Fruit Waste to Nano-Wonders: Green Synthesis of Silver Nanoparticles for Microbial Application

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Abstract

Resistance of microbes developed as one of the most persistent worldwide threats to the health, which lead to the crucial need for advanced and sustainable antimicrobial solutions. The silver nanoparticles gathered a substantial consideration as a potential alternate to commercial antibiotics because of their antimicrobial activity against the pathogens that show the resistance against the drugs. However, AgNPs synthesis through the conventional methods majorly contains the use of harmful chemicals and involvement of intense energy procedures that cause risks to the health and environment as well. In this regard, green synthesis proposes an environment-friendly and economical method, where the natural materials such as fruit waste oils are utilized to produce AgNPs. The given review inspects the synthesis of the silver nanoparticles (AgNPs) using fruit oil acting as a reducing and stabilizing agent following the green approach, this procedure addresses not only the issue of food waste but also helps to minimize the ecological footprints caused by the production of nanoparticles. The synthesis process is explained in depth, while concentrating on the reduction and formation of silver ions and nanoparticles having the stability. The characterization of the AgNPs that are synthesized is carried out using a number of techniqies, including X-ray diffraction (XRD), UV-Vis spectroscopy and transmission electron microscopy (TEM), these techiques give the insights into the morphology, size and crystalline structure of the nanoparticles (NPs). Additionally, the AgNps are assessed for their antimicrobial properties, which underlines the working of the AgNps against the bacteria that are pathogenic in nature. Eventually, this work stresses on the formation of silver nanoparticles using the fruit waste oil following the green synthesis approach, aligning with the concept of sustainability and effective utilization of the resources, this provides an innovative way to fight against the microbes that are resistant and involvement in the sustainability of the environment.

Keywords: Silver nanoparticles, green synthesis, antimicrobial resistance, orange peel oil, microbial applications, fruit waste, sustainability

1. Introduction

Antibacterial resistance is arising as a global problem, as the infections are becoming harder to treat because of the antimicrobial resistance against the usually used antibiotics [1]. As the Fig 1. shows the development process of the resistant strains where, the high number of bacteria are present and few of them are resistant to antibiotics, the antibiotics kill bacteria causing the illness, as well as good bacteria protecting the body from infection, then the resistant bacteria now have preferred conditions to grow and take over, so the bacteria can now even transfer their drug-resistance to other bacteria, causing more problems and the development of the resistant strains.

Now this issue lead to the need of development of eco-friendly alternative agents having the anti-microbial properties. In this regard the silver nanoparticles are considered as an alternative source because of having a wide spectrum of antimicrobial properties [2]. But usually, the chemicals used in the traditional nanoparticle formation processes are highly toxic and require a higher consumption of energy as well and are noxious to the environmental and human health [3].

