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EFFECT OF COLLOIDAL SOLUTIONS OF METAL NANOPARTICLES AND LASER IRRADIATION ON BIOLOGICAL ACTIVITY OF THE EDIBLE MEDICINAL MACROFUNGUS *Pleurotus eryngii* (*Pleurotaceae, Agaricales*) *in vitro*

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Aim. The goal of our work was to study the effect of colloidal solutions of metal nanoparticles (NPs) on the synthesis of mycelial mass, polysaccharides, phenolic compounds, and the antioxidant activity of the edible medicinal macrofungus *Pleurotus eryngii*, as well as the effects of photocatalytic activity of NPs after exposure to low-intensity laser radiation under submerged cultivation conditions.

Methods. Traditional mycological methods and unique photobiological methods were used. The effect of light on the biosynthetic and biological activity of *P. eryngii* was studied using low-intensity coherent monochromatic blue laser light (λ = 488 nm). The experiment used colloidal solutions of metal nanoparticles (FeNPs, MgNPs, AgNPs) based on the method of volumetric electric spark dispersion of metals patented in Ukraine.

Results. Treatment of the inoculum with colloidal solutions of FeNPs and MgNPs increased the amount of mycelial mass of *P. eryngii* by 38–53%, while irradiation of the inoculum with blue laser light (λ = 488 nm) in a medium with NPs increased the growth activity of the *P. eryngii* mycelium by 6.8–18.2%. All nanoparticles suppressed the biosynthesis of extracellular polysaccharides. The most significant effect was observed with the addition of MgNPs — 21.4%. While the use of photoinduced nanoparticles stimulated the synthesis of extracellular polysaccharides, the most excellent effect was observed for MgNPs — 100%. The addition of all NPs to the *P. eryngii* inoculum reduced the amount of intracellular polysaccharides in the mycelial mass by 9.4% (MgNPs) and by 22% (AgNPs). The use of NPs photoinduced by blue laser light increased the amount of intracellular polysaccharides in the mycelial mass of *P. eryngii* by 28.1% (AgNPs) and by 50% (MgNPs). Treatment of the inoculum with colloidal solutions of AgNPs, FeNPs and MgNPs and laser light-induced nanoparticles increased the amount of phenolic compounds in the mycelial mass. The highest total phenolic content (TPC) values in ethanol extracts were recorded when using photoinduced MgNPs — 59.51±0.4 mg GAEs/g dry mass.

Conclusions. The results of the studies provided grounds to consider metal nanoparticles (FeNPs, MgNPs), and lowintensity blue laser radiation as promising regulators of the synthesis of polysaccharides and phenolic compounds in the mycelial mass of *P. eryngii* under submerged cultivation conditions.

Key words: colloidal solutions nanoparticles metals, laser, mycelial mass, polysaccharides, total phenol compounds, antioxidant activity.

Modern advancements in nanotechnology have significantly expanded the horizons for the application of metal nanoparticles (NPs) across various fields of science and industry, including biology, medicine, genetic engineering, and the food and chemical industries [1–3]. The integration of nanotechnology into biology has led to the development of new fields, such as nanomedicine and nanobiotechnology, which focus on creating innovative solutions. These include the creation of nano vectors for precise delivery of active substances into cells, targeted drug delivery, manipulation of biomolecules at the nanoscale to study their functions, and the use of nanoparticles for disease diagnosis with advanced bioimaging techniques [1, 4]. These achievements were made possible through the integration of nanotechnology with biological systems, significantly enhancing the efficiency and precision of scientific research and development. In the coming years, the importance of nanotechnology is expected to grow, making it a key tool in addressing global scientific and medical challenges [1, 5, 6].

In recent years, the influence of metal NPs on the development of fungi at various stages of their life cycle, from spore germination to fruiting body formation, has been actively studied [3, 7, 8]. Particular attention is given to the "green synthesis" of metal NPs using xylotrophic macrofungi [9–15]. However, the effects of metal nanoparticles, as well as their combined use with laser radiation on the inoculum and physiological processes after their application in fungal cultivation, remain poorly understood [16–18]. The synergistic effect of metal nanoparticles and laser radiation may reveal new mechanisms for regulating biosynthetic processes, particularly through photocatalytic mechanisms that enhance biological activity. According to the literature, under the influence of light, in some instances, the catalytic properties of metal nanoparticles can be improved, as demonstrated in several studies [19–22].

Previous studies have established the impact of colloidal solutions of metallic nanoparticles such as AgNPs, FeNPs, and MgNPs on the biosynthetic activity of medicinal fungi *Inonotus obliquus* (Ach.: Pers.) Pilát and *Laricifomes officinalis* (Vill.) Kotl. and Pouzar [23, 24]. Furthermore, numerous studies confirm that low-intensity laser radiation can be effectively used as an environmentally friendly growth and biosynthetic activity stimulator for edible and medicinal macrofungi with high biotechnological value [25–30].

