Laser, Plasma, and Magnetic Seed Treatments: Emerging Non-Chemical Technologies for Sustainable Agriculture

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ABSTRACT

Seed quality is critical to obtaining high agricultural output, but standard chemical seed treatments have environmental, ecological, and health implications. As a result, non-chemical seed treatments like laser irradiation, non-thermal plasma, and magnetic field exposure have emerged as viable and creative options. These physical approaches improve seed germination, vigour, and stress tolerance by stimulating natural physiological, biochemical, and molecular processes that leave no chemical residues or induce pathogen resistance. Laser treatment improves hormonal balance and photosynthetic efficiency via photoreceptor-mediated signalling; plasma treatment increases seed coat permeability and redox signalling via reactive species; and magnetic treatment stimulates water uptake, enzyme activity, and gene regulation. Collectively, these technologies provide major agronomic benefits, including increased yield and quality and compatibility with modern sustainable farming methods. Despite obstacles with standardization and large-scale adoption, ongoing mechanistic research and field validation demonstrate the huge potential of non-chemical seed treatments for climate-smart and sustainable agriculture.

INTRODUCTION

Seed quality is a critical component of crop productivity. Traditionally, chemical treatments such as fungicides, insecticides, and growth regulators have been used heavily to protect seeds and encourage germination. While successful, chemical techniques have environmental and human health implications, encourage disease resistance, and can harm soil biota. With a growing global population, there is a growing interest in developing management practices that reduce the infection potential while ensuring sustainability, cost effectiveness, and a healthy ecosystem. One such tool is 'seed treatment' (Sharma *et al.,* 2015). Laser, plasma, and magnetic seed treatments are cutting-edge, non-chemical technologies that improve seed performance, vigour, and stress resilience. Although environmentally friendly chemical seed treatments are safer than traditional pesticides, non-chemical or physical seed treatment methods such as laser, plasma, and magnetic treatments have particular advantages that make them desirable in many cases. These procedures produce no chemical residues, reducing the possibility of soil contamination, phytotoxicity, or impact on beneficial microbes and physical treatments do not cause pathogen resistance, ensuring long-term efficacy (Yadav *et al.,* 2025). These approaches use physical energy fields to modify seeds at the molecular and cellular levels and thus activate the seed's own physiological and metabolic processes rather than introducing foreign chemicals, which improves germination, vigour, and stress tolerance in a more natural way (Javed *et al.,* 2022).

1. LASER SEED TREATMENT

Laser, which stands for light amplification by stimulated emission of radiation, is an optical device that can produce monochromatic and highly coherent light. Maiman (1960) invented the first functional laser, which quickly became known as 'a solution looking for a problem'. Lasers have been employed in a variety of scientific and technological disciplines during the last few decades, including medicine, material processing, communication, and so on. However, recent research has shown that the use of lasers could lead to significant gains in agricultural food production (Nadimi *et al.,* 2021). Laser irradiation of seeds in pre-sowing treatment appears to be a promising area in modern agriculture, aligned with the concept of ecological farming and energy conservation. This approach, known for its non-toxicity and efficiency, aims to improve seed germination rates, consequently increasing agricultural productivity (Nadimi *et al.,* 2022). Laser bio stimulation involves irradiating seeds with low-power laser light for predetermined durations of time. The incident light energy is converted into chemical energy, which activates physiological and metabolic processes within the seed, potentially enhancing its growth dynamics. Ability of a seed to absorb and store radiant energy is critical in the bio stimulation process. Plants absorb light via photoreceptors such as phytochromes, cryptochromes, and phytotropins, which typically absorb radiation in the red-far red (600-750 nm), red-blue (500-630 nm), and UV-blue (320-500 nm) areas. When laser wavelengths align with certain absorption regions, the absorbed energy can be transformed into chemical energy, thereby activating physiological and biochemical processes known as laser bio stimulation. The He-Ne laser (632.8 nm) has been widely employed in seed and plant bio stimulation research (Nadimi *et al.,* 2021).

1.1 Mechanisms of Action

Laser seed treatment largely regulates seed germination and early seedling growth via phytochrome and hormone-mediated signalling pathways. Laser irradiation improves seed performance by increasing gibberellic acid (GA) biosynthesis genes while decreasing abscisic acid (ABA) levels and modulating catabolic genes, resulting in a higher GA/ABA ratio, which is critical for breaking seed dormancy and accelerating germination. Also, laser irradiation increases the expression of phytochrome genes (PhyA and PhyB1), which improves light perception and signal transduction during germination (Swathy *et al.,* 2021).

