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LASER TREATMENT OF COTTON SEEDS: A LITERATURE REVIEW ON OPTICAL ACTIVATION

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Abstract

This literature review consistently analyzes scientific studies on pretreatment of cotton seeds with laser light (optical preactivation). In cotton, uniform and rapid emergence of seedlings (uniform field coverage), early development and final yield largely depend on the physiological state of the seed, storage conditions and stress factors at the time of sowing. Laser irradiation is considered a physical method that produces less waste than chemical seed treatment, and is rapidly automated. The review summarizes the main optical treatments for seeds (blue-spectrum diode laser, various light-emitting diodes, ultraviolet treatments) and their associated mechanistic explanations (activation of photoreceptors, balance of reactive oxygen species, membrane permeability and mobilization of reserve substances). Based on spectroscopic evidence, the nonlinear response of laser dose to “hormesis” is highlighted as a persistent problem: a tendency to stimulate at low doses and inhibit at higher doses. The strengths and weaknesses of the available evidence—experimental design, repeatability, seed lot (lot) variation, external validity in field conditions, parameter standardization, and engineering limitations in transferring the technology to industrial scale—are also critically assessed. Finally, specific research gaps on the topic are identified and a practical agenda for future research is proposed, including a minimum reporting standard, dose–response optimization, and multisite field trials.

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1. Introduction

In cotton (Gossypium hirsutum L.) production systems, seed quality and early seedling development are fundamental factors for crop formation. In practice, mechanical damage to seeds (during ginning and delinting processes), oil peroxidation during storage, as well as disturbances in the moisture-temperature regime reduce seed vigor, leading to delayed and uneven germination in the field. As a result, uniform field coverage is disrupted, competition between plants within rows increases, weed pressure increases, and crop

stability decreases. Seed quality problems are especially acute during hot and humid seasons, early sowing periods, when the risk of salinity and frost damage is high (Mylsamy et al., 2025).

Pre-sowing seed treatment is widespread in practice, and there are approaches such as chemical treatment, seed coating, hydropretreatment (wet activation), osmotic pretreatment, and biological pretreatment. However, the environmental footprint, operator safety, resistance and residues of chemical treatments remain a pressing issue. In this context, methods that fall under the category of "physical seed activation", such as the use of electromagnetic fields, ultrasound, plasma and light, are considered promising (Araújo et al., 2016). Physical methods are generally rapid, do not require reagents and may be suitable for integration into production lines.

Laser irradiation (low-power laser seed treatment) is one of the most discussed and practical forms of optical pre-treatment. The main advantage of laser is the ability to precisely control the dose and spectrum, i.e. wavelength, power density (irradiance), energy density (fluence) and exposure time in a reproducible manner. However, there is no "universal" protocol for laser treatment: the state of the seed delinquent, the thickness of the seed coat, pigments, humidity and storage age, and even the microflora load of the seed all modify the optical response. Therefore, laser treatment often exhibits a nonlinear response, characteristic of "hormesis": at low doses, a stimulating effect is observed, and at higher doses, an inhibitory effect (Araújo et al., 2016).

The aim of this literature review is to provide a consistent and critical analysis of the available scientific research on laser (and, more broadly, optical) pre-treatment of seed. The review outlines (i) key empirical findings on the seed; (ii) technical parameters determining laser dose and their reporting standards; (iii) possible mechanisms (photoreceptors, reactive oxygen species balance, membrane, and metabolism); (iv) methodological limitations and reproducibility issues; (v) requirements for industrialization and implementation; and (vi) specific gaps and practical agendas for future research.

Due to the limited number of studies on laser irradiation of seeds, this review selected sources in two layers. The first layer is direct studies that provide laboratory and field results of optical pretreatment for seeds of cereals (for example, extensive experiments on optical activation, and works based on spectroscopic analysis of lasers). The second layer is review and methodological articles that discuss physical pretreatment technologies in general terms, and evidence from other crops that shed light on the general mechanisms of laser stimulation. This approach mitigates the problem of "poor knowledge" on seeds, but requires caution in drawing conclusions, since the structure and biochemistry of seeds in different crops differ.