Edible and medicinal macrofungi are not only a valuable dietary product but also a source of various pharmacologically active compounds with a wide range of biological activities [31, 32]. One such fungus is *Pleurotus eryngii* (DC.) Quél, known as the king oyster mushroom, possesses a variety of pharmacological properties due to the presence of bioactive components such as polysaccharides, polyphenols, terpenes, and flavonoids. These compounds exhibit antioxidant, antimicrobial, anti-inflammatory, and immunostimulatory effects [33, 34].

Modern advancements in the biotechnology of edible and medicinal mushrooms are focused on the effective use of fungal resources to improve human health and promote economic development [35]. One of the key tasks is to establish parameters that will allow for the targeted regulation of the synthesis of biologically active metabolites, creating the foundation for highly efficient and environmentally friendly biotechnologies. In particular, studying the influence of metal nanoparticles and low-intensity laser light on fungal metabolism opens new opportunities for developing processes aimed at obtaining specific bioactive compounds.

Studies on the spectral sensitivity of *P. eryngii* regarding fruiting and the antioxidant activity of fruiting body extracts have been conducted by several researchers [36, 37]. However, submerged cultivation represents a promising approach that allows for the production of target products in a short time with minimal costs and environmental impact [38, 39]. The available literature does not provide data on the influence of metal nanoparticles and laser light on the synthesis of phenolic compounds and antioxidant activity in *P. eryngii* under submerged cultivation conditions.

Materials and Methods

Mushroom sample. The subject of the research was a pure culture of the edible and medicinal mushroom *P. eryngii* IBK 2035, which is preserved in the Mushroom Culture Collection at the M.G. Kholodny Institute of Botany, National Academy of Sciences of Ukraine (acronym IBK) (occurrence dataset available: https://www.gbif.org/occurrence/2580369484, accessed on November 30, 2024). The taxonomic status of the *P. eryngii* IBK 2035 has been confirmed at the species level using molecular genetic methods and deposited in the NCBI database available at GenBank (accession number: MN646251.1) (https://www.ncbi.nlm.nih.gov/nuccore/MN646251.1).

Preparation of Colloidal Solutions of Metal Nanoparticles. Colloidal solutions of biogenic metals, water-based, such as Fe, Mg, and Ag, produced by a patented method of bittern colloidal solutions of the above metals were used [40]. The maximum size of NPs is no more than 100 nm. Colloidal solutions of nanometals were used in a concentration of 10^{-10} M. When choosing the concentration, we were guided by our data and the results obtained by other researchers who studied the possibilities of using them to increase the productivity of agricultural plants [24, 41, 42].

Inoculum preparation and culture conditions. Cultivation of the inoculum of *P. eryngii* was carried out on a basic liquid nutrient medium and its modification with the addition of a colloidal solution of metal nanoparticles. Basic medium (control) glucose-peptone-yeast (GPY), g/l: glucose — 25.0; peptone — 3.0; yeast extract — 2.0; KH_2PO_4 — 1.0; K_2HPO_4 – 1.0; $MgSO_4 \times 7H_2O$ — 0.25; pH 6.5. Modification with the addition of a colloidal solution of metal nanoparticles: medium A: GPY with silver nanoparticles (AgNPs); medium B: GPY with iron nanoparticles (FeNPs); medium C: GPY with magnesium nanoparticles (MgNPs). 100 ml of liquid medium was placed in Erlenmeyer flasks of 0.5 L volume, then sterilized in an autoclave for 0.5 h at a temperature of 120 °C. After inoculation of the mycelium *P. eryngii*, it was cultivated in the dark at 26 °C for 12 days under vibration at a speed of 120 rpm.

Effect of biogenic metal nanoparticles and laser light on growth characteristics and biosynthetic activity. The study of the effects of AgNPs, FeNPs, MgNPs, and low-intensibiosynthetic and biological activity of *P. eryngii in vitro* was performed using a methodology specifically developed by the authors [23]. Physiologically active inoculum of *P. eryngii*, precultivated to ensure optimal metabolic activity, was introduced at 10% of the total volume into 0.5 L Erlenmeyer flasks, each containing 100 ml of nutrient medium. Following inoculation, a portion of the flasks was designated as the control group (not subjected to irradiation), while the remaining flasks were exposed to blue laser light ($\lambda = 488$ nm). The experimental setup aimed to evaluate the effects of NPs and laser irradiation on the biosynthetic processes and antioxidant activity of *P. eryngii*.

