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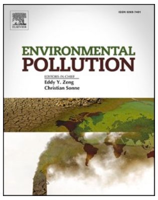

Review

# Use of metal nanoparticles in agriculture. A review on the effects on plant germination☆

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ABSTRACT

Agricultural nanotechnology has become a powerful tool to help crops and improve agricultural production in the context of a growing world population. However, its application can have some problems with the development of harvests, especially during germination. This review evaluates nanoparticles with essential (Cu, Fe, Ni and Zn) and non-essential (Ag and Ti) elements on plant germination. In general, the effect of nanoparticles depends on several factors (dose, treatment time, application method, type of nanoparticle and plant). In addition, pH and ionic strength are relevant when applying nanoparticles to the soil. In the case of essential element nanoparticles, Fe nanoparticles show better results in improving nutrient uptake, improving germination, and the possibility of magnetic properties could favor their use in the removal of pollutants. In the case of Cu and Zn nanoparticles, they can be beneficial at low concentrations, while their excess presents toxicity and negatively affects germination. About nanoparticles of non-essential elements, both Ti and Ag nanoparticles can be helpful for nutrient uptake. However, their potential effects depend highly on the crop type, particle size and concentration. Overall, nanotechnology in agriculture is still in its early stages of development, and more research is needed to understand potential environmental and public health impacts.

## 1. Introduction

According to FAO data, the world population will reach 9.8 billion people in 2050, representing an increase of 1/3 of the current population (Searchinger et al., 2019; van Dijk et al., 2021). Thus, increasing agricultural production and improving food security are necessary to feed this population. However, agricultural production is not growing at the same rate as the population, mainly due to i) biotic and abiotic stresses to which certain exceptional soils are subjected and ii) environmental pollution (Pandey et al., 2017; Godoy et al., 2021; van Dijk et al., 2021). Because of this high demand for quality agricultural products, there is increased pressure to establish new strategies to improve food production, quality and safety, making them more efficient and environmentally friendly (Tomlinson, 2013; van Dijk et al., 2021). According to Searchinger et al. (2019), the food and land gaps will be an issue for food production since this population increase will demand an increase of 56% in crop calories, and near than 590 million Ha will be needed compared to the needed in 2010.

In recent decades, nanotechnology, which has had many applications in the fields such as materials, health and medicine, physics and chemistry, has also been successfully applied to agriculture. The rapid growth of nanotechnology has accelerated the transformation of conventional food and agriculture through the use of nanoparticles that can be used as nanosensors (Omanović-Mikličanin and Maksimović, 2016), nanoherbicides and nanofungicides (Chaud et al., 2021), antimicrobial and nanofertilizing agents (Ashraf et al., 2021; Fatima et al., 2021) and as promoters of plant productivity by increasing tolerance to adverse conditions such as abiotic stress by the salinity of soil contamination by

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heavy metals (Abdel Latef et al., 2018; Chatterjee et al., 2021; Rodríguez-Seijo et al., 2022). However, using nanoparticles in agriculture can also lead to adverse effects (Rajput et al., 2018; Ali et al., 2021) that must be avoided to maintain the sustainability of agricultural systems.

Among all these applications, this manuscript focuses on using inorganic nanoparticles in crop germination, obviating other applications, and highlighting both potentially adverse and beneficial effects. Germination is the primary step in a plant's life and, consequently, a critical factor in the survival and conservation of plant species, since modern agriculture needs rapid, vigorous and successful seed germination for appropriate growth and crop yield. Hence, any factor that affects germination inevitably affects the subsequent development of the plant (Khan et al., 2022).

Germination is also a key factor in the recovery of degraded soils where a certain vegetation cover is to be achieved, but also in food production for humanity since it conditions the productivity of crops. The measurement of germination is usually carried out through two parameters: i) The germination percentage (GP), which is a measure of the ratio of germinated seeds to the total number of seeds and, ii) the seedling vigor index (SVI), which can be calculated using a variety of methods, but all take into account the weight or length of the roots and the weight or length of the leaves (Arnott et al., 2021; González-Feijoo et al., 2023).

### 1.1. *Obtaining and types of inorganic nanoparticles*

Although some nanoparticles may be of natural origin (e.g., magnetite), most are of synthetic origin. Synthesis techniques can be physical, chemical and biological (Ansari et al., 2020). Physical methods consist of size reduction by grinding, laser sputtering and evaporation-condensation. Chemical methods include reduction, microemulsion, wet synthesis, spray pyrolysis, precipitation and microwave combustion. Biological methods consist of using microorganisms and green synthesis using substances extracted from different plants and parts of those plants. These different types of synthesis result in nanoparticles of various physical, chemical and biological properties. These properties include.

i) *Size.* The European Union recommends defining nanomaterial as "a natural or manufactured material containing particles, either as free, aggregated, or agglomerated state, where 50% or more of the particles in the number size distribution is the size range 1–100 nm" (European Commission, 2011). However, despite this definition, many authors extend the range of nanomaterials to between 1 and 1000 nm (Prabha et al., 2016).

ii) *Shape.* According to Wang et al. (2018), nanoparticles may have three dimensions, such as nanospheres, nanocubes, nanostars, and nanoprism; two dimensions, such as graphene layers; one dimension, such as nanotubes and; zero dimension, such as dots-shaped nanoparticles.

iii) *Type of material.* Nanoparticles can be inorganic, such as metallic nanoparticles or organic particles, like carbon nanotubes, hydrogels, etc. As explained in the title of this manuscript, this review focuses on inorganic metallic nanoparticles with different characteristics and composition.

iv) *Area and surface charge.* Both surface area and charge are properties that affect the chemical reactivity of the particles. In this sense, it affects both the particle size -smaller size implies a larger surface area and, therefore, higher reactivity- and the surface charge, which depends on the particle conformation with more or less the presence of reactive surface groups.

Nanoparticles used as fertilizers can be divided as classical fertilizers into those with primary (N, P, K) and secondary (Ca, Mg, S) main components and those with microelements. However, many nanoparticles can benefit crops without providing any essential plant elements. Therefore, it is possible to classify nanoparticles into two groups: metallic nanoparticles that provide essential microelements and metallic nanoparticles that do not provide essential elements.

Inorganic nanoparticles that provide essential microelements for plants can be highlighted.

* *Zinc nanoparticles.* Zn is an essential element for plants. Although some studies have indicated that photosynthetic parameters can be affected (e.g., Wang et al., 2016; Pedruzzi et al., 2020), these adverse impacts are usually size-dose dependent. In general, Zn has the potential to increase the biosynthesis of photosynthetic pigments, plant biomass and defense mechanism (e.g., improving the antioxidant response system and a reduction on reactive oxygen species and lipid peroxidation) (e.g., Singh et al., 2016; Faizan et al., 2018; Reddy Pullagurala et al., 2018; Salam et al., 2022a). So its application can be very useful, especially under abiotic stress such as metal contamination (Boonchuay et al., 2013; Reddy Pullagurala et al., 2018; Iqbal et al., 2020; Salam et al., 2022a).
* *Copper nanoparticles.* Cu is an essential element for plants. Deficiencies of this element can occur in certain soils and with certain crops. Moreover, its role as an antifungal is well known, so it is applied to many crops, mainly vineyards and fruit trees (Yruela, 2009; Vázquez-Blanco et al., 2023). Applying foliarly Cu nanoparticles improves important plant processes such as increasing abscisic acid content in tomatoes (López-Vargas et al., 2018) or improving photosynthesis and resistance under abiotic stress (Iqbal et al., 2020).
* *Iron nanoparticles.* Fe nanofertilizers can replace traditional fertilizers, improving the production and quality of these products (Jeyasubramanian et al., 2016). For example, Fe nanoparticle application improves root and stem growth and biomass produced in *Arachis hypogaea* (Rui et al., 2016). Similarly to Zn nanoparticles, Fe nanoparticles can also improve plant photosynthesis and reduce oxidative stress for crops grown on contaminated soils (Khan et al., 2020; Rodríguez-Seijo et al., 2022).
* *Nickel nanoparticles.* These nanoparticles have been tested mainly as effective against plant diseases and mixed with Fe nanoparticles on several occasions (Nazarova, 2022; Zhou et al., 2023).

Among the inorganic nanoparticles that do not provide essential microelements for plants, Ag and Ti nanoparticles should also be highlighted. Other nanoparticles are also used, although to a lesser extent, such as Au, Se, Ce, Si and Al nanoparticles, which can positively affect certain plants that help improve the productivity or safety of agricultural products.

* *Silver nanoparticles.* They have healing effects on different microbial diseases and a positive effect on plant growth, even at low concentrations (±20 mg $kg^{-1}$) (Salama, 2012).
* *Titanium nanoparticles.* Ti nanoparticles applied to soil improve soil salinity, increasing plant leaf length and dry weight (Fatima et al., 2021). They also favor the germination of some seeds, as reported for commercial crops such as onion (Laware and Raskar, 2014), spinach (Zheng et al., 2005) or mung bean (Mathew et al., 2021).

## 2. Effects of nanoparticles on germination

It is common to use a low-cost technique that moistens the seeds in a solution or combines them with a solid matrix, after which the seeds are dried and planted (Seed priming, Rehman et al., 2012; Arnott et al., 2021). There are different seed conditioning methods (Khalaki et al., 2021) to favor seed germination, such as seed immersion in water (hydropriming), in saline solutions (osmopriming), treatment with growth regulators (hormo-priming), treatment with temperature changes (matrix-priming), treatment with dissolved organic matter (bio-priming) and recently treatment with nanomaterials (nano-priming). Many nanoparticles have been used to alleviate seed dormancy and promote germination and germination vigor for agricultural and forestry species (Rahimi et al., 2016; Ali et al., 2020; Rhaman et al., 2022), since nanoparticles reach the seed coat and can improve the accumulation of reactive oxygen species, and therefore, they can activate biochemical processes involved into break seed dormancy and activate seed germination (Khan et al., 2022). The effects on the germination of different plant species are generally performed on petri dishes or in pots where the nanoparticles are mixed with the soil. The effect of nanoparticles on germination depends on several factors, such as.

