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THE ROLE AND PERSPECTIVE OF THE USE OF METAL NANOPARTICLES IN THE CULTIVATION OF AGRICULTURAL CROPS

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The development of the nanoindustry over the past 15-20 years allows us to consider substances containing nanomaterials as an alternative to existing chemical means of control in the cultivation of agricultural crops, in particular as components of mineral nutrition and protection of field crops. Taking into account the relevance of this issue, in recent years, the use of colloidal forms of metals as elements of micronutrient plant nutrition has been made and substantiated by our own research. Nanotechnology provides sustainable solutions by replacing traditional fertilizers with nanoparticles. These nanoparticles have unique properties to overcome bioavailability issues and enhance mineral uptake, increase yields and reduce fertilizer losses, helping to protect the environment. Recent studies emphasize the effect of nanoparticles of basic and essential elements on plant growth, physiology and development, taking into account their size, composition, concentration and method of application. Key aspects of the research include evaluating the effectiveness of methods of their use and the impact of nanoparticles on the nutritional quality of agricultural crops.

It is noted that foliar fertilization with biogenic metals is important in providing plants with nutrients and enriching them with useful elements. Attention is also focused on the size of nanoparticles, as this factor determines their unique physicochemical properties and ability to penetrate plant cells, which can affect their physiological response and ability to absorb useful or toxic elements.

The review presents the findings regarding the positive and negative aspects of nanoparticles, their impact on agricultural development and environmental sustainability. At the same time, emphasis is placed on the need for further research for the development of nanofertilizers aimed at improving food production and preserving the environment.

Key words: *synthesized nanoparticles, nanomaterials, biogenic metals, agricultural crops, biogenic metals.*

Fig. 2. Ref. 64.

1. Problem formulation

The problem lies in the need to find effective and more sustainable ways of controlling the cultivation of agricultural crops that meet modern environmental requirements and contribute to the sustainable development of the agricultural sector. Traditional methods of using chemicals can have a negative impact on the environment and human health, so there is a need for new, more environmentally friendly approaches. The production and application of nanomaterials in agriculture can open up new opportunities for increasing productivity, protecting plants from stress factors, and reducing the negative impact on the environment. However, there are certain challenges associated with the development of effective methods for growing and applying nanomaterials that must be addressed to achieve optimal results.

The main idea behind the use of nanomaterials is based on such considerations as the natural biogenicity of the metal, the size and concentration of the nanoparticles. At the same time, it is proposed to consider one of the criteria of biological functionality as the internal structure of a nanoparticle [1-2], which can consist of several elements and compounds, such as metal oxides, metals and various organic substances [3]. The general hypothesis is based on the idea that defects in the crystal structure of dispersed objects are a reflection of the physical processes that accompany the formation of a nanoparticle. Based on this, the method of obtaining crystalline nanoparticles is taken into account [4].

2. Analysis of recent research and publications

Comparing the biological properties of nanomaterials obtained by different methods confirms the assumption that nanoparticles do not have the same effect on biological organisms depending on the synthesis method [5]. The main factor that we take into account is the biogenicity of the metal, which means the presence of biological functions. For example, a metal such as silver does not have a pronounced biogenic function, but its small concentrations in almost all biological studies have a positive effect on the growth and development of plants [6], [7]. However, an increase in the concentration of silver can inhibit the development of plants and microorganisms [8].

3. The purpose of the article

The purpose of the article is to create an objective and informative review that will contribute to expanding the understanding of the potential of synthesized nanoparticles in agriculture and their impact on sustainable development. It is noted that the concentration of metal nanoparticles significantly affects the yield, as far as this parameter determines the mass fraction of nanoparticles in the solution or on the soil surface, affecting their interaction with plants and the biological environment.

4. Results of the researches

Thus, in work [9], foliar feeding of onions (*Allium cepa)* was used with the addition of silver to the working solution of 20 ppm Ag NPs. The authors established the highest average values of morphological indicators of vegetative plants, yield and quality of the final product compared to other concentrations of silver.