Irradiation. Argon ion laser (modified model LGN-106M1 manufactured by NPO "Plasma") with wavelengths of 488.0 nm was used as the source of coherent visible light [23]. The laser irradiation system was developed at the Institute of Physics of the National Academy of Sciences of Ukraine. Irradiation of flasks containing inoculum mycelial was carried out in flasks where the thickness of the layer of nutrient medium with mycelial did not exceed 1 cm). After irradiation, all experimental variants, both irradiated and non-irradiated, were cultured under the conditions described previously.

Measurement of mycelia growth. The mycelial biomass produced in each treatment was harvested by vacuum filtration to separate the culture broth. The fungal biomass was washed several times with distilled water and oven-dried at 60 °C until constant weight.

Quantification of extracellular polysaccharides (EPS). The content of extracellular polysaccharides (EPS) in the culture liquid was determined by the weight method [28]. For the determination of EPS, the obtained culture fluid after mycelia removal was concentrated in a vacuum evaporator three times from the initial volume, precipitated with 96% cooled ethanol in a ratio of 1:2, and placed in a refrigerator 4 °C for 24 h. The precipitate was isolated from the supernatant by centrifugation at 8,000×g for 15 min. After separation, EPS was dried at 60°C to constant weight. The yields of EPS were expressed as the g dry weight/L of the culture liquid [28].

Quantification of intracellular polysaccharides (IPS). For IPS extraction, the whole mycelium obtained from one flask was dried at 60 °C, homogenized in a laboratory blender, then supplemented with distilled water (1:10 by weight), and boiled in a water bath (100 °C) for 18 h. Cytoplasmic contents were removed by multiple centrifugations (3,000 g for 15 min) of the homogenized mycelium suspended in distilled water. The washing procedure was stopped only when the optical density of the supernatant at 280 nm did not exceed 0.132. The obtained extracts were concentrated two- or three-fold with a rotary evaporator (60 °C), treated with 96% ethanol (volume ratio 1:1) at a temperature of 4 °C, and allowed to stand until complete precipitation. The precipitate(IPS fractions) was separated by centrifugation and then dialyzed against distilled water for 3 days. The dialysis IPS was precipitated with ethanol (volume ratio 1:2), washed with ethanol, ether, and acetone, and dried at 40 °C. The IPS content was calculated in % of absolute dry mycelial mass.

Preparation of Aqueous-Alcoholic Extracts of Mycelial Mass. Ethanol (70%, v/v) and methanol were used as extraction sol-

vents to obtain the mycelial mass extract. Extracts were prepared at the rate of 20 mg of dry mycelial mass per 1 ml of solvent according to a previously described method [23].

Determination of Total Phenols Content. Total phenols of *P. eryngii* extracts were determined according to the method [43]. The absorbance was measured at 750 nm using a spectrophotometer (U-1800, Hitachi Hightechnologies Co., Tokyo, Japan), with gallic acid used as a standard. The content of total phenols was calculated based on the calibration curve of gallic acid [the equation of standard curve: absorbance at 750 nm = $0.0025C_{\text{gallic acid}}$ (μg/mL) + 0.0982, $R^2 = 0.985$]. Results were expressed as milligrams of gallic acid equivalents (GAEs) per gram of mushroom extract. The studies were carried out in triplicate.

Scavenging Activity on 1,1-Diphenyl-2-Picrylhydrazyl (DPPH) Radicals. The free radical scavenging activity of *P. eryngii* extracts was measured using 1-diphenyl-2-picrylhydrazyl (DPPH) according to a standard procedure [43]. 800 μl of 0.1 mM DPPH (Alfa aesar®, Nimecchina) dissolved in a defined source (ethanol or methanol) were added to 200 μl of extract mycelium. The mixture was shaken vigorously and left in the dark for 30 min. The free radical scavenging activity of the mycelial mass extracts was measured using a UV-1280 spectrophotometer (Shimadzu Corporation) at λ = 517 nm. The DPPH radical scavenging activity was expressed as:

$$S\,(\%) = (A_0 - A_1)/A_0 \times 100\%,$$

where: A_0 was the absorbance of the DPPH solution, A_1 was absorbance of the samples.

Statistical Analysis. Experiments were conducted in five replicates. The Statistica 6.0 software was used for results processing. The significance of the differences between the results was assessed using the Student's t-test, and significance was accepted for $P < 0.05$.

Results and Discussion

Effect of colloidal solutions of metal nanoparticles and laser irradiation on the growth of Pleurotus eryngii under submerged cultivation conditions. The addition of AgNPs to the *P. eryngii* IBK 2035 inoculum did not affect the synthesis of mycelial biomass. In contrast, colloidal solutions of FeNPs and MgNPs stimulated growth by 38–53% compared to the control (mycelium without NPs). The accumulation of mycelial biomass for FeNPs and MgNPs ranged from 12.2 ± 0.3 g/L (FeNPs) to 13.6 ± 0.4 g/L (MgNPs) on the tenth day of cultivation.