Each empirical study was assessed according to the following blocks: (1) description of the seed material—variety, type of delint, percentage of moisture, storage age, and initial germination rates; (2) optical device parameters — wavelength, power, spot area, irradiance (W/cm²), fluence (J/cm²), exposure time, pulse/continuous mode, illumination geometry; (3) experimental design — control groups, randomization, number of replicates, laboratory and field linkage; (4) outcome measures — germination percentage and rate, vigor index, seedling biometric parameters, stress tests, field yield; (5) statistical processing and validity of conclusions. In the critical analysis, the completeness of the parameter definition and the possibility of reproducibility (replication) were taken as central criteria.

2. Scientific basis of laser and optical processing technology

The physical basis of the interaction between seeds and laser light is the absorption, scattering and reception of energy (mainly by chemical bonds or pigments). In the case of seeds, the seed coat may be thick, the surface may be uneven and there may be remnants of delinquent matter; this increases the reflection and scattering of light, reducing the photon flux reaching the embryo. Therefore, when choosing a wavelength, the absorption spectrum of the seed coat and internal tissues, as well as the sensitive ranges of photoreceptors, should be taken into account. The blue range (approximately 400–470 nm) is expected to activate the cryptochrome and phototropin systems more, and the red range (approximately 630–660 nm) is expected to activate the phytochrome system more.

The goal of low-power laser processing is to generate a photobiological signal without significantly heating the seed. However, “low power” is relative: the irradiance can be high due to a very small light spot or close distance to the seed. Therefore, if the thermal effect is not controlled, the mechanism is closer to thermal stress than to photobiomodulation. Furthermore, the outcome of optical treatments is often nonlinear and there is an “optimal dose window”: doses below the optimum do not produce significant changes, while doses above the optimum do may reduce germination through oxidative stress and membrane damage. This is explained by the concept of “hormesis” and has been widely discussed in the literature on physical treatments (Araújo et al., 2016).

From a technological perspective, the first problem is dose uniformity. Seeds shade each other as they move through the flow, with some seeds exposed to direct light and others to diffusely scattered light. In laboratory experiments, seeds are usually spread in a thin layer and held at a uniform distance; in a factory setting, seed turning, vibrating feeders, multi-source lighting, or optical diffusers are required to ensure dose distribution. Otherwise, “under- and over-dosed” seeds in the same batch will be mixed, increasing the dispersion of results and reducing statistical precision. The second problem is the initial state of the seed. Seed moisture (e.g., 7% or 12%), storage age, type of delinting (mechanical, acidic, or gaseous), degree of seed coat damage, and microflora load can dramatically change the response to optical treatment (Mylsamy et al., 2025). For example, acid delint can clean the seed surface and facilitate the penetration of light, but if done incorrectly, it can weaken the skin and increase sensitivity to optical stress. Therefore, laser treatment should not be seen as a “universal recipe”, but as a technology that can be adapted to the seed lot, with precise parameters and quality control.

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The third important issue concerns outcome assessment metrics. The effects of laser treatment are often more evident in germination rate, vigor index, seedling root length, or performance under stress conditions, rather than in final germination percentage alone. Consequently, reliance solely on final germination rates may lead to underestimation of laser effects. A robust scientific design should integrate germination kinetics (e.g., emergence rates within 24–72 hours), seedling biometric parameters, and field-level indicators such as stand establishment (field uniformity).

3. Empirical evidence on laser and optical activation in seed germination

Although optical activation studies in seeds are still limited, some studies provide field results in addition to laboratory data. Atta et al. (2023) compared several optical pre-activation options (blue and redlight diodes, diode laser, UV-B and UV-C treatments) and reported germination and vigor performance in the laboratory, followed by field trials under different conditions. The authors show that some protocols can significantly increase germination performance and have a positive impact on field yield. The strength of this work is its attempt to validate laboratory results in the field, since the economic and agronomic value of optical treatment is evident in the field.

