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REVIEW PAPER

Potential application of gold nanoparticles in food packaging: a mini review

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Abstract

In the past few decades, there have been remarkable advances in our knowledge of gold nanoparticles (AuNPs) and synthesizing methods. AuNPs have become increasingly important in biomedical and industrial applications. As a newly implemented method, AuNPs are being used in nanopackaging industries for their therapeutic and antibacterial characteristics as well as their inert and nontoxic nature. As with other NPs, AuNPs have privileges and disadvantages when utilized in the food sector, yet a significant body of research has shown that, due to the specific nontoxic characteristics, AuNPs could be used to address other NP flaws. In this mini review, we present synthesizing methods, food industry applications, and mechanisms of action of gold nanoparticles. Regarding the investigations, gold nanoparticles can play a major role to reduce microbial load in foodstuff and therefore can be implemented in food packaging as an effective approach.

Keywords Gold nanoparticle · AUNPs · Nanopackaging · Antimicrobial · Synthesize

Introduction

As a precious substance, gold has been highly regarded throughout human history [1]. Because gold atoms possess very unique and special characteristics, the chemistry of gold has garnered remarkable attention. In addition to the application of gold in cosmetics, jewelry, dentistry, and, of course, as money, gold has been widely used for medicinal, material sciences and catalysis purposes over the years [2–4]. For example, more recently, gold compounds have been used as antibacterial agents and antifungals against a wide spectrum of microbes. In addition to the antimicrobial and antifungal characteristics of gold compounds, antiamoebic, antileishmenic, and antitrypanosomical activity has been proven [5, 6]. Numerous gold compounds with various ligands such as phosphine type ligands and N-heterocyclic-L-cysteine as well as chloroquine have been used as antimicrobial agents against a wide array of microbes [7].

In recent years, there has been significant interest on application of packaging containing different nanoparticles due to the effects on shelf life, gas barrier properties, and mechanical characteristics [8–10]. Additionally, the effects of NPs on inhibition of bacterial growth have led to further research on evaluation of the size, shape, and concentration of applied NPs in packaging [11–13]. Depending on the foodstuff, the type of packaging matrix is of great importance. The addition of metal NPs such as silver, cooper, TiO_2, and gold to polymer matrices, mechanical properties, thermal resistance, gas barrier properties, and antimicrobial properties is considered to be improved in comparison with the usual polymers [14, 15]. Moreover some of these NPs increase the packaging resistance such as thermal and mechanical resistance under high pressure. Examples of these coatings for foodstuff include antifungal-coated packaging for cherries, silver-zeolite antibacterial packaging for raw meat, and antioxidant coating used for mushrooms [6, 16].

Although silver NPs have gained much more applications in the food industry, with respect to some unique characteristics of gold NPs, these kind of packaging can be implemented in specific portions of food industry[17, 18]. D AuNPs have received considerable interest in both the medical and food packaging industries due to therapeutic activity, the inert and

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nontoxic nature of gold NPs, and oxidative catalytic characteristics [15, 18]. Nanotechnology applications in the food industry such as the migration of NPs into foodstuff can help to reduce the incidence of foodborne pathogens [19]. The high surface to volume ratio of AuNPs increases their reaction with biomolecules and bacterial cell bonds and, eventually, bacterial deterioration occurs [20, 21]. In the following section, we have provided some points on syntheses and mechanism of action of gold NPs with respect to their potential application in the food industry.

Synthesis of AuNPs

A wide array of methods has been suggested for synthesizing AuNPs with controlled size, shape, functionality, and surface area. Turkevich et al. synthesized AuNPs using HAucl4 and citric acid at 100 °C [22]. Other researchers tried to further develop this method by changing the reducing agent [16, 18, 21]. The size of NPs produced by the Turkevich method was 10–20 nm, though larger NPs can be synthesized by this method. The utilization of citrate in synthesis of gold nanoparticles can lead to agglomeration of nanoparticles. As a result, numerous methods have been developed to address this issue using different solutions such as Tween 20, thiolic acid, and various surfactants [15].

In 1994, Brust et al. conducted a study on the application of thiolic groups to produce non-aggregate and redispensable solutions of AuNPs [23]. More recently, in green synthesis of nanoparticles, different reducing agents have been used to synthesize AuNPs [24–26]. Synthesis of gold NPs generally can be achieved by two different methods: (a) producing NPs from bulk gold and (b) synthesizing gold NPs using atomic steps [25, 27]. Aerosol technology, UV radiation reduction, and laser ablation are also famous methods. However, among the aforementioned methods, chemical reduction has gained much more attention due to its lower expense on simple instrumentation. According to Fig. 1, the general reduction method involves two steps [11, 28]:

(1) Reduction of the gold salt solution using reducing agent such as citrate and borohydrate
(2) Preventing agglomeration of AU particles through using stabilizing agents

Changing the size, shape, and morphology of NPs leads to different characteristics, so researchers have paid much more attention to synthesizing gold NPs of other shapes such as nanorods, nanocubes, and triangular NPs [17, 25].