Using photoactivated *P. eryngii* inoculum (without NPs) enhanced mycelial biomass synthesis by 60.1% compared to the control (without irradiation and NPs). However, irradiation of the *P. eryngii* inoculum with blue laser light (λ = 488 nm) in a medium containing NPs reduced the biomass accumulation induced by FeNPs and MgNPs (Fig. 1).

The interaction of nanoparticles (NPs) with biological objects, including fungal mycelium, occurs at the cellular level and promotes the enhancement of biochemical processes [44]. The physiological availability of metal NPs is determined by their size, internal structure, preparative form, and ability to form bonds with biological molecules [41]. Research in this field includes both review and experimental studies investigating the interaction of metal NPs with plant and fungal cells [41, 44–47]. Parameters such as dissociation energy, chemical bond energy, and the desorption of atoms from the NP surface are critical for determining their biological functionality.

The biological role of FeNPs and MgNPs in our experiment is determined by the fact that iron and magnesium are essential components of physiological processes occurring in fungal cells, serving both structural and catalytic functions. Specifically, iron and magnesium are critical microelements for fungal metabolism as they participate in DNA synthesis, enzymatic reactions, and redox processes. These metals are classified as essential elements required for fungal growth and development, providing optimal conditions for key biochemical reactions [48, 49].

Both physical and chemical processes occur on the surfaces of nanoparticles (NPs), influencing the physiology and metabolism of living organisms [44]. Physical processes on NP surfaces include the redistribution of electric charges, excitation of surface oscillations — such as plasmons and surface excitons — and alterations in the physical structure of the surface. Chemical interactions involving NPs result in the formation of new chemical compounds, where NPs act as catalysts [41].

The influence of colloidal solutions of nanoparticles and laser irradiation on the synthesis of polysaccharides. The results of

our study showed that the addition of AgNPs, FeNPs, and MgNPs to the culture medium with *P. eryngii* IBK 2035 inoculum inhibited the synthesis of extracellular polysaccharides, with the most significant effect observed when adding MgNPs, which was 21.4% (Fig. 2). Irradiation of the *P. eryngii* inoculum with blue laser light in a medium without NPs stimulated an increase in the synthesis of both extracellular and intracellular polysaccharides by 39% and 44%, respectively (Fig. 2). When using photoinduced inoculum in the presence of AgNPs, FeNPs, and MgNPs, an increase in the number of extracellular polysaccharides was observed. The excellent stimulating effect was observed for photoinduced MgNPs — 100%.

The addition of all NPs to the *P. eryngii* inoculum reduced the amount of intracellular polysaccharides in the mycelial biomass by 9.6% for MgNPs and FeNPs, and by 22% for AgNPs. Irradiation with blue laser light in the presence of NPs increased the amount of intracellular polysaccharides in the mycelial biomass of *P. eryngii* by 28.1% for AgNPs and by 50% for MgNPs. It is noteworthy that the amount of intracellular polysaccharides did not statistically exceed

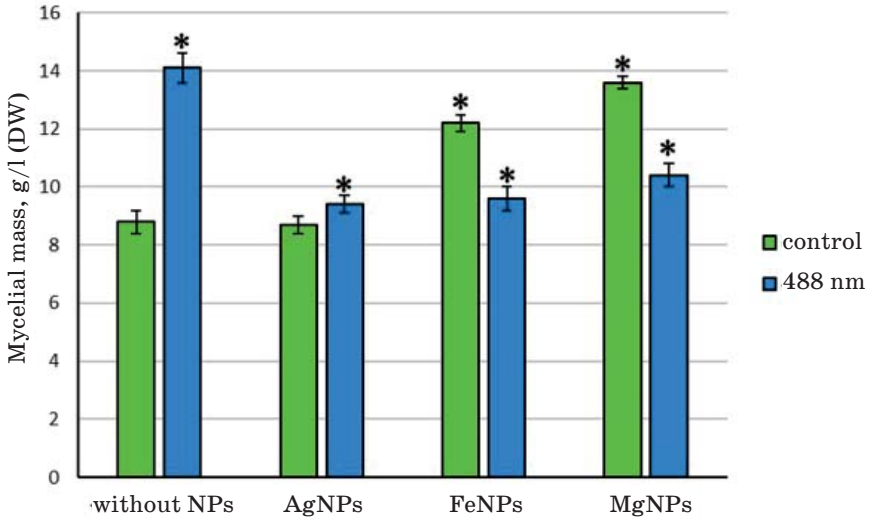

Fig. 1. **Growth activity of *Pleurotus eryngii* IBK 2035 after exposure to colloidal solutions of nanoparticles and low-intensity laser irradiation (λ = 488 nm) in a medium with nanoparticles**
The data are presented as mean ± standard error of the mean.
*$P < 0.05$ as compared to control (without NPs and irradiation)

