 2023).

Preservation of food is therefore required to ensure that its quality remains intact over the period (Nwosu et al., 2022). It entails a number of procedures or methods that aim at regulating the internal and external forces leading to food spoilage and its main aim is to increase its shelf life without altering the original nutritional, color, texture and flavor properties (Zhao et al., 2021). In order to overcome these mechanisms of spoilage, the methods of food preservation have been designed and improved throughout centuries (Khalid *et al*., 2024).

The purposes of such methods include facilitating the shelf life of foods, food safety, and the preservation of food sensory characteristics (Edo, 2022). Refrigeration, freezing, canning, drying, fermentation, and use of preservatives, are the major food preservation ways, and they are common (Sridhar *et al*., 2021). Each of these approaches possesses its advantages and disadvantages, and the choice of the approach will be based on the type of food, the span of shelf life that it is expected to have, and the goal of the food storage (Hassan *et al*., 2023).

Despite the common use of chemical preservatives to prevent the growth of microbes, the overuse or continued use has been credited to negative health consequences such as allergies, toxicity, and

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possible carcinogenicity. Nevertheless, owing to these adverse consequences of it, scientists have paid more attention to finding natural and safe substitutes that could preserve the quality of the food and increase the shelf life. Because of the increasing worry on the negative health impact triggered by chemical preservatives, natural preservatives have been introduced as safer preservatives in food preservation as shown in figure 2.

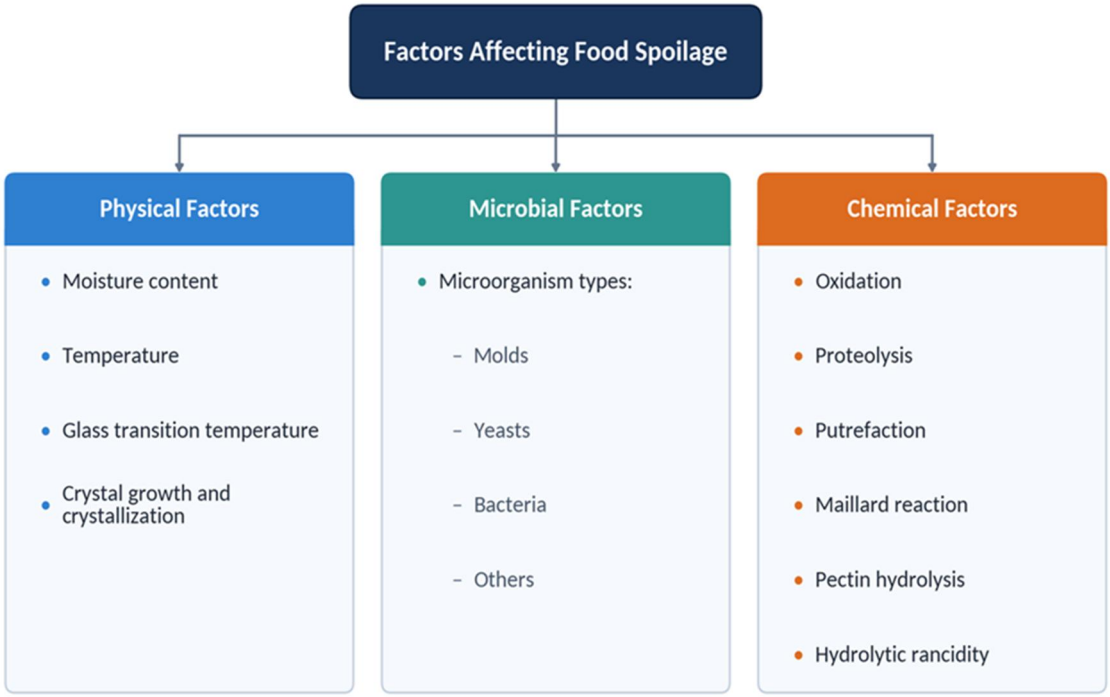


Fig. 1: Schematic diagram illustrating the primary physical, microbial, and chemical Factors that contribute to food spoilage (Amit *et al.,* 2017).

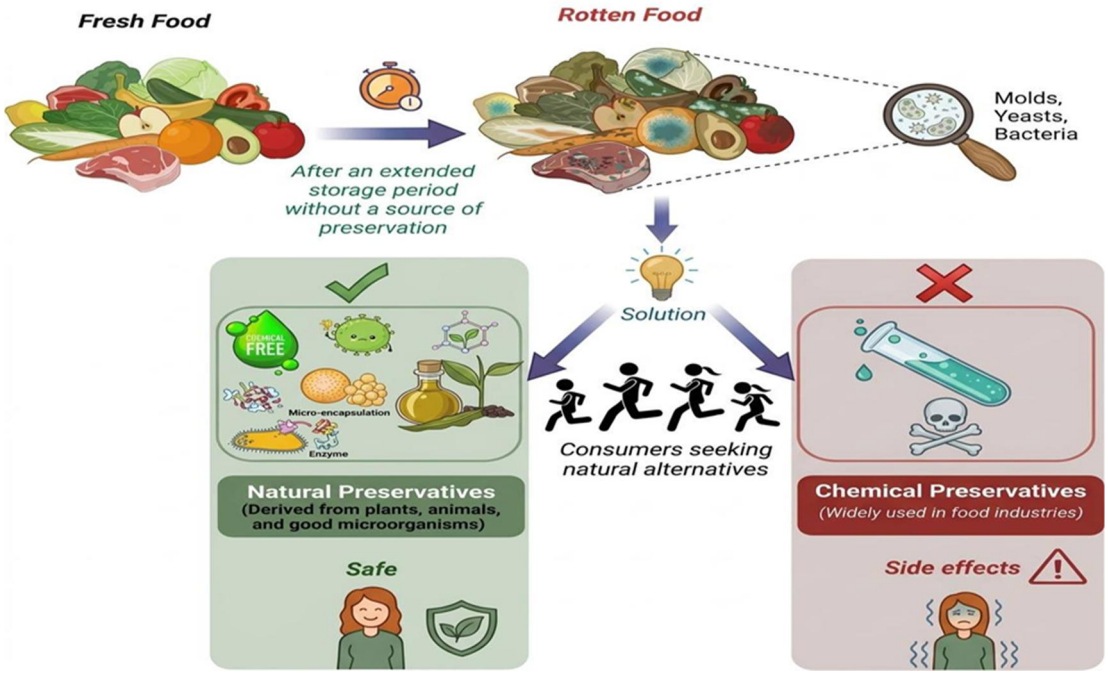


Fig. 2: Graphical illustrating showcasing the degradation of fresh food into rotten products over time, and the consumer trend driving the choice toward safe natural preservatives instead of synthetic chemical alternatives (El Alami El Hassani *et al.,* 2025).

Some of the most promising natural agents have included spirulina, chitosan and nano-selenium. All these compounds confer different biological characteristics that render them to be prospective substitutes of natural food preservation. Spirulina has a great human and animal nutritional value potential. It is composed of proteins, vitamin, minerals, essential fatty acids and bioactive substances in the form of phycocyanin pigment, polysaccharides and cartenoids in food, feed, and medicine.

