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Effect of Laser Biostimulation on Germination of Sub-Optimally Stored Flaxseeds (*Linum usitatissimum*)

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Abstract: Sub-optimal storage of grains could deteriorate seed germination and plant viability. Recent research studies have established that laser biostimulation of seeds could be used as a safe and sustainable alternative to chemical treatment for improving crop germination and growth. Herein, the efficacy of this novel technique is evaluated to see if poor germinability caused by sub-optimal storage of flaxseeds (*Linum usitatissimum*) could be reversed using laser biostimulation. Healthy flaxseeds were first subjected to sub-optimal storage conditions (30 °C for ten weeks) to degrade their germinability. Two low-cost lasers, including a single-wavelength red laser (659 nm) and a dual-wavelength green/infrared laser (531 and 810 nm (ratio ~10:1)) were then used on two groups viz. healthy (properly stored) and sub-optimally stored (artificially degraded (AD)) seeds and irradiated for 0 (control), 5, 10, and 15 min using total power densities of 7.8 and 6.2 mW/cm^2, respectively. In the case of AD seeds, 5-min dual-wavelength laser treatment was found to be the most efficient setting as it improved the mean germination percentage, mean germination time, germination speed, germination rate index, wet weight, and dry weight by 29.3, 16.8, 24.2, 24.2, 15.7, and 20.6%, respectively, with respect to control samples. In the case of healthy seeds, dual-wavelength laser treatment could induce significant enhancement in seeds' root length, wet weight, and dry weight (improved by 26, 23, and 8%, respectively) under 10 min of irradiation. On the other hand, the effect of applied red laser treatment was not very promising as it could only induce significant enhancement in the mean germination time of AD seeds (improved by 17%). Overall, this study demonstrates the potential of laser biostimulation in reversing the adverse effect of poor crop storage. We believe these findings could spur the development of a physical tool for manipulating seed germination and plant growth.

Keywords: biostimulation; dual-wavelength laser; laser; flaxseeds

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1. Introduction

Over the past decade, optical techniques have been widely researched in crop and fruit quality monitoring [1–6]. Improving the growth and development of agricultural crops using optical methods is also of great interest as it can reduce the harmful effects of chemical use on the environment while enhancing food safety [7,8]. Recently, laser biostimulation has emerged to be a promising optical method to enhance crop germination and growth [8]. In laser biostimulation, seeds are irradiated with low-power laser light for pre-determined specific durations of time. The incident light energy is transformed into chemical energy and triggers physiological and biochemical processes within the seed that could enhance its growth dynamics [8,9]. A seed's ability to absorb and store radiant energy plays a crucial role in the biostimulation process.

The effect of laser biostimulation on enhancing the growth characteristics of various seeds has already been demonstrated, such as wheat [10–12], pea [13], eggplant [14–16], radish seeds [17], sunflower [18], soybean [19,20], white lupine, faba bean [21], tomato [22],

alfalfa [23], etc. In addition, plant tolerance to biotic and abiotic stresses has also been shown to be enhanced through laser treatment [24–32]. In the majority of reported studies, a He-Ne gas laser has been used as the laser source [8,9,33].

Though the positive influences of laser biostimulation on seed growth have been reported many times, research results around this topic lack consistency [7–9,34–39]. This may be attributed to the selection of different laser settings (such as wavelength, power, dosage, exposure time, etc.) used in the various experiments that have been conducted on a variety of different samples. Therefore, an essential task in ongoing research in this area is to establish appropriate laser parameters for each plant species, with special emphasis placed on seeds of higher economic and commercial importance [8,9].

Even though there are evident benefits to the laser biostimulation of seeds, such methods will be better adopted if they are made more affordable to agricultural producers. Recently, Nadimi et al. [40] reported the promising application of a low-cost green/infrared dual-wavelength laser to enhance the germination of high-quality Canadian wheat. In the present work, we aimed to utilize a similar low-cost laser biostimulation system to evaluate the feasibility of manipulating the germination of Canadian flaxseed before and after exposing the seeds to sub-optimal storage conditions (30 °C for ten weeks).