However, the large number of parameters in Atta et al. (2023) makes it difficult to disentangle the cause-effect chain. When multiple spectra, multiple time ranges, and different environments are given within a single design, it is difficult to say with certainty which factor played the dominant role.

Furthermore, the issue of completely standardizing and reporting fluence and irradiance in optical processing protocols is not always addressed with the same precision. This limits the ability of other laboratories to reproduce the protocol. The problem of reproducibility is particularly important in laser processing, since small geometric differences (distance, beam spot, seed layer thickness) can radically change the dose distribution.

A study that approaches the **molecular effects of laser treatment on cotton seeds** is that of Ahmed and Marouf (2025), who applied a blue diode laser (405 nm) and analyzed changes in absorption and vibrational bands of seed components using ultraviolet–visible (UV–Vis) spectroscopy and Fourier-transform infrared (FTIR) spectroscopy. The authors identified the presence of an "optimal dose" within a low fluence range (approximately 0.167–0.667 J/cm²), beyond which germination may be inhibited. The scientific value of this work lies in its attempt to directly link biological outcomes (germination) with physicochemical signals (spectral changes). However, from a methodological perspective, bridging spectroscopic signals to biological mechanisms requires additional biomarkers (e.g., oxidative stress markers, enzyme activity, water uptake); otherwise, it is difficult to definitively establish the biological basis of the observed spectral differences.

In studies focusing on optical pre-activation using ultraviolet radiation rather than laser irradiation, Jawdat et al. (2020) reported that treatment of long-stored cotton seeds with a combination of ultraviolet-A, -B, and -C radiation increased germination rates and improved seedling growth under salinity (sodium chloride) and osmotic stress (polyethylene glycol) conditions. They also demonstrated transient activation of certain stress-responsive genes. These findings suggest that optical treatment may not only provide energy input but also trigger adaptive mechanisms to stress via signal transduction pathways. However, since ultraviolet treatment carries a higher risk of photochemical damage compared to laser irradiation, it should be cautiously interpreted and not directly generalized as equivalent to laser-based treatments.

Due to the limited number of studies specifically on cotton seeds, evidence from other crops provides important context for understanding the general biological patterns of laser irradiation. For example, Perveen et al. (2021), in experiments on safflower seeds, gradually increased the dose of a helium–neon laser (632.8 nm) and demonstrated the existence of an optimal dose associated with changes in germination and metabolite profiles; the authors linked this effect to enzyme activity involved in the mobilization of reserve substances. Similarly, Klimek-Kopyra et al. (2022) showed under field conditions that pre-sowing laser stimulation of soybean seeds can influence yield as well as the protein and oil fractions of the seeds. Although these findings cannot be directly extrapolated to cotton, they provide useful general evidence supporting the existence of an "optimal dose window" and the potential for translating laser treatment into agronomic benefits.

4. Mechanisms: Photobiological and Biochemical Explanations

Two main, complementary concepts are proposed to explain the effects of laser irradiation on seed germination: (i) signal transduction via photoreceptors and (ii) adaptation through low-level stress (hormesis). In the first concept, blue-spectrum light may activate cryptochromes and phototropins, while red-spectrum light activates the phytochrome system. Through photoreceptor-mediated signaling, processes such as hormonal balance (e.g., the ratio of gibberellins to abscisic acid), cell wall loosening, endosperm–embryo interaction, and gene expression are modulated. In seed physiology, this can be interpreted as a form of "pre-signaling," which may accelerate the activation of metabolic pathways required for the initiation of germination.