Antimicrobial characteristics

Gold nanoparticles can be evaluated from various aspects such as antibacterial, antifungal, and anticancer. Additionally, AuNP complexes such as those with antibiotics and chemicals have been investigated widely [29, 30]. Tables 1 and 2 indicate that numerous studies have been conducted to evaluate the antimicrobial characteristics of AuNPs synthesized through different methods such as chemical reduction and green synthesizing as well as incorporation of AuNPs with other NPs. Some of these novel studies are discussed below.

A number of researchers evaluated the antifungal effects of AuNPs synthesized through chemical as well as green

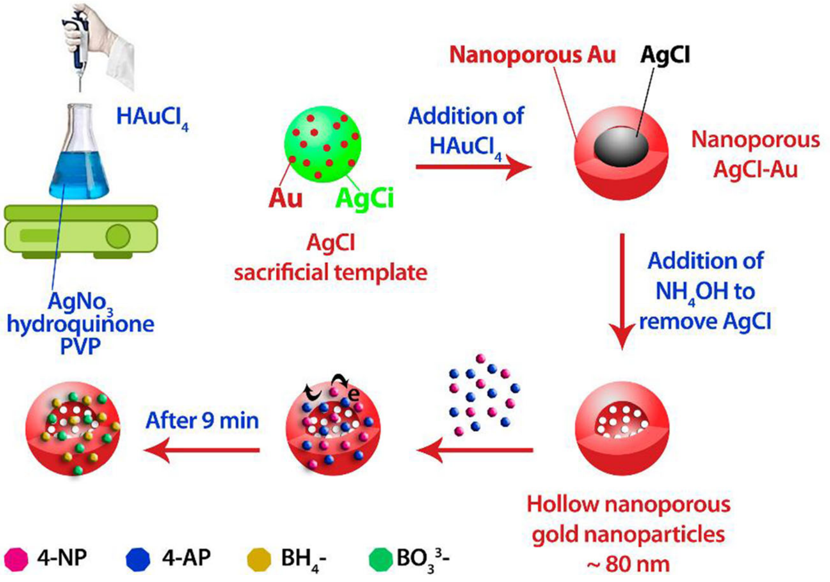

Fig. 1 Synthesizing of AuNPs by reduction of $HAuCl_4$ and $NaBH_4$ as reducing agent

Table 1 Antibacterial effects of AuNPs against *E. coli*

	Size	Matrix, ligand	Effectiveness	Reference
1	15–35 nm	Green synthesize phytochemicals	Effective	[31]
2	1–22	CTAB	Highly effective	[32]
3	80–100 nm	*C. zeylanicum* lead	Effective	[33]
4	15–25 nm	*Mumbellatum* extract	Effective (200 μg/μl)	[34]
5	5–12 nm	*Shewanella oneidensis*	Not effective	[35]
6	6–70 nm	*E. hirta* L.	Effective	[36]
7	25–60–120	*Dextrose*	Effective	[37]
8	33–65 nm	*T. decandra*	Effective	[38]
9	5 nm	*Chemical reduction*	Not effective	[39]
10	150 nm	*Mentha piperita*	Effective	[40]

methods against prevalent human pathogens such as *Candida albicans*. According to the literature, strong antifungal effects of AuNPs have been proved, with size, shape, and concentration being the primary determinants of fungicidal effects [47]. Wani and Ahmad conducted a study to evaluate synthesized polyhedrons and disks of gold nanoparticles (25–30 nm). The results showed high antifungal activity against *Candida albicans*. Moreover, higher antifungal effects were reported for nanodisks in comparison with polyhedral AuNPs (Table 1). Likewise, Nidhin et al. (2019) investigated the effects of 5 nm AuNPs against *C. albicans*. MIC results revealed that a 0.5 mM concentration was highly effective against *C. albicans* [54].

The antibacterial effects of AuNPs are a controversial topic. Although numerous researchers have reported high antibacterial effects of gold NPs [32, 33], others have stated that AuNPs have no effect on the reduction of bacterial loads. According to skeptics, the reported antibacterial results from other researchers are probably due to chemical agents that are bonded to the surface of AuNPs [39, 55]. Rajathi et al. (2012) investigated the application of *Stoechospermum marginatum* for synthesizing AuNPs. In this study, 1 g of *S. marginatum* was mixed with 100 ml $HAuCl_4$ to produce 40–80 nm AuNPs. According to the results, 95% of bioreduction occurred during the first 12 h of reaction. A UV-Vis spectrum (300–800 nm) was used for recording the light absorbance spectrum. In addition, TEM, FTIR, and FESEM analyses were carried out for further examination of the size and morphology of produced NPs. Then, the antibacterial effects of AuNPs were evaluated against *Pseudomonas aeruginosa*, *Klebsiella oxytoca*, *Enterobacter faecalis*, *Klebsiella pneumonia*, *Salmonella typhimurium*, and *Proteus vulgaris.* The results demonstrated that produced AuNPs were highly bactericidal against *K. pneumonia* although no inhibition zone was recorded for *E. coli* [56].