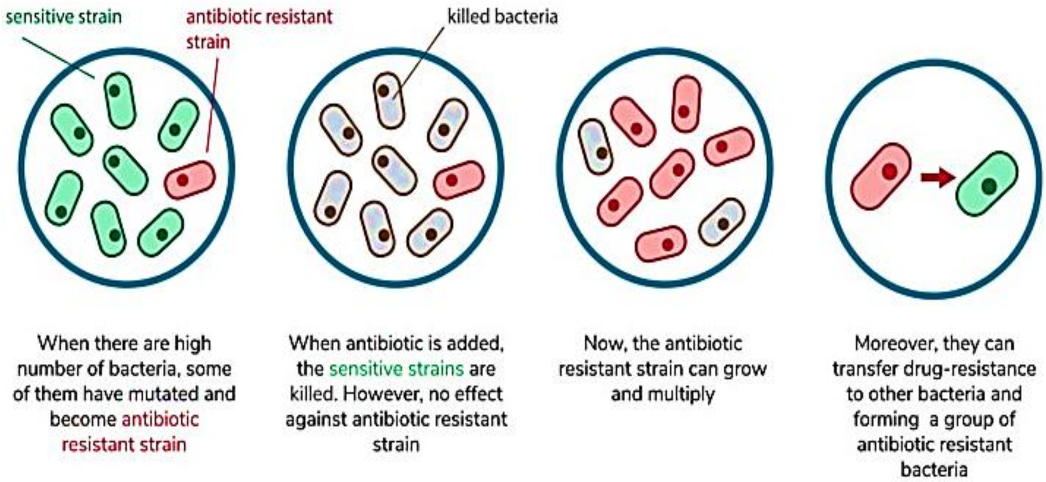

Fig 1. The resistance development process adopted by microbes

The green synthesis of nanoparticles using biological means like bacteria, plant extract and fruit waste is now a major area of interest due to its sustainable and eco-friendly nature. Different oils extracted from the fruit waste like orange peels have shown a promising role in the green synthesis procedure due to the presence reducing agents, so the reduction and stabilization of the nanoparticles is highly dependent on these oils. Moreover, the problem of food waste management can be addressed through the utilization of fruit waste [4]. The review helps to explore the formation of silver nanoparticles using orange peel oil through the green synthesis route, it also focuses on their antimicrobial application and characterization, while addressing the issue of development of anti-microbial resistance [5].

1.1 Nanoparticles and their Metallic Nature

Nanoparticles pose unique physical and chemical properties because of their nanoscale dimensions, which usually range from 1 to 100 nanometers [6]. Different nanoparticles like silver are known to have distinctive optical, thermal and electrical properties [7]. These nanoparticles have increased reactivity and studied to have enhanced interaction with the living systems when compared with the materials in bulk, this is because of the higher surface to volume ratio. Over time the silver nanoparticles have gained interest because of their antimicrobial and catalytic properties, which make them an appropriate choice for application in different fields like environmental remediation, medicine, cosmetics and electronics [8].

1.2 Green Synthesis of Nanoparticles

Green synthesis basically follows route to produce nanoparticles that are eco-friendly through different biological means such as fruit waste, plant extract and different microorganisms, where they act as reducing agents [9]. It is considered a more reliable route as the traditional nanoparticle synthesis procedures often involve the use of toxic chemicals and they usually consume intensive energy as well, whereas the green synthesis results in the reduction of usage of non-renewable resources, harmful byproducts and energy utilization [10]. As mentioned in the Fig 2. there are a number of routes that can be followed to synthesize the nanoparticles like top-to-bottom where the nanoparticles are formed from the bulk and bottom-to-top approach where the nanoparticles are formed from the atomic size, these are further divided into other categories based on the use of varied precursors. In recent times the fruit waste oils, like those from the orange peels are being considered beneficial for the synthesis of nanoparticles, as they are rich in bioactive compounds which are responsible for the reduction of the metal ions, like Ag^{+2} into Ag^{o}. They also help in the prevention of nanoparticles from agglomeration and make sure that the NPs are uniform throughout [3]. During this process the change in color is the first indication for the formation of NPs [9].

