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Review

An Updated Review of the Antimicrobial Potential of Selenium Nanoparticles and Selenium-Related Toxicological Issues

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Abstract: Discovered in mid-1817 by Jöns Jacob Berzelius, selenium, belonging to Group 16 of the periodic table is an essential trace element for human and animal health, due to its biocompatibility and bioavailability. Additionally, it is known for having different oxidation states, which allows it to interact with distinct chemical elements to form various compounds. Selenium exhibits two forms, organic and inorganic; the latter is known for its genotoxicity. Selenium nanoparticles have been investigated as an alternative to mitigate the toxicity of this element. With antidiabetic, antiviral, chemopreventive, and antimicrobial properties, SeNPs possess significant biomedical potential and can be synthesized using chemical, physical, or green methods, offering new solutions for combating microbial resistance and other diseases. This review discusses the historical discovery of selenium, preparation methods, the versatility of combinations for synthesis, morphological characteristics, and sizes, as well as the impact of SeNP applications obtained through different approaches against medically relevant microorganisms, particularly those exhibiting resistance to conventional antimicrobials.

Keywords: selenium nanoparticles; nanotechnology; biogenic synthesis; chemical synthesis; physical synthesis; antimicrobial activity

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1. Introduction

The discovery and research of selenium began in 1817 in Sweden by the "father of Swedish chemistry", Jöns Jacob Berzelius (1779–1848) [1,2]. The investigation commenced when Berzelius was called to examine a disease affecting workers at a Swedish sulfuric acid production plant [3,4]. Berzelius observed that the lead chambers used in the acid production process contained a red residue, initially suspected to be tellurium. The residue was isolated, and its properties were analyzed, including gas formation and reactivity with oxygen and metals [1,4–6]. Initially, Berzelius classified selenium as a metallic element due to its characteristic luster; however, it is now categorized as a metalloid due to its intermediate properties between metals and non-metals. Selenium, with atomic number 34 and atomic mass 78.963, belongs to group 16 of the periodic table and is notable for its ability to assume various oxidation states, allowing it to interact with different chemical elements and form new compounds [7].

In nature, selenium is found in two main forms: organic and inorganic. Organic forms are often used in biological applications due to their bioactive properties, such as antioxidant, anticancer, antimicrobial, antiviral [8,9], antidiabetic, and antidepressant effects [10],

as well as being nutritional sources [11], and modulators of cardiovascular, immunological, metabolic, and thyroid functions [12–15]. Inorganic forms, although considered important in biological and biogeochemical cycles [9,11,16,17], are widely recognized for their genotoxic role in various contexts, such as compromising genomic stability through induction of DNA strand breaks and oxidative damage [7,18], and inhibiting cell growth and proliferation through cytotoxicity [7].

Nanotechnology, derived from the Greek words "*nános*" (dwarf), "*téchne*" (technology), and "*lógos*" (study), is the science aimed at establishing a new paradigm in the production, application, and behavior of materials such as polymers, metals, semiconductors, and composites at the nanoscale through the control and manipulation of matter [19–22]. A notable advancement in the development of nanomaterials with comprehensive applications is evidenced by progress in the research and manufacturing of nanoparticles (NPs). NPs are characterized as particles with a domain size ranging from 0.1 to 100 nanometers (nm), exhibiting distinct physicochemical properties such as a high surface-to-volume ratio, increased mobility, bioavailability, and notable efficacy when associated with other compounds. Mostly, these characteristics make them preferred options compared to bulk particles, as in the case of selenium nanoparticles (SeNPs) synthesis, which are considered more advantageous in various applications [19,23,24].

In recent decades, SeNPs have emerged as promising materials in scientific and technological fields due to their therapeutic and theranostic potential, as they exhibit better bioactivity, biocompatibility, and low toxicity, making them more effective and safer compared to bulk selenium particles and their derivatives [25–27]. SeNPs can perform various therapeutic functions, including reducing inflammation, improving cardiovascular dysfunction and reproductive performance, regulating blood glucose levels, and protecting the central system [28], as well as theranostic roles, performing diagnostic tasks, including associated techniques such as fluorescence and photoacoustic imaging, radiosensitization, chemotherapy sensitization, photothermal dynamics, and enhanced immunotherapy [29]. Recent studies highlight that toxic forms of selenium, particularly inorganic ones, when reduced to the nanometer scale, can be transformed into stable, bioavailable, and low-toxicity SeNPs, enhancing antimicrobial activity, such as in bacteria, by impairing the function of mitochondrial enzymes involved to the process of cellular respiration and oxidative phosphorylation [30,31].

The functionality of SeNPs has been recognized for their antidiabetic [32,33], antiviral [34], antioxidant [13], and chemopreventive properties [25], particularly notable for their antimicrobial activities against pathogenic bacteria and fungi [26,35], as well as their bioactive properties in scavenging free radicals, both in vivo and in vitro [25]. Additionally, studies demonstrate that compounds containing selenium are considered potentially detoxifying against mercury, methylmercury, cadmium, silver, lead, and other elements considered hazardous [36], as shown by [37], who demonstrated the activity of SeNPs as bioabsorbents of lead and chromium.

2. Chemistry of Selenium

Initially, Berzelius classified selenium as a metallic element due to its characteristic luster, subdividing metals into two distinct classes: those capable of forming acids and those functioning as bases, placing selenium among the acidifiable metals. Currently, selenium is recognized as a metalloid, exhibiting properties that combine metallic and non-metallic characteristics. It is located between sulfur and tellurium, belonging to the 16th group of the Periodic Table, known as the chalcogens, along with oxygen and polonium, with an atomic number of 34 and an atomic weight of 78.96 [5,6,38,39].

Selenium is recognized for its versatility and unique ability to interact with various chemical elements, consequently forming new compounds. Naturally, it occurs in six distinct and stable isotopic forms (74, 76, 77, 78, 80, and 82), resulting from variations in the number of neutrons present in the nucleus of its respective isotopes, with different abundance percentages (0.87%, 9.02%, 7.85%, 23.52%, 49.82%, and 9.19%, respectively) [5]. Furthermore, it exhibits oxidation states (selenates (+6), selenites (+4), elemental (0), and selenides (−2)), directly linked to its potential chemical and biological roles [7].

Regarding polymorphic structures, the elemental allotropes of selenium can exhibit crystalline or amorphous structures. The crystalline forms display an ordered structure, resembling needles, and are considered the most stable among the allotropes, being harmful to cellular integrity and homeostasis, whereas the amorphous forms, with surface deviations, are globular and less disruptive, impacting physical properties and other characteristics [40]. Studies emphasize that amorphous forms are recognized for spontaneously converting to the crystalline form at 70–120 °C [41]. From the perspective of the vibrational dynamics of these materials, the crystalline and amorphous forms do not exhibit differences in the vibrational density of states; however, the allotropic transition between these forms is significantly important from a biotechnological standpoint [42].