Table 2 Antibacterial effects of AuNPs against *S. aureus*

	Size	Matrix, ligand	Effectiveness	Reference
1	80 nm	PVP	Effective (200 μg/μl)	[41]
2	4–8 nm	Polyamidamine	Effective (2 μg/μl)	[30]
3	nm	Phosphine	Effective	[42]
4	150 nm	*Mentha piperita*	Not effective	[40]
5	1–3 nm	Cationic peptide	Effective	[43]
6	33–65 nm	*T. decandra*	Effective	[38]
7	nm	*Tinctorius* flower	Effective	[44]
8	nm	*Chinensis*	Effective	[45]
9	5–30 nm	*Euphorbia hirta* L.	Effective (512 μg/μl)	[36]
10	nm	Grapefruit	Effective	[46]

In a study conducted by Emam et al. (2017), H_2O_2 was used as an enhancer for reducibility of starch as a reducing agent for synthesizing AuNPs. MIC (960 μl/ml) results showed that synthesized AuNPs (40–80 nm) were significantly bactericidal against *S. aureus* samples [25].

Kurtjak et al. (2017) investigated the antimicrobial effects of AuNPs (10–15 nm) functionalized with arginine and hydroxyapatite containing Ga^{3+} ions. Results showed that AuNPs had antibacterial effects against *E. coli* and *S. aureus*, while disk diffusion results did not exhibit any inhibition zone against the *P. aeruginosa* MW1 strain. However, AuNPs + Ga^{3+} NPs could significantly reduce bacterial loads in the samples ($p < 0.01$) [16]. On the contrary, Grace et al. (2006) studied the effects of aminoglycosidic antibiotic–protected gold nanoparticles. The results revealed that gold nanoparticles acted as a proper carrier of nanoparticles due to the high surface to volume ratio. However, the nanoparticles did not have any independent antibacterial effects against *S. aureus*, *Micrococcus luteus*, and *Pseudomonas aeruginosa* using the inhibition zone method [21]. This could probably be due to the higher size of AuNPs (85 nm) in comparison with that of Kurtjak et al. [16].

Ramakritina et al. (2013) evaluated the effects of PVA-AuNPs composites against both Gram negative and Gram positive (*E. coli* and *S. aureus*) bacteria. Results showed that green synthesized *Phyllanthus emblica* could exert a 1 cm inhibition zone in 24 h ($p < 0.01$) [18]. In comparison with

Table 3 Antifungal activity of AuNAPs and gold complex

	Type	Size	Effectiveness	Reference
1	*Candida* spp.	7–15 nm	Highly effective	[48]
2	*Candida* spp.	25–30 (nano-disk polyhedral)	Effective	[49]
3	*P. graminis*	*45–75 nm*	Effective	[50]
4	*Candida albicans*	*45–75 nm*	Effective	[50]
5	*C. albicans* ATCC 70231	36–74 nm	Effective	[38]
6	*C. albicans MTCC 1833*	*18–80 nm*	Effective	[51]
7	*Candida* spp.	Gold phosphine complex	Effective	[52]
8	*Cryptococcus* spp.	Gold phosphine complex	Effective	[52]
9	*Aspergillus* spp.	Gold phosphine complex	Effective	[52]
10	*Candida* spp.	5 nm	Effective	[53]

Significance of row 1: $P<0.01$

Significance of other rows: $P<0.05$

Nirmala, a lower size (2–4 nm) of produced AuNPs could be the reason of this significant difference in the bactericidal effect. Likewise, Nazari et al. reported that no inhibition zone was proved for *Pseudomonas aeruginosa* using AuNP disks (2–100 nm) [57].

Mechanism of action

In opposite of silver nanoparticles as far as we surveyed, to date, little studies have been conducted on evaluating the mechanism of action of sole gold nanoparticles against different bacteria and they were evaluated capped with other agents and chemicals. However, according to nanoscience, the transformation of molecules to nanoparticles leads to different effects. Among them, increasing the surface to volume ratio [11], existence of Au ions in the environment of bacterial cells, and production of radical oxygen are probably the main reasons of antibacterial mechanism of gold nanoparticles [58]. Li reported that synthesized AuNPs could significantly interact with both Gram negative and Gram positive bacteria resulting in the formation of aggregation patterns that lead to lysis of microbial cells [11].

Conclusion

Nanotechnology has opened new horizons in a variety of research area applications including the food sector. Implementation of AuNPs in coatings and packaging has been a controversial issue as most scientists believe that AuNPs along with many other NPs can exert antimicrobial effects on pathogenic organisms. A wide range of Gram negative and Gram positive bacteria have been examined, among which *E. coli* has been the most controversial. Although the size and morphology of NPs are important criteria, the synthesizing method and reducing agent may also affect the results. The application of gold nanoparticles is thus highly suggested as antibacterial agents for high-end, luxury products such as caviar.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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