Spirulina has great potential to serve as a natural preservative of food because it has a wide range of biological properties, such as antioxidants, anti-inflammatory, immunomodulatory, antiviral, antimicrobial, anticancer, antidiabetic, and lipid lowering effects (Spinola *et al*., 2024).

Chitosan (CS) is another natural biopolymer which has attracted attention in food preservation because it is a biopolymer that has been derived out of chitin.

Some of the best biopolymers in the world include chitin and its derivatives, which are chitosan, which are procured out of the shell of crustaceans and the cell wall of fungi. (Kabanov & Novinyuk, 2020).

Characteristic properties of chitosan that make it to have high chemical and biological activities. Chitosan possesses many properties as polycationite, film former, antimicrobial, and antioxidant agency. (Kabanov & Novinyuk, 2020).

All these features are what have led to its application in the industry, technology, medicine, food preservation, food packaging materials.

Selenium is another potentially effective natural agent is used as an essential trace element in the diet, but its toxicity may cause severe harm at different dosages and depending on the form of administration. The so-called selenium nanoparticles (SeNPs) are a new type of nutritional supplementation due to lower toxicity and the possibility to release selenium after intake (Skalickova *et al*., 2017).

1. Spirulina as natural preservative

1.1. Definition and Importance of Algae

The term algae is a common word to describe a group of different water-dwelling eukaryotes that carry out photosynthesis. The size of the algae represents an appropriate distinguishing characteristic as microalgae, which are typically unicellular organisms, can only be observed under a microscope (below 100 μm), and macroalgae are visible in the naked eye (Moheimani *et al*., 2015). Algae have been used as food, food supplements, and food additives in a number of regions across the world for millennia because it has special organoleptic characteristics and because it contains various nutritional benefits as well as health benefits.

The sources of proteins, minerals, fiber, well-balanced essential amino acids, pigments, and fatty acids, etc., and other relevant metabolites in human nutrition are renewed through algae (Mendes *et al*., 2022). Algae, microalgae (including cyanobacteria), and seaweed (or sea vegetables) as a source of food were in use since the medieval times (Mendes *et al*., 2022). There are additional applications of algae besides serving as a source of food, such as animal feed, bio-fertilizers, bioremediation, or as an added-value biochemical source (Mendes *et al*., 2022).

Algae may be eaten or be used in prepared food, in a fresh, fermented, dried or frozen form, whole or milled to a variety of sizes into flakes, granules or powders (Mendes *et al*., 2022). Increased interest is given to algae foods which is a natural source of micro and macronutrients, traces that adds to their nutritional and pharmacological properties (Mendes *et al*., 2022).

Furthermore, an alga is an environmentally friendly source of natural high-value bioactive substances, and could be used to produce new products to human diets (Mendes *et al*., 2022).

1.2. Microalgae: Characteristics and Applications

A microalga is a unicellular photosynthetic organism that has recently received potential demand and is currently exploited in food, nutraceuticals, pharmaceuticals, animal feed, and cosmetic and bio-fertilizers industry. Microalgae are valuable sources of various bioactive compounds of high value that can be applied to human health and prevent and treat many disease conditions. (Udayan *et al*., 2021). There is also an increase in the microalgae as food ingredients being utilized as flavor active, texture modifier, or as a form of nutrient (Coleman *et al*., 2022).

Arthrospira platensis (Spirulina) and Chlorella vulgaris are the most well-known species of microalgae and have a potential source of vegan proteins rich in 50 percent -60 percent of dry weight,

complete range of essential amino acids and vitamin B12 (Matos, 2019). The nutraceutical market, which deals with dietary supplementation, is one of the largest spheres of such applications, where they are considered convenient sources of macro- and micronutrients of commercial interest in their natural form (Mendes *et al*., 2022). The market is offered with most microalgae powders under the common name of Chlorella and Spirulina (Mendes *et al*., 2022).

1.3. Spirulina: Definition, Composition, and Application

In reality, when it began to receive an encouraging label of possible food use, in 1967, Spirulina was pronounced by the International Association of Applied Microbiology as a wonderful future food source and was subsequently recognized by the United Nations (UN) world food conference of 1974 as the best future food (Mendes *et al*., 2022). Spirulina- Limnospira platensis is a microalga due to its good nutritional value and varied bioactivity compounds, thereby being a useful functional food, feed, and therapeutic agent. The chemical composition of spirulina, its high protein content, essential fatty acids, vitamins, minerals, polysaccharides, and carotenoids in food, feed, and medicine. These substances have several pharmacological actions, antioxidant, anti-inflammatory, immunomodulatory, antiviral, anticancer, antidiabetic and lipid-lowering. Potential in preventing oxidative stress, improving immune performance, and preventing the growth of tumors make spirulina one of the prospective candidates in the prevention of chronic diseases. Also, the animal feed industry is beginning to pay attention to spirulina as a growth performance stimulator, enhancing immune systems, disease resistance in livestock, poultry, and aquaculture (Spinola *et al*., 2024). Spirulina is a microalga also famous in the complex and rich chemical structure, which contributes to its usefulness in a number of food, pharmaceutical, nutraceutical, and animal feed purposes. Spirulina composition mainly is described by its rich content in proteins, lipids, carbohydrates, vitamins, minerals, and pigments, which play a role in the biological activities of spirulina as indicated in figure 3.

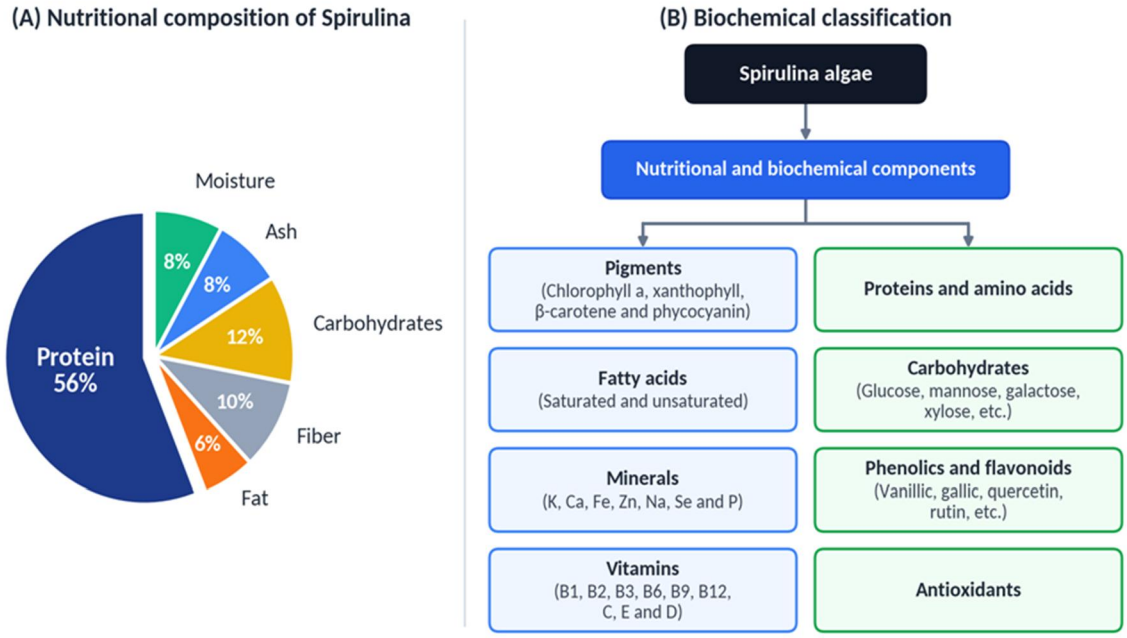


Fig. 3: Nutritional and biochemical profile of spirulina biomass: (A) percentage distribution of major nutritional macronutrients, and (B) classification of specific bioactive components, including pigments, essential minerals, amino acids, and antioxidant fractions (AlFadhly et al., 2022).