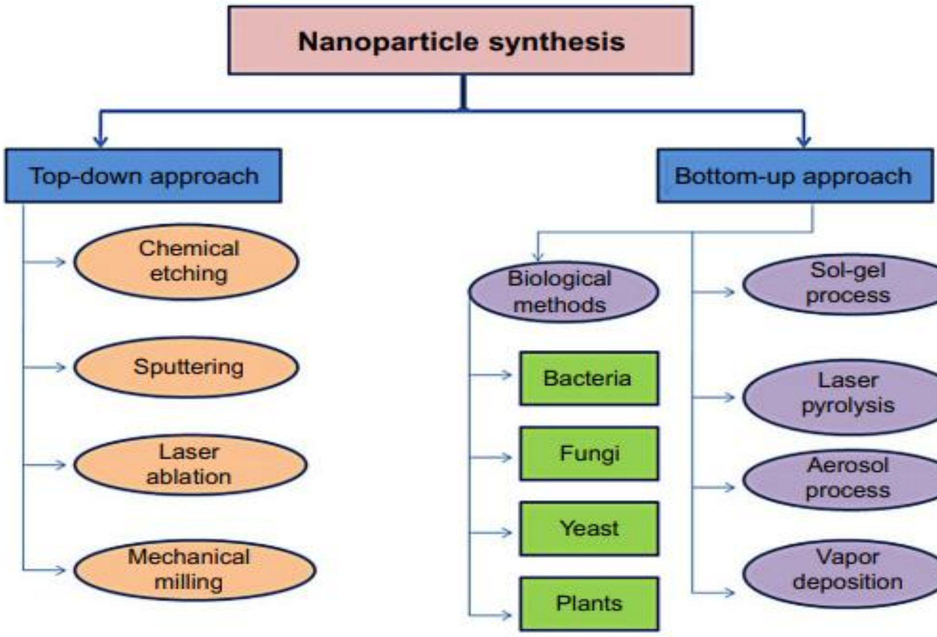

Fig 2. Different approaches for the formation of nanoparticles

1.3 Comparison of Green vs. Traditional Synthesis Methods

Traditional nanoparticles formation procedures by means of chemicals are harmful to the environment as it involves the use of chemicals like sodium bicarbonate or hydrazine which act as reducing agents and generates the toxic byproducts that go in the environment and contaminate it and pose great threat to human health as well [11]. These traditional methods also need intense energy input, usually aided by microwave radiation or high heating which makes this less sustainable and leaves environmental footprints. The chemicals involved in the process are also costly, which further reduces the viability of this procedure [12].

In contrary to this, the green synthesis involves the use of natural and biological materials like, plants, microbes and their wastes which act as reducing and stabilizing agents. These materials by nature are easily degradable, non-toxic, and are obtained from renewable resources which make this process more sustainable [10]. Moreover, the green synthesis formation process occurs under room temperature or marginally higher temperatures resulting in reduced energy consumption [8]. Through the environmental point of view, the utilization of food waste like fruit peels lines up with the concept of circular economy as it reuses the materials which or else are considered as waste, which makes the green synthesis process not only environmentally viable but also as a cost-effective method for nanoparticles formation [5].

1.4 Treatment Feasibility

As far as treatment feasibility is considered, the green and traditional synthesis processes both result in the formation of nanoparticles that contain the antimicrobial properties, yet the nanoparticles obtained through green synthesis are more biocompatible because there are no toxic chemicals utilized in this process, so this makes them more potent when it comes to the healthcare, and preservation of food and overall safety of humans [12].

Even though the traditional methods result in more defined size and distribution of nanoparticles, the green synthesis process is more promising when it comes to the environmental safety and fewer ecological footprints. But regardless, the green synthesis has its own shortcomings like less scalability resulting in lesser yield, and the inconsistency in the characteristics of the particles such as size, so this area requires more research to overcome these related challenges [13].

1.5 Properties of Silver Nanoparticles

Sliver nanoparticles are widely recognized for their immense antimicrobial properties; this makes them suitable for several applications in medical and environmental fields [14]. AgNPs are known to prevent the bacterial fungal, and viral growth by a number of mechanisms. These mechanisms contain disturbance in bacterial membranes, the reactive oxygen species (ROS) generation, and hindrance in replication of microbial DNA [15]. This multi-purpose application makes AgNPs work best against both Gram-positive and Gram-negative bacteria and even target the drug-resistant strains for example MRSA (methicillin-resistant *Staphylococcus aureus*) [13].

Moreover, silver nanoparticles have some exceptional optical properties, which in turn make them beneficial in fields like biosensing and medical imaging. The AgNPs have their role in diagnostic and imaging applications, as they can absorb and scatter the light at different wavelengths this is because of the surface plasmon resonance (SPR) effect [11]. The properties of silver nanoparticles are based on their size, shape, and overall chemistry of the surface [7]. Smaller nanoparticles are known to have improved antimicrobial properties because of the greater surface area, which results in increased interaction with the bacterial cells. Spherical nanoparticles, which are made through the green approach have shown to be more efficient in the disruption of the bacterial membranes [16].

1.6 Mechanism of Antibacterial Action of Silver Nanoparticles

There are several mechanisms through which the AgNPs kill the bacteria. As shown in the Fig 3. they interact with the cell membrane of the bacteria, which results in increasing the permeability of the cell wall and ultimately the cell dies [17]. AgNPs are also responsible for the generation of ROS which destructs the cellular components such as, proteins, DNA and lipids. AgNPs are also known to prevent the production of bacterial enzymes, which disrupts the cellular functions further more [18].