Flaxseed is the sixth largest crop in Canada and for the 2020–2021 cropping year the area seeded for flaxseed increased by 10%. It is grown primarily in western Canada as the second most important oilseed crop. Flax cultivars are well-adapted to the Canadian prairies, where the cool climate results in seed production with high oil concentration and quality. Flax is a valuable oilseed with applications in various products, including food, animal feedstock, paints, etc. High contents of the omega-3 fatty acid, alpha-linolenic acid, lignans, and soluble fiber are some of the features of flaxseed that make it attractive for human and animal diets [41]. Hence, enhancing the germination and quality of flaxseed is of great interest to the agricultural industry.

To the best of the authors' knowledge, the impact of dual-wavelength laser biostimulation on the germinability of flaxseed has not been previously researched. Moreover, this study is the first effort in assessing the effect of laser biostimulation on reversing the consequences of poor storage. Therefore, the outcomes of this study will contribute to the fundamental knowledge base on the biostimulation of crops and inform scholars on how the germination and growth of seeds may be enhanced to improve yields without the use of environmentally hazardous chemicals or genetic modification.

2. Materials and Methods

2.1. Sample

The flaxseeds used in this study were obtained from a local farm in Arborg, MB, Canada. Upon receival, the initial seed moisture content was measured to be ~8% (wet basis), according to the procedure described in [41,42]. The seeds were conditioned to a moisture content of 11.5% (wet basis) (the process described in [41,42]) and then randomly divided into two categories. One of the two batches was kept in a freezer at −5 °C, and the other was stored in artificially created sub-optimal conditions at 30 °C with a relative humidity of ~85% for ten weeks. This condition for sub-optimal storage was chosen as it is known to degrade the seed germinability [42]. For the rest of this manuscript, the former and latter categories were labeled as healthy flaxseeds (HF) and artificially degraded flaxseeds (ADF), respectively.

2.2. Laser Treatment

Two low-cost, focusable, and portable lasers were implemented as biostimulation sources for flaxseed samples. They included a single-wavelength continuous-wave red semiconductor laser (λL = 659 nm) (Sunshine-Electronics, 445/450MD-2300-TO5, China) and a dual-wavelength continuous-wave green/infrared laser [λL = 531 and 810 nm (ratio ~10:1)] (model: green laser 303) [This laser was purchased from a local store (a similar model is manufactured by Ningbo Topcom Lighting Co., Zhejiang, China)]. The laser

sources' original powers were 100 and 80 mW, respectively. The laser power on seeds was reduced by ~45% (using a filter) to make the power more suitable for inducing the biostimulation effect. The original spectra of lasers are provided elsewhere [40].

Figure 1 depicts the experimental setup used for seed treatments in this study. Each laser was mounted on a stand at a height of ~40 cm. The laser light was focused on a circular area with a diameter of ~3 cm. Each laser source simultaneously treated 25 seeds at a single dose for the duration of 0 (control), 5, 10, and 15 min. The laser power densities on seeds were 7.8 and 6.2 mW/cm^2 for the red and dual-wavelength lasers, respectively.

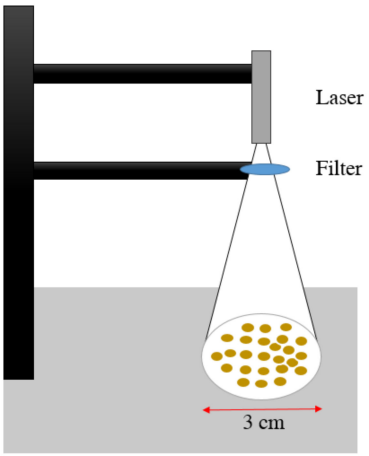

Figure 1. Schematic laser setup used for seed treatment.