The paper [10] provides data on the use of silver colloid (non-ionic form) for feeding plants, both foliar and root treatment. The authors note that exposure to roots caused higher phytotoxicity, Ag was found to be absorbed and subsequently moved from exposed plant parts to other parts regardless of the route of exposure. The obtained results indicate the toxicity of the particles and demonstrate that the accumulation and movement of silver nanoparticles must be taken into account in the assessment of environmental risks and food safety in plant processing.

In the paper [11], when processing grain and leguminous crops, the authors noted an increase in the accumulation of silver particles by 17-200 times in the leaves compared to the roots. Also, in the study [12], the authors noted that the intracellular distribution of Ag and its chemical forms differed depending on the route of exposure. It was found that the effect of Ag NPs on the roots led to more significant consequences than the effect on the leaves.

Many studies have been dedicated to investigating the effects not only of silver on biological organisms, but also of other metals such as gold, platinum, titanium, chromium, lead, cadmium, carbon, and others, which do not participate in biochemical processes as cofactors and may induce toxicity or have limited physiological impact [13], [14].

In the work referenced [15], the mechanism of entry into plant organisms of metals such as lead and cadmium, which enter from the atmosphere through technological emissions, is examined. The authors carefully analyzed the presence of metals on leaf surfaces and identified factors of metal translocation and global enrichment factors in plants. Based on studies of shoot growth, plant dry weight, photosynthesis, transpiration conductance, and fatty acid ratios, the effect of dissolution after foliar absorption was established. Despite the absence of significant changes in plant biomass, there is emphasized a serious health risk for humans associated with the consumption of field crops exposed to metal nanoparticles, especially in the cases of PbO and CdO. This is further confirmed in the work [16], where the authors investigated the phytotoxicology, uptake, and translocation of PbS nanoparticles in maize plants (*Zea mays* L.) under different hydroponic treatments. The results indicate that PbS nanoparticles can penetrate the cell wall and exist in the intercellular space and cytoplasm of cortical cells of maize seedlings through apoplastic and symplastic pathways. In the work referenced [17], the experiment showed that multiwalled carbon nanotubes (MWCNTs) at high concentrations of 1000 mg/l and 2000 mg/l can significantly reduce the length of roots and shoots of plants, especially red spinach and lettuce, indicating their high sensitivity to the toxic effects of these materials. However, other species, such as chili, ladyfinger, and soybean, showed lower sensitivity or even the absence of a toxic effect.

A significant number of publications studying the impact of nanoparticles on plant organisms are dedicated to metals such as iron, zinc, and copper [18]. The results presented in study [19] relate to the effect of nanoparticles on morphological parameters of field crops, such as root length, shoot height, leaf area, and biomass accumulation.

Dosage, nanoparticle concentration, chemical interaction with soil, and interaction with soil microorganisms all influence the final effect of cultivating agricultural crops in open soil. Thus, uncontrolled or excessive use of preparations containing metal nanoparticles can affect the growth and development of crops