- *Dose and treatment time.* The doses and treatment time are crucial in establishing the beneficial effects and studying the toxicological and ecotoxicological aspects that may be generated in living organisms (Rhaman et al., 2022; Rutkowski et al., 2022; Salam et al., 2022b).

The doses used vary widely and depend fundamentally on four aspects.

- *Application method.* It includes foliar application on plants in both liquid and emulsion forms. In soils, it can be applied in different states, both solid and liquid. It can be applied directly to seeds, usually in liquid or suspension form. Foliar doses applied to different crops ranged from 10 to 500 mg $L^{-1}$, while doses applied to seeds ranged from 10 to 200 mg $L^{-1}$; doses applied to soil ranged from 15 to 200 mg $kg^{-1}$ (Mahapatra et al., 2022).
- *Type of nanoparticle.* The bibliographic data indicate that different doses are used depending on the type of nanoparticle, which is probably related to the greater or lesser effect on plants, both at the production level and, conversely, at the toxicity level. For example, in soil applications, Mohammadi et al. (2013) use 500–2000 mg $kg^{-1}$ with nanoparticles of $TiO_2$, while Najafi Disfani et al. (2016) use 15 mg $kg^{-1}$ with nanoparticles of $Fe/SiO_2$. It is also important to highlight the solubility of the nanoparticles, which has a decisive influence on the presence of the metals in the solution. This is closely related to their effect on plant germination, with dissolved metal ions being more toxic than the corresponding nanoparticles, which has been mentioned for maize crops with Cu and Zn nanoparticles (Ahmed et al., 2021).
- *Type of plant.* The germination benefits of the different nanoparticles are different depending on the target crop. In this sense, applying Ag nanoparticles enhances root nodulation and soil biodiversity in crops of *Vigna Sinensis* (Pallavi et al., 2016) while improving chlorophyll content and catalase activity in *Solanum tuberosum* (El-Batal et al., 2016). It also applies to possible toxicological effects, such as CuO, which negatively affects the germination of *Lactuca sativa*, or decreases more than 13% of the stems and 59% of the roots in *Triticum aestivum* (Rajput et al., 2018).
- *Media conditions.* It is essential when nanoparticles are applied to the soil. The most relevant variables affecting nanoparticles are pH, dissolved organic matter, ionic strength, soil moisture, and temperature. All these variables influence the speed of the reactions that affect the solubility and penetrability of the nanoparticles into the plants. The dissolved organic carbon prevents nanoparticle aggregation and increases the nanoparticle's available surface area, as well as pH and ionic strength (Aiken et al., 2011; Axson et al., 2015; Wang et al., 2015; Arenas-Lago et al., 2019). The pH affects the solubility of the nanoparticles, but the addition of different nanoparticles also affects the pH of the soil. This effect is a function of the type and concentration of nanoparticles, the type of soil and the type of plant. For example, applying Fe nanoparticles does not affect the pH of alkaline soils but does affect the pH of acid soils (Gil-Díaz et al., 2016). A greater effect on soil rhizosphere of adding nanoparticles in ryegrass than in red leaf crop has also been described (Lyu et al., 2018). Ionic strength has been less studied, but an increase in ionic strength leads to an increase in salinity, which causes plant stress. In this sense, nanoparticle addition can reduce this abiotic stress (Abdel Latef et al., 2018; Iqbal et al., 2020). For example, Ti nanoparticles ($nTiO_2$) can reduce the adverse effects of salinity on broad beans (*Vicia faba*) (Abdel Latef et al., 2018). This similar effect was also reported by Hojjat et al. (2019) and Nejatzadeh (2021) for Ag nanoparticles on bitter vetch (*V. ervilia)* and summer savory (*Satureja hortensis)*, respectively. The effects of temperature and humidity are less well studied, although the temperature may alter the interaction of nanoparticles such as Zn with plants (López-Moreno et al., 2017).

Treatment times also vary widely, ranging from 24 h to 150 days, depending on the type of crop and the type of experiment and variables to be studied, as reviewed by Mahapatra et al. (2022).

### 2.1. Effects of nanoparticles containing essential elements on germination

#### 2.1.1. Zinc nanoparticles

Zn is an essential plant element for many metabolic processes such as enzyme activation, biomembrane stabilization, proteosynthesis, carbohydrate, lipid and nucleic acid metabolism (Al Jabri et al., 2022)), affecting its deficiency in practically all crops. Applying Zn nanoparticles can mitigate deficiency problems and reduce fertilizer application costs with micronutrients based on Zn compounds. There are several types of Zn nanoparticles, among which the following may be mentioned zinc oxide (ZnO), zinc sulfide (ZnS), zinc ferrite ($ZnFe_2O_4$), zinc phosphide ($Zn_3P_2$), Zinc selenite ($ZnSeO_3$) and Zinc telluride (ZnTe) (Ali et al., 2018). Although these nanoparticles have numerous applications in industry, the environment, and food, this review focuses on the application of these nanoparticles in plant germination.

The effects of Zn nanoparticles on plant germination are shown in Table 1. Some results indicate that the addition of Zn nanoparticles favors the germination of certain plants, such as beans (Nguyen et al., 2021), *Capsicum annuum* (García-López et al., 2018), *A. hypogaea* (Prasad et al., 2012), *T. aestivum* and *Linum usitatissimum* (Bayat et al., 2022), *Zea mays* (Estrada-Urbina et al., 2018), *Citrus reticulata* (Hussain et al., 2017), *T. aestivum* (Davydova et al., 2019). In general, the effects on different germination parameters indicate a dependence on the concentration of Zn nanoparticles, showing no effect or positive effect at low concentrations and an inhibitory effect at higher concentrations of these nanoparticles. These effects have been described or several crops such as *Z. mays* (Ahmed et al., 2021; López-Moreno et al., 2017), *S. lycopersicum* (Raliya et al., 2015; Singh et al., 2016), *L. sativa* and *Raphanus sativus* (Ko and Kong, 2014; Singh and Kumar, 2019), *Sinapis alba* (Landa et al., 2016), *L. sativa* (Liu et al., 2016), *Allium cepa* (Raskar and Laware, 2014) and *Phaseolus vulgaris* (Savassa et al., 2018).

Some studies indicate an inhibition of germination that affects different crops, as in the case of *L. sativa* and *R. sativus* (Ko and Kong, 2014; Kolesnikov et al., 2021a, b) and other studies that indicate no influence on germination, as is the case of *S. lycopersicum* (Zhao et al., 2021) and *Oryza sativa* (Li et al., 2021). The response of plants to the presence of nanoparticles depends on the plant and the type and concentration of nanoparticles, among other factors (Bayat et al., 2022).

The kind of experiment performed may also influence the results obtained. For example, the effects of adding Zn nanoparticles are usually more important when experiments are carried out with hydroponic cultures or in petri dishes than when experiments are carried out with soil (Ahmed et al., 2021). It is also generally accepted that the presence of Zn ions in soil solution usually has a higher toxicity than the corresponding nanoparticles, described in experiments with *Z. mays* (Ahmed et al., 2021) and with *P. vulgaris* (Nguyen et al., 2021). In this regard, Subbaiah et al. (2016) indicated a greater positive effect of Zn nanoparticles compared to the control soil treated with $ZnSO_4$ in a water solution. On the other hand, Zn nanoparticles can penetrate plant organs inducing apoptosis, which has been mentioned in experiments with *Z. mays* (Ahmed et al., 2021) and *Nicotiana tabacum* (Khodakovskaya