In nature, selenium manifests in two distinct forms: organic and inorganic, behaving as an ambiguous element, which determines its bioavailability, function, and toxicity. Organic selenium compounds, such as selenomethionine, a naturally modified amino acid with sulfur and selenium, and selenocysteine, resulting from the oxidation of the diselenide of the amino acid selenocysteine, are often used in biological applications due to their role in biochemical processes, including antioxidant, anticancer, antiviral, and antitumor activities [9,11,43]. Meanwhile, the inorganic forms, represented by the selenite and selenate anions, are considered important in biological and biogeochemical cycles, although they are also recognized for their genotoxic role in different contexts [9,11,16,17].

3. The Two Faces of Selenium: From Toxicity to Essentiality

Selenium is known for its ambiguous behavior, as it can provide health benefits to living organisms, but also act as a toxic element, depending on the level of consumption and absorption [44,45].

3.1. Selenium Distribution on Planet Earth

Due to the absence of natural synthesis by living organisms, selenium is obtained through natural and anthropogenic processes. Natural processes include geophysical and biological phenomena, such as its release from geological sources and the availability of compounds in aquatic and terrestrial ecosystems, which directly influence its presence in water and, consequently, in food [7,17,46,47]. Anthropogenic processes are related to its redistribution in the environment, resulting from industrial activities such as copper refining, glass production, and electronics manufacturing, as well as drainage waters, mining, and fertilizer use [5].

Due to this absence, selenium intake becomes crucial for living organisms, primarily through food sourced from the soil. The amount of selenium present in these foods can vary according to the physico-chemical conditions of the soil, such as pH and redox potential, which are determined by the cultivation environment [8,48]. In soil, the main forms of selenium are selenate and selenite, with the latter being the least bioavailable due to its strong absorption by iron oxides and hydroxides [8].

3.2. Toxicity

The inorganic form of selenium is frequently reported as one of the main causes of systemic toxicity, highlighted by its genotoxicity, leading to the compromise of genomic stability through the induction of DNA breaks and oxidative damage [7,18], as well as inhibiting cell growth and proliferation through cytotoxicity [7]. Among the toxicological impacts, especially those associated with selenium accumulation in soil and plant species, stand out, directly affecting its consumption and supplementation. Studies indicate that both high and low doses of selenium intake pose risks to human health, highlighting the existence of a broad therapeutic window [7,49].

Studies indicate that the insufficient intake of foods from selenium-poor soils (<0.13 mg/kg) and the excessive intake of foods grown in selenium-rich soils (>3.00 mg/kg) are associated with the etiology of various diseases, with a greater understanding of the effects of deficiency than of excess [48,50]. Low selenium intake in deficient soils is associated with diseases such as necrotizing cardiomyopathy, conduction disorders, peripheral myopathy, neurological changes followed by malabsorption syndromes, leading to immune problems and increased susceptibility to pathogens [17,18,47,51], increased pathogen virulence, fertility problems, autoimmune thyroid disease, and type 2 diabetes [50]. On the other hand, the excessive intake of foods from selenium-rich soils may lead to tumorigenesis, amyotrophic lateral sclerosis, and cardiovascular diseases [47], as well as selenosis, alopecia, dermatitis [50], nerve damage, paralysis, hyperglycemia, and death (in extreme cases) [52].

The etiology of diet-related diseases is directly associated with selenium toxicity in different botanical species. Classic studies have demonstrated that animals feeding on local plants suffered selenium poisoning due to the accumulation and incorporation of this element into the amino acids present in the plants [53]. Over the years, studies have shown that the absorption rate by plants can vary depending on several factors, such as: plant species (including its tissue, physiological conditions, and developmental stage), physicochemical characteristics of the soil (such as pH, moisture content, soil texture, and organic matter content) and the properties of the element itself (such as concentration and chemical form) [7,54,55].

3.3. Essentiality

Despite the consequences of selenium toxicity, more than 100 years after its discovery by Jacob Berzelius, a study by Klaus Schwarz and Calvin Foltz explored the benefits of ingesting this element. The researchers demonstrated that, when associated with balanced diets, selenium was able to attenuate and protect mice against hepatic necrosis [56]. Other studies revealed the importance of the element beyond mammals, demonstrating its remarkable activity in bacteria [57] as well as in animals [58]. Since then, numerous studies have been conducted to better understand the benefits of selenium in various fields of knowledge, particularly in the biological sciences.

The significant benefits derived from selenium in human and animal health are attributed to balanced and correct micronutrient supplementation. According to guidelines developed by the Food and Nutrition Board (FNB) at the Institute of Medicine of the National Academies in the United States, reference values used to define the recommended dietary allowance (RDA) and adequate intake (AI) vary depending on the age and sex of the individual. From birth to 6 months and from 7 to 12 months of age, regardless of gender, individuals should have a daily AI of 15 µg and 20 µg, respectively, to ensure nutritional adequacy. For individuals aged 1–3, 4–8, and 9–13 years, the recommended dietary intake (RDI) to meet the nutritional needs of 97–98% of individuals is 20, 30, and

40 μg, respectively. For individuals aged 14 years or older, the RDI is 55 μg, with variations during pregnancy (60 μg) and lactation (70 μg) [59].

Classic studies emphasize the importance of adequate and balanced selenium intake due to its positive biological effects. Studies reveal that insufficient Se levels in humans impact the production of selenoproteins, leading to a decrease in glutathione peroxidase (GSH-Px), the first identified selenoenzyme with a crucial role for human and animal health, which can result in a reduced ability of cells to withstand the harmful effects of oxidative stress, affecting the production and breakdown of nucleic acids, proteins, and enzymes, as well as compromising cell division, reproduction, immunity, and the development of metabolic diseases [60]. Other studies point out that adequate intake prevents slow growth in male rats and the development of aspermatogenesis [53]; prevents heart diseases, such as Keshan disease, a frequently fatal form of endemic cardiomyopathy in regions of China with selenium-deficient soils [53]; and protects against thyroid diseases, where selenium deficiency deregulates the synthesis, activation, and metabolism of thyroid hormones, mediated by the action of the enzyme thyroxine 5-deiodinase [61].

In the field of botany, despite the fine line regarding toxicity due to accumulation in plants, its presence is crucial for maintaining their life cycle, promoting the maintenance and fluidity of chloroplasts and plasma membranes, increasing yield, reducing oxidative stress, enhancing respiratory potential, and providing protection against insects, pathogens, and herbivores, at adequate doses. Beyond the animal and plant contexts, selenium's application is interdisciplinary, being used in metallurgical, chemical, pigment, and electronics industries [47], in addition to its use in the manufacturing of rectifiers, photovoltaic cells, bleaching agents, pigments, lubricants, and aerospace devices [2].