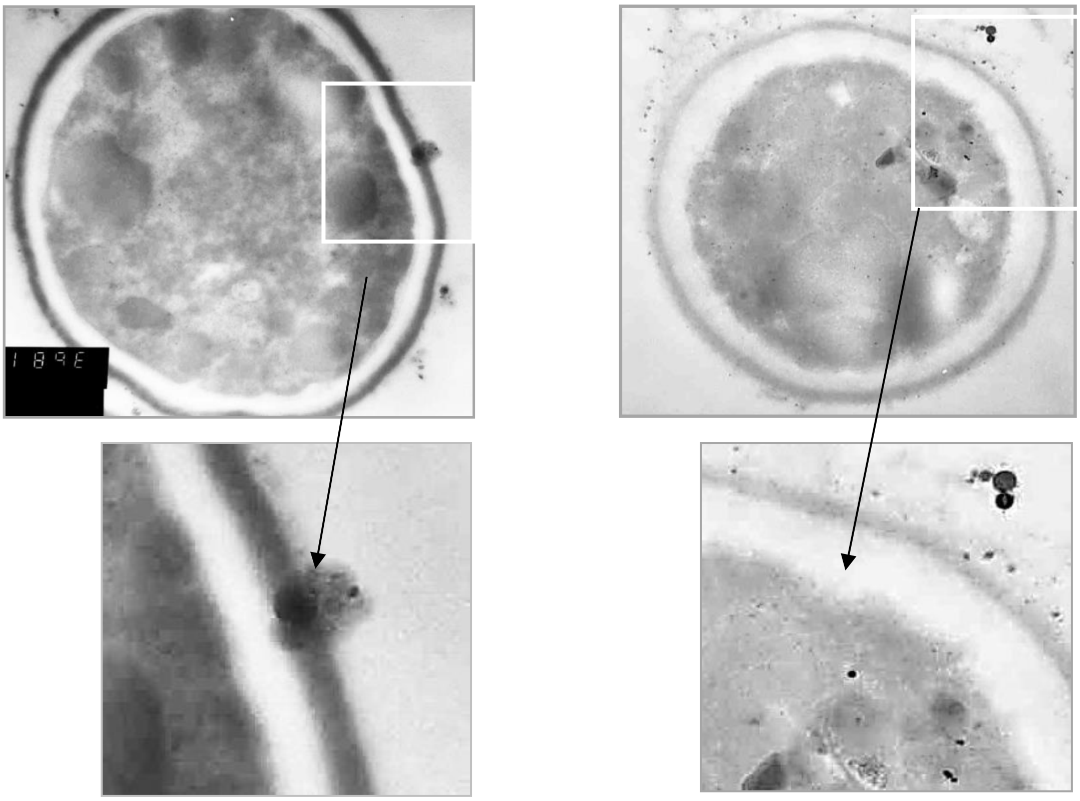
[20]. In the study referenced [21], fertilization with Zn and Cu nanoparticles contributed to the improvement of qualitative and quantitative characteristics of basil plants, particularly at specific treatment concentrations, such as 4000 ppm Zn NPs + 2000 ppm Cu NPs. The application of Zn and Cu nanoparticles significantly influenced the concentration of chlorophyll and other pigments in basil plant leaves. As a result, nanoparticles can enhance plant growth and development by improving nutrient uptake, enhancing photosynthesis, and increasing antioxidant activity [22]. They can also enhance plant resistance to biotic and abiotic stress factors such as pests, diseases, and drought [23]. On the other hand, high concentrations of nanoparticles can lead to growth inhibition, reduced biomass, and changes in root morphology, ultimately affecting crop yields [24]. The duration of nanoparticle exposure is also a key factor determining the extent of their impact on plant morphological parameters [25]. Short-term exposure to low concentrations of nanoparticles may have positive effects, while prolonged exposure to high concentrations may have negative effects.

The infusion of metals, such as silver, zinc and magnesium, was observed to stimulate the growth of micromycetes and inhibit the synthesis of polysaccharides and flavonoids. The results demonstrated a more than twofold stimulation of melanin due to the influence of silver particles. Meanwhile, magnesium particles contributed to the accumulation of endopolysaccharides, flavonoids, and melanin pigments in the experimental culture of Inonotus obliquus [26]. In the study presented in [27], the results showed that magnesium nanoparticles, at an optimal concentration of 20 ppm, were applied to the surface of wheat leaves. They penetrated through the stomata and improved leaf sunlight absorption by 24.9%. Some metals are traditionally considered as means of protecting plant organisms from pathogenic microorganisms [28]. Specifically, silver, zinc, and copper in nanoparticle form may exhibit antimicrobial, antioxidant, and fungicidal properties [29]. In the study described in [30], the effect of silver colloid solution on *E. coli* 1257, *Candida albicans*, and *Aspergillus niger* F-171 at various concentrations and exposures was investigated. The disinfectant action of silver colloid solutions on the tested microorganisms was found to be somewhat higher depending on the concentration. This confirms the assumption of the primary inactivating factor being silver ions, as the dispersed phase of the colloid serves as a source of silver cations. It has been shown that *Aspergillus niger* F- 171 exhibits high resistance to the influence of silver ions and its nanoparticles at concentrations below 0.4 mg/l.

For the development of cereal crops, zinc is considered an important component, but at high concentrations, it can be toxic. In a study conducted by the authors [31], reactions induced by doses of zinc (ranging from 0 to 200 mg/l) in the form of zinc oxide nanoparticles (ZnO NPs) on wheat and maize over a period of 21 days were analyzed. It was noted that zinc accumulation increases with dose escalation in both wheat and maize, with higher doses resulting in higher concentrations in wheat (121 mg/kg in roots and 66 mg/kg in shoots) compared to maize (95 mg/kg in roots and 48 mg/kg in shoots).