**Table 1**
Effects of Zn nanoparticles on seed germination of different plant species.

| Species | Cultivation media | Concentration | Effect | Reference |
|---|---|---|---|---|
| *Allium cepa* | Petri dishes | 0.00–0.04 mg mL$^{-1}$ | Germination increases at low concentrations (<0.02 mg mL$^{-1}$) and decreases at high concentrations. | Raskar and Laware (2014) |
| *Arachis hypogaea* | Petri dishes | 0.4–2.0 mg mL$^{-1}$ | Promotes seed germination and seeding vigour, especially under intermediate dose (1 mg mL$^{-1}$) | Prasad et al. (2012) |
| *Brassica nigra* | Agar, In vitro culture | 0.5–1.5 mg mL$^{-1}$ | Decrease germination under higher concentrations (>1 mg mL$^{-1}$) | Zafar et al. (2016) |
| *Brassica oleracea* | Nursery beds | 0.0001–0.00059 mg mL$^{-1}$ | Decrease germination | Singh et al. (2013) |
| *Capsicum annuum* | Petri dishes | 0.0–0.5 mg mL$^{-1}$ | Improves germination speed and germination vigour. | García-López et al. (2018) |
| *Citrus reticulata* | In vitro | 0.03 mg mL$^{-1}$ | Germination increased | Hussain et al. (2017) |
| *Cucumis sativus* | Petri dishes | 0–1.6 mg mL$^{-1}$ | At a dose of 1.6 mg mL$^{-1,}$ the germination increases by 10%. | de la Rosa et al. (2013) |
| *Lactuca sativa* | Petri dishes | 0.00002–0.0080 mg mL$^{-1}$ | No effect at concentrations lower than 0.005 mg mL$^{-1}$. Reduction for higher concentrations | Liu et al. (2016) |
| | Petri dishes | 0.00–0.03 mg mL$^{-1}$ | Decreased germination as the concentration of nanoparticles increased. Ec$_{50}$ 0.018 mg mL$^{-1}$ | Ko and Kong (2014) |
| *Lepidim sativum* | Phytotoxkit test | 10, 100, 1000 and 10, 000 mg kg$^{-1}$ | No effects on germination | Jośko and Oleszczuk (2013) |
| *Linum usitatissimum* | Petri dishes | 0.0–0.15 mg mL$^{-1}$ | Promotes seed germination | Bayat et al. (2022) |
| *Medicago sativa* | Petri dishes | 0–1.6 mg mL$^{-1}$ | Decreases by 40% | de la Rosa et al. (2013) |
| *Oryza sativa* | Petri dishes | 0.0–0.1 mg mL$^{-1}$ | No effect on germination | Li et al. (2021) |
| | Not indicated | Not indicated | Increase in germination speed | Parveen et al. (2022) |
| *Phaseolus vulgaris* | Petri dishes | 0.001–5 mg mL$^{-1}$ | Does not affect germination speed. Inhibition germination at high concentration (>0.1 mg mL$^{-1}$) | Savassa et al. (2018) |
| | Petri dishes | 0.01 mg mL$^{-1}$ | Positively affected the germination ratio | Nguyen et al. (2021) |
| *Raphanus sativus* | Petri dishes | 0.0–0.5 mg mL$^{-1}$ | Decreased germination as the concentration of nanoparticles increased. Ec$_{50}$ 0.04 mg mL$^{-1}$ | Ko and Kong (2014) |
| *Raphanus sativus* | Petri dishes | 0.0–1.0 mg mL$^{-1}$ | Negative effect on germination at concentrations greater than 0.01 mg m$^{L-1}$ | Singh and Kumar (2019) |
| | Pot experiment | 100–10,000 mg kg$^{-1}$ | Germination inhibition | Kolesnikov et al. (2021a) |
| *Sinapis alba* | Petri dishes | 0.01–1.0 mg mL$^{-1}$ | Decreased germination as the concentration of nanoparticles increased | Landa et al. (2016) |
| *Solanum lycopersicum* | Petri dishes | 0.002–0.01 mg mL$^{-1}$ | Stimulates germination at low concentrations. Germination reduction at high concentrations | Singh et al. (2016) |
| | Petri dishes | 0–1000 mg kg$^{-1}$ | Germination not affected up to 750 mg kg$^{-1}$. At 1000 mg kg$^{-1,}$ decrease | Raliya et al. (2015) |
| | Petri dishes | 0–1.6 mg mL$^{-1}$ | Decreases by 20% | de la Rosa et al. (2013) |
| | Nursery beds | 0.0001–0.00059 mg mL$^{-1}$ | Increased germination | Singh et al. (2013) |
| | Seeding tray with soil (greenhouse) | 0.0003–0.003 mg mL$^{-1}$ | No effect on germination | Zhao et al. (2021) |
| *Triticum aestivum* | Petri dishes | 0.015–0.50 mg mL$^{-1}$ | Stimulating effect on germination | Singh et al. (2019) |
| | Petri dishes | 0.8 mg mL$^{-1}$ | Increase germination energy | Davydova et al. (2019) |
| | Petri dishes | 0.0–0.15 mg mL$^{-1}$ | Promotes seed germination | Bayat et al. (2022) |
| | Petri dishes | Ni-doped ZnO nanoparticles: 0, 0.005, 0.01, 0.02, 0.04, and 0.08 mg mL$^{-1}$ | No effect on germination | Doğaroğlu et al. (2021) |
| *Vigna angularis* | Petri dishes | 0.01 mg mL$^{-1}$ | Positively affected the germination ratio | Nguyen et al. (2021) |
| *Vigna mungo* | Paper towel method | 0.1–0.6 mg mL$^{-1}$ | Maximum germination at a dose of 0.6 mg mL$^{-1}$ | Raja et al. (2019) |
| *Zea mays* | Agar, hydroponic medium and soil | 0.0–2 mg mL$^{-1}$ | Inhibition germination (87%) at 2 mg mL$^{-1}$ | Ahmed et al. (2021) |
| | Petri dishes | 0.0–1.6 mg mL$^{-1}$ | The function of temperature and concentration (at 20 °C and 0.4–1.6 mg mL$^{-1}$ reduces germination) | López-Moreno et al. (2017) |
| | Paper towel method | 1.6 mg mL$^{-1}$ | Promotes seed germination | Estrada-Urbina et al. (2018) |
| | Petri dishes | 0.05–2.00 mg mL$^{-1}$ | Higher germination percentages for a concentration of 1.5 mg mL$^{-1}$ | Subbaiah et al. (2016) |

et al., 2012); although this penetration capacity in the different plant organs depends on the characteristics of the nanoparticles such as size and type of nanoparticles (Lin and Xing, 2007; Singh et al., 2016).

Larger nanoparticles can bind to soil particles and release Zn via dissolution, while smaller nanoparticles can be absorbed and transported by the apoplast and symplast (Servin et al., 2015; Raliya et al., 2018). Also, Savassa et al. (2018) determined by microprobe X-ray analysis that a considerable amount of Zn was trapped in the seed coat while a small part was in the cotyledon of *P. vulgaris*. In this line, de la Rosa et al. (2013) determined how Zn nanoparticles can undergo plant transformation processes by X-ray absorption spectroscopy.

Likewise, a combined effect of temperature and nanoparticle concentration has been described. López-Moreno et al. (2017) reported no effect on the germination of *Z. mays* at 25 °C and 0.4 mg mL$^{-1}$ of N nanoparticles and a reduction in germination at 20 °C with Zn nanoparticle concentration between 0.4 and 1.6 mg mL$^{-1}$.

### 2.1.2. *Copper nanopartícles*

Copper is an essential element for plants involved in several metabolic processes such as photosynthesis and respiration, carbohydrate and nitrate metabolism, membrane permeability, reproduction and resistance to adverse factors. Copper is used in agriculture for its antifungal action and is added to soils and certain crops to avoid deficiencies and prevent the development of diseases. In several cases, Cu application increases its concentration in soils above the toxicity limits, as in soils dedicated to vine cultivation (Fernández Calviño et al., 2009).

The application of Cu nanoparticles can improve both deficiency and toxicity problems. For this reason, many Cu nanoparticles have been developed using different salts as precursors, such as $CuCl_2$, $CuSO_4$ and Cu $NO_3$ (Chakraborty et al., 2022).

Table 2 shows publications on the effects of Cu nanoparticles on the germination of different plants. The effects of adding Cu nanoparticles depend on the concentration and plant species.

The findings indicated that the addition of such nanoparticles has little or no effect on the germination of certain plants such as *Z. mays* (Ahmed et al., 2021), *S. lycopersicum* (Zhao et al., 2021), *P. vulgaris* (Duran et al., 2017) and *L. sativa* (Liu et al., 2016; Shah and Belozerova, 2009). There are also results with other crops that harm germination, as in the case of *Eruca sativa* (Zaka et al., 2016), *L. sativa* and *R. sativus* (Ko and Kong, 2014), although most commonly, there is a positive effect or no effect at low concentrations of nanoparticles and an inhibitory effect for high concentrations that affects several crops (Table 2). As in the case of Zn, Cu nanoparticles can penetrate the cell wall and generate new pores that favor water absorption and therefore favor germination, described by Kausar et al. (2022). Also, some plants, such as tobacco, can synthesize metabolites, minimising Cu nanoparticles' toxicity, thus decreasing the toxic effect. This has been demonstrated for Ag nanoparticles (Štefanić et al., 2018), but the same may occur with Cu nanoparticles.

On the other hand, increasing the concentration of Cu nanoparticles decreases germination and therefore increases toxicity due to the higher presence of $Cu^{2+}$ in the solution. This was observed in species such as *E. sativa* and *L. sativa* which are very sensitive to the presence of $Cu^{2+}$ in solution. Plants and seeds can directly assimilate copper nanoparticles, which can cause damage that inhibits the germination and development of roots and plants (Wang et al., 2020). On the other hand, the redox properties of Cu may contribute to favor its toxicity since $Cu^{2+}$ increase the production of reactive oxygen species (Kadri et al., 2022), causing oxidative stress oxidative (Mortezaee et al., 2019; Ortega-Ortíz et al., 2022) and resulting in damage to lipids, nucleic acids and proteins (Rao et al., 2018). Depending on the oxidation state of Cu in the nanoparticle, differences have been found in the effect on wheat germination. It was