4. Nanoscience and Nanotechnology: SeNPs

Given the inherent duality of the element, especially when employed in its pure and inorganic form, there has been a growing interest in the application/production of selenium through nanotechnology. Recently, SeNPs have gained attention from the scientific community as a possible source of the element, due to their chemical stability, biocompatibility, and low toxicity when compared to other forms of the element, such as selenate and selenite ions [62]. Additionally, SeNPs are recognized for their unique physicochemical properties, which provide exceptional functionalities at the nanometric scale, such as potential as drug delivery vehicles, which may replace or enhance drug action [62–64]. The potentialities of the element, including to reduce toxicity, especially of the inorganic form, are related to the synthesis processes of SeNPs and, consequently, the smaller surface area per unit volume occupied by the NPs, in addition to being less interactive and releasing selenium more slowly [62].

4.1. Preparation of SeNPs

The preparation of SeNPs is crucial for their efficacy in therapeutic applications, as it involves the precise control of factors such as the concentration of precursor, reducing and stabilizing agents, pH, reaction temperature, and preparation time, which determine essential properties of SeNPs such as size, polydispersity index (PDI), purity, zeta potential (ZP), surface functionality, composition, and different morphologies [62,65]. Regarding their composition, they can be classified as organic, containing some biological material, such as liposomal, micellar, and hydrogel polymeric NPs, and inorganic, containing chemical materials, such as metallic and metal oxide NPs [53]. Morphological studies reveal that SeNPs can take on different shapes, such as nanowire (NWs) [66], nanotube (NTs) [67], nanoneedle [68], nanorod (NRs) [69], nanoflowers [70], nanobelts [71], and nanospheres [72], depending on the reagents or solvents used, the distinct nucleation forms

the NPs underwent, and the conditions of the medium they were subjected to during preparation [73,74]. Of these, nanospheres are the most prominent for their pharmacological and biological functionalities [74,75].

Considering the commercial potential and the wide range of application fields of NPs, another essential aspect related to synthesis is the preparation methods, aiming to ensure high yield and controlled quality [76]. Among the methods used for NP synthesis are (a) top-down approaches, which involve the reduction of material to nanostructures by physical and mechanical methods; and (b) bottom-up approaches, which involve the coalescence/construction/assembly of nanomaterials from atoms and molecules [23,77,78] (Figure 1).

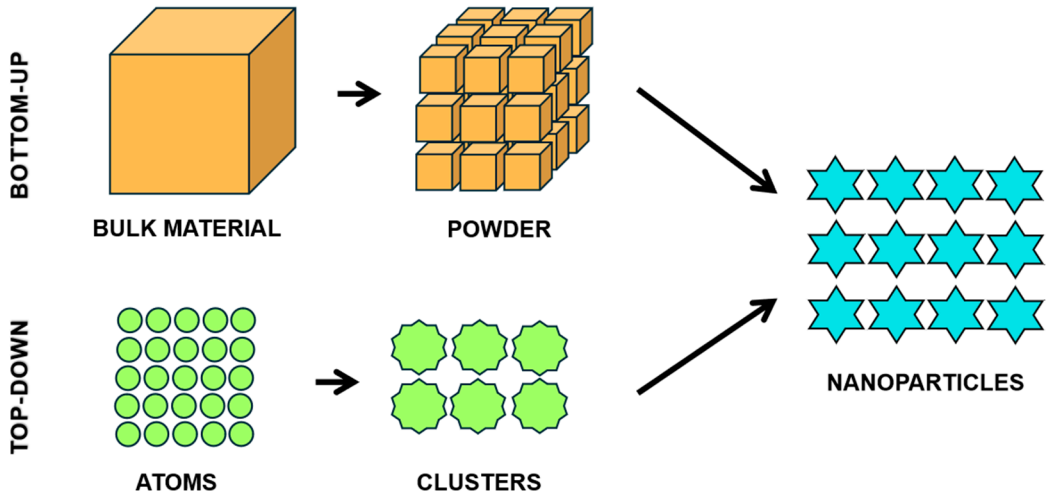

Figure 1. Scheme of nanoparticle preparation methods: bottom-up and top-down.

Synthesis methods are frequently used to enhance the characteristics of NPs, such as size, stability, and crystallinity, and can be categorized into the following three preparation methods: (a) physical methods; (b) chemical methods; and (c) biological methods [40,75] (Figure 2). Physical and chemical methods are less prevalent due to their disadvantages compared to biological methods, which stand out for being environmentally safe and sustainable, as well as offering fast synthesis and high reproducibility [40]. However, studies present in indexed databases show the predominance of chemical methods over physical.

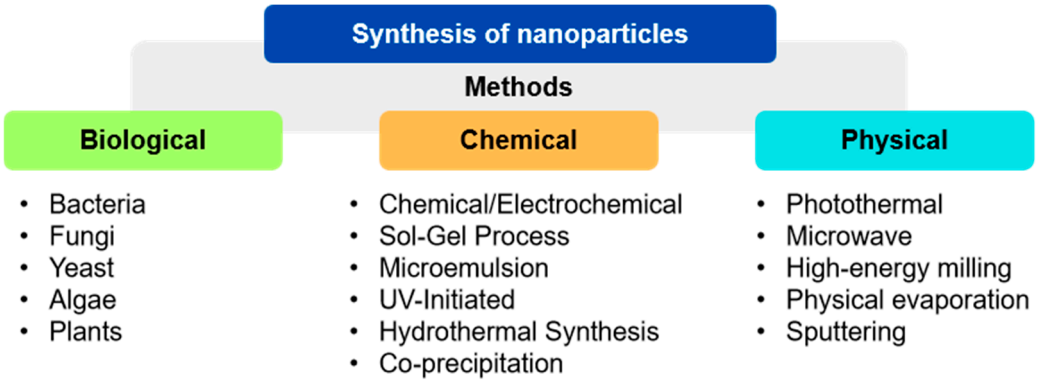

Figure 2. Scheme of synthesis methodologies using biological, chemical, and physical methods.

Physical (photothermal, microwave, high-energy milling, physical evaporation, and sputtering) and chemical (chemical/electrochemical, sol-gel, microemulsion, UV-initiated,

and hydrothermal synthesis) methods, although extensively studied, exhibit significant limitations, including low energy efficiency, high costs, the use of multiple hazardous reagents, and the consequent generation of waste, making them less appealing. In contrast, biological methods stand out as an environmentally safe, non-toxic, and sustainable synthesis alternatives, offering advantages such as rapidity, high reproducibility, and the use of organisms such as bacteria, fungi, yeasts, algae, and plants in the synthesis process [40,79].