2.3. Germination Parameters

To perform the germination study, eight replicates from each group from each sample category were tested (Figure 2). Each replicate consisted of 25 seeds placed on Whatman grade 4 germination paper in a 9-cm diameter Petri dish. Five mL of distilled water was added to each Petri dish. Samples were placed in stacks of 8 Petri dishes in a germination chamber (Home Herb Cultivator, Danby Inc., Guelph, ON, Canada) and the seeds were allowed to germinate at 23 °C for 7 days in complete darkness. In total, 2800 seeds were tested for germination (=25 (number of seeds for each treatment) × 8 (number of replicates) × 7 (number of groups including 5-, 10-, and 15-min red/dual-wavelength treatment + control) × 2 (storage categories)).

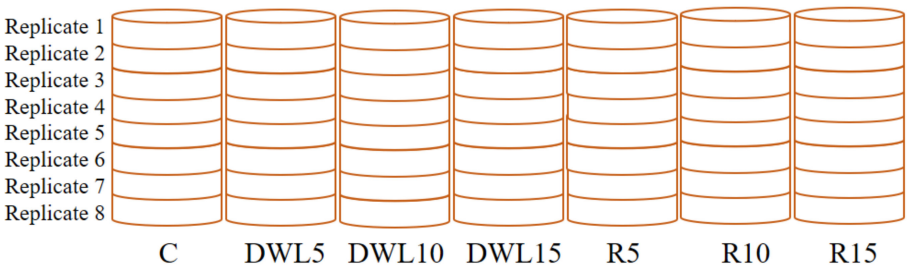

Figure 2. Germination test arrangement. C: Control. DWL5/10/15: Samples treated with dual-wavelength laser for 5/10/15 min, respectively. R5/10/15: Samples treated with red laser for 5/10/15 min, respectively. Each replicate consisted of 25 flaxseed kernels.

The number of germinated seeds in each Petri dish was recorded on a daily basis for one week. Additional distilled water was added to Petri dishes, if needed. A germinated seed constituted any seed with a radicle of 2 mm or larger in length.

A total of seven parameters to evaluate seeds germinability and/or early growth were calculated, including germination percent (GP), mean germination time (MGT), germination rate index (GRI), germination speed (GS), primary root length (RL), wet weight (WW), and dry weight (DW).

Equation (1) was used to calculate seed GP [11].

$$\mathrm{GP} = \frac{N_g}{N_t} \times 100 \quad (1)$$

where N_g and N_t represent the number of germinated seeds (at the end of the germination period) and the total number of seeds, respectively.

Equation (2) was employed to calculate MGT [19].

$$\mathrm{MGT} = \frac{\sum D \times n}{\sum n} \quad (2)$$

where D and n represent the number of days counted from the start of the germination test and the number of seeds germinated at day D, respectively.

Equation (3) was used to calculate seeds GS [19].

$$\mathrm{GS} = \sum \frac{n}{D} \quad (3)$$

where n represents the number of germinated seeds in day D.

Equation (4) was used to calculate the GRI [43].

$$\mathrm{GRI} = \sum \frac{G}{D} \quad (4)$$

where G is the germination percentage at day D.

At the end of the germination period, germinated seeds from each Petri dish were photographed and the lengths of the grown roots were measured using ImageJ software. To dry the germinated seeds, they were placed in an oven at 105 °C for 5 h.

2.4. Statistical Analysis

SPSS software was used for statistical analysis. Analysis of variance (ANOVA) was performed to evaluate the significant effect of laser-induced germinability traits on seeds. Prior to applying classic ANOVA (CA), the normality and variance homogeneity of distributions were explored. Shapiro-Wilk and Levene's techniques were used for such tests, respectively. If both conditions were satisfied, classical one-way ANOVA was used for data analysis. Upon violation of the former and latter conditions, Kruskal-Wallis mean rank (KW) and Welch's ANOVA (WA) tests were used for data analysis, respectively. If both conditions were violated, the data were transformed to an appropriate form and a relevant test was applied. For post hoc tests, the Dunnet two-sided test and Games-Howell methods were utilized for CA and WA tests, respectively.