**Table 2**
Effects of Cu nanoparticles on seed germination of different plant species.

| Species | Cultivation media | Concentration | Effect | Reference |
|---|---|---|---|---|
| *Brassica nigra* | Agar medium | 0.0–1.5 mg $mL^{-1}$ | Decreased germination as nanoparticle concentration increased | Zafar et al. (2017) |
| *Citrus reticulata* | In vitro | 0.03 mg $mL^{-1}$ | Germination increase. | Hussain et al. (2017) |
| *Eruca sativa* | MSO Medium | 0.03 mg $mL^{-1}$ | Decreased germination | Zaka et al. (2016) |
| *Glycine max* | Petri dishes in laboratory and Field experiments | 0.080–0.320 g $ha^{-1}$ | Increased germination at a lower dose (0.08 g $ha^{-1}$) in laboratory and field experiments | Ngo et al. (2014) |
| *Hordeum vulgare* | Petri dishes | 0.01–2.0 mg $mL^{-1}$ | From 0.005 to 0.25 mg $mL^{-1,}$ germination increases. Above 0.5 mg $mL^{-1}$, germination decreases | Kadri et al. (2022) |
| *Lactuca sativa* | Petri dishes | 0.00–0.003 mg $mL^{-1}$ | Decreased germination as nanoparticle concentration increased. $EC_{50}$ = 0.00046 mg $mL^{-1}$ | Ko and Kong (2014) |
| | Petri dishes | 0.0002–0.300 mg $mL^{-1}$ | Low doses do not affect or even increase germination (around 0.04 mg $mL^{-1}$), while high doses inhibit germination (above 0.04 mg $mL^{-1}$). | Trevisan-Peregrino et al., 2020 |
| | Petri dishes | 0.00002–0.0080 mg $mL^{-1}$ | No effect on germination | Liu et al. (2016) |
| | Soil in a Styrofoam cup | 0.013–0.066% (w/w) | Little effect on germination. Effects were only visible after 15 days of incubation | Shah and Belozerova (2009) |
| *Linum usitatissimum* | Petri dishes | 0.0–0.15 mg $mL^{-1}$ | Promotes seed germination | Bayat et al. (2022) |
| *Oryza sativa* | Water soaked cotton | 0.0–0.1 mg $mL^{-1}$ | Germination decreases with increasing nanoparticle concentration | Shaw and Hossain (2013) |
| | Petri dishes | 0.0–2.0 mg $mL^{-1}$ | Germination is inhibited, especially at high concentrations. | Wang et al. (2020) |
| *Phaseolus vulgaris* | Petri dishes | 0.001–1.0000 mg $mL^{-1}$ | Germination is not affected | Duran et al. (2017) |
| *Pinus sylvestris* | Petri dishes | 0.002–0.1 mg $mL^{-1}$ | Germination increase | Polischuk et al. (2019) |
| *Raphanus sativus* | Petri dishes | 0.0–0.2 mg $mL^{-1}$ | Decreased germination as nanoparticle concentration increased. $EC_{50}$ = 0.026 mg $mL^{-1}$ | Ko and Kong (2014) |
| | Petri dishes | 0.0–1.0 mg $mL^{-1}$ | Negative effect on germination (concentration greater than 0.01 mg $mL^{-1}$) | Singh and Kumar (2019) |
| | Pot experiment | 100–10,000 mg $kg^{-1}$ | Decreased germination | Kolesnikov et al. (2021a) |
| *Silybum marianum* | MSO medium | 0.03 mg $mL^{-1}$ | Germination increase | Khan et al. (2016) |
| *Sinapis alba* | Petri dishes | 0.01–1.0 mg $mL^{-1}$ | Decreased germination as nanoparticle concentration increased | Landa et al. (2016) |
| *Solanum lycopersicum* | Seeding tray with soil (greenhouse) | 0.0003–0.003 mg $mL^{-1}$ | No effect on germination | Zhao et al. (2021) |
| *Trigonella foenum-graecum* | Petri dishes | 0.0–0.5 mg $mL^{-1}$ | Germination decreases as nanoparticle concentration increases. | Kavitha et al. (2022) |
| *Triticum aestivum* | Petri dishes | 0.0–0.15 mg $mL^{-1}$ | Promotes seed germination | Bayat et al. (2022) |
| | Petri dishes | 0.0–0.1 mg $mL^{-1}$ | Maximum germination at 0.025 mg $mL^{-1}$. At higher concentrations, germination decreases. | Kausar et al. (2022) |
| | Petri dishes | 0.0–6.0 mg $mL^{-1}$ | Low doses improve germination (0.5 mg $mL^{-1}$). Inhibition at high doses (6 mg $mL^{-1}$) | Ortega-Ortíz et al. (2022) |
| | Petri dishes | 0.00–0.43 mg $mL^{-1}$ | Low doses improve germination (0.06 mg $mL^{-1}$). Inhibition at high doses (0.43 mg $mL^{-1}$) | Essa et al. (2021) |
| *Vigna mungo* | Paper towel method | 0.1–0.6 mg $mL^{-1}$ | Maximum germination at a concentration of 0.3 mg $mL^{-1}$ | Raja et al. (2019) |
| *Vigna radiata* | Petri dishes | 0.1–0.5 mg $mL^{-1}$ | Improve seed germination. Best germination rate under 0.2 mg $mL^{-1}$ | Paulraj et al. (2022) |
| | Petri dishes | 0.0–0.5 mg $mL^{-1}$ | Germination decreases as nanoparticle concentration increases. | Kavitha et al. (2022) |
| *Zea mays* | Agar, hydroponic medium and soil | 0–2 mg $mL^{-1}$ | Non-significant effects on seed germination at 2 mg $mL^{-1}$. Great effect of $Cu^{+2}$ | Ahmed et al. (2021) |

found that $Cu^{2+}$ had a positive effect at low concentrations, but $Cu^{1+}$ had no effect on germination (Essa et al., 2021).

The size of nanoparticles can affect germination; for example, Zuverza-Mena et al. (2015) find that a smaller size of Cu nanoparticles generates a greater inhibition of germination in *Coriandrum sativum*.

### *2.1.3. Iron nanoparticles*

Iron is an essential element for plants with several functions, such as being part of several proteins, intervening in the formation of chlorophyll, acting as part of organic complexes in several electronic transfer mechanisms of photosynthesis, participating in the reduction of nitrites and sulfates, directly involved in the metabolism of nucleic acids and in a multitude of redox reactions that take place in the plant.

Iron nanoparticles can improve fertilization efficiency in cases of deficiencies, which are very common since Fe tends to immobilize in poorly soluble forms in different soils. The most commonly used forms of Fe nanoparticles in agriculture are magnetite ($Fe_3O_4$), maghemite ($\Upsilon$-$Fe_2O_3$), hematite ($Fe_2O_3$) and ferrihydrite (paracrystalline Fe oxide) (Tombuloglu et al., 2022; González-Feijoo et al., 2023). These nanoparticles applied to agriculture promote growth by regulating hormone

**Table 3**
Effects of Fe nanoparticles on seed germination of different plant species.

| Species | Cultivation media | Mineral and Concentration | Effect | Reference |
|---|---|---|---|---|
| *Arachis hypogaea* | Petri dishes | 0.001–0.008 mg $mL^{-1}$ | No effect in germination. | Li et al. (2015) |
| *Avena sativa* | Pot experiment | Magnetite (250–1000 mg $kg^{-1}$) | Inhibition of germination at concentrations greater than 750 mg $kg^{-1}$ | Klekotka et al. (2022) |
| *Cucumis sativus* | Petri dishes | $Fe_3O_4$. 0.0–5.0 mg $mL^{-1}$ | Inhibition of germination | Mushtaq (2011) |
| | Not available | $Fe_3O_4$. 116 µg $mL^{-1}$ | Significant reduction effect on germination index | Barrena et al. (2009) |
| *Glycine max* | Petri dishes | 0.08, 0.2 and 0.32 g $ha^{-1}$ | Increase germination at 0.08 and 0.2 g $ha^{-1}$ | Ngo et al. (2014) |
| *Hordeum vulgare* | Petri dishes | 0.0–5.0 mg $mL^{-1}$ | Decreased germination from 0.25 mg $mL^{-1}$. | El-Temsah and Joner, 2012 |
| | Petri dishes | 0.00–1.00 mg $mL^{-1}$ | Greater germination increase at 0.1 mg $mL^{-1}$. In all cases greater than the control sample. | Serpoush et al. (2022) |
| | Petri dishes | Maghemite and Magnetite (0.05–0.20 mg $mL^{-1}$) | Both particles favor the speed of germination but more the magnetite. | Tombuloglu et al. (2022) |
| | Plastic glasses and soil | Fe/$SiO_2$. 0.0–25.0 mg $kg^{-1}$ | Increase germination rate. | Najafi Disfani et al. (2016) |
| *Lactuca sativa* | Not available | $Fe_3O_4$. 116 µg $mL^{-1}$ | Significant reduction effect on germination index (up to 50%) | Barrena et al. (2009) |
| *Linum usitatissimum* | Petri dishes | 0.0–5.0 mg $mL^{-1}$ | Decreased germination from 0.5 mg $mL^{-1}$. | El-Temsah and Joner, 2012 |
| *Lolium perenne* | Petri dishes | 0.0–5.0 mg $mL^{-1}$ | Decreased germination from 0.25 mg $mL^{-1}$. | El-Temsah and Joner, 2012 |
| *Nicotiana tabacum* | Petri dishes | 0.003–0.03 mg $mL^{-1}$ | Negative or positive effects depending on concentration and particle size (10 and 20 nm size increased germination, while 5 nm reduced germination) | Alkhatib et al. (2021) |
| *Oenthera biennis* | Paper plates | α-$Fe_2O_3$. 0.0–1.0 mg $mL^{-1}$ | Increase germination at low and medium concentrations. | Asadi-Kavan et al., 2020 |
| *Oryza sativa* | Paper method | Magnetite. 0.00–0.05 mg $mL^{-1}$ | The maximum germination is reached with a concentration of 0.05 mg $mL^{-1}$. | Jat et al. (2022) |
| | Petri dishes | 0.05–0.15 mg $mL^{-1}$ | Increase germination (65%) mainly at 0.05 mg $mL^{-1}$. | Khan et al., (2020) |
| | Hydroponics | 0.1 mg $mL^{-1}$ | Improve germination (up to 15%) | Chatterjee et al. (2021) |
| | Not available | 0.02–0.04 mg $mL^{-1}$ | Increase germination (up to 50%). | Afzal et al. (2021) |
| | Paper roll towel method | α-$Fe_2O_3$ (0.01–0.2 mg $mL^{-1}$) | Enhances germination at 0.025 mg $mL^{-1}$ | Prerna et al. (2021) |
| | Moist filter papers | 0.01–0.16 mg $mL^{-1}$ | Low doses increased seeding vigour. At high doses (0.08–0.16 mg $mL^{-1}$), they inhibit germination. | Guha et al. (2018) |
| *Phaseolus vulgaris* | Petri dishes | Magnetite. 0.0–1.0 mg $mL^{-1}$ | The germination rate was not affected. | Duran et al. (2018) |
| *Pinus sylvestris* | Petri dishes | 0.002–0.1 mg $mL^{-1}$ | No effect on germination. Decrease for highest concentration. | Polischuk et al. (2019) |
| *Quercus macdougallii* | Plastic tray | Magnetite. 0.75 mg $mL^{-1}$ | Increase germination. | Pariona et al. (2017b) |
| *Raphanus sativus* | Pot experiment | Magnetite (250–1000 mg $kg^{-1}$) | Inhibition of germination at concentrations greater than 750 mg $kg^{-1}$ | Klekotka et al. (2022) |
| *Sinapis alba* | Phytotoxkit test assay | Maghemite and Zero-valent iron nanoparticles. (3% v/v) | Maghemite and Zero-valent iron nanoparticles improved germination (6–10 and 10%, respectively) under Cd-contaminated soils. | González-Feijoo et al. (2023) |
| *Sorghum bicolor* | Petri dishes | n-$Fe_2O_3$. 0.0–0.50 mg $mL^{-1}$ | Improve germination. | Maswada et al. (2018) |
| *Triticum aestivum* | Petri dishes | 0.00–1.00 mg $mL^{-1}$ | Greater germination increase at 0.1 mg $mL^{-1}$. In all cases greater than the control sample. | Serpoush et al. (2022) |
| | Petri dishes | 0.025–0.600 mg $mL^{-1}$ | A pronounced increase in germination at 0.2–0.4 mg $mL^{-1}$. | Sundaria et al. (2019) |
| | Petri dishes and field trials | 0.08 mg $mL^{-1}$ | Increase germination energy | Davydova et al. (2019) |
| *Zea mays* | Paper roll towel method | α-$Fe_2O_3$ (0.01–0.2 mg $mL^{-1}$) | Enhances germination at 0.025 mg $mL^{-1}$ | Prerna et al. (2021) |
| | Petri dishes | 0.01–0.10 mg $mL^{-1}$ | Increases germination loaded with NPK and in combination with Chitosan and Moringa. | Tovar et al. (2020) |
| | Petri dishes | Hematite and Ferrihidrite. 1.0–6.0 mg $mL^{-1}$ | No effect in germination. | Pariona et al. (2017a) |
| | Plastic glasses and soil | Fe/$SiO_2$. 0.0–25.0 mg $kg^{-1}$ | Increase germination rate. | Najafi Disfani et al. (2016) |