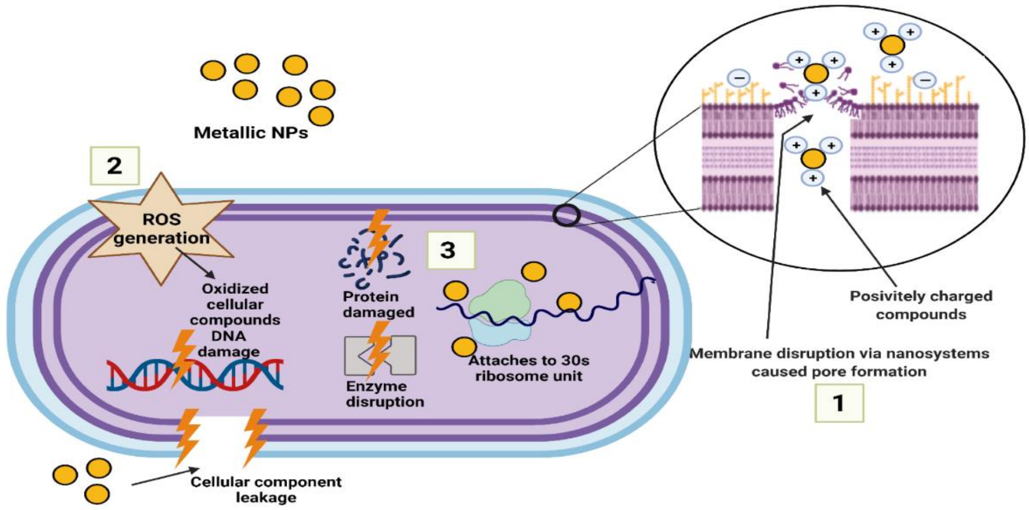

Fig 3. Mechanism involved in the inhibition of bacterial cell by the silver nanoparticles

1.7 Properties of Orange Peels Oil

Orange peels oil is studied to have the reducing properties which aid the synthesis of nanoparticles following the green approach, it is because the orange peels oil has several bioactive active compounds present in it [19]. Among bioactive compounds are terpenes and limonene are prominent having exceptional reducing properties [20]. Limonene is known to play a major role in the reduction of silver ions (Ag^{+}) to silver nanoparticles (Ag^{o}) [21]. Moreover, orange peels oil has different other compounds like flavonoids and phenolic compounds, these compounds have antioxidants and stabilizers that improve the constancy of nanoparticles [3]. Oil is both non-toxic and are easily degradable which makes them a suitable alternative to the chemical regents used in the traditional methods [22]. Using the oils for nanoparticle formation adds worth to unwanted fruit waste, which supports both sustainability and waste management concepts [23]. The Table 1. represents the previous work related to use of essential oils and to assess their anti-microbial properties, where different essential oils like clove, cumin, pepper, lemon, thyme, lavender and tea tree where used against different bacterial strains like *E. coli, B. subtilis, S. Typhimurium, S. aureus* where these oils showed potential to kill these bacterial strains, these even showed antimicrobial, anti-inflammatory, cytotoxic potential as well as worked against the production of bio-films as shown in the previous studies [24, 25].

Table 1. Previous studies related to the essential oils and their potential antimicrobial activities.

Precursor	Method	Bioactive potential	Reference
Cumin + Pepper oil	Mechanical stirring	*E. coli* and *S. enteria*	[24]
Clove essential oil	Mechanical stirring	*E. coli , B. subtilis, S. Typhimurium, S. aureus*	[25]
Clove + thyme essential oil	Ultrasound	Antibacterial, antibiofilm and anti-cancer potential	[8]
Fish By-Products + Lemon oil	Ultrasound	Antimicrobial, anti-inflammatory, cytotoxic potential	[20]

***Lavandula angustifolia* EOs**	Ultrasound	Multidrug-resistant wound-causing Bacteria	[3]
Tea tree EOs + AgNPs	Ultrasound	*E. coli* and *S. aureus*	[23]

1.8 Characterization of Silver Nanoparticles Synthesized Using Fruit Waste Oils

When synthesized by the green methods, nanoparticles are thoroughly characterized to confirm their characteristics like size, shape, crystalline structure, and stability. These characteristics are vital to determine the efficiency of nanoparticles, such as their antimicrobial applications. The following progressive characterization techniques are extensively used:

1.8.1 Ultraviolet-Visible (UV-Vis) Spectroscopy

Nanoparticles formation is confirmed through UV-Vis spectroscopy. This technique is based on surface plasmon resonance (SPR), this is an optical property displayed by the NPs, it is due to the electron oscillations on the surface when light strikes them. The AgNPs typically has the peak around 400-450 nm as shown in Fig 4., this confirms the formation of the silver nanoparticles and a successful reduction. The shifts in the peaks can give information about the nanoparticles size as well [26].