According to the application of ZnO nanoparticles, an increase in alpha-amylase activity and a decrease in dehydrogenase activity were observed. Plant length, biomass, and photosynthetic pigments increased less with the application of ZnO NPs. The content of malondialdehyde progressively increased in the roots and shoots of both plants. However, antioxidant enzymes (superoxide dismutase, ascorbate peroxidase, guaiacol peroxidase, and catalase) increased at lower concentrations (100 mg/l) of ZnO NPs compared to higher levels of ZnO NPs (150–200 mg/l) in both wheat and maize. The results indicate that a lower concentration of ZnO NPs (100 mg/l) can stimulate plant growth and may be recommended as a zinc fertilizer source for crops. One of the key parameters of nanoparticles that affects plant development indicators is their linear size [32]. A common paradigm in the use of metal nanoparticles on biological entities is the direct interaction between particle sizes and their biological effectiveness. However, for particle sizes smaller than 5-10 nm, their potential toxic impact may exceed permissible concentration limits. Meanwhile, particles larger than 200-300 nm do not show noticeable biological effectiveness [33]. Therefore, in addition to the natural biogenicity of the metal, the nanoparticle size should also be considered, as their average size influences the plant's uptake of mineral components and subsequent solid phase biodegradation and translocation [34].

Various nanoparticles (NPs) are used as nanocarriers for delivering exogenous cargo and can range in size from 10 nm to over 100 nm. The mechanism of interaction is such that NPs penetrate into the outer layers (Figure 1) and travel through apoplastic and simplistic pathways to access various plant cells and tissues. Plant structures have limitations on NP movement: the cell wall size is limited to 5-20 nm, the Kasparian strip size is less than 1 nm, and the cytoplasmic membrane size is limited to 3–50 nm in diameter. Some NPs can create larger pores in cell walls, plasmalemma, and cuticles. Plants respond to NP exposure differently, determined by their physicochemical properties: Elevated concentration can lead to negative consequences, while reduced concentration may have a positive effect on the plant system. Size plays a crucial role as smaller NPs are more readily taken up by the plant, resulting in increased interaction and having a potent direct impact [36].



а *б*

Fig. 1. Manganese particles integrate (a) into the cell membrane and dissolve in the cell cytoplasm (b) [35]

Analyzing publications from renowned authors who have studied the impact of metal nanoparticle complexes on the development of agricultural crops, particularly cereals, it should be noted that the use of biogenic metal nanoparticles typically leads to a positive influence on the morphological indicators of these crops [37]. One of the most harmful environmental factors is considered to be drought stress, which complicates the growth and development of plants, leading to reduced yields and economic losses.

In the study [37], a specific biogenic element, silicon (Si), was investigated. It was noted that silicon exhibits a preventive effect under conditions of biotic and abiotic stress. However, it is important to control the active concentration of the metal, considering its toxic effect on certain plant species.

Recently, Si NPs (silicon nanoparticles) have been documented as a new source of Si, which can be used to enhance plant resilience under adverse environmental conditions. However, it should be noted that various characteristics of Si NPs, such as their shape and size, directly or indirectly influence plants when used [39], [40], [41]. Regarding the effectiveness of Si NPs, it has been found that their application to the soil is more effective compared to foliar application, i.e., leaf application [42]. It has been noted that nano-silicon fertilizer improved leaf area index, net assimilation rate, relative growth rate, and soybean yield (Glycine max (L.) Merrill) [43].

It was also found [44] that the application of Si NPs by seed soaking led to positive results in common sunflower (*Heliánthus ánnuus*). An improvement in the length of shoots and roots, an increase in biomass and an increase in seedling vigor were observed.