and antioxidant enzyme activity (Rui et al., 2016; Kaningini et al., 2022; Rodríguez-Seijo et al., 2022). Their influence on seed germination of different plants is presented in Table 3. In general, a positive effect has been observed at low concentrations of Fe nanoparticles that can improve germination when used in conjunction with other molecules, such as citrate and chitosan, becoming negative when the concentration of nanoparticles exceeds a certain threshold (Asadi-Kavan et al., 2020; Tovar et al., 2020). Negative effects on germination are observed above a certain concentration (0.25–0.5 mg L$^{-1}$), which is dependent on the target crop (El-Temsah and Joner, 2012) (Table 3). These results, regardless of Fe minerals, have a favorable effect at low concentrations and an inhibitory effect at high concentrations (Table 3) for different crops, such as *O. sativa* (Khan et al., 2021; Jat et al., 2022), *T. aestivum*, *Hordeum vulgare* (Serpoush et al., 2022) among others (Table 3). In general, magnetite and maghemite favor germination, especially magnetite, as described in experiments with *H. vulgare* (Tombuloglu et al., 2022). On the other hand, hematite and ferrihydrite do not have a marked effect on the germination of *Z. mays* (Pariona et al., 2017a). At the same time, maghemite or zero-valent nanoparticles (20–40 nm) can improve germination and be more safety than the application of hydroxyapatite nanoparticles for S. *alba* germination (González-Feijoo et al., 2023).

Depending on the combination of concentration and particle size, a positive or negative effect on *N. tabacum* has also been described (Alkhatib et al., 2021).

In general, these results are obtained in laboratory studies (mainly on petri dishes or plastic trays), with fewer field experiments but with results indicating a similar trend as the study of Davydova et al. (2019) with *T. aestivum* or the study of Polischuk et al. (2019) with *Pinus sylvestris.*

In general, it has been observed that Fe nanoparticles accumulate in aggregates surrounding the roots (Duran et al., 2018) rather than within the cytoplasm, suggesting that Fe nanoparticles move through the apoplast in roots (Yuan et al., 2018; Alkhatib et al., 2021). Total inhibition of chlorophyll formation and the occurrence of deformations in cells and vascular tissues of the xylem have been described in germination experiments with *N. tabacum* and Fe nanoparticles between 5 and 10 nm (Alkhatib et al., 2021). On the other hand, an important reduction of germination has been described due to the decrease of other essential elements such as Ca, Mg, K and P for high concentrations of Fe nanoparticles, which are adsorbed by the Fe nanoparticles (Kornarzyński et al., 2020).

Also, Fe nanoparticles at low concentrations can increase the germination of *O. sativa*, increasing α-amylase activity and starch hydrolysis compared to $FeSO_4$, penetrating the seed coat and facilitating the diffusion of water and $H_2O_2$ into the seed (Afzal et al., 2021). The production of reactive oxygen in seeds treated with Fe nanoparticles can be increased and favor the germination of *O. sativa* and *Z. mays* (Prerna et al., 2021). Besides, Fe nanoparticles can enhance oxidative stress response through biochemical cascades and increase plant growth by seed germination and root growth (Guha et al., 2018; Polischuk et al., 2019; Khan et al., 2022), although higher doses (e.g., 0.08–0.16 mg mL$^{-1}$) can increase oxidative stress, damage tissues and reduce germination as reported by Guha et al. (2018) for *O. sativa*.

### 2.1.4. Nickel nanoparticles

Nickel is a micronutrient that has been considered essential for plants several years ago, being this element necessary for nitrogen metabolism and plant germination (Brown et al., 1987; Dalton et al., 1988; Shahzad et al., 2018). Nickel deficiency inhibits the action of urease, and this leads to urea accumulation causing necrotic spots on leaves. Also, Ni affects the metabolism of ureides, amino acids, and organic acids, stimulating the accumulation of oxalic and lactic acid in the leaves (Bai et al., 2006; Shahzad et al., 2018). The application of Ni nanoparticles can be used to improve the efficiency of fertilization or to promote certain processes that increase plant vigor. Table 4 shows the results of the influence of these nanoparticles on the germination of different plants. This metal has been less studied than the three previous ones, but the results achieved to date are similar to those indicated for Zn, Cu and Fe. In general, at low concentrations, contradictory results were found within the same crop, as in the case of studies with *R. sativus*; so, in two different studies using green Ni nanoparticles, a decrease in germination was observed over 100 mg kg$^{-1}$ (Kolesnikov et al., 2021a,b). On the other hand, a positive effect on germination has also been described in studies with *V. radiata* for concentrations below 0.005 mg mL$^{-.1}$ (Singh et al., 2022). At high concentrations, it has also been described that the use of Ni nanoparticles can negatively affect this species' germination (e.g., >0.25 mg mL$^{-1}$) (Uddin et al., 2021; Singh et al., 2022). In studies where the concentration of nanoparticles is not varied, favorable generally the germination, as in the case of *Glycine* max (Bezerra de Oliveira et al., 2022) and *O. sativa* (Li et al., 2022) (Table 4).

Experiments with G. max showed that, in all treatments, Ni remained attached to the seed coat (especially the hilum) and did not transfer to the emerging cotyledons and was finally absorbed by the radicle or primary roots of seedlings. Furthermore, electron microscopy analyses indicated that the distribution of Ni throughout the seed is a function of nanoparticle size, finding that, in seeds treated with smaller nanoparticles, these nanoparticles are agglomerated near the edge of the pre-emergence root (Bezerra de Oliveira et al., 2022).

## 2.2. Inorganic nanoparticles with non-essential elementsa

Some nanoparticles of different elements have been used in agriculture, such as Au, Al, Ce, Se, Si, Ti and Ag. Rock dust, a mixture of different minerals, has also been used as a germination improver for different plant species (e.g., Barrena et al., 2009; Arnott et al., 2021). Also, Au nanoparticle studies improved plant germination, as indicated for corn under 5 mg kg$^{-1}$ concentration (Mahakham et al., 2016), cucumber and lettuce under 10 μg mL$^{-1}$ (Barrena et al. (2009) and for onion (Acharya et al., 2019). Normally, Al is considered a toxic element for plants, inhibiting cell division in roots and thus blocking their growth; however, some experiments indicate that they favor an increase

**Table 4**
Effects of Ni nanoparticles on seed germination of different plant species.

| Species | Cultivation media | Concentration | Effect | Reference |
|---|---|---|---|---|
| *Berberis balochistanica* | Petri dishes | 0, 0.03, 0.06, 0.12, 0.25, 0.5 and 1 mg mL$^{-1}$ | Not affected at low concentrations (<0.12 mg mL$^{-1}$). Inhibition at high concentrations (>0.25 mg mL$^{-1}$). | Uddin et al. (2021) |
| *Glycine max* | Petri dishes and rhizotron | 360 mg kg$^{-1}$ | Increased germination speed. | Bezerra de Oliveira et al. (2022) |
| *Lepidim sativum* | Phytotoxkit test | 10, 100, 1000 mg kg−1 | No effects on germination | Jośko and Oleszczuk (2013) |
| *Oryza sativa* | Petri dishes | 0.15 mg mL$^{-1}$ | Improves germination speed | Li et al. (2022) |
| *Raphanus sativus* | Pot experiment | 0, 100, 1000 and 10,000 mg kg$^{-1}$ | Decreased germination over 100 mg kg$^{-1}$. | Kolesnikov et al. (2021a),b |
| *Vigna radiata* | Petri dishes | 0.005–0.0 mg mL$^{-1}$ | Stimulating effect at low concentrationsand inhibitory effect at high concentrations (>0.005 mg mL$^{-1}$). | Singh et al. (2022) |

in biomass (Juhel et al., 2011; Hayes et al., 2020) and the growth of some plants such as soybean under flooding stress conditions (Mustafa et al., 2015). The Ce can positively affect germination, plant growth and increase chlorophyll and saccharide contents (Cao et al., 2017; Wu et al., 2017; Ramírez-Olvera et al., 2018; Murugadoss et al., 2023). Also, this element may favor gas exchange and improve $CO_2$ assimilation due to the stimulation of stomata opening (Landa, 2021). Treatment with Se at low concentrations can improve crop yields (Bano et al., 2021). The Si can enhance the production of certain plants and mitigate biotic stress. (Naidu et al., 2023). Finally, Ti and Ag deserve a particular treatment due to the greater number of publications and are discussed in the following subsections.