3. Results

3.1. Healthy Flaxseeds

Table 1 depicts the effect of laser treatments on the germination traits of HF. This high GP of 87% of control HF is an indicator of the high quality of the tested seeds. GPs of seeds exposed to 5-min dual-wavelength and red lasers were significantly low compared to the control. On the other hand, the highest GPs were 90.5 and 89% for the dual-wavelength (15 min) and red laser (10 min), respectively. Statistical analysis indicates that the observed enhancements were not statistically significant.

The effect of laser treatments on the MGT of HF is also shown in Table 1. The average MGT of control samples was calculated to be 2.1 days. The best performance among the treated seeds was achieved under 10-min dual-wavelength laser irradiation with ~3% enhancement in MGT. All other treatments for dual-wavelength and red laser extended the MGT. Indeed, the significant change only occurred under 10-min red laser treatment where MGT increased by 32%.

Table 1. Effect of dual-wavelength and red laser treatments on germination parameters of HF.

Dual-Wavelength Laser							
Exposure Time (Min)	**Germination Percentage**	**Mean Germination Time (Days)**	**Germination Speed (Number of Germinated Seeds/Day)**	**Germination Rate Index (%/Day)**	**Primary Root Length (mm)**	**Wet Weight (mg)**	**Dry Weight (mg)**
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Control	87.0 ± 7.4	2.1 ± 0.2	11.3 ± 1.0	45.0 ± 4.1	55.0 ± 4.3	24.7 ± 5.6	3.5 ± 0.3
5	79.5 ± 8.4 *	2.2 ± 0.2	9.6 ± 1.3 ***	38.3 ± 5.2 ***	52.1 ± 3.9	25.5 ± 5.0	3.5 ± 0.2
10	88.0 ± 4.3	2.0 ± 0.3	11.3 ± 0.7	45.1 ± 2.7	69.3 ± 3.7 *	30.3 ± 3.1 *	3.8 ± 0.3 *
15	90.5 ± 4.2	2.3 ± 0.2	10.5 ± 0.8	41.9 ± 3.3	64.6 ± 4.7	28.7 ± 4.3	3.7 ± 0.3
Test of significance	KW	CA	CA	CA	CA	CA	CA
Red Laser							
Exposure Time (Min)	**Germination Percentage**	**Mean Germination Time (Days)**	**Germination Speed (Number of Germinated Seeds/Day)**	**Germination Rate Index (%/Day)**	**Primary Root Length (mm)**	**Wet Weight (mg)**	**Dry Weight (mg)**
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Control	87.0 ± 7.4	2.1 ± 0.2	11.3 ± 1.0	45.0 ± 4.1	55.0 ± 4.3	24.7 ± 5.6	3.5 ± 0.3
5	79.0 ± 5.6 **	2.2 ± 0.3	9.7 ±1.3 **	38.9 ± 5.3 **	48.8 ± 12.5	23.1 ± 7.1	3.4 ± 0.5
10	89.0 ± 5.6	2.8 ± 0.6 ***	8.6 ± 1.6 ***	34.5 ± 6.2 ***	47.3 ± 16.1	24.9 ± 7.4	3.8 ± 0.4
15	87.5 ± 5.8	2.3 ± 0.2	10.1 ± 0.7	40.3 ± 2.7	53.9 ± 9.3	22.9 ± 5.1	3.7 ± 0.4
Test of significance	CA	KW	CA	CA	KW	CA	CA

The values are rounded to one decimal place. Control stands for no laser treatment. ***, **, * represent significant at 0.01, 0.05, and 0.10, respectively.

