DEPRESSIVE EFFECTS OF DIODE LASER ON SELECTED WEEDS IN FIELD CONDITIONS

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Abstract. This study investigates the depressive effects of diode laser radiation on commonly found weed species in the Northwest Anatolian conditions. Unlike previous laboratory-based experiments, this pilot study conducted in natural environments aims to understand weed reactions to laser application under field conditions. Cleavers (*Galium aparine*), small scabious (*Scabiosa columbaria*), and sun spurge (*Euphorbia helioscopia*) were selected for observation. A diode laser (5500 mW power, 450 nm wavelength) was applied to plant apical meristems and stems at four doses for each species. Regression analyses using dry-based remaining biomass and laser doses were performed with the logistic growth model. The ED_{90} values, indicating a 90% reduction in plant growth on the stem, were determined as 14.42 J for cleavers, 11.04 J for scabious, and 18.04 J for sun spurge. For apical meristem applications, plant growth reduction was less than 90% at maximum energy doses, with rates of 72.18% for cleavers and 41.64% for scabious. These results support the thesis that laser application to the apical meristem region of the weed may not be sufficiently effective beyond the cotyledon period. However, the study concludes that laser application to the plant stem can successfully control all three weed species.

Keywords: *non-chemical weed control, damage model, effective dose, logistic growth model, apical meristem, plant stem*

Introduction

One of the most important factors affecting the yield in crop production is the correct management of the presence of weeds growing around the plants. For this reason, many chemical and non-chemical methods are used to keep weed presence below the economic threshold (Tu et al., 2001). The most common method used in weed control, in addition to classical methods such as hoeing and tillage, is the use of herbicides (Bayat et al., 2017; Young and Pierce, 2014). While methods based on the use of chemicals are questioned due to their negative effects on the environment and human health (Arwal et al., 2019; Tiryaki et al., 2010), other traditional methods such as hoeing, plucking, and soil cultivation also bring about some negative features such as high energy, time, and labor costs. Therefore, industry and researchers are working on the development of various alternative methods that reduce or eliminate the use of chemicals and have low energy consumption. Some examples can be given for alternative weed control methods that are used or intended to be used. Biological methods, for instance, rely on the elimination of weeds by exposing them to certain animals, insects, microorganisms, or plant species considered as natural enemies of weeds. Another approach is the solarization method, where weeds are controlled by covering the soil with a transparent cover, thereby increasing the temperature of the soil

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through solar energy. There is also a method that involves controlling the weed by freezing it using refrigerants such as liquid nitrogen or CO_2. Thermal methods encompass controlling the weeds by directly exposing them to flame, hot water, or hot steam. Moreover, there is a method based on controlling the weeds by exposing them to electricity or electromagnetic radiation, such as infrared, ultraviolet, UHF, microwave, and laser beams (Uygur and Uygur, 2010; Yıldız et al., 2018). Moreover; as a result of technological developments in fields such as remote sensing, imaging, computer vision, software and robotics, there is a tendency to design machines used in agriculture as autonomous systems, as in many different sectors. In this context, the use of laser technology in weed control is considered as an important alternative. This is primarily due to its ease of adaptation to precision agriculture practices and autonomous systems. Laser technology is recognized for features like energy efficiency, making it suitable for the design of systems that can be fed from sustainable energy sources (Şahin and Çay, 2019).

The term “Laser” derived from the acronym “Light Amplification by Stimulated Emission of Radiation,” is extensively employed in various fields, including medicine, manufacturing systems, defense industry, and information technologies. Currently, lasers find application in agriculture for tasks such as measuring plant sizes and stimulating seed sprouting (Hernandez et al., 2010). Numerous types of lasers exist; the most commonly ones in agriculture include CO_2, Argon, Diode, He-Ne, Nd: YAG, and Nitrogen lasers (Hernandez et al., 2010).

Although laser technology is not yet widely implemented in weed control practices, extensive studies on the effectiveness of laser application on weeds and the utilization of laser technology in this field have been conducted for a considerable period (Kaierle et al., 2020; Rakhmatulin and Andreasen, 2020; Xiong et al., 2017; Çay et al., 2015; Marx et al., 2012a, b; Wöltjen et al., 2008; Mathiassen et al., 2006; Heisel et al., 2002, 2000). The intended method involves the absorption of heat energy transferred by laser beams by the plant, causing damage to plant tissues and either completely halting or weakening their development. Heisel et al. (2000) demonstrated that effective weed control could be achieved by cutting the plant stem using a laser. However, as plant identification is primarily performed through a top-down view using computer vision technology, it has been proposed that laser application to the plant stem may not be practically integrated with image processing technology, and targeting the apical meristem can be more feasible. Another study predominantly focused on the effects of laser application to the apical meristem of the plant. Nonetheless, one of these studies observed that laser application to the apical meristem yielded effective results during the cotyledon period of plants, suggesting that additional applications may be necessary at different points in later stages (Mathiassen et al., 2006).