### 2.2.1. *Silver nanoparticles*

Silver nanoparticles have been widely used in various fields as an antimicrobial agent, as a component of shampoos and soaps, in wastewater treatment, food storage and as part of the composition of paints, among other applications (Rai et al., 2009; Wijnhoven et al., 2009).

In the last two decades, Ag nanoparticles have also been widely used in agriculture with very positive results, improving the productivity of different crops. Thus, Ag nanoparticles can promote the growth and heat tolerance of *T. aestivum* (Iqbal et al., 2019), salinity tolerance (Hojjat et al., 2019; Nejatzadeh, 2021) and increase efficiency in water and fertilizer use (Lu et al., 2002). Also, these nanoparticles increase root nodulation and soil microbial diversity in a crop of *V. sinensis* (Pallavi et al., 2016), enhance chlorophyll concentration in *Brassica juncea* (Sharma et al., 2012), and the biomass of seedlings of *Arabidopsis thaliana* (Kaveh et al., 2013), and inhibits the growth of pathogenic bacteria in experiments with *V. unguiculata* (Vanti et al., 2020).

Different publications studying the effect of Ag nanoparticles on germination are presented in Table 5. According to Mahajan et al. (2022), the results can vary depending on the crop type, particle size and the nanoparticle's concentration, confirming that the application of Ag nanoparticles may show positive and negative aspects on the development of cultivated plants. The crop type is an important factor because of its different nanoparticle sensitivity.

For example, in experiments with the same dose of Ag nanoparticles with different crops, these nanoparticles did not significantly affect germination energy; germination capacity; length, number and abnormal sprouts of barley, peas and rape seeds. However, these Ag nanoparticles did benefit the germination energy of radish and cucumber seeds, especially under thermal stress conditions (Jaskulski et al., 2022).

Similar results on the effects of nanoparticles and their relation to crop type have been highlighted by Tymoszuk (2021). Table 5 shows many examples of germination promotion of different crops, such as *V. faba* (Saied et al., 2022), *S. tuberosum* (Salih et al., 2022), *S. lycopersicum* (Rutkowski et al., 2022), *T. dicoccum* (Smirnov et al., 2022), *T. aestivum* (Manaf et al., 202), *O. sativa* and *Z. mays* (Mahakham et al., 2017; Iqbal et al., 2021), *Cucurbita pepo* (Dziwulska-Hunek et al., 2021), *G.* max (Sharif et al., 2021) and *Z. mays* (Kumar et al., 2020), among others. There are also several examples of germination inhibition in different crops, such as *V. radiata* (Anwar et al., 2021; Anju et al., 2022), *N. tabacum* (Biba et al., 2020), *O. sativa* (Huang et al., 2020) and even as the inhibitory effect can be maintained for several generations as has been reported for *A. thaliana* (Geisler Lee et al., 2014). Some experiments highlight the non-effect of Ag nanoparticles on the germination of different crops, as in the case of *Pisum sativum* (Szablińska-Piernik et al., 2022), *C. pepo* (Stampoulis et al., 2009) and *Cucumis sativus* and *L. sativa* (Barrena et al., 2009). It may even happen that the results for the same plant are opposite, as is the case of *O. sativa*, improving germination according to Iqbal et al. (2021) or inhibiting such germination as described by Huang et al. (2020). This indicates that crop is an important factor, but other factors, such as nanoparticle size and concentration, also play a role. In fact, most of the studies mentioned in Table 5 indicated that the use of Ag nanoparticles is dependent on the concentration of these nanoparticles, showing an inhibitory effect at high concentrations but no effect or a stimulatory effect at low nanoparticle concentrations (Thuesombat et al., 2014; Malathi and Palani, 2016; Asanova et al., 2019; Prażak et al., 2020). Smaller Ag nanoparticles have a greater effect than larger Ag nanoparticles since they may penetrate more easily into the tissues or be more easily transported and enter the protoplasm, which has been highlighted by Yin et al. (2011) and Mazumdar and Ahmed (2011) in experiments with *Lolium multiflorum O. sativa*, respectively.

The solubility of Ag nanoparticles can also be key to establishing their toxicity in different crops. In this sense, the higher the solubility of Ag, the higher the toxicity of the nanoparticles, as has been described in experiments with different crops such as *T. aestivum*, *Sorghum bicolor*, *Lepidium sativum*, *S. alba*, where the toxicity of $AgNO_3$ was higher than equivalent Ag nanoparticles (Matras et al., 2022). Similar results have been obtained in experiments with *Ricinus communis* (Yasur and Rani, 2013).

Toxicity on germination can increase due to the co-solvents used to obtain Ag nanoparticles, as Barrena et al. (2009) indicated in an experiment with *L. sativa* and *C. sativus* where sodium borohydride (2.64 mM) was used as a solvent and germination was decreased in comparison for Ag without solvent. The results depend on the type of co-solvent used, being able to increase the toxicity, for example, with a mixture of sodium borohydride and cysteamine hydrochloride, or decrease the toxicity with a mix of sodium borohydride and trisodium citrate (Matras et al., 2022), or even not reduce the toxicity of Ag nanoparticles with cysteine (Yin et al., 2011). Reducing agents such as xylose with Ag nanoparticles may limit microbial disease development and stimulate germination speed in experiments with *S. lycopersicum* (Rutkowski et al., 2022).

Different mechanisms underlying nanopriming-induced seed germination were proposed, including the creation of nanopores for enhanced water uptake, reactivation of ROS/antioxidant systems in seeds, generation of hydroxyl radicals for cell wall detachment, and nanocatalyst for accelerated starch hydrolysis (Mahakham et al., 2017). In this sense, Ag nanoparticles interact with α-amylase, contributing to starch hydrolysis (Salih et al., 2022), and thus, the seeds can generate available sugars to support embryo development. Silver nanoparticles can also increase the activity of antioxidant enzymes and the concentration of soluble sugar, protein and chlorophyll contents, favoring seed germination (Kumar et al., 2020).

### 2.2.2. *Titanium nanoparticles*

Titanium occurs in nature in the form of $TiO_2$ and is mainly organized in three different crystalline structures such as brookite (orthorhombic structure), anatase (tetragonal structure) and rutile (tetragonal structure) titanite. Titanium nanoparticles are used in various processes such as cosmetics manufacturing, food and medicine (Grand and Tucci, 2016). Titanium nanoparticles applied to the soil can improve soil salinity and increase leaf length and plant dry weight, as proven in a *V. faba* crop (Fatima et al., 2021). The effects of Ti nanoparticles on plant germination are presented in Table 6. In general, the effects of Ti nanoparticles have been studied to a lesser extent than Ag nanoparticles, but the conclusions drawn are very similar in view of the current knowledge. In this sense, the available data indicate that the presence of Ti nanoparticles does not affect germination as in the case of *T. aestivum*, *B. napus* and *A. thaliana* (Larue et al., 2011); *B. campestris*, *L. sativa* and *P. vulgaris* (Song et al., 2013a); and *S. lycopersicum* (Song et al., 2013b). This may be attributed to the non-penetration of nanoparticles into the seed coat and endosperm, described in a study with *S. lycopersicum* (Song et al., 2013b) and may be attributed to agglomeration of the nanoparticles (Cox et al., 2016). However, Ti nanoparticles penetrated plant tissues with crops such as *B. campestris*, *L. sativa* and *P. vulgaris* (Song et al., 2013a). In this regard, Du et al. (2011) indicated that only a small part of $TiO_2$ nanoparticles can penetrate the rhyzoderm of primary roots in experiments with *T. aestivum*.