Protein is the richest ingredient of spirulina with a composition of 50-70 percent of the dry weight (Spinola *et al*., 2024). Spirulina lipids are found in smaller amounts as compared to proteins and are yet significant to the entire chemical composition of it (Spinola *et al*., 2024). carbohydrates make about 1520 percent of the total dry weight of the spirulina (Spinola *et al*., 2024). Spirulina constitutes a good source of necessary vitamins and minerals. It is also full of B-complex vitamins, especially thiamine (B1), riboflavin (B2), niacin (B3), and folate (B9), which are vitamins that play a dominant role in

energy metabolism and cellular activity (Spinola *et al*., 2024). Another distinguishing feature of spirulina is high content of pigment, which has made it have blue green colour. Phycocyanin is the main pigment in spirulina a blue pigment protein complex that may constitute up to 47% of its dry weight (Spinola *et al*., 2024). Besides its core constituents, spirulina also has an array of secondary metabolites that are also responsible in its bioactivity. They are polyphenols, sterols, and phenolic acids, which have a great biological impact (Spinola *et al*., 2024).

1.4. Applications for Food and Preservation

Spirulina has found numerous applications in the food industry as a functional food ingredient and dietary supplement because of its rich nutritional value. Spirulina is usually put in the powder form or tablets and mixed in smoothies or energy bars among other foodstuffs. Also, it serves as a natural colourant because its pigmentation is high in phycocyanin, which can give vivid blue colour to foods, drinks, and health products (Spinola *et al*., 2024). The spirulina has healthy effects that lead to the introduction of spirulina in food products. Its high level of the essential amino acids, vitamins (mostly the B-complex vitamins and 2-carotene), and mineral content of iron, calcium, etc, make it have higher nutritional value. Spirulina can be used in food to enhance the nutritional value especially in mal-nutritional areas where deficiency of certain nutrients occur. Furthermore, spirulina added food was found to reduce the levels of blood cholesterol and blood sugar, and this ratio has an improvement in cardiovascular and metabolic health (Spinola *et al*., 2024). Spirulina is also an excellent antioxidant and thus becomes an important functional food ingredient in controlling oxidative stress. With the use of spirulina in daily foodstuffs, this will provide immunity against chronic illnesses, such as heart disease, cancer, skin illness, and arthritis. Moreover, the antimicrobial activity of spirulina has resulted in a tendency to add it in preservation of food, and this has increased the shelf-life of the perishable food items (Spinola *et al*., 2024). The therapeutic nutritional effects of Spirulina such as anti-oxidant, anti-inflammatory, and antimicrobial effects as demonstrated in Figure 4.

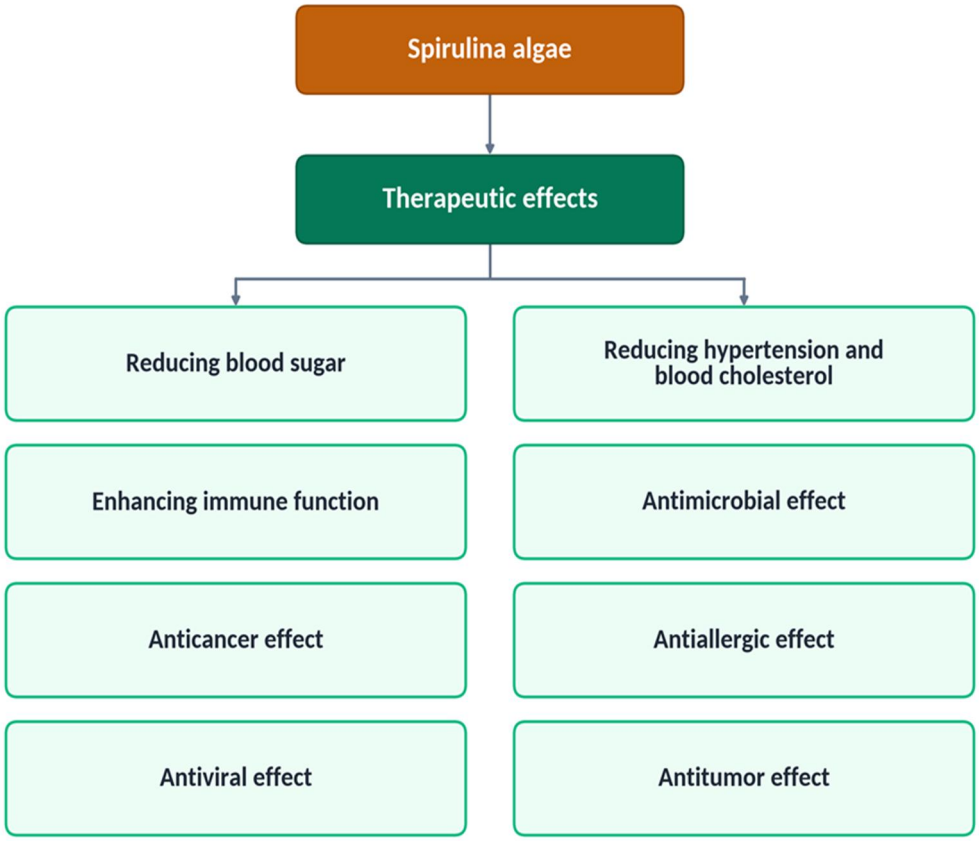


Fig. 4: Flowchart highlighting the diverse therapeutic effects and biomedical properties of spirulina algae biomass (AlFadhly *et al.,* 2022).

2. Chitosan

2.1. Introduction to biopolymer- based packaging materials

Biopolymer packaging materials have gained the attention of the world by virtue of the fact that they can be degraded, renewed and biocompatible. Over the last few years, several biopolymers, including starch, chitosan, carrageenan, polylactic acid, etc., have been explored as the means of food packaging (Perera *et al*., 2023).

Such materials are biopolymers, which are alternatives to synthetic packaging materials since they are eco-friendly, biodegradable, nontoxic, renewable, and biocompatible (Perera *et al*., 2023). Polysaccharide (starch, cellulose, chitosan, etc.), proteins (soy protein, collagen, zein, etc), and aliphatic polyesters are considered the biopolymers that are usually used to package food and preserve it, as well as to extend its shelf-life (Perera *et al*., 2023).