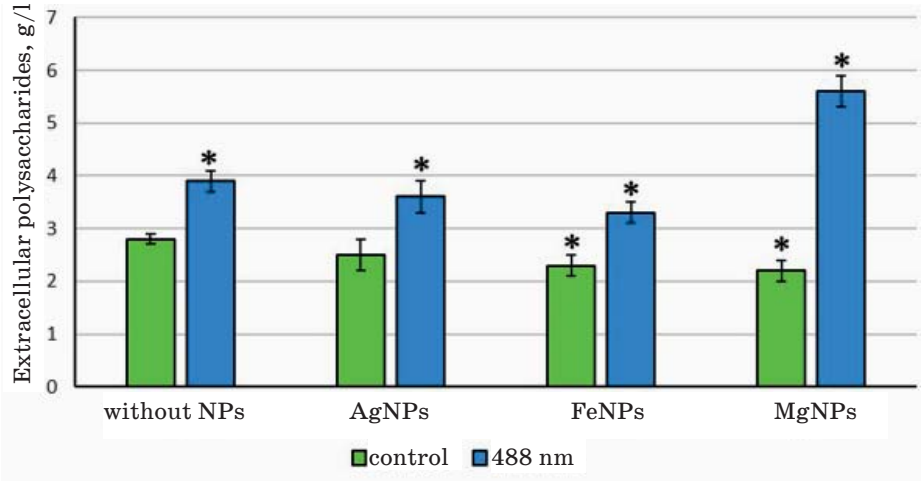

Fig. 2. **Synthesis of extracellular polysaccharides of *Pleurotus eryngii* IBK 2035 after exposure to colloidal solutions of nanoparticles and low-intensity laser irradiation (λ = 488 nm) in a medium with nanoparticles.**
The data are presented as mean ± standard error of the mean.
*$P < 0.05$ as compared to control (without NPs and irradiation)

Table 1. **Values of Total Phenolic Content (TPC) of the extracts mycelial *Pleurotus eryngii* IBK 2035 (n = 3, X±SD)**

Irradiation modes	TPC mg of GAE/g DM			
	Ethanol extract		Methanol extract	
	Without exposure to low-intensity laser radiation	After exposure to low-intensity laser irradiation (488 nm)	Without exposure to low-intensity laser radiation	After exposure to low-intensity laser irradiation (488 nm)
control	32.57±0.2	47.12±0.2	30.14±0.4	44.22±0.3
AgNPs	45.88±0.3	50.34±0.2	44.42±0.3	49.03±0.3
FeNPs	42.80±0.4	59.11±0.4	47.59±0.3	51.97±0,.3
MgNPs	51.50±0.3	59.51±0.2	48.13±0.3	52.17±0.3

Note. The data are presented as mean ± standard error of the mean.*$P < 0.05$ as compared to control (without nanoparticles and irradiation).

the levels observed in the photoinduced inoculum grown on a medium without NPs (Fig. 3).

The influence of colloidal solutions of nanoparticles and laser irradiation on the total content of phenolic compounds and antioxidant activity. The analysis of the obtained results regarding the impact of colloidal metal NP solutions and the combined action of NPs and laser irradiation revealed specific effects on the synthesis of phenolic compounds in the mycelial biomass of *P. eryngii* (Table 1). The addition of colloidal solutions of AgNPs, FeNPs, and MgNPs to the *P. eryngii* inoculum stimulated phenolic compound synthesis in the mycelial biomass by 31.4–60% compared to the control (without NPs and irradiation). The most significant effect for ethanol extracts was observed with AgNPs and MgNPs, with phenolic compound levels of 45.88±0.3 mg GAE/g dry mass (AgNPs) and 51.50±0.3 mg GAE/g dry mass (MgNPs) on the twelfth day of cultivation (Table 1). The highest phenolic compound content—59.51±0.2 mg GAE/g dry mass—was recorded after treatment with photoinduced MgNPs. The effects of AgNPs and FeNPs on phenolic compound synthesis were less pronounced compared to MgNPs.

The differences in the impact of the studied colloidal metal NP solutions and laser