4.1.1. Chemical Synthesis Methods

Chemical synthesis methods are considered methodologically simple, as they do not require advanced technological instruments or the incubation of bio-organisms [74]. Nonetheless, they present challenges related to ecology and toxicology, as well as risks associated with the use of hazardous chemical compounds [40]. Among the chemical methods that can be applied for the synthesis of SeNPs are the sol-gel method, microemulsion, hydrothermal, polyol synthesis, vapor phase synthesis, and chemical vapor deposition, with the chemical reduction technique being the most prominent due to its simplicity of action [40,76].

Chemical reduction is the most common and widely recognized methodology in the literature, consisting of two main steps: reduction and stabilization. In the reduction step, reducing agents such as ascorbic acid ($C_6H_8O_6$), acetic acid (CH_3COOH), oxalic acid or ethanedioic acid ($C_2H_2O_4$), glucose ($C_6H_{12}O_6$), and L-cysteine ($C_3H_7NO_2S$) transform selenium salts like sodium selenite (Na_2SeO_3), selenium tetrachloride ($SeCl_4$), and sodium selenosulfate (Na_2SeSO_3) into SeNPs, adjusting reaction conditions to control the size and shape of the NPs [40]. In the stabilization step, stabilizers are employed to prevent NPs aggregation by creating repulsive forces that control NP growth, thereby influencing their size and final shape [80]. This step is of utmost importance, as unstabilized SeNPs tend to precipitate within a few days, losing their homogeneity and properties over time [74].

4.1.2. Physical Synthesis Methods

Physical methods, although they do not generate many chemical byproducts, demand more energy and special equipment [30,75,76]. Some of the most frequently used physical methods for generating NPs in general include electrodeposition, synthesis associated with photothermal and microwave methods [27,46], high-energy milling, physical evaporation, sputtering [76], and pulsed laser ablation (PLA) [74].

Among this set of techniques, the synthesis of SeNPs through microwaves is widely recognized as the most conventional approach for heating in laboratories, employing selenium salts in an aqueous solution. This technique offers benefits such as rapid and uniform heating and reaction, as well as higher reaction rates and reduced energy consumption [74]. Another widely used physical technique in the production of SeNPs is PLA. In this method, PLA is dissolved in deionized water, resulting in the transformation of selenium pellets into colloidal solutions. The electric charge present in the medium prevents the agglomeration of SeNPs, generating an electric charge on the surface of the particles [74].

4.1.3. Biological Synthesis Methods

Differing from chemical and physical approaches, the synthesis of SeNPs using bioagents is seen as a positive potential alternative to conventional methodologies. The green synthesis of SeNPs is achieved through the process of bioreduction and stabilization of precursor agents (sodium selenite, selenium tetrachloride, sodium selenosulfate, and others) from biomolecules present in biological organisms, avoiding the use of harmful reducing agents [40,81]. The observed reduction can be attributed to the induction caused by functional groups, such as amines and alkanes, present in metabolites like flavonoids, tannins, alkaloids, steroids, and terpenoids, resulting in red-colored SeNPs [74,79,82]. Additionally,

phenolic compounds, polysaccharides, saponins, enzymes, proteins, and sugars can also play significant roles in this process [83].

Various classes of biological agents are investigated for their crucial roles in biosynthesis, including yeasts, actinobacteria, enzymes [82], fungi, protozoa [74], photosynthetic organisms such as plants and algae [83,84], and bacterial strains (anaerobic, aerobic, and anoxic) [74,83]. Additionally, studies report an increase in the use of aerobic and anaerobic bacteria due to their effectiveness in reducing inorganic selenium and rapidly forming SeNPs [36]. This capability was also investigated by Bafghi et al. (2021) [85] in pathogenic fungi, such as *Aspergillus flavus* and *Candida albicans*, highlighting the versatility of these biological processes.

The biosynthesis of SeNPs by Gram-positive and Gram-negative bacteria occurs as described in the following four phases: (1) transport of selenium oxyanions from sulfate transport proteins (permeases) into the cells; (2) reduction of selenium to amorphous red elemental selenium (Se^0) by bacterial proteins, with subsequent release into the extracellular medium; (3) formation of SeNPs through the continuous reduction of selenium oxyanions to Se^0; and (4) separation of SeNPs from bacterial cells and other cellular components by centrifugation and filtration. To optimize the process, it is essential to control factors such as temperature, rotation, the pH of the growth medium, incubation time, selenium salt concentration, minimum inhibitory concentration (MIC), and the reducing potential of the microorganisms [74].

When compared to fungi and bacteria, the use of plant extracts is widely addressed in the literature for the biosynthesis of SeNPs. This is due to their higher bioavailability, safety, and ease of manipulation, as well as the use of less toxic solvents and a more efficient production process [74]. The nanostructures can be prepared from leaves, shoots, fruits, seeds, or pulp of plants [83]. Another important point is the use of plant extracts derived from agricultural waste, such as fruit peels, which are increasingly valued due to their rich composition of bioactive compounds. These can include various functional groups such as lignin, proteins, lipids, hydrocarbons, and starch [37]. Additionally, this practice promotes sustainability by utilizing by-products that would otherwise be discarded, considering the abundance of such waste in agricultural countries [35,86].

5. Antimicrobial Activities of SeNPs Synthesized by Different Routes

According to the World Health Organization (WHO), the global spread of multidrug-resistant microorganisms (MDR) is considered one of the major concerns for society today. WHO estimates that, by 2050, around ten million deaths could occur annually due to infections caused by pathogenic microorganisms [87]. The main cause of the increase in antimicrobial resistance (AMR) in widely used therapies is the growing adaptation of microorganisms to the excessive use of these drugs [88].

Throughout evolution, bacteria and fungi have developed resistance to multiple antimicrobials, facilitated by both excessive use and genetic modifications, over the years [89,90]. In response to the challenge of combating microorganisms and the exponential increase in microbial resistance—considering historical changes such as enzymatic degradation, antibiotic modification, and alterations in bacterial cell wall permeability [89,91]—the concept of "human chemical evolution" emerges. In this context, humans have sought to develop safer, more effective, and more bioavailable therapeutic methods [90].

The antimicrobial activity of NPs is evidenced by several studies, highlighting their dependence on physicochemical properties such as size and surface charge [15,75,92], as the adherence of NPs to the cell walls and membranes of microorganisms can lead to the destruction of bacterial and cellular membranes, interruption of energy transfer, inhibition of enzymatic activity, and DNA synthesis [85,93].

Studies demonstrate that SeNPs can damage cellular structures, inducing the production of reactive oxygen species (ROS), and altering signal transduction mechanisms in certain biological organisms, such as fungi and bacteria, due to their physical, chemical, electrical, optical, magnetic, semiconducting, catalytic, and biological properties [85].

5.1. Biogenic SeNPs

5.1.1. Antifungal Properties

Due to their antifungal potential, recent studies have investigated the properties of green SeNPs, which utilize plants and microorganisms to reduce selenium ions to NPs, acting against various pathogenic species, and their potential is noteworthy.