2.2. Functional properties of biopolymer packaging

These food packaging materials regulate exchange of gases, moisture, aroma and lipids between the food product and the external environment and have antimicrobial activity that can preserve the food product to the crimes of the surrounding environment and [3] protect the loss of tasty ingredients like flavor and texture (Perera *et al*., 2023). Antimicrobial agents and antioxidants, flavors, vitamins, or nutrients can be delivered by means of biopolymer matrices, thus helping to enhance the quality, safety, nutritional value, and sensory food attributes (Perera *et al*., 2023).

These materials are biopolymers that are substitutes to synthetic packaging materials as these materials are eco-friendlier, biodegradable, nontoxic, renewable, and biocompatible (Perera *et al*., 2023). Polysaccharide (starch, cellulose, chitosan, etc), proteins (soy protein, collagen, zein, etc), and aliphatic polyesters are said to be considered the biopolymers typically used to package food and preserve it as well as to extend the shelf-life of food (Perera *et al*., 2023).

2.3. Applications and challenges of biopolymer packaging

The attributes of the packaging material barrier, mechanical, chemical and thermal property are also significant and have add values in increasing the shelf-life in addition to the maintenance of the quality of the foodstuffs. The most essential parameter of food packaging that determines the shelf-life of the food item is the barrier properties of the biopolymer to be used as a packaging material (Perera *et al*., 2023).

Biopolymers composed on polysaccharides or a combination of polysaccharides with proteins, lipids and food-grade additives give us edible films that can be consumed by humans and increases the shelf-life and quality of foodstuffs. In spite of all this potential, the challenge related to such types of packaging exists in the form of poor elongation, safety and health, costliness, complexity in its processing, unfamiliarity, culture issue, and its acceptance by the client (Perera *et al*., 2023).

2.4. Definition and origin of chitosan

One of the most common natural polysaccharides, the structure of which crustacean shells or fungal walls of cells consists of, is chitosan poly- 2 -(1,4)-d -glucosamine, although it is a deacetylated form of the other polysaccharide chitin -poly- 2 -(1,4)- N -acetyl-d - glucosamine (Kabanov and Novinyuk, 2020). The chitin and chitosan attract tremendous scientific and practical interest as the peculiarities of biocompatibility, safety, biodegradability, the performance of heavy metals and radio nuclides to chitin and chitosan (Kabanov & Novinyuk, 2020).

Chitosan is a bio-product, which is obtained through the process of deacetylation of chitin. The deacetylation process can be done by either chemical or biological processes. Chitosan can be produced using the huge amount of chitins that are regarded as bio- waste (Reshad *et al*., 2021). Fishery is one of the most rapidly developing food industries in the world. Over the last couple of years, there has been a tremendous growth in the shrimp business particularly in Asia. But in the shrimp industries, head and skin (exoskeleton) of the shrimp are removed and only meat is extracted.

The exoskeleton is subjected to bio-waste. In processing, around 45-55% of the raw shrimp is disposed of as a waste product (Reshad *et al*., 2021). Because it is a natural biopolymer, chitosan has been created as a new sustainable substitute of ordinary chemicals used in the food preservation process, food processing, food packaging, and food additives because of a wide variety of functional groups and excellent biological works (Kabanov & Novinyuk, 2020).

2.5. Structure and physicochemical characteristics

The chitosan is a nontoxic, biodegradable, polycationic copolymer that is made out of chitin through deacetylation. When the pH of the media is below 6.5 it dissolves to form polycations that are insoluble in water and the organic solvents. The attractive properties that make chitosan a highly researched biodegradable biopolymer are its biocompatibility, capability to form a film, antioxidant properties, antimicrobial properties, mechanical property, selective permeability to both CO2 and O2, and UV barrier, as well as desirable optical, transparency, flexibility, and fat and oil resistance properties (Perera *et al*., 2023).

The chitin may easily be converted to chitosan that is a fiber substance. But chitosan is not like plant fiber (like cellulose). Chitosan possesses a positive ionic charge; that is why it could be utilized in binding of the negatively charged substances namely the negatively charged fat, ions, lipids, cholesterol, proteins etc (Reshad *et al*., 2021), Chitosan is formed by deacetylation of chitin and it becomes a biodegradable polycationic polymer with unique physicochemical characteristics, as shown in the Figure 5.

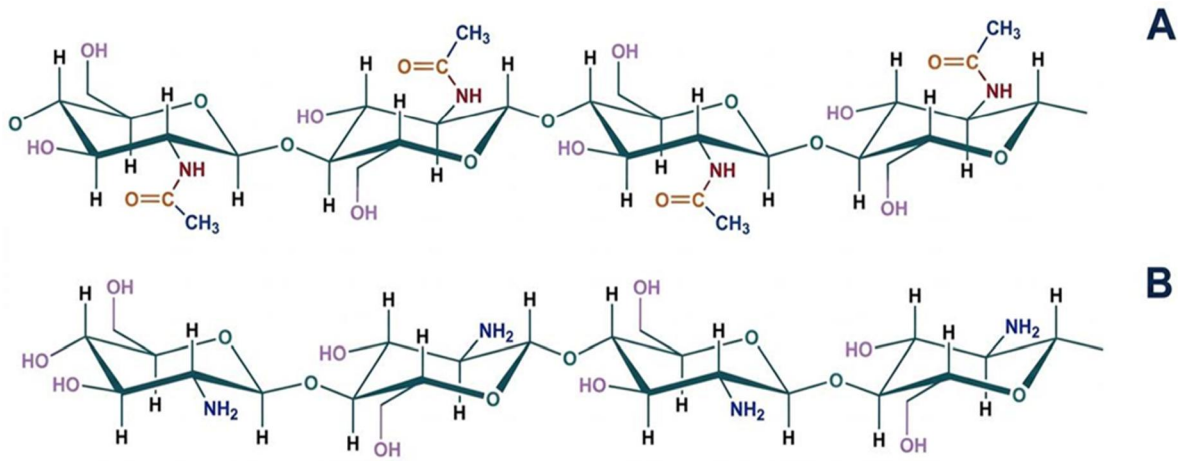


Fig. 5: Chemical structures of (A) chitin and (B) chitosan, showing the deacetylation process and polymeric backbone (Muñoz-Tebar *et al.,* 2023).

2.6. General Application in Food and other Industries

Chitosan is a non-toxic, natural bio-degradable and biocompatible compound and can be used in broad applications. Chitosan could be anti-microbial and antioxidant. Moreover, it might also have the usage in drug delivery, biotechnology, bio-nanotechnology, food technology, regenerative medicine, medicine, numerous industrial applications, gene therapy, cancer therapy, agriculture, environmental protection, etc. (Reshad *et al*., 2021). Moreover, bioavailability, non-toxic, adsorption and biodegradable, such properties render it very useful in various categories of applications in various fields like wound dressing, drug carrier, and food packaging, dietary supplement, chelating agent, pharmaceutical and biomaterial, etc. (Reshad *et al*., 2021).