Research has also been conducted on the influence of metal nanoparticles (NPs), such as silver, gold, copper, and metal oxides (Fe_2O_3, TiO_2, and ZnO), on plants under stress conditions, such as drought, highlighting the beneficial role of nanomaterials. The application of metal nanoparticles during vegetation helps plants cope with drought by improving plant growth indicators and increasing biomass. The effect of the impact is associated with enhanced water and nutrient uptake. Treating plants with metal nanoparticles helps retain water by modifying cell walls and regulating stomatal closure [45]. It is reported that the photosynthetic parameters of plants treated with nanoparticles improved with increased pigment content and photosynthetic rate. Additionally, the impact of nanoparticles has led to the activation of enzymatic and non-enzymatic antioxidants, which play a key role in the plant defense system against stress. The accumulation of secondary metabolites and phytohormones (abscisic acid, auxin, gibberellin, and cytokinin), which scavenge reactive oxygen species, plays an important role in water retention and enhances the plant's strategy to overcome drought stress [46].

In work [47], during an experiment on winter wheat, namely the use of mineral fertilizers (NPK) with the addition of Cu, Zn, Mn, it was established that the use of mineral fertilizers (NPK) with the addition of Cu increased the content of Cu (13.0%). Fertilizer with zinc significantly reduced the content of monomeric gliadin and increased the content of polymeric glutenin in grain, which contributed to a decrease in the ratio of gliadin:glutenin (0.77). Mineral fertilizers with the addition of Mn increased the content of Fe in wheat grains (14.3%). Also, the content of protein (3.8%) and gluten (4.4%), green sedimentation index (12.4%) and grain hardness (18.5%) increased significantly. Foliar feeding of Mn increased the content of gliadin fractions ω, α/β and γ (19.9%, 9.5% and 2.1%, respectively), as well as glutenins HMW and LMW (high and low molecular weight) - (18.9 % and 4.5%, respectively). Application of mineral NPK in combination with trace elements (Cu + Zn + Mn) increased the content of Cu and Zn in grain (22.6% and 17.7%, respectively). The content of ω, α/β, and γ gliadins increased (20.3%, 10.5%, and 12.1%, respectively), as well as VM glutenins (7.9%). This is confirmed by the study [48], in the course of which an experiment was conducted, establishing that foliar application of zinc (Zn) and manganese (Mn) significantly influences the yield and accumulation of dry matter in chickpea plants (*Cicer arietinum*). Spraying with Zn affected parameters such as plant height, number of pods per plant, number of seeds per plant, 100-seed weight, grain yield, biological yield, and dry weight of leaves, seeds, and overall plant count, while spraying with Mn influenced the increase in dry weight of stems and pods, as well as protein content.

Furthermore, the study [49] highlights the potential use of Fe and Mn metal oxide nanoparticles as fertilizers and sorbents in agriculture. It is noted that these nanoparticles could become economically efficient and sustainable technologies for immobilizing agricultural pollutants in soils.

However, during the experiment [50], it was found that the phytoremediation potential, expressed in parameters such as the bioconcentration factor and translocation factor, tends to increase with increasing Mn concentration. The translocation factor remains below 1 at low Mn concentrations (<0.5 mol/L), but exceeds this value when the Mn concentration exceeds 100 moll/L. The distribution of Mn in different tissues showed its highest concentration in the leaves, followed by stems and roots. Analysis of the root system structure indicated its promotion at low Mn concentrations (1 mol/L). At low doses of Mn treatment, positive effects on physiological growth indicators of plants were observed, such as chlorophyll increment, enzyme activity, and carbohydrate content in grains. However, high doses of Mn (30 ppm) led to a decrease in these indicators. The Mn content in shoots and grains significantly increased at high treatment doses, indicating its accumulation in the plant. This is also supported by a study [51] where doses of Mn (10, 20, 30 ppm Mn as $MnSO_4H_2O$) were investigated on different varieties of upland rice on acidic soils. At lower Mn treatment doses, a higher increment in total chlorophyll (27.17%), chlorophyll-a (26.72%), and chlorophyll-b (27.77%), nitrate reductase activity (35.39%), carbohydrate content in grains (9.04%), and cell membrane stability (37.06%) was observed. The highest Mn treatment dose (30 parts per million) decreased all these physiological properties in the study. However, the Mn content in shoots (87%) and grains (87.9%), as well as the distribution of Mn content in intercellular spaces (84.21%) and exchange sites (74.84%), significantly increased with the treatment of 30 ppm Mn.

Structure and phase composition of metal nanoparticles.