**Table 5**
Effects of Ag nanoparticles on seed germination of different plant species.

| Species | Cultivation media | Concentration | Effect | Reference |
|---|---|---|---|---|
| *Allium cepa* | Greenhouse and field studies | Not available | Significanlty enhanced seed emergence after six days | Acharya et al. (2019) |
| *Arabidopsis thaliana* | Hydroponics | 0–0.5 mg L$^{-1}$ | Toxicity dependent on size and concentration | Geisler-Lee et al. (2013) |
|  | Petri dishes | 0–0.075 mg L$^{-1}$ | Germination decreases for several generations | Geisler-Lee et al. (2014) |
| *Cicer arietinum* | Petri dishes | Not available | Inhibition at high concentrations | Jomol et al. (2022) |
|  | Petri dishes | 0.0025, 0.005 and 0.008 mg L$^{-1}$ | Enhance germination in all concentrations. | Debnath et al. (2020) |
|  | Filter papers | 0–100% | Promote germination (high concentrations) | Jose et al. (2021) |
| *Citrus reticulata* | In vitro | 0, 10, 20, 30 and40 mg L$^{-1}$ | Promote germination. Best results under 30 mg L$^{-1}$ | Hussain et al. (2018) |
| *Cucumis sativus.* | Not available | 100 μg mL$^{-1}$ | No effect to slight germination reduction (with or without solvent) | Barrena et al. (2009) |
| *Cucurbita pepo* | Petri dishes | Not available | Promote germination | Dziwulska-Hunek et al. (2021) |
|  | Petri dishes | 1000 mg L$^{-1}$ | No effects | Stampoulis et al. (2009) |
|  | Petri dishes | 0.05, 0.1, 0.5, 1, 1.5, 2 and 2.5 mg L$^{-1}$ | Promote germination under higher concentrations (0.5–2.5 mg L$^{-1}$) | Almutairi and Alharbi (2015) |
| *Glycine max* | Petri dishes | 0–100 mg L$^{-1}$ | Germination increase (50 mg $^{L-1}$) | Sharif et al. (2021) |
| *Lactuca sativa* | Not available | 100 μg mL$^{-1}$ | No significant effect without solvent. Reduced germination with solvent. | Barrena et al. (2009) |
| *Lens culinaris* | Petri dishes | 0–100 mg L$^{-1}$ | Inhibition at high concentrations (100 mg L$^{-1}$) | Ghosh et al. (2022) |
| *Lepidium sativum* | Phytotestkit test | 50 mg L$^{-1}$ | No effects on germination of nanoparticles. Negative effects of AgNO$_3$ | Matras et al. (2022) |
| *Nicotiana tabacum* | Petri dishes | 25–100 μM | Decrease germination | Biba et al. (2020) |
| *Oryza sativa* | Agar medium | 0–40 mg L$^{-1}$ | Not affect germination percentage. Promotes seedling growth | Gupta et al. (2018) |
|  | Pot experiment | 0–1000 mg L$^{-1}$ | Inhibition at high concentrations. The effect is dependent on the size of the nanoparticles | Thuesombat et al. (2014) |
| *Oryza sativa* | Petri dishes | 0, 5, 10 and 20 mg L$^{-1}$ | Promote germination under 5 and 10 mg L$^{-1}$ | Mahakham et al. (2017) |
|  | Petri dishes | 50–150 mg L$^{-1}$ | Promote germination | Iqbal et al. (2021) |
|  | Petri dishes | 100 mg L$^{-1}$ | Germination inhibition | Huang et al. (2020) |
| *Pennisetum glaucum* | Petri dishes | 2 mg L$^{-1}$ | Promote germination | Sable et al. (2018) |
|  | Petri dishes | 0–50 mg L$^{-1}$ | Enhances germination | Parveen and Rao (2015) |
| *Phaseolus mungo* | Hydroponic culture | 0–80 mg L$^{-1}$ | No significant effects | Kim et al. (2018) |
| *Phaseolus vulgaris* | Petri dishes. Field experiments | 0, 1.25 and 2.5 mg L$^{-1}$ | The positive effect at low concentration. No effect at high concentration | Prażak et al. (2020) |
| *Physalis peruviana* | Phytotestkit test | 0–15.4 mg L$^{-1}$ | Germination was not affected at low concentrations. Reduction of root length at high doses | De Oliveira Timoteo et al. (2019) |
| *Pisum sativum* | Petri dishes | 0.02–0.05 mg mL$^{-1}$ | No effect on germination | Szablińska-Piernik et al. (2022) |
|  | Petri dishes | 0.0025, 0.005 and 0.008 mg L$^{-1}$ | Enhance germination in all concentrations | Debnath et al. (2020) |
|  | In vitro | 0–0.05% | Not affect germination at low concentrations and inhibits it at high concentrations. | Barabanov et al. (2018) |
| *Ricinus communis* | Petri dishes | 0–4000 mg L$^{-1}$ | No effect on germination. Negative effects of AgNO$_3$ | Yasur and Rani (2013) |
| *Silybum marianum* | Murashige and Skoog Media | 30 mg L$^{-1}$ | Promote germination | Khan et al. (2016) |
| *Sinapis alba* | Phytotestkit test | 50 mg L$^{-1}$ | No effects on germination of nanoparticles. Negative effects of AgNO$_3$ | Matras et al. (2022) |
| *Solanum lycopersicum* | Petri dishes | 0.0–75 mg L$^{-1}$ | Promote germination at higher concentrations (75 mg L$^{-1}$) | Rutkowski et al. (2022) |
|  | Soil + sand + farmyard manure | 0–50 mg L$^{-1}$ | With 10 mg L$^{-1}$ increase in germination. Decreases at higher concentrations | Malathi and Palani (2016) |
|  | Petri dishes | 0–100 mg L$^{-1}$ | Increased germination. Depends on the tomato variety. Decrease in some cases. | Mehrian et al. (2016) |
| *Solanum tuberosum* | Murashige-Skoog Media | 0, 2.5, 5, 10 and 25 mg L$^{-1}$ | Positive effect on germination at intermediate concentrations (5 mg L$^{-1}$) | Salih et al. (2022) |
| *Sorghum bicolor* | Phytotestkit test | 50 mg L$^{-1}$ | No effects on germination of nanoparticles. Negative effects of AgNO$_3$ | Matras et al. (2022) |
| *Triticum aestivum* | Phytotostkit test | 50 mg L$^{-1}$ | No effects on germination of nanoparticles. Negative effects of AgNO$_3$ | Matras et al. (2022) |
|  | Petri dishes | 0–40.0 mg L$^{-1}$ | No effects on germination | Lahuta et al. (2022) |
|  | Petri dishes | 0–30 mg L$^{-1}$ | Promote germination | Manaf et al. (2021) |
|  | Petri dishes | 0–10 mg L$^{-1}$ | No effect for low concentrations (0.001–0.5 mg L$^{-1}$). Higher concentration inhibitory effect. | Asanova et al. (2019) |
|  | Hydroponic culture | 0–80 mg L$^{-1}$ | No significant effects | Kim et al. (2018) |
|  | Petri dishes | Not available | Promote germination | Smirnov et al. (2022) |
| *Vicia faba* | Petri dishes | 1.0 mg mL$^{-1}$ | Promote germination | Saied et al. (2022) |
| *Vigna radiata* | Petri dishes | Not available | Germination inhibition (100%) | Anju et al. (2022) |
|  | Petri dishes | 0–20 mg L$^{-1}$ | Reduce germination (up to 20%) | Anwar et al. (2021) |
|  | Petri dishes | 0.0025, 0.005 and 0.008 mg L$^{-1}$ | Enhance germination in all concentrations | Debnath et al. (2020) |
| *Zea mays* | Petri dishes | 50–150 mg L$^{-1}$ | Promote germination | Iqbal et al. (2021) |
|  | Pot assay | 50 mg L$^{-1}$ | Promote germination | Kumar et al. (2020) |

**Table 6**
Effects of Ti nanoparticles on seed germination of different plant species.

| Species | Cultivation media | Concentration | Effects | Reference |
|---|---|---|---|---|
| *Allium cepa* | Pots | 0, 2, 4, 6, 8 and 10 mM | Genotoxic effects that can reduce germination | Ghosh et al. (2010) |
|  | Petri dishes | 0–50 mg L$^{-1}$ | At low concentrations, it enhances germination. Inhibits germination at high concentrations. | Laware and Raskar (2014) |
| *Arabidopsis thaliana* | Petri dishes | 0–500 mg L$^{-1}$ | Germination increase | Tumburu et al. (2015) |
|  | Hydroponic culture | 0–100 mg L$^{-1}$ | No effects on germination | Larue et al. (2011) |
| *Brassica campestris* | Petri dishes | 0–5000 mg L$^{-1}$ | They do not affect the speed of germination | Song et al. (2013a) |
| *Brassica napus* | Hydroponic culture | 0–100 mg L$^{-1}$ | No effects on germination | Larue et al. (2011) |
| *Foeniculum vulgare* | Petri dishes | 0, 5, 20, 40, 60 and 80 mg L$^{-1}$ | Improve germination. Best results under intermediate dose (40 mg L$^{-1}$) | Feizi et al. (2013) |
| *Lactuca sativa* | Petri dishes | 0–5000 mg L$^{-1}$ | They do not affect the speed of germination | Song et al. (2013a) |
| *Lepidim sativum* | Phytotoxkit test | 10, 100, 1000 and 10, 000 mg kg$^{-1}$ | No effects on germination | Jośko and Oleszczuk (2013) |
| *Mentha piperita* | Petri dishes | 0, 100, 200 and 300 mg L$^{-1}$ | Inhibits germination. Full inhibition at higher concentration (300 mg L$^{-1}$) | Samadi et al. (2014) |
| *Nicotiana tabacum* | Pot experiment | 0, 2, 4, 6, 8 and 10 mM | Genototic effects that can reduce germination | Ghosh et al. (2010) |
| *Ocimum basilicum* | Pot experiment | 0–750 mg kg$^{-1}$ | Inhibits germination | Tan et al. (2017) |
| *Oryza sativa* | Petri dishes | 0–2000 mg L$^{-1}$ | No effects on germination | Yang et al. (2015) |
| *Phaseolus vulgaris* | Petri dishes | 0–5000 mg L$^{-1}$ | They do not affect the speed of germination | Song et al. (2013a) |
| *Solanum lycopersicum* | Petri dishes | 0–5000 mg L$^{-1}$ | Not effects on germination | Song et al. (2013b) |
|  | Petri dishes | 0–1000 mg kg$^{-1}$ | Germination is not affected up to a concentration of 750 mg kg$^{-1}$. At 1000 mg kg$^{-1}$, there is a decrease. | Raliya et al. (2015) |
| *Spinacia oleracea* | Petri dishes | 0–6‰ | Germination increase | Zheng et al. (2005) |
| *Triticum aestivum* | Hydroponic culture | 0–100 mg L$^{-1}$ | No effects on germination | Larue et al. (2011) |
| *Vicia narbonensis* | Petri dishes | 0–4‰ | Germination delay | Ruffini Castiglione et al. (2011) |
| *Vigna radiata* | Filter paper | 0–250 mg L$^{-1}$ | Germination increase | Mathew et al. (2021) |
| *Zea mays* | Petri dishes | 0–4‰ | Germination delay | Ruffini Castiglione et al. (2011) |
|  | Petri dishes | 0–2000 mg L$^{-1}$ | No effects on germination | Yang et al. (2015) |

On the other hand, some studies indicate inhibition of germination in *V. narbonensis* and *Z. mays* (Ruffini Castiglione et al., 2011), *Mentha piperita* (Samadi et al., 2014) and *Ocimum basilicum* (Tan et al., 2017).