The application of chitosan in numerous technologies, antimicrobial activity of chitosan in medicines and food industry versatile application of chitosan both to extend shelf life of food, great emulsifying properties offer a chance to avoid using surfactants, synthetic ones, in food technologies, and chitosan may be taken as a functional ingredient against hypercholesterolemia, hypertension and inflammations as well as to encapsulate nutrients to create a functional food. Polyelectrolyte and flocculant action of chitosan at the same time makes the use of this compound as an efficient clarifying agent of beverages and prior purification of drinking water possible (Kabanov & Novinyuk, 2020).

2.7. Chitosan in Food Packaging

The chitosan-based system of packaging food improves the emulsifying action, the intrinsic flavor, the texture attributes, the deacidification, and the color preservation of the food products, thus improving the quality, safety and shelf-life of the food. However, the limitation of pure chitosan in food packaging is found to be weakened water vapor barrier properties; thus, it is highly sensitive to moisture, and a film developed from chitosan is found to be brittle with low elasticity (Perera *et al*., 2023).

The most promising use of chitosan in food shelves life extending is edible film coating. Edible films are taken as that type of packaging which is mainly meant to cushion foods against any outside influences as well as they can be employed as mover of active ingredients like preservatives, flavors and colorants. Edible Coatings that cause a reduction in weight loss during storage block oxygen permeability, displays antimicrobial and antioxidant property to extend the shelf life of processed foods by a considerable margin. The chitosan based compositions which do contain the protein e.g. caseins and gelatin have been found to comprise of good mechanical properties, low vapor permeability and UV-shielding owing to peptide bond absorption. Coating composition to which soy protein or beeswax was added to promote film hydrophobicity (Kabanov & Novinyuk, 2020), the action mechanisms of bioactive compounds incorporated into chitosan edible films against Gram-positive and Gram-negative bacteria are depicted in Figure 6.

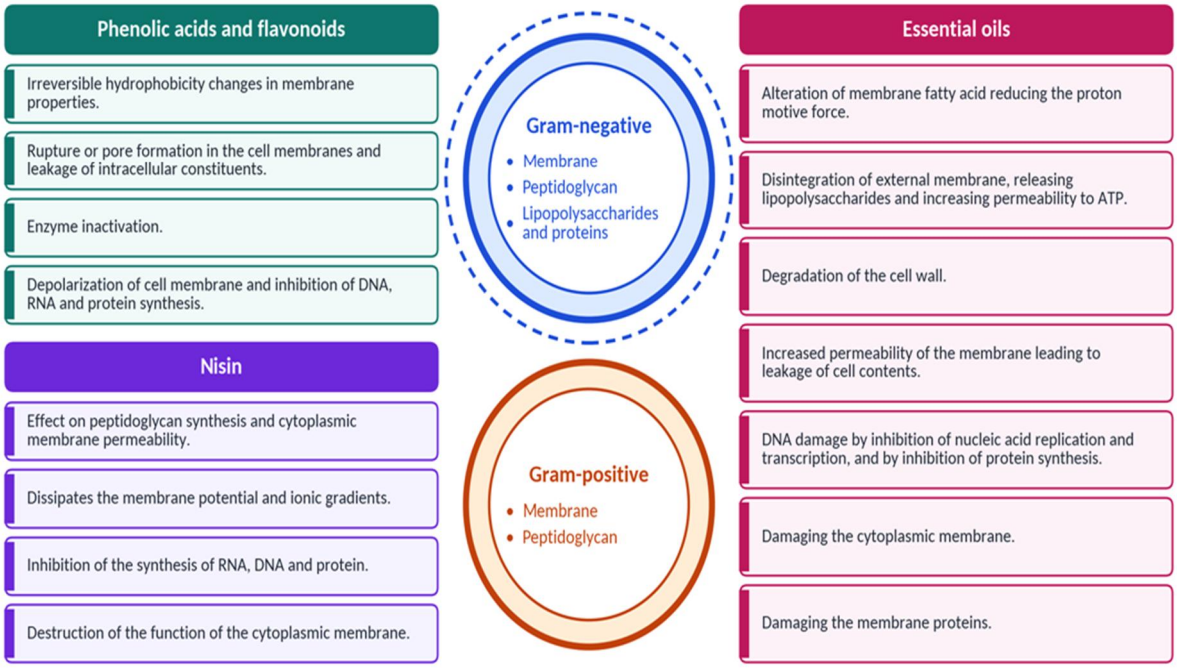


Fig. 6: Schematic illustration detailing the various mechanisms of antimicrobial action of phenolic acids, flavonoids, nisin, and essential oils against the structural components of both Gram-negative and Gram- positive bacterial cell walls (Muñoz-Tebar *et al.*, 2023).

The high biocompatibility, emulsifying capacity, polycationicity and hypoallergenic nature of chitosan means it can be utilized as a carrier in the encapsulation and controlled delivery of the probiotic ingredients in functional food products. Components encapsulation is employed to avoid chemical alterations throughout the preparation procedure or in acidic media such as stomachs, to administer lipophilic components like vitamins or flavonoids by polymers and to control the release of nutraceuticals and cover the odor and flavor of certain substances.

The simplest technique of encapsulating nutraceutics is ion gelation by using polyanionites, which is tripolyphosphate or proteins as the gelling agent. Chitosan characteristics determine the extent of the particle size which is greater with a low DD and MW corresponding to a reduction in zeta potential which is ascertained by unsaturated amino groups of the macromolecule which connects to polyanionites. The nanoparticles with vitamins C and B2, dyes, curcumin and lutein, flavonoids catechins and quercetin, bioactive minerals selenium and zinc can be obtained (Kabanov and Novinyuk, 2020).

3. Selenium Nanoparticles

3.1. Introduction to Selenium

Selenium is a trace nutrient, which has nutritional and nutraceutical applications, but the narrow nutritional range of selenium intake restricts its application (Chen et al., 2023). Selenium is a trace and

very fundamental micronutrient of the well-being of people, animals and microorganisms (Bisht et al., 2022). Elemental selenium (Se) is very significant to physics, chemistry as well as biology. Naturally, there are two types of selenium, inorganic (selenite and selenate) and organic (selenomethionine and selenocysteine) (Bisht et al., 2022).

3.2. Why Nano-Selenium (SeNPs)?

Selenium nanoparticles (SeNPs) are safer and more bioavailability than the conventional forms of selenium and imply that SeNPs can be used to substitute conventional forms of selenium in food and/or biomedical applications (Chen et al., 2023).

SeNPs are more stable, bioavailable and less toxic (Chen et al., 2023). As such, their application as a higher bioactivity selenium nanoparticles has been extensively applicable in a number of biomedical fields (Bisht et al., 2022).

3.3. Synthesis of SeNPs

Inorganic selenium can be converted to SeNPs by physical, chemical or biological means (Chen et al., 2023), Selenium nanoparticles (SeNPs) can be produced in different biological and chemical ways, as it is shown in Figure 7.