The structure and phase composition of nanoparticles depend on their material, synthesis method, and manufacturing conditions [52]. The structure of nanoparticles can vary depending on their shape, size and chemical nature. However, the main components of any nanoparticle are its surface, core, and possible additional layers or shells.

The surface of a nanoparticle is the outer layer that interacts with the environment. It can be a layer of atoms or molecules that form a crystal lattice or an amorphous structure.

The core of a nanoparticle is the central part, which usually consists of atoms or molecules that make up the main component of the particle. It can be a monocrystalline core, a polycrystalline core or a core with inclusions.

Additional layers or shells (if present): Some nanoparticles may have additional layers or shells around their core. These layers can be nanocrystalline materials, molecular lattices or coatings that change the properties of the particle [53].

Nanoparticles can have different shapes, such as spherical, rectangular, fibrous, etc., and the structure of each will be slightly different. It is also important to consider that the presence of defects, impurities, and other factors can affect the structure of a nanoparticle and its properties [54].

The color of ferrum (iron), copper (copper), zinc, and manganese nanoparticles (Fig. 2) may vary depending on their shape, size, and environmental conditions.

Fig. 2. Colloidal solutions of nanoparticles of various metals

Iron in its usual form (for example, in the form of powder or particles) has a gray or metallic gray color. Copper has a red-brown color. Zinc has a gray metallic appearance. Manganese has a gray-blue color.

Changing the size and shape of nanoparticles can affect their optical properties, including color, due to quantum confinement effects and plasmon resonances [55]. By dimension, they are divided into 0D (zero dimension). These are nanoparticles that have the same dimensions in all three spatial directions. An example can be quantum dots. 1D (one-dimensional) are nanoparticles that have one external dimension much larger than the other two. An example can be nanowires or nonconductors.

2D (two-dimensional) are nanoparticles that have two external dimensions much larger than the third. The most famous example is graphene, which consists of a single atomic layer of carbon.

3D nanoparticles have dimensions in all three spatial directions. Most of the materials we commonly see are three-dimensional [56]

Different nanoparticle manufacturing methods differ in the way the material is transformed into nanoparticles, as well as the conditions and parameters used in the synthesis process. Here are some key characteristics that distinguish these methods:

Mechanical Grinding: Uses mechanical energy to break a material into smaller particles. The method can be used to grind solid materials to nanosize. Mills, ball mills, etc. are used [57];

Chemical deposition: Nanoparticles are formed from a solution by a chemical deposition reaction. Chemical conditions, such as pH, temperature, and concentration of reagents, are controlled [58];

Laser ablation: Laser evaporation of the material is used to create hot plasma, which then condenses into nanoparticles. This method allows the extraction of pure nanoparticles without additional reagents [59];

Gas-phase synthesis methods: Gas-phase reactions are used to synthesize nanoparticles in the gas phase. Here, reactive gases or material vapors are formed, which react with each other or condense on the surface of the carrier materials [60];

Sonification: Vicor ultrasonic tubes for the upgrading of material aggregates into nanoparticles in rare media [61].

Methods of chemical depositing from the gas phase: The material is deposited on the pad from the gas phase as a result of the chemical reactions that occur in the gas phase [62].

Electrochemical methods: Use electric current to form nanoparticles by electrodeposition from a solution.

These methods can be combined or modified to achieve certain nanoparticle properties such as size, shape, size distribution, purity, and crystallinity [63].

The method of electrospark synthesis is one of the methods of obtaining nanoparticles and nanomaterials, which is used for the production of nanomaterials with the help of electric discharges. This process uses electrical discharges between electrodes in a special atmosphere or solutions containing the starting material for the synthesis of nanoparticles [64]. The main features of the electrospark synthesis method:

Generation of electrical discharges: The method consists in creating electrical discharges between electrodes, which causes certain chemical and physical reactions in the environment around them.

Formation of nanoparticles: During electric discharges, processes of combustion, melting, evaporation and condensation of material occur, which ultimately leads to the formation of nanoparticles.

Control of synthesis parameters: Parameters such as the amount of electric power, discharge modes, chemical composition of the medium and material can be controlled to obtain nanoparticles with certain properties.

Wide range of applications: The electrospark synthesis method is used to produce a variety of nanomaterials, including metals, oxides, carbides, nitrides, etc., and has the potential to produce nanoparticles with different structures and properties.