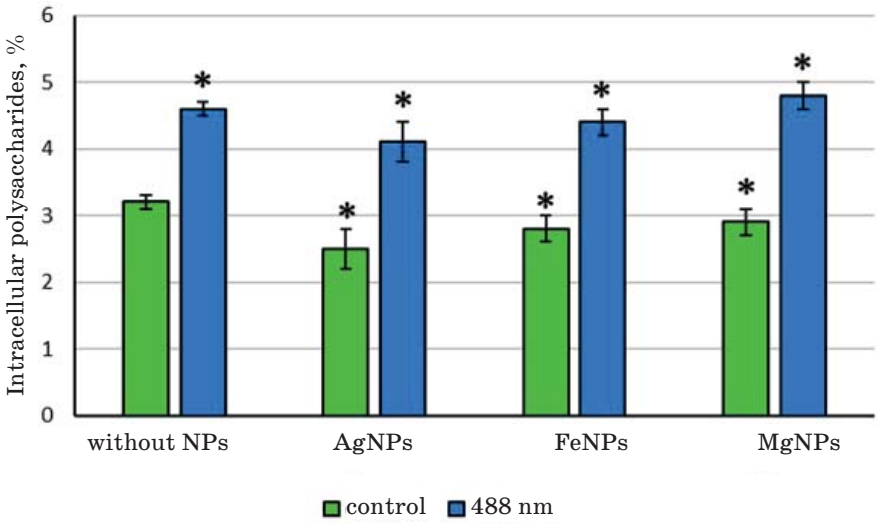

Fig. 3. **Synthesis of intracellular polysaccharides of *Pleurotus eryngii* IBK 2035 after exposure to colloidal solutions of nanoparticles and low-intensity laser irradiation (λ = 488 nm) in a medium with nanoparticles.** The data are presented as mean ± standard error of the mean. *****$P < 0.05$ as compared to control (without NPs and irradiation)

irradiation on the biosynthetic activity of *P. eryngii* can be attributed to variations in their ability to penetrate fungal cells, differing biochemical mechanisms of action, and optical properties.

In recent years, numerous studies have been published on the use of photoactivated metal NPs, highlighting significant interest and the potential importance of this topic [16, 50]. Under certain conditions, metal NPs exhibit catalytic properties in a range of biochemical reactions when exposed to light [16]. Specifically, photocatalysis involving metal NPs is actively utilized in fields such as wastewater treatment technologies and agricultural practices [20, 21]. This growing interest encourages experiments with variable parameters to explore new methods for influencing the development of biological systems and to expand the experimental data on potential mechanisms of NP biological activity. Indeed, the stimulating effects of light with specific spectral compositions on various stages of the development of fungal mycelial cultures have been confirmed by numerous experiments [17, 18, 51, 52].

A number of studies have shown that the presence of NPs in an environment through which light passes induces several effects, such as the excitation of local plasmons [53], the formation of regions with increased light concentration around the NPs, scattering of light by the NPs [54], and changes in the fluorescent properties of molecules under their influence [55]. The excitation of surface electromagnetic oscillations (plasmons) on the surface of NPs under the action of light alters the conditions for their interaction with biological systems, including cell membranes and the extracellular environment [50, 56]. At the same time, the role of surface effects, related to the speed of chemical reactions and catalytic activity—factors crucial for biological processes—becomes significantly more pronounced and may become dominant.

Colloidal solutions of biogenic metal NPs, such as Ag, Cu, Fe, Mg, Mn, Mo, and Zn, are currently used in agriculture at very low concentrations (10^{-4} M) to produce environmentally friendly products. Due to their nanoscale size, these particles can easily penetrate plant cells, influencing growth and development [41, 57]. They also possess antibacterial and antioxidant properties, activating internal protective mechanisms. Moreover, these solutions optimize metabolic processes and promote the realization of the adaptive and productive potential of plants under various weather and climatic conditions during their development. Additionally, research is being conducted on colloidal solutions of biologically active metals obtained through nanotechnology, which possess anti-stress properties and enhance the resistance of plants, bacteria, and fungal cells to various adverse factors. Behra et al. (2013) studied the bioavailability of NPs and silver ions from both a chemical and biochemical perspective [58]. The results of the study on ethanol and methanol extracts of *P. eryngii* mycelial biomass showed high free

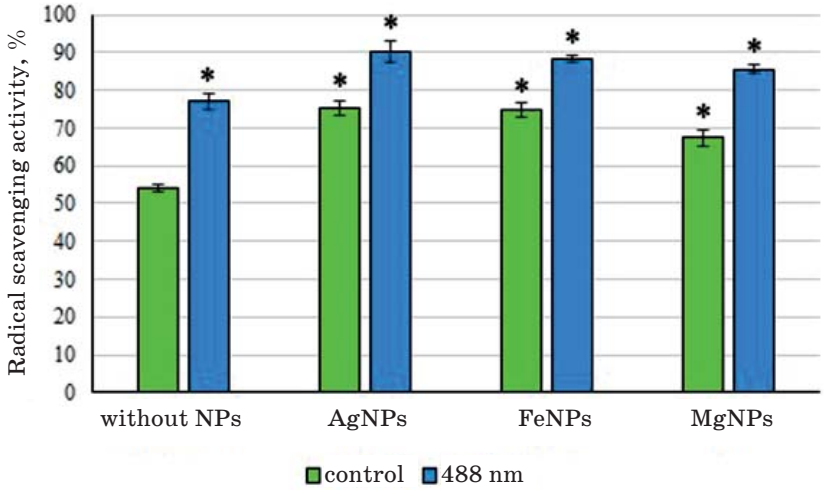

Fig. 4. **Radical scavenging activity (RSA) of ethanol extract mycelial mass extracts of the *Pleurotus eryngii* IBK 2035 after exposure to colloidal solutions of nanoparticles and low-intensity laser irradiation (λ = 488 nm).**
The data are presented as mean ± standard error of the mean.
*$P < 0.05$ as compared to control (without nanoparticles and irradiation)