Data on the beneficial effects on germination have also been described with different medicinal and aromatic plants (Hatamie et al., 2014), also studies with *Spinacia oleracea* (Zheng et al., 2005), *A. thaliana* (Tumburu et al., 2015), *V. radiata* (Mathew et al., 2021) and *Foeniculum vulgare* (Feizi et al., 2013). Germination enhancement mechanisms are related to increased water absorption and the formation of active oxygen in the form of $H_2O_2$ and hydroxide ions that reactivate seed germination (Zheng et al., 2005; Aslani et al., 2014). It has also been hypothesized that the effect in some cases is related to the size and surface area of Ti nanoparticles, with improvements in germination being obtained even at high nanoparticle concentrations with larger seeds compared to smaller seeds (Hatamie et al., 2014).

Other results indicate that the inhibitory or germination-enhancing effects are dose- and nanoparticle-size-dependent. Clément et al. (2013) suggested that germination toxicity appeared above 1 mg L$^{-1}$ but decreased above 100 mg L$^{-1}$. Toxicity could be due to the increased antimicrobial activity of Ti nanoparticles, which increases plant resistance to stress. Results according to those obtained by Feizi et al. (2012) in studies with *T. aestivum* in which Ti nanoparticles can penetrate seed coat, which would be unlikely for bulk $TiO_2$.

The crystallographic organization of the different $TiO_2$ minerals also influences the toxicity of these nanoparticles. For example, the rutile structure forms long aggregates in aqueous media, which confers lower toxicity than anatase, as confirmed in a study with wheat by Silva et al. (2016). The crystallographic organization conditions the external structure of Ti nanoparticles, which in turn conditions their phytotoxicity and has to be considered when adding such nanoparticles to agricultural soils, highlighted by Wang et al. (2021) in experiments with *Daucus carota*.

The contact period between seeds and nanoparticles is also important in establishing the phytotoxicity of Ti nanoparticles, which has been highlighted in experiments with *T. aestivum* (Silva et al., 2017).

### 2.2.3. Comparison among different nanoparticles

In many cases, mixtures of nanoparticles are used in two sorts of experiments: i) those that compare the effect of two or more nanoparticles separately and ii) those that study the simultaneous effect of two or more nanoparticles.

- *Comparison of nanoparticles added together.*

The results indicate that adding bimetallic nanoparticles favors germination; for example, the presence of ZnS/AgS nanoparticles favors the germination of *T. aestivum* and *O. sativa* concerning the control samples, with only distilled water (Iqbal et al., 2022). However, as with individually added nanoparticles, the effects on germination are concentration dependent. Khan et al. (2021) synthesized ZnO nanoparticles with different Ni concentrations and found that the germination of *T. aestivum* increased when adding Ni concentrations $\leq$3%. However, with Ni at 5%, there was a sharp decrease in the germination percentage. Germination vigor, root and leaf length follow the same trend.

- *Comparison of nanoparticles added individually.*

In this kind of experiment, the effects on the germination of two or more nanoparticles are compared by establishing toxicity sequences. For example, when comparing the toxic impact of Ag and Ti nanoparticles, Ag nanoparticles are more toxic than Ti nanoparticles (Cox et al., 2016). Similar results were obtained by Song et al. (2013b), who indicated that Ag nanoparticles inhibit the germination of *S. lycopersicum* while Ti nanoparticles have no such toxic effect on seed germination.

On the other hand, El-Temsah and Joner (2012) indicated that Fe nanoparticles could be used at low concentrations favoring germination, while Ag nanoparticles inhibit the germination of Fe nanoparticles of *L. usitatissimum, L. perenne* and *H. vulgare*. Davydova et al. (2019)

determined that both Fe and Zn nanoparticles have a positive effect on the germination of *T. aestivum,* but Zn has a greater positive effect.

Sequences of toxicity or positive effects on the germination of different nanoparticles are also established. For example, Yang et al. (2015) indicated that the oxides of 7 elements (Fe, Si, Ti, Al, Ce, Zn and Cu) did not affect the germination of maize and rice, while CuO and ZnO significantly inhibited root elongation at 2000 mg $L^{-1}$, and Al was slightly toxic only to maize. Toxicity was found only with the nanoparticles and not with the soluble elements of $Cu^{2+}$, $Zn^{2+}$ and $Al^{3+}$. In general, these effects depend on the type of crop; in this regard, Ahmed et al. (2019) studied the effect of different nanoparticles (Ti, Zn, Al and Cu) on four plants (radish, cucumber, tomato and alfalfa). They indicated that the effects depend on the type of culture and the concentration of the metal nanoparticles. Zinc nanoparticles had the highest inhibitory effect among the different metals, followed by Cu nanoparticles. However, opposite results were also found, indicating that Zn nanoparticles have a greater positive impact on the germination of *C. reticulata* than Cu nanoparticles (Hussain et al., 2017). Similar results were obtained by Singh and Kumar (2019), establishing the following sequence of toxicity in germination studies with *R. sativus* (CuO > CuO + ZnO > ZnO); and by Ko and Kong (2014) with the toxicity sequence: $CuO > ZnO > NiO > Co_3O_4 > Fe_2O_3 > TiO_2$. The increased toxicity of Cu nanoparticles has also been shown in experiments with different types of soils; Kolesnikov et al. (2021a) indicated that toxicity on *R. sativus* germination in a Cambisol-type soil follows the sequence $Cu \geq Zn > Ni$; similar results to those obtained in an Arenosol (nanoparticle concentration of 100 mg $kg^{-1}$), although this sequence is dependent on nanoparticle concentration (Kolesnikov et al., 2021b).

## 3. Remarks and future prospects

In general, nanomaterials applied to agriculture are in the early stages of development, and the experiments carried out are in the laboratory or pilot testing phase. Therefore, there is a lack of information on the benefits of many nanoparticles and the environmental and public health problems that may arise from their use when applied under field conditions. Consequently, it is of particular interest to establish the efficacy of these compounds applied to the soil and promote more environmentally friendly practices and the sustainability of agricultural systems.

Regarding the effects of the application of metallic nanoparticles on germination, it can be said that, generally, the effects of the application of metallic nanoparticles are very positive. Unfortunately, most experiments are carried out in the laboratory under controlled conditions. The results indicate that the effects depend on the type of nanoparticle, its concentration, and the kind of plant. In general, smaller particles have a greater capacity to accumulate in plant tissues, which is also favoured by increasing the concentration. The solubility of the nanoparticles is also a key aspect since it also affects the entry of the nanoparticles inside the roots, exerting both their positive and toxic effect. It is necessary to continue deepening this kind of experiment to reach an objective that allows to standardize of both the synthesis and the characterization of nanoparticles and to clarify the protocols of the different methods necessary for the good use of these nanoparticles. This also includes standardizing the appropriate germination experiments for each plant or group of plants. In this way, possible toxicological effects on plant seeds and effects on soil organisms and humans could be clarified, and an ethical, safe and responsible use of these nanoparticles could be achieved. The immediate effects on germination depend on the time scale established in the laboratory tests, which depend on the characteristics of the nanoparticles and the environmental conditions, as well as on the different organisms that may be affected.

At a subsequent step, it would be useful to carry out experiments closer to reality with greenhouse and field experiments to establish the most suitable physicochemical conditions for the application of different doses of nanoparticles and thus identify the most detrimental or ideal scenarios for both crops and the environment. In this regard, it should be noted that the effect of a nanoparticle can be different depending on the type of soil, taking into account variables such as the presence of organic matter in solid or dissolved phase and inorganic components, which can decisively affect the behaviour of these nanoparticles.

Other factors, such as pH and ionic strength of the medium, also seem to be key to establishing the interaction of nanoparticles with plant roots. Another aspect to be considered is the establishment of the best conditions for nanoparticle application, mainly soil application or foliar application. The final objective should be establishing the ideal germination conditions when nanoparticles interact with plants and soils. This kind of greenhouse and field experiments would make it possible to establish the effect in the medium and long term (from months to years) but require a significant financial investment.

The application of nanoparticles, partly due to their small size, presents several potential risks from an environmental point of view, such as easy dispersion and transport, the ability to cause adverse effects in different organisms (ecotoxicity), persistence in the environment, the ability to bioconcentrate or bioaccumulate in higher organisms and possible reversibility of the processes. These characteristics result in potential environmental problems, so further studies on the toxicity and ecotoxicity of the different nanoparticles on aquatic and terrestrial organisms from the food web would be necessary. Therefore, risk assessment studies are needed to know the potential effects on non-target organisms, but also with an essential role for healthy soils and crop yield. Besides, this small size will represent that nanoparticles can act more quickly than larger-sizer nanoparticles, and therefore, more research is also needed to know how they can interact with cellular molecules and, therefore, to know their role in biochemical responses through oxidative stress mechanisms.

Public health problems are related to inhalation or exposure to nanoparticles through contaminated air, ingesting contaminated food and water or skin contact. The effects described so far include oxidative stress, lipid peroxidation, genotoxicity or lung diseases. Other more important problems have also been described as mutations in the DNS damage cells. Consequently, nanoparticle use must be careful until the necessary safety conditions for proper use are established. Once the ecological and public health impact is known, countries, responsible institutions or organizations can develop appropriate regulations and legislation for using these nanoparticles in agriculture.

## Credit author statement

VSM: Formal analysis, investigation, Writing - original draft, Writing - Review & Editing; MAE: Conceptualization, methodology, formal analysis, investigation, writing - original draft; Funding acquisition; ARS: Methodology, formal analysis, investigation, Writing - Review & Editing. DAL: Conceptualization, methodology, investigation, Writing - original draft, Review & Editing; Funding acquisition.

## Statements & declarations

Ethical Approval, Consent to Participate and consent to publish.
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## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

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