Table 1 also indicates the effect of laser treatments on GS of HF. The average GS of untreated seeds was calculated to be 11.3 seeds/day. Again, except for the 10-min dual-wavelength laser irradiation that had slight enhancement, all other dual-wavelength and red laser treatments had an adverse effect on mean GS. The most significant laser-induced changes for the dual-wavelength and red lasers occurred under 5-min and 10-min treatment, respectively. The former and latter decreased the mean GS by ~23 and 15%, respectively.

Table 1 also illustrates the effect of laser treatments on GRI of HF. The average GRI of control samples was calculated to be 45% per day. Once more, except for the 10-min dual-wavelength laser irradiation that showed slight improvement, all other dual-wavelength and red laser treatments had an adverse effect on mean GRI. The most significant laser-induced changes for the dual-wavelength and red lasers occurred under the treatments of 5 min (−23%) and 10 min (−15%), respectively.

Table 1 also presents the effect of laser treatments on RL of HF. The average RL of control samples was calculated to be 55 mm. Among the applied treatments, the only significant change occurred under the 10-min dual-wavelength laser where 25% enhancement in RL was observed. The effect of laser treatment on WW and DW of HF is also shown in Table 1. Again, the only significant change occurred under 10-min dual-wavelength laser where 13 and 8% enhancement in WW and DW, respectively, were observed.

3.2. Artificially Degraded Flaxseeds

Table 2 shows the effect of laser treatment on the germination traits of ADF. A low GP of 49.5% is an indicator of the degradation of the tested seeds. It can be seen that both 5-min and 10-min dual-wavelength and red laser treatment could improve the GP. However, the significant change only occurred under a 5-min dual-wavelength treatment where mean GP increased to 64%.

Table 2. Effect of dual-wavelength and red laser treatments on germination parameters of ADF.

Dual-Wavelength Laser							
Exposure Time (Min)	**Germination Percentage**	**Mean Germination Time (Days)**	**Germination Speed (Number of Germinated Seeds/Day)**	**Germination Rate Index (%/Day)**	**Primary Root Length (mm)**	**Wet Weight (mg)**	**Dry Weight (mg)**
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Control	49.5 ± 11.3	4.4 ± 0.3	3.1 ± 0.8	12.3 ± 3.2	33.1 ± 3.6	17.9 ± 4.0	2.8 ± 0.6
5	64.0 ± 12.5 **	3.7 ± 0.5 **	3.8 ± 0.8 *	15.3 ± 3.3 *	32.0 ± 7.2	20.7 ± 2.2	3.4 ± 0.4
10	56.5 ± 10.8	4.2 ± 0.4	3.1 ± 0.6	12.5 ± 2.6	26.6 ± 4.7 *	18.8 ± 3.8	3.2 ± 0.8
15	42.0 ± 8.6	3.6 ± 0.7 ***	2.2 ± 0.5 *	8.9 ± 1.8 *	29.2 ± 6.7	14.3 ± 4.2	2.3 ± 0.8
Test of significance	CA	CA	CA	CA	CA	CA	CA
Red Laser							
Exposure Time (Min)	**Germination percentage**	**Mean Germination Time (Days)**	**Germination Speed (Number of Germinated Seeds/Day)**	**Germination Rate Index (%/Day)**	**Primary Root Length (mm)**	**Wet Weight (mg)**	**Dry Weight (mg)**
	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD	Mean ± SD
Control	49.5 ± 11.3	4.4 ± 0.3	3.1 ± 0.8	12.3 ± 3.2	33.1 ± 3.6	17.9 ± 4.0	2.8 ± 0.6
5	56.5 ± 13.8	3.8 ± 0.2 **	3.4 ± 1.0	13.7 ± 3.9	31.3 ± 9.1	20.4 ± 9.7	3.0 ± 1.4
10	61.0 ± 16.0	4.6 ± 1.6	3.4 ± 1.1	13.6 ± 4.3	25.6 ± 4.7 ***	23.7 ± 13.2	4.1 ± 2.3
15	42.0 ± 14.0	4.0 ± 0.9	2.3 ± 0.7	9.1 ± 2.8	24.9 ± 6.2 **	17.7 ± 9.0	2.9 ± 1.7
Test of significance	CA	KW	CA	CA	WA	WA	CA

The values are rounded to one decimal place. Control stands for no laser treatment. ***, **, * represent significant at 0.01, 0.05, and 0.10, respectively.