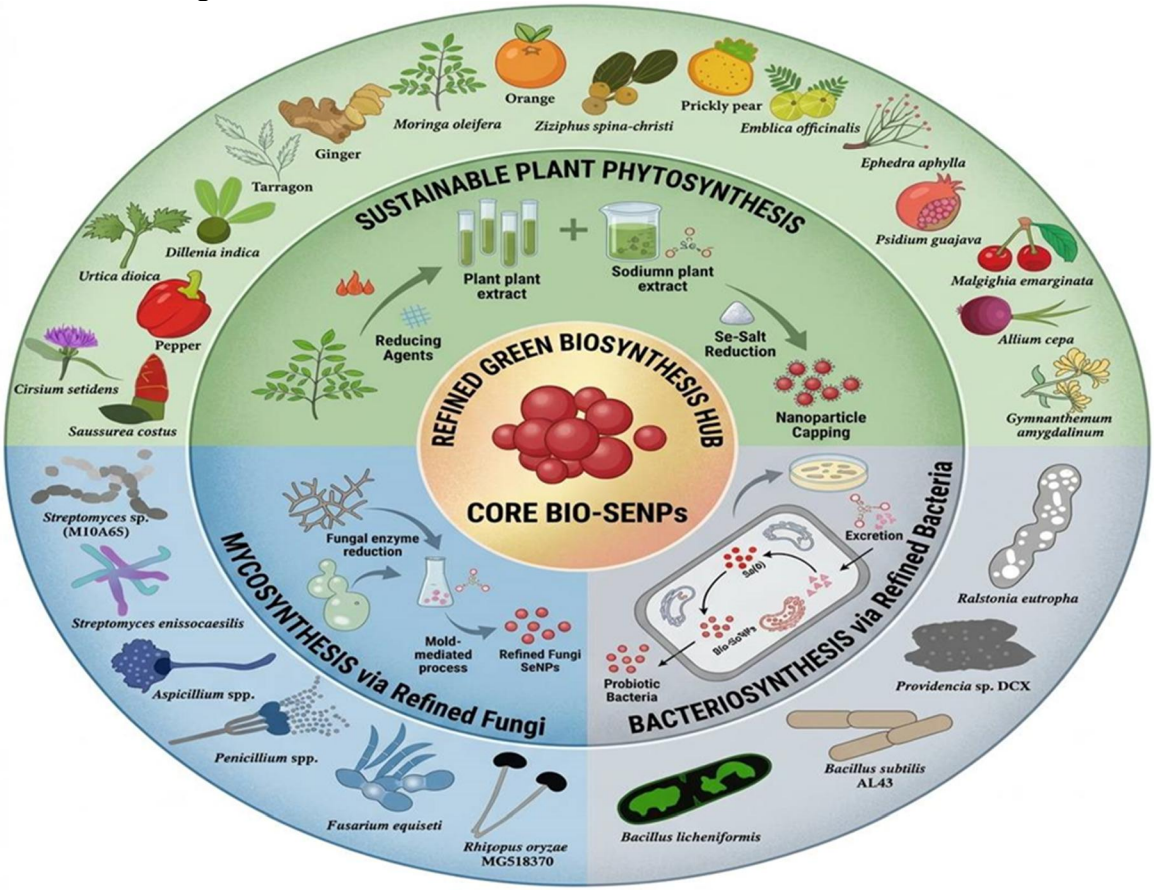


Fig: 7. Technical routes for Bio-SeNPs synthesis based on plant extracts, bacteria, and fungi (inner ring) and representative organisms used in the synthesis (outer ring) (Ao et al., 2023).

Selenium nanoparticles can typically be produced through physical, chemical, and biological procedures. SeNPs have been synthesized by various procedures. All these techniques can be broadly classified as two categories, which are reduction which is biological and chemical. The use of a biological Reduction technique involves the reduction of different forms of organic/inorganic selenium by the biology of bacteria or plant extracts and then their transformation to non-toxic and useful SeNPs. Chemical reducing agents are used in chemical reduction. The approach can also be subdivided, based on the source of energy that is utilized or the apparatus that is used in the reaction. Hydrothermal,

microwave, and sonochemical processes are the ones primarily cited by researchers in this category (Bisht *et al*., 2022).

Selenium nanoparticles (SeNPs) are very popular entities of nanotechnology. The necessity to create environmentally friendly, non-toxic, and inexpensive approaches provides special benefits to the concept of the green synthesis because this need is increasingly increasing. This review takes the biosynthesis of bacteria, fungi, algae, and plants, and the application of different biological substances to the action of reducing selenium compounds into SeNPs and the subsequent packaging (Mikhailova, 2023).

3.4. Biological and biomedical applications

SeNPs are superior to the classical selenium form in the synthesis of selenoproteins such as glutathione peroxidases. SeNPs are able to restructure the digestive system in order to aid digestion and absorption processes of nutrients. SeNPs have demonstrated a great potential in the adjunctive therapy of cancer patients, immune system improvement, diabetes management as well as prevention of rheumatoid arthritis. Also, the anti-pathogenic action of SeNPs is good, and it can be combined with other antimicrobial agents in the fight against pathogenic bacteria, fungi, or viruses (Chen *et al*., 2023). The review gives the different synthesis techniques used to prepare them and their use in the biomedical sphere as in the treatment of funal, bacterial and parasitic infections, cancer and diabetes. They are also capable of serving chemopreventive purposes, anti-inflammatory purposes and antioxidants (Bisht *et al*., 2022).

Modern information and approaches to the possible biomedical use of selenium nanoparticles are presented: antimicrobial, antiviral, anticancer, antioxidant, anti- inflammatory, and other properties, as well as the mechanisms of these processes, that have important potential therapeutic value (Mikhailova, 2023).

3.5. Application of selenium nanoparticles in food bio preservation

Food spoilage caused by microorganisms does not only lead to food wastes but also food-borne illnesses. Food preservatives and rigorous food preservation measures are also typical methods of inhibiting the development of microorganisms in an attempt to further food safety and minimizing the food waste. In more recent years, there was a tendency to pay attention to SeNPs that demonstrated the effects of antioxidant and antimicrobial (Skalickova *et al*., 2017; Gunti *et al*., 2019; Wang *et al*., 2022; Filipovic *et al*., 2021; Lin *et al*., 2021; Sentkowska and Pyrzynska, 2022; Kieliszek *et al*., 2022) in protecting the quality of food and inhib Moreover, it was stated that SeNPs could prevent human pathogenic microorganisms, B. cereus, MRSA, S. aureus, S. agalactaie, E. coli, E. faecalis, and L. monocytogenes (Filipovic *et al*., 2021; Yang *et al*., 2018; Salem, 2022; El-Deeb *et al*., 2018; Mosallam *et al*., 2018; Alghuthaymi *et al*., Notably, some of them, including the E. coli and the L. monocytogenes, are typical food-borne bacteria.

Selenium nanoparticles demonstrate various antibacterial actions, which can work on diverse cell structures as illustrated in Figure 8.

In case SeNPs can be used as food additives, they can not only slow down the process of food spoilage by not only preventing the growth of microorganisms but also other factors, preventing the oxidation of food, and benefiting consumers who are deficient in selenium (Yuan *et al*., 2023). Therefore, the question to test is whether SeNPs can suppress the proliferation of a broader set of food-borne bacteria. The goal of this research was to explore the possibility of SeNPs to prevent the growth of several widespread food-borne bacteria, as well as their use in food preservation (Yuan *et al*., 2023).

