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Effects of Gold Nanoparticles on *Mentha spicata* L., Soil Microbiota, and Human Health Risks: Impact of Exposure Routes

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Abstract: Nanoparticles, due to their extensive production and application, can have significant consequences for the environment, including soil and plant pollution. Therefore, it is very important to assess how nanoparticles will affect plants depending on the exposure pathways. The effect of gold nanoparticles in a concentration range of 1–100 mg/L on *Mentha spicata* L. during a 28-day experiment was investigated. Two routes of nanoparticles exposure were applied: root and foliar. Transmission electron microscopy was used to characterize nanoparticles and their effect on plant leaves' ultrastructure. Gold content in soil and plant segments was determined using k0-neutron activation analysis. For root exposure, gold was mainly accumulated in soil (15.2–1769 mg/kg) followed by root systems (2.99–454 mg/kg). The maximum accumulation of gold in leaves (5.49 mg/kg) was attained at a nanoparticle concentration of 100 mg/L. Foliar exposure resulted in the maximum uptake of gold in leaves (552 mg/kg) and stems (18.4 mg/kg) at the highest applied nanoparticle concentration. The effect of nanoparticles on the *Mentha spicata* L. leaves' biochemical composition was assessed. Nanoparticles affected the content of chlorophyll and carotenoids and led to an increase in antioxidant activity. Root exposure to gold nanoparticles resulted in an increase in the number of starch grains in chloroplasts and also suppressed the activity of the soil microbiota. Gold extraction from mint leaves into herbal infusion varied from 2 to 90% depending on the concentration of nanoparticles in the solution and the exposure route. The health risk as a result of gold exposure via herbal tea intake was assessed through estimated daily intake. The hazard quotient values were found to be less than the cutoff, indicating that a cup of tea infusion should not cause a serious impact to human health.

Keywords: gold nanoparticles; foliar spraying; root irrigation; spearmint; k0-based neutron activation analysis; biochemistry; herbal infusion

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1. Introduction

The extensive growth of nanomaterial production is a result of wide application of engineered nanoparticles in medicine and the pharmaceutical industry, the agricultural sector, electronics, water treatment, etc. Besides industrial application, nanoparticles are present in various consumer products, including cosmetics, suntan lotions, paints, and stain-resistant clothing [1–5]. Thus, gold and silver nanoparticles are used as components of lotions, antiperspirants, and anti-aging face creams, and they help to eliminate lesions and improve skin condition. The size of gold nanoparticles (AuNPs) used in skin care products usually ranges from 5 to 400 nm [6,7]. It should be noted that AuNPs play an important role in medicine, where they act as carriers of drugs, amplifiers and optical signal converters, and are used in the diagnosis and treatment of cancer tumors [8–11]. Due to the increased production of engineered nanoparticles and their use in various fields, their release into natural and artificial ecosystems becomes inevitable [12].

AuNPs are often introduced into agricultural ecosystems—both accidentally and intentionally. In recent years, nanoparticles have been actively used as fertilizers and pesticides since it was proven that particles with sizes less than 100 nm have higher biological activity as compared to larger materials—due to their higher surface-area-to-volume ratio [13,14]. It was suggested that nanofertilizers or nanoencapsulated nutrients have beneficial effects on crops. Thus, to combat plant diseases and to increase plant productivity, nanotechnological techniques for targeted particle delivery have been developed. In experiments with *Cucurbita pepo*, it was demonstrated that iron–carbon nanoparticles applied thought injections and spraying were able to penetrate and migrate in the plant body [13]. Field spraying of *Brassica juncea* leaves with AuNPs positively influenced various parameters related to plant growth and yield, including plant height, stem diameter, and number of branches and pods [14]. Another study reported an increase in the rate of seed germination and growth of *Gloriosa superba* after treatment with AuNPs at a concentration of 1000 μM [15]. The use of AuNPs as fertilizer improved the synthesis of ginsenosides in ginseng and enhanced the anti-inflammatory effects of red ginseng [16]. In *Arabidopsis thaliana*, AuNPs in concentrations up to 80 μg/L enhanced total seed yield and improved seed germination rate, vegetative growth, and free-radical-scavenging activity [17].

At the same time, extensive use of engineered nanomaterials results in their release in the environment and accumulation in soil [18], which in turn leads to their uptake by plants, resulting in potentially negative impacts on human health [19–21]. A number of studies showed that nanoparticles present in the atmosphere can settle on leaves, penetrate them through trichomes or stomata, and then be transferred to other plant tissues [22]. Luo and Cao [20] found that the plants *Erigeron canadensis* and *Boehmeria nivea* collected in the Guangdong Province of China contained AuNPs of various shapes with a diameter of 5–50 nm [20].

Since gold is not one of the biologically important trace elements, its accumulation in plants, besides beneficial effects, can lead to toxic impacts as well [12]. Thus, the length of *Arabidopsis thaliana* L. roots when grown in the presence of 100 mg/L AuNPs was 75% shorter [23]. AuNPs can also affect the soil microbial community. Maliszewska [24] reported that AuNPs showed toxicity towards soil microorganisms involved in carbon and nitrogen transformations. Nanoparticles can be accumulated in plants through roots and leaves, and while the accumulation through roots is relatively well-studied, their uptake through leaves is less investigated and requires additional research. Accumulation of nanoparticles in plants consumed as food by the human population may result in their transfer into the human body. To our knowledge, there is no research on the complex impact of metal nanoparticles on soil microbiota, plants, and human health.

The aim of the present study was to assess the effect of AuNPs applied in different concentrations through root and foliar application on *Mentha spicata* L. The objectives of this study included the following: (i) assessment of gold accumulation in soil and different segments of plants using neutron activation analysis; (ii) investigation of the AuNPs effect on soil microbiota and Mentha biochemical composition; (iii) calculation of the percentage of gold extraction in herbal infusion; and (iv) evaluation of the potential health risks of spearmint infusions containing AuNPs.

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