The effect of laser treatments on the MGT of ADF is also evident in Table 2. The average MGT of control samples was calculated to be 4.4 days. Dual-wavelength treatment at 5 and 15 min and red laser treatment at 5 min could induce significant improvement by decreasing the MGT by 20, 18, and 15%, respectively.

Table 2 also indicates the effect of laser treatments on GS of ADF. The average GS of untreated seeds was 3.1 seeds/day. Similar to GP, it can be observed that both 5-min and 10-min dual-wavelength and red laser treatment could improve the GS. However, the significant enhancement only occurred under a 5-min dual-wavelength treatment where mean GS increased by 24%. For GRI, a similar trend was observed. Indeed, in both of the aforementioned germination traits, the 15-min dual-wavelength induced a significant adverse effect by diminishing GS and GRI by 28%.

Table 2 also presents the effect of laser treatments on the RL of ADF. The average RL of control samples was calculated to be 33.1 mm. Among the applied treatments, the 10-min

dual-wavelength and 10- and 15-min red lasers induced significant adverse effects and diminished the root length by 20, 23, and 25%, respectively.

The effect of laser treatment on WW and DW of ADF is also shown in Table 2. While the effects of laser light were not statistically significant, the 5- and 10-min dual-wavelength and red laser treatments increased the weights. The best performance was achieved under 5-min irradiation for the dual-wavelength laser, where WW and DW increased by 16 and 21%, respectively. In the case of red laser, the best performance was achieved under 10-min treatment where 32 and 43% enhancement in WW and DW were recorded, respectively.

4. Discussion

Considering there have not been any previous attempts to examine the effect of continuous-wave red and dual-wavelength lasers on the germination of flaxseed, we are unable to compare our results to other similar studies on flaxseed. Indeed, we could compare the effect of laser biostimulation on ADF with HF. Moreover, we can compare the performance of dual-wavelength and red lasers with control.

Our results clearly indicate that poor storage reduces the viability of flaxseeds. Suboptimal storage deteriorated the GP, MGT, GS, GRI, RL, WW, and DW by 43, 112, 73, 73, 40, 28, and 20%, respectively. Similar results have previously been shown for other crops such as soybeans [44], flax [42], wheat [45], canola [46], rye [47], and pinto beans [48].

Applying dual-wavelength laser light to HF for 10 and 15 min generally induced positive effects on flaxseeds. On the other hand, 5-min dual-wavelength laser irradiation generally had an adverse effect on the germination parameters. The best performance under dual-wavelength laser irradiation for HF was achieved under 10-min treatment where GP, MGT, GS, GRI, RL, WW, and DW were enhanced by 1.1, 3.3, 0.2, 0.2, 26, 22.7, and 7.7%, respectively. The changes in the last three parameters were statistically significant. In the case of red laser, the effect of irradiation was primarily detrimental. Indeed, the negative effects were more pronounced under 5-min red treatment where the aforementioned traits were modified by −9.2, −4.3, −13.7, −13.7, −11.3, −6.7, and −4.6%, respectively.

In the case of ADF, the 5- and 10-min red and dual-wavelength laser treatments generally had positive effects on germination traits, and the 15-min treatment had variable effects. The best overall performance under dual-wavelength and red laser treatments for ADF was achieved at 5-min irradiation. For the dual-wavelength laser GP, MGT, GS, GRI, RL, WW, and DW were changed by 29.3, 16.8, 24.2, 24.2, −3.3, 15.7, and 20.6%, respectively. For the red laser, the laser-induced modifications were 14.1, 14.7, 11.6, 11.6, −5.4, 13.9, and 5.0%, respectively.