Studies on laser weed control have historically been conducted on plants grown in controlled environments such as laboratories or pots to facilitate easier standardization of experimental and control groups (Kaierle et al., 2020; Rakhmatulin and Andreasen, 2020; Xiong et al., 2017; Çay et al., 2015; Marx et al., 2012a, b; Wöltjen et al., 2008; Mathiassen et al., 2006; Heisel et al., 2002, 2000). Identifying and targeting plants of the same species simultaneously grown in controlled environments is more feasible. However, challenges arise when dealing with plants in natural environments, where different species coexist, plants may be covered by cultivated plants or other weeds, and sizes and developmental stages vary. This necessitates a multifactorial selective approach for effective laser weed control.

The designed system must exhibit distinct behavior in cultivated plant areas and other spaces, allowing it to observe and target plants from various angles. It should determine the weed’s developmental stage, identify the most effective targeting area, and establish the appropriate energy dose and laser focus accordingly. In addition, the impact of laser application on plants in controlled environments versus wild plants in natural settings is anticipated to differ. In contrast to previous studies, this study focused on spontaneously growing weeds in their natural habitat at later developmental stages beyond the cotyledon stage.

By developing a mechanism that applies laser beams to these weeds from different angles, the study designed a system capable of targeting both the plant stem and apical meristem. The effectiveness of applications from these two points on selected weeds was compared, and the findings were discussed in relation to previous studies. The study also aimed to ensure efficient energy use by determining doses that significantly reduce weed presence, keeping them below the economic threshold. Information on the reactions of three different weed species in the natural environment to diode laser application, along with data on the required energy doses to significantly reduce their growth, has been added to the literature. Furthermore, while previous studies focused on laser weed control experiments conducted in laboratory conditions, this pilot study aims to reveal weed reactions under field conditions.

Materials and methods

Determination of weeds for the experiment

The trials were conducted in agricultural fields where wheat and vetch are produced at the Dardanos Research and Application Unit of the Faculty of Agriculture of Çanakkale Onsekiz Mart University, which has northwestern Anatolian conditions (40° 07’ N, 26° 36’ E), Türkiye. where weeds are naturally observed. The slope exhibited minimal incline and the soil under investigation corresponds to Typic Eutric Vertisols (as classified by FAO/UNESCO). This region features a Mediterranean climate characterized by an average annual rainfall of 625 mm, with 75-80% of precipitation falling within the October–June cropping period and the mean annual temperature stands at 15.2°C according to the long-term data from 1929 (Anonymous, 2024).

Three of the most common weed species Cleavers (*Galium aparine*), Small scabious (*Scabiosa columbaria*) and the sun spurge (*Euphorbia helioscopia*) were selected, and each trial was carried out in an area of 300 m^2. Control and experimental groups were established among these weeds. Various doses of diode laser radiation were administered to some experimental groups from the plant stem close to the soil level, while the remaining part received laser treatment at the apical meristem (*Fig. 1*). Detailed information about these weeds was shown in *Table 1*.

Table 1. *Weeds species selected in the experiments*

Row number	Weed	Growth stage	Initial dry mass (g)
1	Cleavers (*Galium aparine*)	10-12 leaf growth stage	0.20
2	Small scabious (*Scabiosa columbaria*)	4-6 leaf growth stage	0.19
3	The sun spurge (*Euphorbia helioscopia*)	8-10 leaf growth stage	0.17

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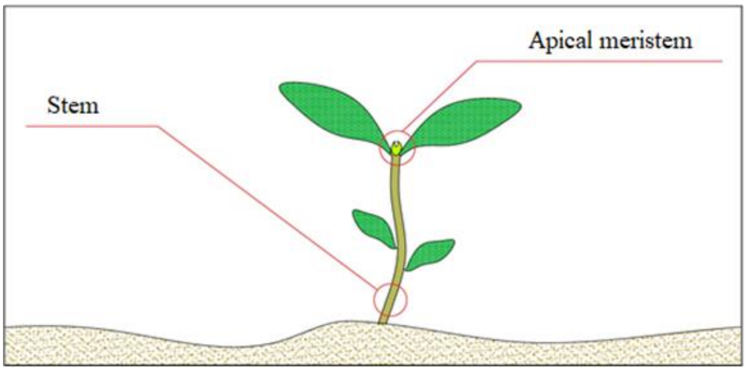

Figure 1. *Demonstration of laser applied areas on a representative plant drawing*

Formation of control and experimental groups

In a previous study, it was emphasized that laser application to the apical meristem is effective during the cotyledon stage but alone may not suffice to halt plant development in later stages (Mathiassen et al., 2006). Thus, to assess the efficacy of laser application to the apical meristem in later plant stages, samples beyond the cotyledon stage were chosen for the relevant species. Control and experimental groups were established for each species at comparable developmental stages in the selected samples. Plants within these groups were marked with wooden sticks distinguished by colored bands. Distinct experimental groups, each comprising 10 samples, were formed to apply the laser solely to the stem for *Euphorbia*, and to both the stem and apical meristem for the other two plants. The details of the control and experimental groups assigned to the specified species are presented in *Table 2*.