A study conducted by El-Saadony et al. (2021) [94] synthesized SeNPs using *Lactobacillus paracasei* cells (HM1) (MW390875) (Lab-SeNPs), a Gram-positive bacterium found in human breast milk, to assess their potential against pathogenic fungi. The study compared the activity of Lab-SeNPs with chemically synthesized SeNPs (Che-SeNPs) at concentrations of 15 at 75 µg/mL. Agar Disk Diffusion tests showed that higher concentrations of Lab-SeNPs produced larger halos, with the largest reaching 29 mm. The MIC revealed that, except for *C. albicans*, which maintained an MIC of 55 µg/mL for both NPs, all other tested strains had a lower MIC with Lab-SeNPs than with Che-SeNPs. For *Candida parapsilosis*, *Fusarium oxysporum*, *Fusarium solani*, *Candida krusei*, *Candida glabrata*, and *Candida tropicalis*, Lab-SeNPs had MICs from 60 to 70 µg/mL, respectively, while Che-SeNPs had MICs from 65 to 80 µg/mL, respectively. To ensure complete fungal death, the minimum fungicidal concentration (MFC) was assessed, showing that Lab-SeNPs (130–180 µg/mL) caused greater mortality compared to Che-SeNPs (98–150 µg/mL). These results indicate higher antifungal efficacy of biosynthesized NPs compared to chemically synthesized ones (Table 1).

Table 1. The antifungal activity of selenium nanoparticles (SeNPs) synthesized by the biogenic method using bacteria.

	NPs	Species	NP Size (nm)	DLS	Color NP Solution	Evaluated Microorganisms	Antifungal Parameters SeNPs	Ref.
BACTERIA	He-SeNPs	*Halomonas elongata*	(SEM) 11–50 (TEM) 5–25	-	-	*C. albicans*	24 h: 55.14–66.17% 48 h: 60.96–70.86% 72 h: 58.31–61.52%	[15]
	Lab-SeNPs	*Lactobacillus paracasei (HMI)* (MW390875)	(DLS) 56.91 ± 1.8 (TEM) 3–50	(ZP) 20.1 ± 0.6 mV	Red	*C. albicans ATCC 4862* *C. parapsilosis ATCC 22019* *F. oxysporum ATCC 62506* *F. solani ATCC 38341* *C. krusei ATCC 14243* *C. glabrata ATCC 64677* *C. tropicalis ATCC 66029*	MIC 55–70 µg/mL MFC 80–130 µg/mL	[94]
	Pt-SeNPs	*Paenibacillus terreus*	(DLS) 200–220 (FESEM) 220–240	(PDI) 0.265 (ZP) −37.77 mV	-	*C. albicans*	MIC 3.90–500 µg/mL	[95]

Dynamic light scattering (DLS); polydispersity index (PDI); zeta potential (ZP); nanometer (nm); transmission electron microscopy (TEM); scanning electron microscopy (SEM); field emission scanning electron microscopy (FESEM); minimum inhibitory concentration (MIC); and minimum fungicidal concentration (MFC).

A study by Nile et al. (2023) [95] investigated the synthesis of SeNPs using *Paenibacillus terreus* (Pt-SeNPs), a Gram-positive bacterium, as a reducing agent, to evaluate the activity

of these NPs, with or without nystatin—a widely used antifungal for topical and oral infections—against *C. albicans* in terms of growth inhibition, morphogenesis, and biofilm formation. The results showed that the antifungal activity of SeNPs is dose-dependent and limited, with growth inhibition below 50% at concentrations of 3.90–500 μg/mL and similar effects on biofilm formation. The activity of nystatin, both pure and in combinations, was also dose-dependent but still inferior to the antifungal activity of pure Pt-SeNPs. In contrast, Pt-SeNPs loaded with nystatin (SeNP@PVP_Nystatin) were effective at all tested concentrations, with more than 50% efficacy at the lowest concentration (3.90 μg/mL), for both antibiofilm action and antifungal activity. These results suggest that SeNP@PVP_Nystatin nanoconjugates may represent an effective strategy in combating fungal infections caused by *C. albicans* (Table 1).

Other studies address the synthesis of SeNPs from bacteria against *C. albicans*. A study conducted by Safaei et al. (2022) [15] biosynthesized SeNPs from *Halomonas elongata* (He-SeNPs), a Gram-negative aerobic γ-proteobacterium, by varying the incubation time and concentrations of glucose and sodium selenite (Na_2SeO_3), in order to evaluate their antifungal action against *C. albicans* using the colony-forming units (CFU) method. Nine synthesis conditions for He-SeNPs were evaluated. One of them inhibited over 70% of growth during 48 h, using the highest concentrations of He-SeNPs and glucose (0.8 and 7.5 mg/mL). The authors concluded that the positive result was due to the concentrations of He-SeNPs, glucose, and incubation time, estimating that, under ideal conditions, He-SeNPs inhibited approximately 72.01% of fungal growth (Table 1).

Bafghi et al. (2021) [85] synthesized SeNPs mediated by strains of *C. albicans* TIMML-1306 (Ca-SeNPs) and *A. flavus* TIMML-050 (Af-SeNPs), with the aim of investigating their potential and comparing them with commercial antifungals. Sodium selenate (Na_2SeO_4) was used for synthesis at various concentrations (0.125 to 64 μg/mL). The results showed that all tested strains were sensitive to the antifungals at concentrations $\leq$ 2 μg/mL, except for *A. flavus*, which was 100% resistant to itraconazole (ITC). The Ca-SeNPs and Af-SeNPs showed a minimum inhibitory concentration starting at 0.25 μg/mL. The combination of Ca-SeNPs + ITC was also evaluated, with sensitivity detected from 1 μg/mL for *C. parapsilosis* and 2 μg/mL for *C. albicans*. However, using 100% Ca-SeNPs, sensitivity was observed at the lowest concentration tested, 0.125 μg/mL (Table 2).

In the same year, the same authors [96] biosynthesized SeNPs and silver nanoparticles (AgNPs) using *Nepeta* extract (Ne-SeNPs) and *Berberine* (Be-AgNPs), respectively, and combined these NPs with the commercial antifungals ITC, amphotericin B (AMB), and anidulafungin (AFG), testing them against the same strains. To evaluate susceptibility, concentrations ranging from 0.125 to 64 μg/mL were tested for both NPs and medications. For *C. albicans* TIMML-1306, Ne-SeNPs (1.0 μg/mL) were more efficient at inhibiting growth compared to pure ITC (64 μg/mL), while the strains *Aspergillus fumigatus* TIMML-025 (*A. fumigatus*), *C. parapsilosis* ATCC-2201, *C. albicans* TIMML-491, and *A. flavus* TIMML-050 were sensitive to AMB and AFG at concentrations of 1 and 4 μg/mL, respectively; meanwhile, Be-AgNPs and Ne-SeNPs were effective at lower concentrations, namely 0.125 and 0.5 μg/mL, respectively. The combination of antifungals with ITC was evaluated, revealing that Be-AgNPs and Ne-SeNPs have similar activity with or without itraconazole, and that Ne-SeNPs + ITC and Be-NP + ITC were effective against *A. flavus* TIMML-050 at concentrations of 1 and 2 μg/mL, respectively, showing similar efficacy when used alone (Table 2).

