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BIOPHYSICAL FOUNDATIONS OF LASER TECHNOLOGIES IN INCREASING AGRICULTURAL PRODUCTIVITY

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Abstract
This article theoretically analyzes the biophysical foundations of using laser technologies to increase agricultural productivity. The effects of laser radiation on plant seeds and tissues, its mechanisms at the cellular level, its role in activating biochemical processes, and the prospects of its application under the agro-climatic conditions of Surkhandarya region are considered. Pre-sowing stimulation of seeds using low-intensity laser radiation is substantiated as an effective method for increasing seed germination energy, plant growth rate, and resistance to stress factors.

Keywords: Laser radiation, biophysics, photobiostimulation, agriculture, seed irradiation, agrotechnology, Surkhandarya climate.

Introduction

Today, increasing productivity in agriculture and introducing environmentally friendly and energy-efficient technologies are among the urgent issues in the field. Alongside traditional agrotechnical measures, the application of innovative methods based on physical factors is becoming an important direction for improving crop yields. One of such promising directions is the application of laser technologies in agriculture.

The climate of the Surkhandarya region is dry and hot, with high solar radiation during the growing season, while soil moisture is often insufficient. Under such conditions, improving the pre-sowing quality of seeds is of great importance for ensuring rapid and healthy plant development. Biostimulation of seeds using laser radiation is considered one of the modern methods for solving this problem.

Physical Nature of Laser Radiation

Laser (Light Amplification by Stimulated Emission of Radiation) is a device based on the principle of amplifying light through stimulated emission. Today, laser

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technologies are widely applied in many fields such as science, industry, medicine, communication systems, and agriculture. Their characteristics, including high precision, localized energy delivery, and controllability, contribute significantly to the advancement of modern technological processes. Thus, lasers have proven to be not only important objects of fundamental physical research but also highly effective tools for solving practical problems [1].

Laser radiation is based on electronic transitions occurring between energy levels of atoms or molecules in an active medium. Three fundamental conditions are required for laser generation:

• **Active medium:** A substance in which population inversion is created between energy levels. Under population inversion, particles in a higher energy state transition to a lower state, emitting photons.

• **Energy source:** A source that supplies external energy to the active medium. This energy is used to excite atoms into higher energy states.

• **Optical resonator:** A system of two opposing mirrors surrounding the active medium. Photons generated in the resonator undergo multiple reflections, are amplified through stimulated emission, and produce directed, coherent radiation.

The principal characteristics of laser radiation—monochromaticity, coherence, and directionality—arise precisely due to population inversion and the optical resonator. As a result, laser light is generated as a high-intensity, stable, and precise source applicable in many scientific and technological fields [2].

Lasers can be classified according to several criteria. One of the most important classifications is based on the type of active medium.

Classification According to Active Medium

1. Gas Lasers

In these lasers, the active medium consists of gas mixtures (for example, CO_2 or He-Ne). Their main advantage is long-term and stable operation. They are widely used in industrial material cutting, medical procedures, and laser shows.

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2. Solid-State Lasers

This type uses crystals or glass as the active medium (for example, YAG—yttrium aluminum garnet). Their major advantages are high energy output and compact size. Applications include laser welding, surface treatment, and military technologies.

3. Semiconductor (Diode) Lasers

The active medium consists of semiconductor crystals (for example, gallium arsenide). These lasers are compact, inexpensive, and energy efficient, and are used in laser pointers, printers, and CD/DVD reading devices [3].

Gas lasers are lasers in which the active medium consists of gaseous substances, and their operation is based on stimulated emission from gas atoms or molecules. One of the most common gas lasers is the Helium-Neon (He-Ne) laser, which uses a mixture of helium and neon gases as its active medium. The He-Ne laser typically emits red light at a wavelength of 632.8 nm and is characterized by low intensity and long coherence, making it widely used in laboratory and experimental conditions [4].