The absorbed laser energy also causes metabolic activation, as indicated by increased concentration of primary metabolites during early germination, which provides energy and substrate for embryo growth, followed by secondary metabolite regulation during later growth stages. Furthermore, laser-irradiated seedlings have improved photosynthetic efficiency, including increased photosynthetic rate, conductance of stomatal pores, and transpiration, which enhances plant growth and vigour. Overall, this treatment works through an integrated mechanism that includes photoreceptor activation, hormonal balance control, metabolic reprogramming, and increased photosynthetic performance, resulting in better germination and seedling development than untreated seeds (Swathy *et al.,* 2021).

2. PLASMA SEED TREATMENT

Due to increased food demand and limited resources, research on plasma-seed interactions has gained traction. Plasma seed treatment is an environmentally friendly strategy that uses plant adaptability to promote germination and seedling growth while lowering reliance on water, nutrients, and agrochemicals, and it has demonstrated positive results on crop performance (Waskow *et al.,* 2021). When energy is applied to a solid, it first melts into a liquid before vaporizing into a gas. With additional energy, gas atoms or molecules become ionized when electrons are stripped away, resulting in an electrically conducting, partially or fully ionized state known as plasma. Plasma properties, such as electron density and temperature, are determined by the type and amount of energy provided. Non-thermal plasma (NTP) is an ionized gas that contains electrons, ions, neutral atoms, UV photons, and a diverse range of reactive oxygen and nitrogen species (RONS), all while retaining a low gas temperature near to ambient conditions. Unlike thermal plasma, where all particles are in equilibrium, NTP has active electrons and comparatively cooler ions and neutrals, making it suited for treating heat-sensitive biological products like seeds. In recent years, NTP has emerged as a potential non-chemical seed treatment technology due to its capacity to improve germination, seedling vigour, and stress tolerance without the use of agrochemicals, which is consistent with sustainable and environmentally friendly farming practices (Mildaziene *et al.,* 2022).

2.1 Mechanisms of Action

Non-thermal plasma (NTP) regulates seed germination and subsequent plant growth by a number of mechanisms, including physical surface change, reactive species signalling, hormonal regulation, and metabolic reprogramming. NTP produces mild scraping and modification of the seed coat at the seed surface, hence enhancing wettability, permeability, and water and oxygen uptake, which is especially significant for seeds in physical dormancy, such as legumes. NTP produces reactive oxygen and nitrogen species (ROS/RNS), such as H_2O_2 and NO, that can enter seed tissues and serve as signalling molecules. These reactive species interact with internal ROS-producing systems, activating redox signalling cascades that modulate phytohormone balance, most notably by decreasing abscisic acid (ABA) and increasing gibberellins (GA), raising the GA/ABA ratio and breaking dormancy, as seen in radish, wheat, and rice seeds. NTP promotes enzymes for reserve mobilization (e.g., α-amylase, proteases) and antioxidant defence (SOD, CAT, POD), resulting in faster germination and higher seedling vigour. At later stages, NTP-induced epigenetic modifications and changed gene expression improve photosynthesis, stress-response pathways, and secondary metabolite synthesis, resulting in increased tolerance to abiotic stresses such as drought and salinity, as seen in wheat, maize, tomato, and rice. These interrelated pathways explain how NTP functions as a potent non-chemical priming agent, improving seed performance and early plant establishment (Mildaziene *et al.,* 2022).

3. MAGNETIC SEED TREATMENT

Magnetic seed treatment is a new, non-chemical pre-sowing approach that exposes seeds to low- to medium-intensity static or pulsed magnetic fields. This approach, discovered in the early twentieth century, has been found to improve seed germination, vigour, and plant development by boosting enzyme activity and improving nutrient uptake, resulting in increased agricultural yields (Raj *et al.,* 2025).

There are three basic ways for magnetic seed treatment (Raj *et al.,* 2025):

3.1 Electromagnetic seed treatment includes exposing seeds to a regulated magnetic field generated by an electromagnet, with field strength and exposure period precisely adjustable. Studies have revealed that soybean seeds treated with electromagnetic fields (150-200 mT) have increased plant height, leaf area, and biomass, with stronger fields yielding better effects.

3.2 Magnetized water treatment involves passing water via a magnetic field before utilizing it for seed soak or irrigation. Magnetization modifies the physical characteristics of water, increasing nutrient availability and absorption. Magnetized water has been demonstrated to improve germination rates, growth, and yield in crops such as cowpea.

3.3 Permanent magnet treatment makes use of static magnetic fields generated by permanent magnets that do not require any external power. Seeds are placed within a magnetic field, frequently with the embryo oriented specifically to enhance ion transport towards the embryonic axis. This approach has been shown to improve germination and early seedling growth through increased metabolic activity.