3.6. Application of selenium nanoparticles in food packaging

Use of SeNPs in active packaging is an underexploited technology that has the potential to initiate the extension of the shelf life of food. This is explained by the fact that SeNPs can have antioxidant and antimicrobial effects on preserved food (Menon *et al*., 2019). SeNPs can be hosted in both nondegradable and biodegradable polymers in active packaging. Nevertheless, biopolymers are more desirable due to their biocompatibility, biodegradability or its non-hazardous properties (Wu *et al*., 2019), which means that packaging waste can be minimized (Kuswandi *et al*., 2018). Biopolymer films are more environmentally friendly, so it is possible to use them in place of synthetic packaging materials (Jamrhoz *et al*., 2019; Peighambardoust *et al*., 2019).

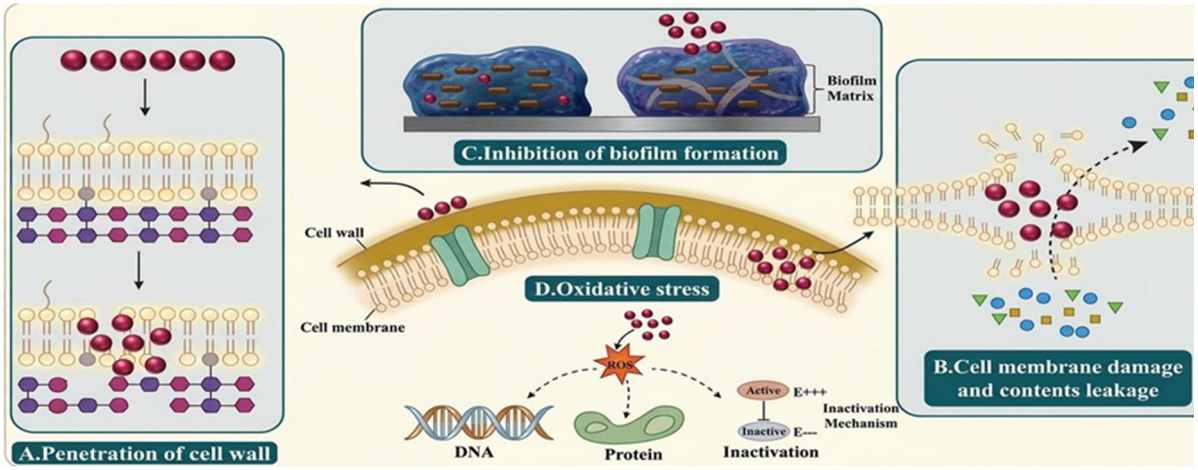


Fig. 8: Schematic diagram showing the multi-targeted antimicrobial mechanism of action of green-synthesized nanoparticles: (A) cell wall penetration, (B) cytoplasmic membrane disruption with cellular leakage, (C) prevention of biofilm development, and (D) generation of intracellular oxidative stress (ROS) leading to downstream biomolecular degradation. Antiba (Ao et al., 2023).

3.7. Safety and toxicity considerations of SeNPs in food applications

Overall, the use of nanoparticles in food packaging involves safety issues because of a potential trigger of nanoparticles to migrate out of packaging into the food, thereby potentially causing toxicological consequences in the human body (Ndwandwe *et al*., 2021). The toxicity associated with selenium is based on the chemistry of the form to which it is cascaded, oxidation state and internal environment (Skalickova *et al*., 2017). Moreover, the SeNPs toxicity depends mainly on the method of synthesis (Hosnedlova *et al*., 2018). In that way, biogenic SeNPs are less toxic and biocompatible (Xu *et al*., 2018).

An adult requires a daily dosage of up to 40–300 µg, and larger amounts may lead to selenium toxicity (Ramya *et al*., 2015; Rajeshkumar *et al*., 2018). Nevertheless, the human body is capable of naturally breaking excess selenium and releasing it through urination (Hoseinnejad *et al*., 2018; Rajeshkumar *et al*., 2018). Recent research suggests that the SeNPs have an equal level of efficacy of other selenium compounds as an antioxidant; although, with a much lower probability of toxicity (Sharma *et al*., 2014; Kokila *et al*., 2017; Nastulyavichus *et al*., 2019; Tang *et al*., 2019).

In an experiment, where Alam *et al*. (2019) identified a possible use of SeNPs in determining cell viability through exposing normal and cancerous cell lines to SeNPs, the lower toxicity of SeNPs compared to sodium selenite was noted against normal cell lines. Against this, migration of SeNPs out of packaging to food should still be reduced, until there is sufficient supply of science-based information on the effects of SeNPs on human health after the exposure has been chronic (Ndwandwe *et al*., 2021). Smolkova *et al*. (2015) claim that subtle alterations of the human body could occur in case of the prolonged exposure to low doses of selenium. Thus, studies regarding the long-term outcomes of SeNPs in the human body require further research.

4. Combined application in food bio preservation

4.1. Synthesis and Characterization of SeNPs-PVA/Chitosan Composite

The identified research will explore the environmentally friendly production, characterization and biological functionality of selenium nanoparticles (SeNPs) integrated into a polyvinyl alcohol/chitosan (PVA/CH) complex used as an antimicrobial, antioxidant, and food preservative (Abdelaziz *et al*., 2025). Orange peel extracts were used to create the SeNPs in the form of a reducing and stabilizing agent (Abdelaziz *et al*., 2025). The nanoparticles of se were more compact and thermally and UV stable toward PVA/CH-SeNPS film (Abdelaziz *et al*., 2025). The aspect of preparation of PVA/CH-SeNPs composite films with different concentrations is shown in figure 9.