The second concept—hormesis—suggests that low doses of laser irradiation may moderately increase reactive oxygen species (ROS), thereby priming the antioxidant system. Although ROS are typically considered damaging agents, at low concentrations they function as signaling molecules. If antioxidant enzymes are activated following optical treatment, seeds may exhibit improved tolerance to stresses such as cold, salinity, or water deficit during the seedling stage. The findings of Jawdat et al. (2020), demonstrating transient activation of stress-responsive genes in cotton seeds, are consistent with this

concept. However, for laser-treated cotton seeds, comprehensive profiling of antioxidant systems and oxidative stress markers remains insufficiently explored.

Spectroscopic evidence can serve as a supportive tool in explaining the underlying mechanisms. Ahmed and Marouf (2025) demonstrated shifts and intensity changes in specific bands of UV–Vis and FTIR spectra following laser treatment; the authors attributed these changes to molecular excitations and redistribution of energy around chemical bonds. However, for spectroscopic changes to be translated into biological conclusions, it is necessary to establish a causal chain linking them with indicators such as membrane lipid oxidation, protein conformation, water-binding states, or enzyme activity. Otherwise, although spectral signals may be informative, they do not fully answer the question of "how" the biological effect occurs.

The literature review reveals several clear gaps in studies on laser irradiation of cotton seeds. The following gaps and corresponding practical recommendations are identified:

1. Lack of a minimum reporting standard for parameters. Each study should, at a minimum, report wavelength, power, beam spot area, seed-to-source distance, irradiance, fluence, exposure time, pulsed/continuous mode, illumination geometry, seed layer thickness, seed delinting type, moisture content, storage duration, and initial germination показатели in a standardized format. Without this, replication and meta-analysis are not feasible.

2. Insufficient dose–response mapping. Most studies are limited to 2–4 dose levels, which is inadequate to identify the hormetic optimum. Future studies should employ response surface methodology (e.g., irradiance × time × wavelength), enabling statistical modeling of optimal conditions with confidence intervals.

3. Limited generalizability across seed lots and cultivars. An optimum identified for one cultivar or seed lot may not be transferable to others. Therefore, validation experiments should include at least 3–5 different seed lots (varying in storage duration and vigor) and 2–3 cultivars. Factors such as delinting method and seed coating should also be incorporated into experimental design.

4. Lack of multi-location and multi-year field trials. The practical value of optical treatment must be assessed under diverse environmental and agronomic conditions. Although Atta et al. (2023) provide initial direction, comprehensive multi-year, multi-location trials using standardized agronomic protocols remain limited.

5. Insufficient mechanistic biomarkers and causal linkage. Parameters such as antioxidant enzyme activity, lipid peroxidation, water uptake, gas exchange, hormonal balance, and kinetics of reserve mobilization should be systematically measured alongside laser dose. This would allow differentiation between signaling and stress effects and provide a biological basis for optimal dosing.

6. Limited evidence on long-term effects and storage stability. It remains unclear whether laser treatment remains effective when applied weeks or months before sowing. For example, long-term effects have been demonstrated for cold plasma treatment in cotton seeds (de Groot et al., 2018), but this question remains open for laser irradiation and is critically important for industrial application.

5. Conclusion

Current scientific evidence on optical activation of seed by laser irradiation shows the positive potential of the technology, but it is premature to issue a general "prescription" due to the fragmentation of the scientific base and methodological differences. Field studies (e.g. Atta et al., 2023) are coming close to demonstrating the agronomic value of the technology, while spectral and molecular approaches (Ahmed & Marouf, 2025) contribute to understanding the dose-response and mechanism. However, inconsistencies in reporting parameters, seed lot heterogeneity and lack of replication limit the generalizability of the evidence.

From a practical perspective, laser treatment can be a relatively environmentally friendly and rapidly automated method, but issues of uniform dose distribution, safety, integration and economic model need to be addressed for industrialization. From a scientific point of view, the main task is to determine the photobiological sensitivity and hormesis optimum of seeds, to demonstrate the causal mechanisms of the

effect through biomarkers, and to consistently confirm the results in multi-site, multi-year field trials. Only when these conditions are met can laser irradiation take its place as an independent and reliable technology in the practical portfolio of seed treatment.

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