Overall, our experiments indicate that dual-wavelength laser promises to partially reverse the effect of poor storage conditioning on seeds germinability. On the other hand, the experimental data suggest that the applied red laser setting was not adequate for inducing significant enhancement to the germination of flaxseed.

One should note that while the effect of a continuous-wave dual-wavelength laser on flaxseed was not reported before, the positive effect of a dual-wavelength laser on germination traits of high-quality Canadian wheat has been recently demonstrated where green/infrared laser enhanced GP, MGT, GS, and GR of Canadian wheat seeds [40]. These two works can open a new pathway for manipulating the germination traits of seeds via new low-cost lasers.

It is worth mentioning that the mechanisms of how plants perceive laser biostimulation and regulate the signal transduction pathway for seed germination are still not fully understood. That could mainly be attributed to the synergistic effect of various simultaneous bio-physico-chemical actions by the cotyledon and endosperm cells inside the seeds upon the absorption of laser light [8,9]. The previous studies evidenced that laser light may increase cells' mitochondria membrane potential, cyclic adenosine monophosphate (cAMP), and adenosine triphosphate (ATP), modify cells' reactive oxygen, affect cell divisions, and induce transcription factors [30]. It is speculated that the aforementioned actions could result in enhanced chlorophyll, carotenoid, and mineral contents [8,9], modifications

of genes/activity of various enzymatic/non-enzymatic antioxidants, including, but not limited to, superoxide dismutase (SOD), peroxidase (POD), catalase (CAT), ascorbate peroxidase (APX), ascorbate acid (AsA), glutathione (GSH), and phenylalanine ammonia-lyase (PAL) [8,9,24,25,28,32]. Higher activities of those enzymes in the seed are liable for solubilizing spare food material in the form of starch, protein, and lipid and delivering energy to germinating embryo for enhanced seeding vigor and overall plant performance. All these works have highlighted the need for more studies to extend our knowledge of the molecular mechanisms involved in laser biostimulation for increased seed germination, higher seedling vigor, and enhanced plant photosynthetic capacity.

In order for the laser biostimulation technique to gain widespread acceptance in the seed industry, optimized laser settings for each crop need to be delineated. Thereafter, an optimized system design is required to treat seeds with a high throughput [49].

Another interesting topic for future work is to explore the capability of laser biostimulation in reversing the effect of poor germination in more severe cases where the germination drops below 30%. Comparing the performance of continuous-wave and pulsed lasers may also reveal new findings. Another interesting topic for future studies could be exploring the comparative performance of single-, dual-, and multi-wavelength lasers. Neodymium-doped solid-state lasers can be used as a laser source for such comparisons [50–58].

Future efforts should also consider evaluating the effect of different laser wavelength ratios (for dual- and multi-wavelength laser treatment), operating wavelengths, power levels, and laser doses to find the optimal settings for the biostimulation effect. The molecular changes in treated seeds should also be elucidated further. Ultimately, field study and yield analysis are required to confirm the applicability of lab-based observations.

5. Conclusions

The efficacy of laser biostimulation in enhancing germination parameters of flaxseeds was explored. It has been demonstrated that 5-min treatment with a green/infrared dual-wavelength laser is an appropriate setting for improving the germination percentage, mean germination time, germination speed, germination rate index, wet weight, and dry weight of poorly stored flaxseeds. Moreover, significant enhancement was achieved in the primary root length, wet weight, and dry weight of healthy seeds under the green/infrared dual-wavelength laser treatment. In the case of the red laser, no remarkable enhancement was observed.

Overall, this study demonstrates the capability of a dual-wavelength laser treatment in reversing the poor germinability of flaxseeds. Manipulating the viability of seeds using laser biostimulation offers a new avenue toward sustainable agriculture by reducing the hazardous effects of chemical use on the environment while enhancing food production and safety.

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