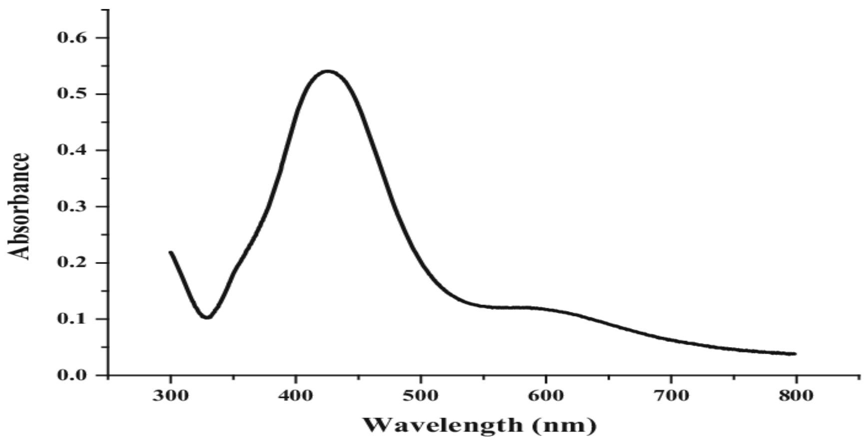

Fig 4. The UV-Vis spectrum for silver nanoparticles is between 400-450 nm

1.8.2 X-ray Diffraction (XRD)

XRD is helps to indicate the crystalline nature of the nanoparticles. By the analyzation of the diffraction pattern when nanoparticles scatter the X-rays, in response the crystal structure and phase composition are identified. For the silver nanoparticles the peak is usually at 38.1^o which parallels to (111) plane of face-centered cubic (FCC) silver, so in this way the crystalline structure is confirmed [27].

1.8.3 Transmission Electron Microscopy (TEM)

TEM gives high-resolution images that confirms the size, shape, and distribution of the nanoparticles. TEM indicates if the nanoparticles are spherical, polyhedral, or irregular in shape as the images in Fig 5. show. The technique helps with the size measurement of the particles as, which is an important aspect for the antimicrobial efficacy of AgNPs, smaller the nanoparticles (10-50 nm) higher is the antimicrobial activity because of the larger surface area-to-volume ratio. TEM also helps in providing information about the particle's uniformity [15].

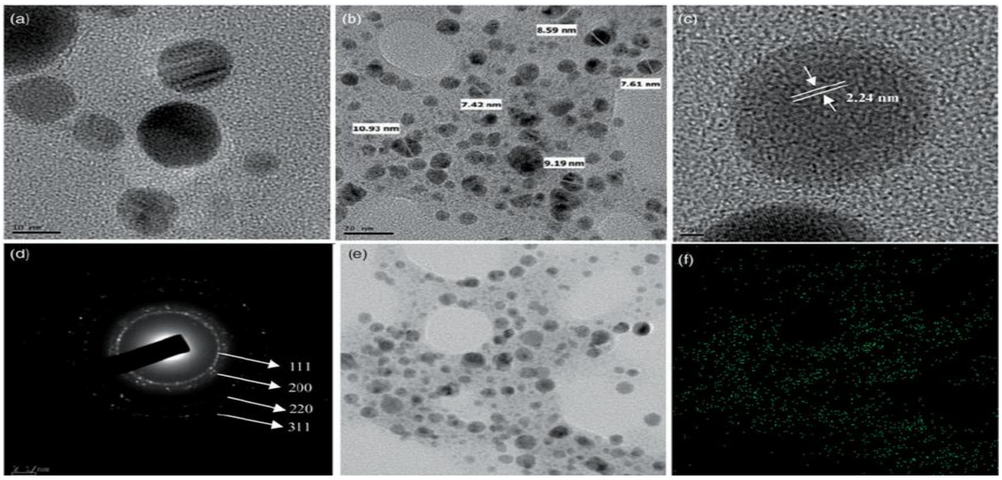

Fig 5. TEM images helps to identify the shapes and sizes of the nanoparticles

1.8.4 Fourier-Transform Infrared Spectroscopy (FTIR)

FTIR is useful in the confirmation of the functional groups existing on the surface of the nanoparticles, which in the case of the fruit waste oils comes from the bioactive. These functional groups, such as hydroxyl (-OH), carbonyl (C=O), and amine (-NH2) groups, play a critical role in reducing the silver ions and in the stabilization as well, which then prevents the agglomeration of the nanoparticles. FTIR spectra have specific absorption bands the functional groups present, which indicate their binding with the nanoparticle's surface [2].

