Recibido: 27-dic-2024 Aceptado: 08-jun-2026 e-ISSN 2954-4890

Sección: Hot Science

Emerging nanoparticles as an alternative to agricultural pesticides

Nanopartículas emergentes como alternativa a los pesticidas

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SUMMARY
Currently, the global population has surpassed 8.09 billion, increasing the demand for agricultural production worldwide. Producing healthy, sufficient, and high-quality food requires a series of practices, ranging from soil preparation to the protection of crops against plant pathogens. To meet these demands, chemical pesticides have been widely used; however, their application has led to soil and groundwater contamination, affecting both the microbial ecosystem and the quality of agricultural products. In this review, we explore the pesticidal properties of silver, copper, zinc, and titanium nanoparticles, as well as their limitations and practical applications.

Keywords: Nanoparticles, phytopathogens, pesticides.

RESUMEN
En la actualidad, la población mundial ha superado los 8.09 mil millones de personas, incrementando la demanda de producción agrícola mundial. La producción de alimentos sanos, suficientes y de calidad requiere procedimientos que abarcan desde la preparación de la tierra hasta la preservación de cultivos libres de patógenos vegetales. Para esto, se han utilizado productos químicos como plaguicidas, que han contaminado suelo y aguas subterráneas, afectando el ecosistema microbiano y la calidad de los productos agrícolas. En este artículo exploramos las propiedades plaguicidas de las nanopartículas de plata, cobre, zinc y titanio, así como sus limitaciones y aplicaciones prácticas.

Palabras clave: Nanopartículas, fitopatógenos, plaguicidas.

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Introducción

Agricultural revolution has shaped communities' ways of life by providing crops, seeds, and fruits for both humans and livestock. Currently, the challenge is to supply these products despite population growth, climate change, and soil and irrigation-water contamination. Thus, food security depends on sustainable agricultural practice. One of the major concerns in agriculture is pathogen infestation of crops, which induces annual losses of 40 billion dollars worldwide [1]. These plant pathogens (phytopathogens) infect diverse crops and are highly persistent in their attack. In contrast, the use of new technologies, such as nanotechnology, has been investigated, assessing the impact of nanoparticles used in agricultural production, particularly during plant-pathogens control [2]. In agriculture, nanoparticles offer sustained ion release kinetics, solubility efficiency, enhanced permeability, and stability, thereby increasing pathogen control efficacy over longer time intervals. Thus, the use of nanoparticles can minimize pesticide dosage to achieve increased efficacy. These features help produce more nutritious and healthy foods while keeping agricultural production free of plant pathogens.

Human-managed agricultural production systems for rice, wheat, barley, corn, soy, and crops from the *Solanaceae* family are widely used as the main commercial crops. However, these systems are highly vulnerable to phytopathogens and pests, as well as to unpredictable environmental conditions. Consequently, the global farming community has been affected, with losses of up to 40% of the total production (Figure 1) [3].

Common treatments for pathogens and plant pests include chemical pesticides, fungicides (chlorothalonil and metalaxil), herbicides (glyphosate and 2,4-dichlorophenoxyacetic acid), and arthropodal options such as malathion, which have been used against resistant pests. However, more frequent pesticide application increases water pollution in surface and/or underground soil, which jeopardizes freshwater availability and supply.

Biological and remedial applications of nanoparticles

Nanoparticles are tiny particles that are not visible to the naked eye and measure between 1 and 100 nm. Colloidal solutions (or materials containing nanoparticles) and their extraordinary characteristics in terms of optical, electronic, thermophysical, and mechanical properties have been studied [4]. Nanoparticles can be applied in different fields, such as in the agricultural sector, where they provide an innovative and novel approach to improving sustainable agricultural practices [5]. This field of science offers a wide range of applications, including but not limited to improving plant growth and development, improving crop production and quality, preventing plant diseases, and increasing plant adaptation to external stressors. The need to implement sustainable novel methodologies and achieve the highest level of crop productivity considers the avoidance of any form of pollution or harm to the agroecosystem in which these nanoparticles are utilized.