Hashem et al. (2022) [97] synthesized SeNPs from the extract of Prickly Pear peel—Indian fig (PPPW-SeNPs)—and applied them against *C. albicans* and *Cryptococcus neoformans*. The antifungal capacity of PPPW-SeNPs was evaluated at different concentrations (1.95–2000 μg/mL) using the agar diffusion method, showing a dose-dependent relationship,

with the highest concentration producing the largest inhibition halo, resulting in zones of 59.5 ± 0.7 mm and 50.2 ± 1.1 mm for *C. albicans* and *C. neoformans*, respectively. The minimum inhibitory concentration (MIC) test was performed with PPPW-SeNPs, isolated extract, and the combination of ampicillin/sulbactam/amphotericin B. Only the extract and the antibiotic combination did not demonstrate satisfactory efficacy, highlighting the superiority of SeNPs over these conventional treatments (Table 2).

Table 2. The antifungal activity of selenium nanoparticles (SeNPs) synthesized using the biogenic method using fungi and plants.

	NPs	Species	NP Size (nm)	DLS	Color NP Solution	Evaluated Microorganisms	MIC_SeNPs	Ref.
FUNGI	Ca-SeNPs	*C. albicans TIMML-1306*	(XRD) 38	(PZ) −19 mV	Red	*C. glabrata TIMML-1316* *C. krusei TIMML-1321* *C. glabrata TIMML-368*	0.25–0.5 µg/mL	[85]
						C. albicans TIMML-1306	<1 µg/mL	
						C. albicans TIMML-183	0.25 µg/mL	
						C. albicans TIMML-491	0.5 µg/mL	
						C. albicans TIMML-1291	0.125–64 µg/mL	
						C. parapsilosis ATCC-2201	0.125–64 µg/mL	
	Af-SeNPs	*A. flavus TIMML-050*	(XRD) 37	(PZ) −21 mV	Red	*A. fumigatus TIMML-025* *A. flavus TIMML-050*	1 µg/mL	
PLANTS	Ne-SeNPs	*Nepeta* (gender)	(SEM) 37–46	-	Red	*C. albicans TIMML-1306*	1 µg/mL	[96]
						C. albicans TIMML-1291	1 µg/mL	
						C. albicans TIMML-491	0.5 µg/mL	
						A. flavus TIMML-050	0.125 µg/mL	
						C. tropicalis TIMML-1316	0.125 µg/mL	
						C. krusei TIMML-1321	0.125 µg/mL	
	PPPW-SeNPs	Prickly Pear Peel Waste (PPPW)	(TEM) 50–150	-	Reddish	*C. albicans*	3.9 µg/mL	[97]
						C. neoformans	7.81 µg/mL	

Dynamic light scattering (DLS); zeta potential (ZP); nanometer (nm); X-ray diffraction (XRD); transmission electron microscopy (TEM); scanning electron microscopy (SEM); minimum inhibitory concentration (MIC).

5.1.2. Antibacterial Properties

The potential of green SeNPs, derived from plants and bacterial species beneficial for human health, is also widely discussed, regarding their antibacterial activities against medically important bacteria (Table 3).

Abbas et al. (2021) [98] synthesized Sp-SeNPs (5 and 10 mM) from algae derived from *Spirulina platensis*, which were applied against Gram-negative bacteria—*Salmonella abony*, *Escherichia coli* and ten clinical isolates of *Klebsiella pneumoniae*. The results showed that the MICs of the SeNPs ranged from 25 to 200 µg/mL, with significant efficacy at 25 µg/mL. The most susceptible strains were *S. albony* NCTC 6017, followed by *K. pneumoniae* and *E. coli*, for 10 mM SeNPs. Among the *K. pneumoniae* isolates, 50% did not exhibit an inhibition zone for SeNPs at any sodium selenite concentration.

Bacteria beneficial for human health, such as probiotics, are also being investigated for the synthesis of SeNPs. An investigation of the production capacity of SeNPs using the probiotic *Bacillus subtilis* BSN313 (Bs-SeNPs) was carried out by Ullah et al. (2021) [36] at different concentrations (100, 150, and 200 µg/mL) and against both Gram-negative bacteria, namely *E. coli* ATCC 8739 and *Pseudomonas aeruginosa* ATCC 9027, and Gram-positive bacteria, namely *Staphylococcus aureus* ATCC 25923. The study indicated that Bs-SeNPs showed the formation of inhibition zones at the highest tested concentration after 24 h of incubation at 35 °C.

In another study, conducted by Alam et al. (2020) [99], strains of *E. coli*, *P. aeruginosa*, *S. aureus*, and *K. pneumoniae* were treated with SeNPs mediated by the probiotic bacterium *Lactobacillus acidophilus* (La-SeNPs) to assess their efficacy on planktonic cells and pre-formed biofilms. The activity of La-SeNPs was compared with gentamicin, a widely used antimicrobial agent. The results indicate that gentamicin has a lower MIC than La-SeNPs for *E.*

coli and *B. subtilis*, whereas, for *S. aureus*, *La-SeNPs* (1.2 µg/mL) exhibited a lower MIC than gentamicin (0.5–2.0 µg/mL). For *K. pneumoniae* and *P. aeruginosa*, La-SeNPs demonstrated high efficiency, with a lower MIC (6.5 µg/mL and 4 µg/mL, respectively) compared to gentamicin (≥120 µg/mL and ≥180 µg/mL, respectively). The results for SeNPs against biofilms were concentration-dependent, showing especially high effectiveness against *E. coli*, *S. aureus*, and *P. aeruginosa*.

The antibacterial activity of SeNPs derived from fruits and agricultural residues is well established. Abou and Abbas (2023) [100] produced biogenic SeNPs from the aqueous extract of pomegranate peel (PPAE), with and without copper sulfate coating (PPAE-SeNPs@CuO and PPAE-SeNPs, respectively), against ten strains of *Helicobacter pylori*. Antibacterial activity was assessed using the agar diffusion test, with wells filled with 100 µg/mL of NPs in pre-inoculated media. The results showed that the inhibition zone of PPAE-SeNPs@CuO (11–15 mm) was larger than that of PPAE-SeNPs (0–9 mm). The MIC test demonstrated that all isolates were resistant to metronidazole (5 µg), clarithromycin (15 µg), levofloxacin (5 µg), amoxicillin/clavulanic acid (20/10 µg), tetracycline (30 µg), and amoxicillin (10 µg), whereas PPAE-CuO@SeNPs (8 µg/mL) was able to inhibit 100% of the multidrug-resistant strains.