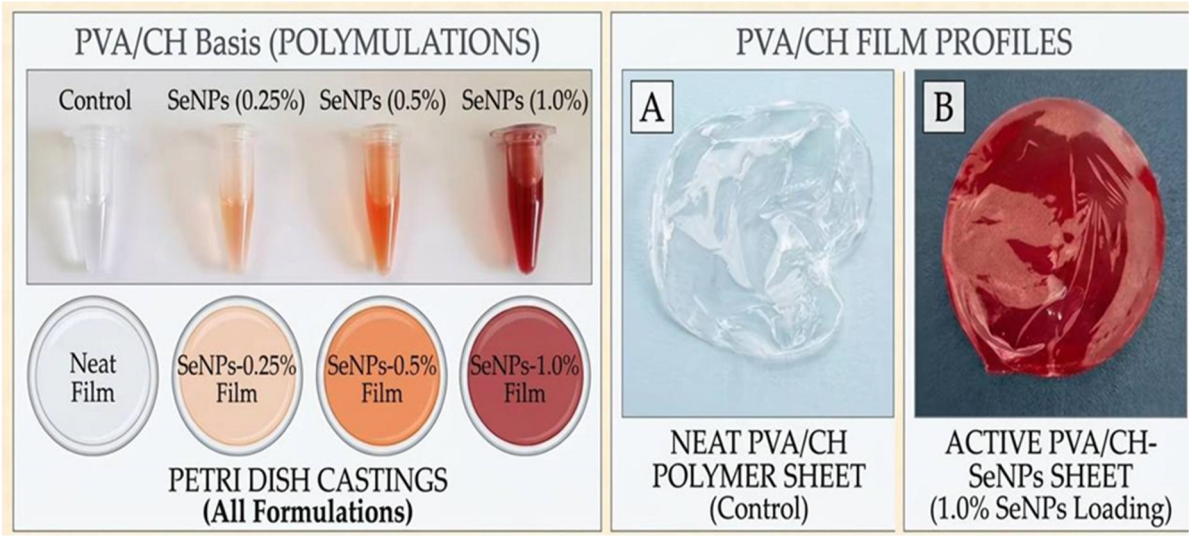


Fig. 9: The PVA/CH-SeNPs composite films of different concentrations were prepared. (A) PVA/CH film. A concentrated solution of the sample was used to prepare (B) concentrated PVA/CH-SeNPs film (Abdelaziz et al., 2025).

4.1.1. Antimicrobial and Antioxidant Activity

The antimicrobial properties of PVA/chitosan (PVA/CH) films containing selenium nanoparticles (SeNPs) were analyzed against five microbial pathogenic strains, and it was found that the antimicrobial activity increased depending on the concentration, and the 1% of SeNPs formulation exhibited the greatest levels of inhibitory zones on all pathogenic bacteria (Abdelaziz *et al*., 2025).

4.1.2. Food Preservation Application

Fruits sprayed with PVA/CH-SeNP experienced remarkably less weight loss and were more firm. They also enhanced the total soluble solids, reduced acidity and increased L-ascorbic acid and anthocyanin levels (Abdelaziz *et al*., 2025).

4.2. Synthesis and Characterization of SeNPs-Spirulina Composite:

The article examined the antimicrobial and antioxidant properties of three Spirulina extracts (hexane, acetone, and methanol) and the biological selenium nanoparticles (SeNPs) produced by Bacillus subtilis AL43 (Abdel-Moneim *et al*., 2022).

4.2.1. Antimicrobial and Antioxidant Activity

Those results showed that Spirulina extracts possessed antimicrobial effects against the pathogens that were tested (Abdel-Moneim *et al*., 2022). Also, the Spirulina extracts had the capacity to scavenge both ABTS and DPPH radicals on a dose-dependent basis (Abdel-Moneim *et al*., 2022). The methanolic extract was better than other extracts because of the increased amount of phenols, antimicrobial activity, and antioxidant activity (Abdel-Moneim *et al*., 2022). We established that the antimicrobial efficacies of the SeNPs on three gram-positive, three gram-negative microorganisms, and three Candida sp. and Aspergillus sp. strains are relatively high (Abdel-Moneim *et al*., 2022). More so, the SeNPs had the ability to inhibit dose-dependently ABTS radical and DPPH radical (Abdel-Moneim *et al*., 2022).

Spirulina extracts, as well as SeNPs were also found to exhibit antimicrobial and antioxidant behavior and the behavioral trends increased with the increase in the concentration of the products (Abdel-Moneim *et al*., 2022). This coupled with the fact that antimicrobial and antioxidant properties of Spirulina methanolic extract had been reported as the best. The high total content of phenolics in the methanolic extract may be the potentially attributed level of this potency of the extract (Abdel-Moneim *et al*., 2022). The correlation between the total phenolic content and the biological activities was found to identify the Spirulina-SeNPs connection (Abdel-Moneim *et al*., 2022). We can conclude that Spirulina and SeNPs with high antimicrobial and antioxidant properties are potential suitable candidates to use as safe and reliable medical agents (Abdel-Moneim *et al*., 2022). We speculate that Spirulina and SeNPs would be intriguing antimicrobial agents and also, natural antioxidant alternative. Hence, they

may be used as substitutes to antibiotics and conventional chemical medication (Abdel-Moneim *et al*., 2022).

Challenges and future perspectives of nanomaterials in food preservation:

A. Potential and Growing Importance of Nanomaterials:

Nanomaterials have a critical contribution to food preservation and food safety that provides clever solutions to sustainable food packaging (Pattnaik *et al*., 2024). With the help of nanomaterials, it is now possible to produce packaging materials with special functional characteristics. Not only does it increase the shelf life of the foods by emitting the preservatives but also makes the food safest by preventing the microorganisms contamination or food spoilage (Pattnaik *et al*., 2024). Notwithstanding these, the recent food consumption trends have pointed out that the nanomaterial-based food packaging will be on the frontline and it will be the dominating aspect of food packaging in the coming many years (Pattnaik *et al*., 2024).

B. Current Challenges and Safety Concerns

Nanoparticle packaging materials have been developed to the benefit of food and beverages (Pattnaik *et al*., 2024). The packaging food industry has not adopted nanoparticle-based packaging materials much because of the possibility of food contamination with nanoparticles that could cause oral toxicity in humans (Kanmani & Rhim, 2014).

Migration, toxicity, and allowable limit of nanoparticles that can be used as the food packaging material should therefore be harshly developed upon (Pattnaik *et al*., 2024). Nevertheless, the toxicity of nanoparticles and nanomaterials is not a household name despite the fact that a rapid development in nanotechnology has already been extended to the sphere of food products (Onyeaka *et al*., 2022). It is because of this fact that nanomaterials may be potentially toxic, therefore, because of the ever-increasing use of the concept in the sphere of food science, they need to be further defined, and their application should become more controlled (Onyeaka *et al*., 2022).We may be having the crisis of nanotoxicity because the molecular conversations between nanoparticles and nanomaterials and food and living organisms are not fully comprehended, yet (Onyeaka *et al*., 2022).

C. Regulatory and analytical limitations

Laws regulating the packaging of nanotechnology are different in countries (Pattnaik *et al*., 2024) which makes the safety of nanotechnology packaging an excellent subject of debate (Pattnaik *et al*., 2024). To detect and profile nanoparticles and their properties in soil, water, air, and food and consumer products to which humans and the ecosystem are exposed, the analysis methods are necessary (Onyeaka *et al*., 2022). Additional studies are also necessary to fully assess the threats and the benefits of nanostructural use in the food industry (Pattnaik *et al*., 2024).

Conclusion

Overall, Spirulina extracts, chitosan, and selenium nanoparticles have strong antimicrobial and antioxidant properties, which warrant their usage in natural and effective bio preservatives. Their usage, either on their own or together provides numerous benefits in the control of the spoilage microorganisms, oxidation, and food preservation. Their incorporation of these natural bioactive into nanotechnology gives the added advantage of stability, bioavailability and overall functionality in the food systems. Nevertheless, even with this promising advancement, the issue of nanoparticles amigration, toxicity, and safety effects in the long run continue to constrain their application in industries. Thus, their interactions with the food matrices and safe allowable levels as well as the formation of clear regulatory guidelines need to be studied more closely. Such development will open the way to safer, more sustainable and innovative bio preservation plans in the food industry.

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