Nanoparticles against phytopathogens

Silver nanoparticles (AgNPs)

Silver is a chemical element well known for its antimicrobial properties and possesses distinctive characteristics that confer efficacy against pathogenic microorganisms. The use of these materials in plant pathogen research has yielded promising results. For example, chemically synthesized nanoparticles are 100% effective in inhibiting the growth of the fungal species *Corynespora casiicola* and *Alternaria solani*. Moreover, they demonstrated

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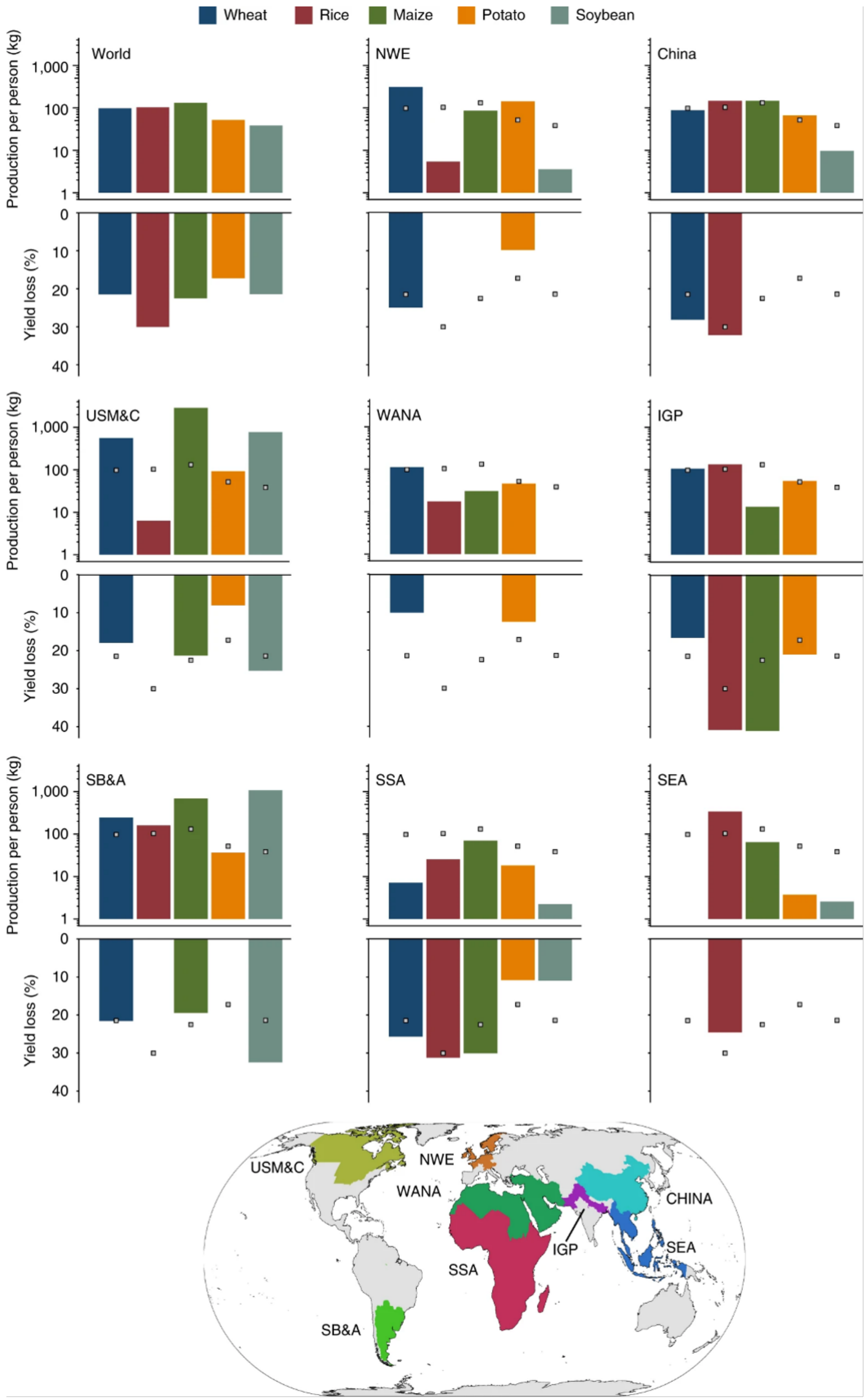

Figura 1. *An overview of the primary crops grown in various regions worldwide USM&C=US Midwest and Canada; SB&A=South Brazil, Paraguay, Uruguay, and Argentina; NWE=Northwest Europe; WANA=West Asia and North Africa; SSA=Sub-Saharan Africa; CHINA=Mainland China; IGP=Indo-Gangetic Plain; SEA=Southeast Asia [3].*

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85% efficacy against the fungal species, *Fusarium* spp. [6]. In contrast, green-synthesized nanoparticles exhibited a significant inhibitory effect of 90% against *C. casiicola*, an impressive effectiveness of 95% against *A. solani*, and 90% against *Fusarium* spp. The fabrication of AgNPs against fungal pathogens showed that the two types of nanoparticles exhibited varying degrees of effectiveness and provided valuable insights into their potential applications in the field of fungal control.