A study by Khudier et al. (2023) [101] synthesized SeNPs from the fruit of *Vaccinium arctostaphylos* (L.) (Va-SeNPs) at different concentrations (500, 250, 125, 62.5, and 31.25 µg/mL) against *S. aureus* ATCC 29213, *E. coli* ATCC 25922, and *Corynebacterium diphtheriae* ATCC 13812. The analysis compared the use of Va-SeNPs with the pure extract and the antibiotic ciprofloxacin (positive control). The results showed that the actions of Va-SeNPs are dose-dependent, with inhibition zones exceeding 12 mm, larger at higher concentrations (500 µg/mL). Compared to the positive control, Va-SeNPs were more effective only at the concentration of 500 µg/mL for *S. aureus*, while the pure extract showed inhibition zones smaller than 12 mm.

PPPW-SeNPs were also used to evaluate antibacterial efficacy against *E. coli*, *P. aeruginosa*, *B. subtilis*, and *S. aureus*, at varying concentrations (1.95–2000 µg/mL), by Hashem et al. (2022) [97]. The activity of the PPPW-SeNPs was dose-dependent, with varying MICs for the tested strains, as follows: *E. coli* and *P. aeruginosa* (125 µg/mL), *B. subtilis* (62.5 µg/mL), and *S. aureus* (15.62 µg/mL). At 2000 µg/mL, PPPW-SeNPs showed inhibition zones of 26.5 ± 0.70 mm for *E. coli*, 24.4 ± 0.85 mm for *P. aeruginosa*, 30.7 ± 0.53 mm for *B. subtilis*, and 48.7 ± 1.06 mm for *S. aureus*. Tests with the pure extract and with ampicillin/sulbactam/amphotericin B (SAM/AMB) showed that the extract had no antibacterial activity, while SAM/AMB inhibited all strains except *E. coli*, with inhibition zones of 14.5 ± 0.5 mm for *P. aeruginosa*, 15.6 ± 0.4 mm for *B. subtilis*, and 10.1 ± 0.9 mm for *S. aureus*.

Table 3. The antibacterial activity of selenium nanoparticles (SeNPs) synthesized using the biogenic method using fungi and plants.

	NPs	Species	NP Size (nm)	DLS	Color NP Solution	Evaluated Microorganisms	MIC_SeNPs	Ref.
BACTERIA	Bs-SeNP	*B. subtilis BSN313*	(DLS) 530 (TEM) 280–630	(PZ) −26.9 mV	Red	*E. coli ATCC 8739* *Staphylococcus aureus ATCC 9027* *Pseudomonas aeruginosa ATCC 25923*	200 µg/mL	[36]
	La-SeNP	*L. acidophilus*	(DLS) 34.13 (TEM) 2–15	(PDI) 0.28 (PZ) +37.86 mV	Reddish-brown	*E. coli* *S. aureus* *B. subtilis* *P. aeruginosa* *K. pneumoniae*	9.4 µg/mL 1.2 µg/mL 3.5 µg/mL 6.5 µg/mL 4 µg/mL	[99]

Table 3. *Cont.*

	NPs	Species	NP Size (nm)	DLS	Color NP Solution	Evaluated Microorganisms	MIC_SeNPs	Ref.
ALGAE	Sp-SeNP	*Spirulina platensis*	(TEM) 79.40 ± 44.26 >100 nm (53.33%)	(PZ) −32.9 ± 8.12 mV	Red orange	*S. abony NCTC 6017* *E. coli ATCC 8739* *K. pneumonia ATCC700603*	25 µg/mL	[98]
PLANTS	PPPW-SeNP	Prickly Pear Peel Waste (PPPW)	(TEM) 50–150	-	Reddish	*E. coli* *P. aeruginosa* *B. subtilis* *S. aureus*	125 µg/mL 62.5 µg/mL 15.62 µg/mL	[97]
	PPAE-SeNPs PPAE-SeNPs@CuO	*Punica granatum*	(HRTEM) 1.97–10.56 (HRTEM) 92.18	-	Red Orange	*H. pylori*	8 µg/mL	[100]
	Va-SeNP	*V. Arctostaphylos* (L.)	(DLS) 246.2 ± 4.51 (FESEM) 50 ± 1.23	(PDI) 0.267 (PZ) −11.5 mV ± 1.24	Red	*S. aureus* *E. coli* *C. diphtheriae*	500–31.25 µg/mL	[101]

Dynamic light scattering (DLS); zeta potential (ZP); nanometer (nm); transmission electron microscopy (TEM); field emission scanning electron microscopy (FESEM); high-resolution transmission electron microscopy (HRTEM); minimum inhibitory concentration (MIC).

These studies confirm that SeNPs, synthesized from various natural reducing agents such as bacteria, fungi, fruit extracts, and agricultural residues, exhibit significant antifungal activity against several pathogenic species, and are often more effective than commercial antifungals, especially when used in combination.

5.2. Chemical SeNPs

Dorazilová et al. (2020) [102] demonstrate the development of polymeric scaffolds based on collagen–chitosan with SeNPs for application in infected and chronic wounds, acting against *S. aureus* and methicillin-resistant S. aureus (MRSA) and *Staphylococcus epidermidis*. In this study, the two SeNPs were prepared from the reduction of sodium selenite (Na_2SeO_3): one with carboxymethyl cellulose (SeCE), using mercaptopropionic acid in the presence of carboxymethyl cellulose, and the other with chitosan (SeCH), using mercaptopropionic acid in the presence of chitosan. The following three concentrations were evaluated: 1, 5, and 10 ppm. The study results demonstrate that the scaffolds prepared with SeNPs (antibacterial agents) increased the material's potential, showing that, even at low concentrations of SeNPs, such as 5 ppm, they showed considerable inhibition activity against the bacterial strains (Table 4).

Table 4. The antibacterial activity of selenium nanoparticles (SeNPs) synthesized by chemical and physical methods.