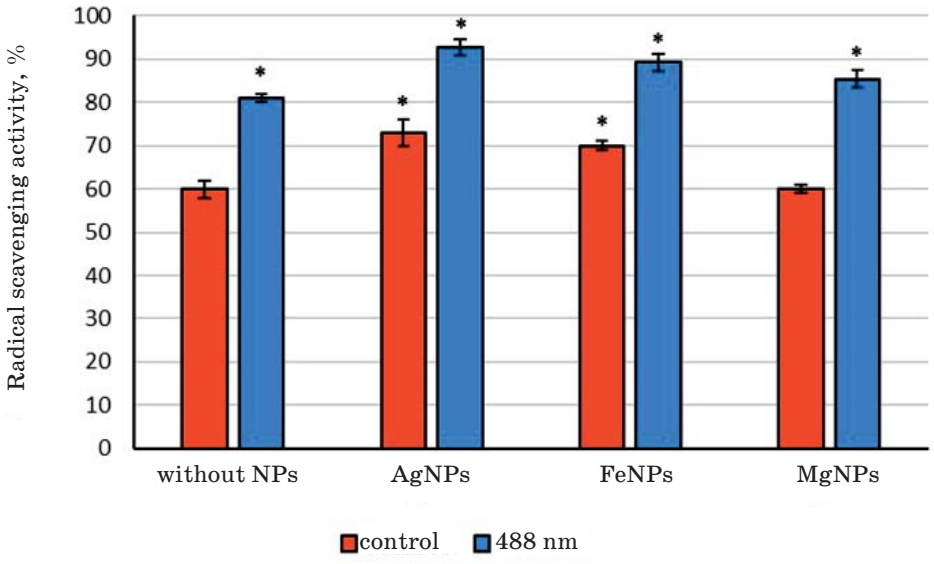

Fig. 5. **Radical scavenging activity (RSA) of methanol extract mycelial mass extracts of the** *Pleurotus eryngii* **IBK 2035 after exposure to colloidal solutions of nanoparticles and low-intensity laser irradiation (λ = 488 nm).**
The data are presented as mean ± standard error of the mean.
*$P < 0.05$ as compared to control (without nanoparticles and irradiation)

radical scavenging activity against DPPH after exposure to NPs and photoinduced NPs on the fungal inoculum (Fig. 4, 5). The highest free radical scavenging values, over 90%, were recorded for the samples obtained from the inoculum treated with colloidal solutions of photoinduced AgNPs (Fig. 4, 5). The lowest values were observed for methanol extracts with MgNPs without irradiation (Fig. 5). Overall, a correlation between high free radical scavenging activity and the number of phenolic compounds was observed in all the studied extracts. However, other antioxidants present in the extracts may also contribute to the antioxidant activity of the mycelial biomass extracts.

Fungal extracts contain a variety of antioxidant compounds that exhibit their specific biological properties at different stages of the oxidative process and through various mechanisms of action. The antioxidant compounds identified in the fruiting bodies and mycelium of fungi include phenols, flavonoids, glycosides, polysaccharides, tocopherols, ergothioneine, carotenoids, and ascorbic acid [43, 59, 60].

Antioxidants present in fungi are divided into two main types: primary antioxidants (those that break the chain of reactions by scavenging free radicals) and secondary or preventive antioxidants, which act through metal deactivation, inhibition of lipid hydroperoxide breakdown, regeneration of primary antioxidants, and singlet oxygen (1O2) quenching. Additionally, some substances found in fungi that exhibit antioxidant activity may act as inducers or signaling molecules, activating critical biochemical processes in cells [61, 62]. These compounds can influence the expression of genes that regulate the synthesis of enzymes responsible for neutralizing reactive oxygen species (ROS). This promotes the activation of antioxidant enzymes such as superoxide dismutase, catalase, and glutathione peroxidase, which reduce oxidative stress and protect cells from damage caused by ROS. Thus, fungal antioxidant compounds not only directly scavenge free radicals but also trigger a cascade of intracellular reactions that enhance the organism's defense system [59, 60]. For this reason, exogenous dietary antioxidants or natural products based on medicinal mushrooms are promising for use as nutraceuticals in chronic diseases [63].