3.4 Mechanisms of Action: Magnetic seed treatment promotes seed germination and plant growth via a variety of physical, biochemical, and molecular pathways. Exposure to a magnetic field enhances water intake by changing the shape and mobility of water molecules, allowing for quicker imbibition and efficient hydration of seed tissues. Rapid water absorption activates metabolic processes and enzymes, including α-amylase, converting stored reserves into energy for germination and early seedling development.

It also stimulates the production of nitric oxide, a critical signalling molecule that regulates germination, increases seed coat permeability, and increases resistance to environmental challenges. Magnetic fields alter gene expression by upregulating antioxidant defence systems as well as growth and stress-related genes, boosting the seed's internal defensive defences. These biochemical and molecular alterations result in physiological advantages such as improved germination, seedling height, root and shoot strength, and biomass accumulation. These factors combine to produce more vigorous seedlings, improved establishment, and increased crop output in both normal and stress circumstances (Raj *et al.,* 2025).

4. AGRONOMIC BENEFITS AND SUSTAINABILITY

4.1 Chemical-Free Enhancements

Non-chemical seed treatments promote sustainable agriculture by replacing or lowering the use of synthetic chemical seed treatments. These strategies, which rely on physical or biological factors rather than agrochemicals, help to reduce soil and water contamination while also lowering the chemical burden on agricultural systems. Furthermore, non-chemical techniques limit the danger of pathogen resistance development, which is becoming increasingly common with repeated chemical usage, ensuring long-term effectiveness and environmental safety (Benabderrahim *et al.,* 2025).

4.2 Yield and Quality Improvements

Numerous studies have found that non-chemical seed treatments increase plant stand establishment and uniformity, resulting in greater biomass accumulation and crop performance. Improved early vigour frequently results in increased grain production and improved quality characteristics such as seed size, weight, and nutritional value. These enhancements boost farm productivity and profitability while lowering input costs, giving significant economic benefits to farmers (Saberi *et al.,* 2018).

4.3 Integration with Other Practices

Non-chemical seed treatments are very suitable with modern and sustainable agricultural methods, such as organic agriculture and precision farming. They can be easily combined with other seed enhancement procedures, including as priming and coating, without affecting seed viability (Paulikienė *et al.,* 2025). This flexibility enables farmers to mix non-chemical treatments with sophisticated agronomic approaches, maximizing resource utilization and crop management efficiency.

5. CHALLENGES AND LIMITATIONS

Non-chemical seed treatments, including as non-thermal plasma, laser, and magnetic field techniques, pose substantial hurdles that must be overcome before they can be widely adopted. The lack of standardized protocols is a significant limitation like studies in plasma agriculture show that differences in device types, gas composition, exposure times, and operating conditions result in inconsistent responses across seed types, making comparability and reproducibility difficult. Furthermore, whereas physical approaches such as cold plasma and lasers necessitate specialized equipment and technical skills, raising costs and accessibility concerns, magnetic treatments are less expensive but lack broad field validation and clear operational recommendations for farmers (Benabderrahim *et al.,* 2025).

6. FUTURE ASPECTS

Looking ahead, research efforts should focus on the creation of crop-specific, reproducible treatment methods that may be expanded to commercial seed processing lines, therefore addressing current heterogeneity in experimental settings and results. Advances in understanding the molecular mechanisms underlying physical treatments, including as hormone signalling, redox control, and gene expression changes, will aid in tailoring treatments for maximum effectiveness and predictability in a variety of crops (Priatama *et al.,* 2022). Large-scale and long-term field trials are essential for confirming laboratory results under practical agricultural settings and creating confidence in farmers and policymakers. Enabling technologies like as portable plasma devices, programmable magnetic field applicators, and optimized laser systems, when combined with precision agriculture equipment, may further cut costs and enhance accessibility (Benabderrahim *et al.,* 2025).

CONCLUSION

Non-chemical seed treatments, such as laser irradiation, non-thermal plasma, and magnetic field exposure, offer viable, environmentally acceptable alternatives to traditional chemical seed treatments. These physical measures can considerably boost seed germination, seedling vigour, and crop establishment by increasing water intake, stimulating metabolic enzymes, regulating hormonal balance, and improving stress tolerance. Although problems such as standardization, mechanistic knowledge, and large-scale adoption persist, ongoing research and field validation are expected to address these limits. Overall, non-chemical seed treatments are compatible with sustainable and climate-smart agriculture, providing a safe and novel way to improve seed quality and agricultural production.

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