The phase composition of a nanoparticle is determined by the material from which it is composed, and can be single-phase or multiphase depending on its chemical composition and synthesis conditions. For example, nanoparticles can be composed of a single material such as gold, silver, silicon, etc., or have a more complex structure that includes several different phases. Among the complex structures can be alloys, which consist of two or more different materials, which can be selected to achieve certain properties, such as strength, elasticity or electrical conductivity. In addition, composites are materials consisting of nanoparticles of one material that are embedded or distributed in a matrix of another material, which can improve various characteristics, including mechanical strength, thermal conductivity, or optical properties.

Such complex structures can have properties that combine the characteristics of each of the components, which opens up wide possibilities for a variety of applications in various fields, including catalysis, electronics, medicine, and others.

5. Conclusion

Summarizing the available research, it can be concluded that the effect of nanoparticles on the morphological parameters of plants and the final indicators of crop quality is complex and depends on the various factors. Therefore, further research becomes crucial for understanding the main mechanisms of the described effects and developing strategies to minimize the negative impact of nanoparticles on the growth and development of various cultures.

Analyzing the literature review, it can be concluded that the replacement of traditional chemical fertilizers with nanoparticles can help reduce the use of chemicals, which can help preserve environmental safety. This is especially important in the context of reducing the negative impact on soil and water resources.

Reducing the use of chemical fertilizers can contribute to the preservation of soil biodiversity and microorganisms. The use of nanoparticles can help preserve soil fertility and support ecosystems. Nanoparticles can contribute to a better use of resources, as their ability to efficiently deliver nutrients to plants can reduce the need for large amounts of mineral fertilizers.

Using nanoparticles as fertilizer substitutes can have long-term benefits, such as reducing pollution, maintaining ecosystem resilience, and improving the quality of grown products. In general, the use of nanoparticles as substitutes for chemical fertilizers looks like a promising direction for preserving environmental safety in agriculture.

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РОЛЬ ТА ПЕРСПЕКТИВИ ВИКОРИСТАННЯ НАНОЧАСТИНОК МЕТАЛЕВ У ВИРОЩУВАННІ СІЛЬСЬКОГОСПОДАРСЬКИХ КУЛЬТУР

Розвиток наноіндустрії за останні 15-20 років дозволяє розглядати речовини, що містять наноматеріали, як альтернативу існуючим хімічним засобам контролю при вирощуванні сільськогосподарських культур, зокрема як компоненти мінерального живлення та захисту польових культур. Враховуючи актуальність даного питання, в останні роки власними дослідженнями було здійснено та обґрунтовано використання колоїдних форм металів як елементів мікроелементного живлення рослин. Нанотехнології пропонують стійкі рішення, замінюючи традиційні добрива наночастинками. Ці наночастинки мають унікальні властивості для подолання проблем біодоступності та покращення поглинання мінералів, підвищення врожайності та зменшення втрат добрив, допомагаючи захистити навколишнє середовище. Останні дослідження підкреслюють вплив наночастинок основних і незамінних елементів на ріст, фізіологію та розвиток рослин, беручи до уваги їх розмір, склад, концентрацію та спосіб застосування. Основними аспектами досліджень є оцінка ефективності методів їх використання та впливу наночастинок на поживні якості сільськогосподарських культур. Зазначається, що позакореневе підживлення біогенними металами є важливим у забезпеченні рослин поживними речовинами та збагаченні їх корисними елементами. Також увага приділяється розміру наночастинок, оскільки цей фактор визначає їхні унікальні фізико-хімічні властивості та здатність проникати в клітини рослин, що може впливати на їх фізіологічну реакцію та здатність поглинати корисні чи токсичні елементи. В огляді представлені висновки щодо позитивних і негативних аспектів наночастинок, їх впливу на розвиток сільського господарства та екологічну стійкість. При цьому наголошується на необхідності подальших досліджень для розробки нанодобрив, спрямованих на покращення виробництва продуктів харчування та збереження навколишнього середовища.

Ключові слова: *синтезовані наночастинки, наноматеріали, біогенні метали, сільськогосподарські культури, біогенні метали.*

Рис. 2. Літ. 64.

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