Titanium dioxide nanoparticles

Titanium dioxide nanoparticles have demonstrated antifungal properties against *Ustilago tritici*. These findings revealed that the nanoparticles were highly efficient in inhibiting fungal growth. This effect was observed using a solution of green-synthesized titanium oxide nanoparticles (0.1 mg/mL) with an average diameter of 15 nm. The combination of titanium atoms with oxygen has the potential to generate reactive oxygen species (ROS), which are highly reactive and toxic molecules capable of dismantling fungal membranes [7].

Copper nanoparticles (CuNPs)

Copper has been used by human civilization since the Bronze Age; however, its application in agro-biotechnology is relatively recent. Cu is an essential micronutrient for plants and is involved in several physiological functions and photosynthetic reactions, as it activates numerous enzymes [8]. The antifungal effect of CuNPs against plant pathogens has been explored by targeting *Curvularia lunata*, *Alternaria alternata*, *Fusarium oxysporum*, and *Phoma destructive*, with positive results. CuNPs have also been used as pesticidal agents to sustain efficiency in food production and to combat agricultural pathogens [9].

Zinc oxide nanoparticles (ZnONPs)

Zinc oxide nanoparticles possess exceptional antibacterial and antifungal properties and have been studied extensively. Previous studies have demonstrated the antifungal activity of ZnONPs against Fusarium oxysporum in tomato plants. It has been ascertained that pathogen inhibition of 81-83% requires a minimal concentration range of 1600–3000 ppm. The green synthesis of ZnONPs using Lantana camara leaf extract has been employed to enhance plant growth and antifungal activity of biosynthesized ZnONPs against *Diplodia seriata*, *Botryosphaeria dothidea*, and *Alicyclobacillus mali*, the major plant pathogens of apple orchards. In these cases, with 100 ppm of ZnONPs, fungal growth was inhibited by 76.7-55.2 % [10]. Therefore, this approach offers a vast array of prospects for exploring additional factors that provide remedies against plant pathogens of economic interest.

Table 1 describes a comparative analysis of diverse recently-reported nanoparticles that possess remarkable antifungal properties. This compilation demonstrates the efficacy of these nanoparticles in combating plant pathogens via an *in vitro* test, thus providing an interesting resource for both the general and specialized public.

Conclusions & Future perspectives

The maintenance of agroecosystems is a central issue in sustaining the global population. Nanotechnologies allow us to explore environmentally friendly alternatives to pathogen control, while remaining effective against aggressive pathogens, which, as we have seen, can diminish agricultural production. Nanoparticles have demonstrated antibacterial and antifungal activities at different concentrations, owing to their reactive properties, principally in vitro. Here, we showed that most nanoparticles exhibit an effective antimicrobial effect at 100 µg/mL, and even at the lower concentration reported of 37 µg/mL. However, additional information is still required for toxicity assessment. Although various nanoparticles are

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__Tabla 1.__ Description of commonly and/or recently used nanoparticles as pesticides against plant pathogens or pests.

Nanomaterial	Plant pathogens	Nanoparticle Size (nm)	Effective concentration	Effects
Silver-based	*Aspergillus niger* *Aspergillus terreus* *Aspergillus flavus* *Aspergillus fumigatus*	27.31	500 µg/mL	Cell wall weakens, and the membrane moves into the cytoplasm, affecting the internal structure of the cell.
	Uncinula necator	10-15	100 µg/mL	Mycelium growth and spores' inhibition
Titanium-based	*Bipolaris sorokiniana*	10-100	40 mg/L	Inhibition of fungal growth
	Ustilago tritici	< 15	75 µg/mL	Production of intracellular ROS.
Copper-based	*Tribolium castaneum*	10-70	37 µg/mL	Oxidative stress and multisystem failure
Zinc-based	*Alternaria citri*	16.8	100 mg/mL	Growth inhibition

highly effective, they have certain limitations. Therefore, it is necessary to conduct extensive studies on the potential human use of these pesticides in large agricultural areas.

Acknowledgement

RM acknowledges that DGAPA-UNAM-PAPIIT grant no. TA200123 and SECIHTI (CBF-2025-I-1373).

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