Conclusions

Our research confirms the possibility of developing effective mycobiotechnologies using colloidal solutions of metal nanoparticles and low-intensity laser irradiation. It has been established that treatment of *P. eryngii* inoculum with colloidal metal

nanoparticle solutions, combined with brief exposure to low-intensity laser light, enhances biosynthetic activity. This includes increased synthesis of mycelial mass, endopolysaccharides, and phenolic compounds, as well as boosting the antioxidant activity of the strains. Optimal regimes and biotechnological parameters necessary for stimulating the biosynthetic activity of *P. eryngii* have been identified. The study of photobiological reactions in fungi and the accumulation of experimental data on the effects of colloidal solutions of biogenic metal nanoparticles and low-intensity laser light on growth characteristics and biosynthetic activity of *P. eryngii* may contribute to a better understanding of the fundamental mechanisms by which nanoparticles and laser light impact fungi.

Author Contributions

Author Contribution O. M. & N. P. planned the work, contributed to the article's conception, manuscript article writing, editing, and conducted a study under submerged cultivation. A. N. defined the light sources design and its modes of operations, calculated the doses of irradiation inoculum, carried out its irradiation, discussed the irradiation effects, and participated in the paper preparation. K. L. provided colloidal solutions of biogenic metal nanoparticles, discussed the nanoparticles effects, and participated in the paper preparation, provided the new literature data for review. All authors contributto the manuscript's revision and read and approved the submitted version.

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ВПЛИВ КОЛОЇДНИХ РОЗЧИНІВ НАНОЧАСТИНОК МЕТАЛІВ ТА ЛАЗЕРНОГО ОПРОМІНЕННЯ НА БІОЛОГІЧНУ АКТИВНІСТЬ ЇСТІВНОГО ЛІКАРСЬКОГО МАКРОГРИБА *Pleurotus eryngii (Pleurotaceae, Agaricales)* У ВИРОЩУВАННІ *in vitro*

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Мета. Робота спрямована на визначення впливу колоїдних розчинів наночастинок металів (НЧ) на синтез міцеліальної маси, полісахаридів, фенольних сполук і антиоксидантну активність їстівного лікарського гриба *Pleurotus eryngii*, та ефекти фотокаталітичної активності НЧ після впливу низькоінтенсивного лазерного випромінювання за умов глибинного культивування.

Матеріали й методи. Використовували традиційні мікологічні методи та унікальні фотобіологічні методи. Вплив світла на біосинтетичну та біологічну активність *P. eryngii* вивчали за допомогою низькоінтенсивного когерентного монохроматичного синього лазерного світла (λ = 488 нм). В експерименті використовували колоїдні розчини наночастинок металів (FeНЧ, MgНЧ, AgНЧ), отримані за запатентованим в Україні методом об'ємного електроіскрового диспергування металів у рідині.

Результати. Оброблення інокуляту *P. eryngii* колоїдними розчинами FeНЧ та MgНЧ збільшило кількість міцелійної маси на 38–53%, тоді як опромінення інокуляту синім лазерним світлом (λ = 488 нм) у середовищі з НЧ підвищувало активність росту міцелію *P. eryngii* на 6,8–18,2%. FeНЧ, MgНЧ, AgНЧ пригнічували біосинтез позаклітинних полісахаридів, причому найбільший ефект спостерігався при додаванні MgНЧ — 21,4%. Водночас використання фотоіндукованих НЧ стимулювало синтез позаклітинних полісахаридів, зокрема найбільший стимулювальний ефект було зафіксовано для MgНЧ — 100%. Додавання FeНЧ, MgНЧ, AgНЧ до інокуляту *P. eryngii* зменшувало кількість внутрішньоклітинних полісахаридів у міцелійній масі на 9,4% (MgНЧ) та на 22% (AgНЧ). Використання НЧ, фотоіндукованих синім лазерним світлом, збільшувало кількість внутрішньоклітинних полісахаридів у міцелійній масі *P. eryngii* на 28,1% (AgНЧ) та на 50% (MgНЧ). Оброблення інокуляту колоїдними розчинами AgНЧ, FeНЧ та MgНЧ, а також фотоіндукованими наночастинками, підвищувало кількість фенольних сполук у міцелійній масі. Найвищий загальний вміст фенольних сполук (ТРС) в етанольних екстрактах зафіксовано при використанні фотоіндукованих MgНЧ – 59,51±0,4 мг GAE/г сухої маси.

Висновки. Результати досліджень дозволяють розглядати наночастинки металів (FeНЧ, MgНЧ) та низькоінтенсивне синє лазерне випромінювання як перспективні регулятори синтезу полісахаридів і фенольних сполук у міцелійній масі *P. eryngii* за умов глибинного культивування.

Ключові слова: колоїдні розчини наночастинок металів; лазер, міцеліальна маса, полісахариди, загальні фенольні сполуки, антиоксидантна активність.