1.9 Influence of Size and Shape on Antimicrobial Activity

The size and shape of silver nanoparticles majorly effect their antimicrobial efficacy. The nanoparticles with smaller sizes have a larger surface area-to-volume ratio, this helps in improving their interaction with the cell membrane of the bacteria, enhancing the antimicrobial performance [28]. The spherical nanoparticles are known to have better performance when it comes to the disruption of the bacterial cell membrane and they display improved colloidal stability and better dispersibility in solutions, which makes them more appropriate for practical applications in healthcare and environmental treatment. The studies show that nanoparticles that are 10-50 nm in size are more viable for antimicrobial application, because these nanoparticles penetrate the cell wall more effectively and the ROS generation is more efficient [22].

1.10 Antimicrobial Applications of Silver Nanoparticles

Silver nanoparticles synthesized by the use of fruit waste oils have shown noticeable antimicrobial properties and applications in a number of different fields. They are used to fight against different microbes such as bacteria, fungi, and viruses, which makes them beneficial in healthcare, preservation of food, and water purification etc. [29]. In healthcare perspective, AgNPs are used in wound prevention, medical device coatings, and antimicrobial creams to avoid and healing infections.

They are known to be efficient against drug-resistant bacteria such as MRSA, hence combating the global issue of multi-drug resistance [30]. In the food industry, these nanoparticles have shown their antimicrobial effect when used as a coating in the packaging of the food, which helps in the preservation and increasing the shelf life of the products [31]. Moreover, a wide number of studies have shown that silver nanoparticles, when incorporated with the water systems, can facilitate the water treatment process and eradicate the harmful pathogens from the system [32].

2. Limitations and Future Directions

Even though the green synthesis of silver nanoparticles (AgNPs) using fruit waste oils suggests substantial benefits, numerous challenges and restrictions are also there. One of the main apprehensions is upholding accurate control on the size, shape, and distribution of the nanoparticles, as these aspects expressively affect the antimicrobial activity of the AgNPs [33]. Differences in the synthesis process can give rise to variations in characteristics of the particles, which then can affect the efficacy of nanoparticles when used against the resistance of microbes. Additionally, a main difficulty is the scalability of these green synthesis methods for production at larger scale [12]. Though synthesis that is laboratory based can yield a good number of results, using this process at industrial scale needs proper optimization so that the yield is high and consistent, at the same time more cost-effective [30]. Moreover, the toxicity related to the silver nanoparticles or for this instance any particle at nano size remains as a major concern. While green synthesis approaches decrease the use of harmful chemicals, the biological and environmental effects of AgNPs are not fully studied yet. Research has revealed that silver nanoparticles may have toxic effect on the human cells, aquatic life, and other constituents of ecosystems, which increases concerns about the lasting safety. Regardless of the likely antimicrobial properties, more research is needed to assess the wide-ranging effects of AgNPs, like their interference with biological systems, bioaccumulation, and persistence in the environment [12].

3. Conclusions

The green synthesis of silver nanoparticles by the use of fruit waste oils offers an advanced and more viable answer to environmental and health challenges. By the in cooperation of the antimicrobial properties of AgNPs and the sustainability of using fruit waste, this method has the ability to fight the antimicrobial resistance and waste reduction. Continuing research in this aspect could result in the further optimization of synthesis methods and investigation on other fruit wastes and natural resources for the production of nanoparticles. The incorporation of green nanotechnology through several industries, such as healthcare, agriculture, and environmental management, could show a long-term influence on the health and sustainability world-wide.

Abbreviations

The following abbreviations are used in this review article:

AgNPs	Silver Nanoparticles
NPs	Nanoparticles

UV-Vis	Ultraviolet-Visible
XRD	X-ray Diffraction
TEM	Transmission Electron Microscopy
FTIR	Fourier-Transform Infrared Spectroscopy
ROS	Reactive Oxygen Species
SPR	Surface Plasmon Resonance
MRSA	Methicillin- Resistant *Staphylococcus aureus*
FCC	Face-Centered Cubic
EOs	Essential Oil

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