He-Ne lasers are used in plant research, particularly for seed pre-sowing treatment, because their monochromatic and collimated radiation can positively affect cellular biological processes. Several scientific studies have shown that seeds treated with He-Ne laser radiation exhibit increased germination and growth efficiency. These effects are explained by photobiomodulation mechanisms that stimulate growth processes [5].

Solid-state lasers are a type of laser in which the active medium is in solid form, usually crystals or glass materials. This medium is doped with trace elements such as neodymium, chromium, erbium, or others, which store and release the energy necessary for laser emission [6]. One of the most common examples is the Nd:YAG laser (neodymium-doped yttrium aluminum garnet), capable of producing infrared radiation at a wavelength of 1064 nm [6].

Solid-state lasers generally operate through optical pumping, where the active medium is excited by high-energy light to create population inversion [6]. This inversion leads to amplification and stimulated emission, generating highly monochromatic and directed laser radiation [6]. Due to their high optical quality, stability under varying thermal conditions, and versatility, solid-state lasers are widely used in scientific research, industry, medicine, and technology [6].

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Semiconductor (diode) lasers are laser sources based on semiconductor materials (such as InGaN and GaAlAs) that convert electrical current directly into optical radiation [7]. Recent studies have shown that these laser diodes are being used as light sources for plants grown in artificial environments, particularly in improving photosynthetic efficiency and growth parameters under red light, where diode lasers have demonstrated advantages over conventional LEDs [7].

In a specific study involving *Lactuca sativa* (lettuce), red-wavelength diode lasers (approximately 660 nm) were found to increase photosynthetic efficiency, carbohydrate accumulation, and biomass production. This occurs because diode lasers deliver narrow-spectrum radiation well matched to the absorption spectra of photosynthetic pigments, improving energy-use efficiency [7]. These findings suggest that semiconductor lasers may become a promising light source in agriculture for optimizing plant growth and increasing productivity, especially in controlled environments such as protected horticulture [7].

Biophysical Foundations

In recent years, low-intensity laser radiation has been widely studied as one of the effective physical factors for regulating plant biophysics. Research indicates that laser radiation exerts a complex influence at the cellular level, affecting energy metabolism, membrane permeability, and enzymatic processes.

Barbara Podleśna (2017), in her studies, systematically analyzed the theoretical foundations of laser biostimulation and demonstrated that low-intensity laser radiation activates intracellular metabolic processes. According to the author, laser exposure enhances oxidative phosphorylation reactions in mitochondria, increasing ATP synthesis. This, in turn, leads to improved seed germination energy and accelerated early growth. It was also noted that increased membrane permeability intensifies ion exchange processes [8].

Aftab Ahmad, Ayesha, and Sikandar (2021) conducted an in-depth analysis of the molecular and biophysical mechanisms of laser biostimulation. According to their findings, laser radiation can induce a controlled increase in reactive oxygen species (ROS) within cells, which activates antioxidant enzyme systems such as catalase, superoxide dismutase, and peroxidase. As a result, cells become more resistant to stress and metabolic processes are accelerated. Furthermore, it was shown that laser exposure may modulate gene expression and stimulate protein synthesis [10].

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Belykh et al. (2020), through experiments conducted on wheat seeds, demonstrated the direct influence of laser radiation on biophysical parameters. According to their results, seeds treated with low-power laser radiation showed increased water absorption rates and changes in electrical conductivity. This phenomenon was explained by microstructural modifications of the seed coat and increased membrane permeability. As a result, germination percentage and germination energy improved [9].

Analysis of the above studies indicates that low-intensity laser radiation affects plant biophysics through the following principal mechanisms:

- Increased permeability of cell membranes;
- Activation of energy metabolism processes (enhanced ATP synthesis);
- Strengthening of the antioxidant defense system;
- Stimulation of photosynthetic activity;
- Modulation of gene expression.

Thus, laser biostimulation, as a physical factor, induces complex biophysical response reactions in biological systems and serves as a scientific basis for improving growth and productivity parameters of agricultural crops.