	NPs	Precursor Agent	Reducing Agent	Stabilizing Agent	NP Size (nm)	Tested Bacteria	Antibacterial Parameters	Ref.
CHEMICAL	SeNPs	(Na_2SeO_3) Sodium selenite	Mercaptopropionic acid	Biopolymer	50–300	*S. aureus* *MRSA* *S. epidermidis*	5 ppm	[102]
	SeNPs	(Na_2SeO_3) Sodium selenite pentahydrate	$C_6H_8O_6$ Ascorbic acid	-	(DLS) 66 ± 8 (TEM) 61 ± 7	*MRSA*	MIC 32 µg/mL	[103]
	SeNP-ε-PL	(SeO_2) Selenium dioxide	$Na_2S_2O_3$ Sodium thiosulfate	PVA/ε-PL	(TEM) 80	*S. aureus* *MRSA* *E. faecalis* *E. coli* *A. baumannii* *P. aeruginosa* *K. pneumoniae* *K. pneumoniae (MDR)*	MIC 6.0–26.2 µg/mL MBC 12.6–63 µg/mL	[104]

Table 4. *Cont.*

	NPs	Precursor Agent	Reducing Agent	Stabilizing Agent	NP Size (nm)	Tested Bacteria	Antibacterial Parameters	Ref.
PHYSICAL	SeNPs	Bulk Se pellets (target)	-	-	(DLS) 144 ± 46	MDR-EC *P. aeruginosa* *S. Aureus* *MRSA*	MIC: 2.35 ppm MIC: 4.45 ppm MIC: 12.77 ppm MIC: 14.26 ppm	[105]
	PVA/CS/SeNPs	Selenium plate	-	-	(XRD) 17	*E. coli* *P. aeruginosa* *S. aureus* *B. subtilis*	10 min 33–56% * 30 min 44–69% *	[106]

Dynamic light scattering (DLS); transmission electron microscopy (TEM); X-ray diffraction (XRD); minimum inhibitory concentration (MIC); and minimum bactericidal concentration (MBC). * Diameter of inhibition zone and activity index of tested samples.

Antibacterial activity in wounds was also evaluated by Golmohammadi et al. (2020) [103]. The authors developed a selenium–chitosan–mupirocin nanohybrid system (M-SeNPs-CCH) against *S. aureus* infection in diabetic rats. Wound healing evaluation was performed macroscopically and microscopically. Macroscopically, the authors observed that wound size contraction decreased with more significance in treatments with the presence of SeNPs over 21 days. A microscopy analysis of the wound tissue confirmed that the treatment with nanoparticles led to an increase in collagenization and epidermization (Table 4).

A study by Huang et al. (2020) [104] evaluated the multimodal capability of SeNPs coated with the antimicrobial polypeptide ε-poly-l-lysine (SeNP-ε-PL) against Gram-negative and Gram-positive bacteria. The SeNPs were synthesized from the precursor Na_2SeO_3. The MIC and minimum bactericidal concentration (MBC) evaluations compared the use of SeNP-ε-PL with pure SeNPs and ε-PL. For Gram-positive bacteria, the authors observed that SeNP-ε-PL exhibited similar or lower MICs compared to the treatment with pure isolates, while Gram-negative bacteria showed a significant reduction in MIC, like the use of pure ε-PL. MBC results, assessed via CFU tests, demonstrated that SeNPs displayed greater activity compared to the use of pure ε-PL, whereas the opposite was observed for Gram-negatives. SeNP-ε-PL exhibited strong antibacterial properties against all strains (Table 4).

5.3. Physical SeNPs

Geoffrion et al. (2020) [105] used the pulsed laser ablation in liquid (PLAL) technique to synthesize SeNPs. In this method, selenium pellets are irradiated with a laser while immersed in deionized water, followed by an ice bath to control the size and aggregation of the particles. The SeNPs were tested against Gram-negative bacterial strains: multidrug-resistant *E. coli* (MDR-EC) and *P. aeruginosa*, as well as Gram-positive strains: MRSA and *S. epidermidis*. The results demonstrated that SeNPs exhibited antibacterial properties in the concentration range of 0.05 to 25 ppm, with more pronounced inhibition in Gram-negative bacteria and higher MICs for Gram-positive bacteria. The results also indicated that the inhibition of MDR-EC was dose-dependent, with a concentration of 1 ppm being sufficient to cause significant inhibition, while at the concentration of 25 ppm, a strong bacterial inhibition was observed in all tested strains (Table 4).

Menazea et al. (2020) [106] used the laser ablation method to synthesize SeNPs from polyvinyl alcohol (PVA) and chitosan (PVA/chitosan/SeNP), aiming to evaluate the antibacterial activity of PVA/chitosan/SeNP and PVA/chitosan on agar plates against *E. coli*, *P. aeruginosa*, *S. aureus*, and *B. subtilis*. The PVA/chitosan/SeNP samples were subjected to ablation for 10 and 30 min, while the other compounds were not exposed. The results demonstrated that the NPs exposed to ablation exhibited higher antibacterial activity

compared to the PVA/chitosan mixture, with longer exposure times (30 min) showing greater activity against all tested strains (Table 4).

6. Antimicrobial Success of SeNPs: Mechanism of Action

The success of the antimicrobial activity of SeNPs, whether isolated or combined with widely used medical drugs, regardless of the synthesis method, against different species of fungi and bacteria, is associated with the antimicrobial mechanisms of action of these particles. Although few studies have thoroughly explored these mechanisms, the following are generally highlighted: (1) cell wall and membrane damage; (2) intracellular penetration and damage; and (3) induction of oxidative stress [107,108].

The damage to the cell wall and membrane by SeNPs is considered the main antimicrobial mechanism of action [107]. The cell wall, as well as the plasma membrane, are recognized as protective barriers against environmental threats, maintaining homeostatic balance and allowing intracellular nutrient transport, which is crucial for the antimicrobial action of nanoparticles [107,109,110]. Studies report that the interaction of SeNPs with the cell wall and membrane begins with the adhesion of the particles, through the electrostatic attraction between the negatively charged microbial membrane and the positively or less negatively charged SeNPs. This interaction causes structural and morphological changes in the membrane, resulting in depolarization, the rupture of cellular integrity, compromised permeability, the disruption of respiratory functions, rupture of the cell wall, and, consequently, cell death [107,111–113].

Upon contact with the plasma membrane, SeNPs also affect metabolic functions, which can be enhanced when DNA and protein damage occurs [107]. The interaction of SeNPs with the surface of microorganisms can also trigger cellular oxidative stress upon absorption. Microorganisms attempt to overcome this stress through defense mechanisms; however, if the stress is relatively high, damage caused by reactive oxygen species (ROS) and free radicals can affect the cell wall and biomolecules present in the organism, such as proteins, lipids, and DNA. Studies show that ROS production is associated with cell death and, when combined with selenium in the form of nanoparticles, this action can be enhanced, explaining the high antimicrobial capacity of SeNPs [107].

7. Conclusions

During the construction of the review for the search of studies on SeNPs applications against fungi and bacteria, a large number of studies were observed, addressing that, among the various synthesis methods, the biogenic route is the most discussed in the literature. This is probably due to the higher activity of SeNPs mediated by biological organisms (plants, seeds, algae, bacteria, and fungi) against microorganisms of therapeutic interest, in addition to the fact that the use of biological agents during the synthesis enables the reduction of toxicity levels in applications and an increase in efficiency compared to other synthesis methods. The information presented in this review will serve as a basis for future research and the development of new applications of SeNPs in various microbiological contexts, facilitating the investigation of antimicrobial activities, as well as the knowledge about selenium and nanoparticles.

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