Advantages of Lasers in Agriculture

In modern agriculture, laser technologies are being studied as a promising method for seed pre-treatment, stimulation of growth processes, and enhancement of crop productivity. Research shows that treating seeds or plants with laser radiation under specific parameters can improve growth rate, germination percentage, stress tolerance, and final yield ([11–13]).

Ivanov and colleagues (2025) found that exposing wheat seeds to laser radiation for 10 minutes increased germination by 23% and plant biomass by 20%. The researchers attributed this effect to increased antioxidant enzyme activity induced by laser radiation, which improved plant resistance to stress [11].

Similarly, Li and colleagues (2018) demonstrated that pre-sowing laser treatment of rice seeds increased final yield from 7.7% to 21% [12].

Chen et al. (2025) reported that laser-assisted seed stimulation significantly accelerated growth processes, promoted faster germination, and reduced germination mean time. They also noted that laser exposure contributed to increases in root and shoot length, as well as biomass accumulation [13].

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Gao and colleagues (2024) showed that low-intensity laser radiation improved growth characteristics in rice and increased final productivity, while activation of antioxidant defense systems enhanced stress tolerance [14].
Martinez et al. (2022) found that pre-treatment of soybean seeds with laser radiation increased yield by an average of 30%, while also increasing pod number, seed weight, and improving protein and crude oil content [15].
Kuznetsov et al. (2021) reported that treatment of sunflower seeds using He-Ne laser radiation increased oil content, phenolic compounds, and nutraceutical components even under stress conditions, thereby improving product quality [16].
As emphasized by Ivanov and colleagues (2025), laser-treated seeds also exhibit greater tolerance to abiotic stresses—particularly drought—through activation of antioxidant defense mechanisms that support plant growth under unfavorable conditions [11,13].
In addition, Thompson et al. (2021) suggested that biological stimulation through laser technologies may reduce the need for chemical fertilizers and growth stimulants, thereby improving ecological sustainability [17].
Laser technologies are therefore considered a promising tool in agriculture for seed pre-treatment, stimulation of growth processes, and increasing final productivity. Studies indicate that:
• Laser-treated seeds significantly improve germination rates and growth parameters [11,12];
• Final yield and product quality are enhanced [15,16];
• Biological stimulation reduces dependence on chemical inputs, supporting ecological sustainability [17].
Thus, laser technologies represent one of the promising directions for increasing agricultural efficiency and ensuring environmental sustainability.

Conclusion
In this study, the physical nature of laser radiation, its biophysical mechanisms of action, and its practical significance in agriculture were comprehensively analyzed. The analysis shows that laser radiation is formed as a highly monochromatic, coherent, and directed energy source based on the phenomena of stimulated emission and population inversion. These physical properties enable laser radiation to exert precise and controllable effects on biological objects.

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From a biophysical perspective, low-intensity laser radiation has been shown to increase cell membrane permeability, activate energy metabolism processes (by enhancing ATP synthesis), stimulate antioxidant enzyme systems, and modulate gene expression. As a result, seed germination energy, early growth rate, and resistance to stress factors are improved.

In agricultural practice, laser biostimulation is characterized by its ability to enhance seed germination through pre-sowing treatment, accelerate vegetative growth, improve photosynthetic efficiency, and increase final yield as well as product quality indicators (protein, oil, and phenolic compounds). Reports of yield increases ranging from 7% to 30% demonstrate that laser technologies are also promising from the perspective of economic efficiency.

Furthermore, biological stimulation using laser treatment may reduce the need for chemical fertilizers and growth regulators, which is an important factor in the development of environmentally sustainable agriculture.

In general, laser technologies represent an innovative method grounded in physical, biophysical, and agronomic principles, possessing significant scientific and practical potential for improving crop growth and productivity. In the future, precise optimization of laser parameters (wavelength, power, and exposure time), together with large-scale field experiments under different agro-climatic conditions, will contribute to the more effective implementation of this approach.

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