Table 2. *Experimental groups and applied energy doses*

Group name	Application region	Energy dose (J)	Number of samples
Control	-	0.00	10
S1	Stem	5.50	10
S2	Stem	11.00	10
S3	Stem	16.50	10
S4	Stem	22.00	10
M1	Meristem	5.50	10
M2	Meristem	11.00	10
M3	Meristem	16.50	10
M4	Meristem	22.00	10

For each weed species, 10 samples were harvested to determine the dry mass at the time of laser application for each application. In total 230 plants were harvested and dried in a laboratory using a Nüve FN 300 model oven at 55°C for approximately 24 h until the weight change ceased. For sun spurge trials, apical meritem results for this weed were not presented since the apical meristem could not be fully targeted in some trials due to plant physiology. Subsequently, the mass of the dried plant groups were measured. These data were recorded as the reference values for the developmental levels of the plant groups on the day the laser was applied.

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Laser type and application procedure

In the trials, an Oxlasers brand diode laser module with a power of 5500 mW, fed by 12 V DC voltage, cooled by an integrated fan, and emitting blue light at a wavelength of 450 nm with adjustable beam diameter and focus was utilized.

Exposed laser energy doses were determined by calculating the application time and laser power to maintain the plant tissue at a level where it would not be completely severed. Previous research results with similar wavelengths and various beam diameters showed a higher depressive effect for a 3 mm beam diameter on plants grown in laboratory environments representing weeds (Çay et al., 2015). Therefore, in this study, the beam diameter applied to the plant was set at 3 mm. The light focus of the laser module was adjusted to create a beam diameter of approximately 3 mm at a distance of 5 cm, and all applications were performed with a 5 cm distance between the plant tissue and the laser lens. For each experimental group, four different doses of laser energy were applied, as indicated in *Table 3*, by adjusting the exposure times to the laser beam using a digital stopwatch.

Table 3. *Applied energy doses in the field experiments*

Dose class	Exposure time (s)	Energy dose (J)
Control	0	0.00
Dose 1	1	5.50
Dose 2	2	11.00
Dose 3	3	16.50
Dose 4	4	22.00

The mechanism designed for laser application comprises a diode laser module, a three-legged fixing apparatus, bendable copper wire, two circuit switches, cables, a 12-V dry battery, 3-V alkaline battery, and a battery chamber. Thanks to the designed circuit, the laser was initially operated at a voltage of 3 V. While the laser pointer was operating at an ineffective dose, the mechanism was secured to the ground with a tripod fixing apparatus. The direction and distance of the laser were then adjusted according to the plant target point using the bendable copper wire to which the laser module was attached (*Fig. 2*). In this manner, the laser beams were ensured to reach the target points steadily and the planned doses of laser were applied to the plants. The plants, previously marked according to the experimental group, had their exposure times adjusted using a digital stopwatch.

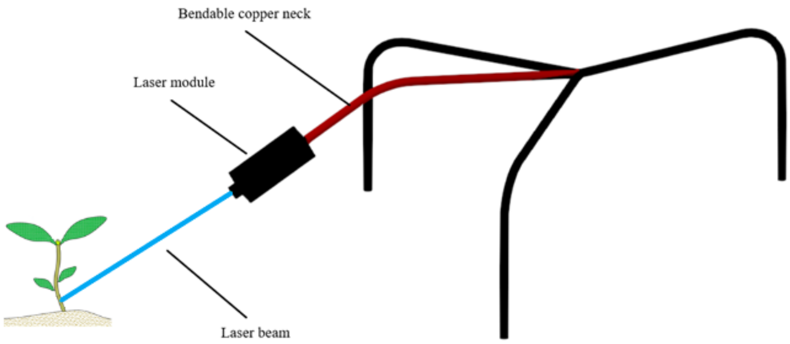

Figure 2. *Schematic view of the laser application mechanism*

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Harvesting weeds and determining their dry mass

According to previous studies (Çay et al., 2015; Heisel et al., 2000; Mathiassen et al., 2006), three weeks after laser applications, the plants were harvested by cutting them at the soil level using scissors. The harvested plants were numbered according to the experimental groups and placed in ziploc bags. Subsequently, the samples were transported to the laboratory and dried in an oven at 55°C for the weight change ceased. After drying, the dry mass measured with a precision scale were recorded for each group (*Fig. 3*).

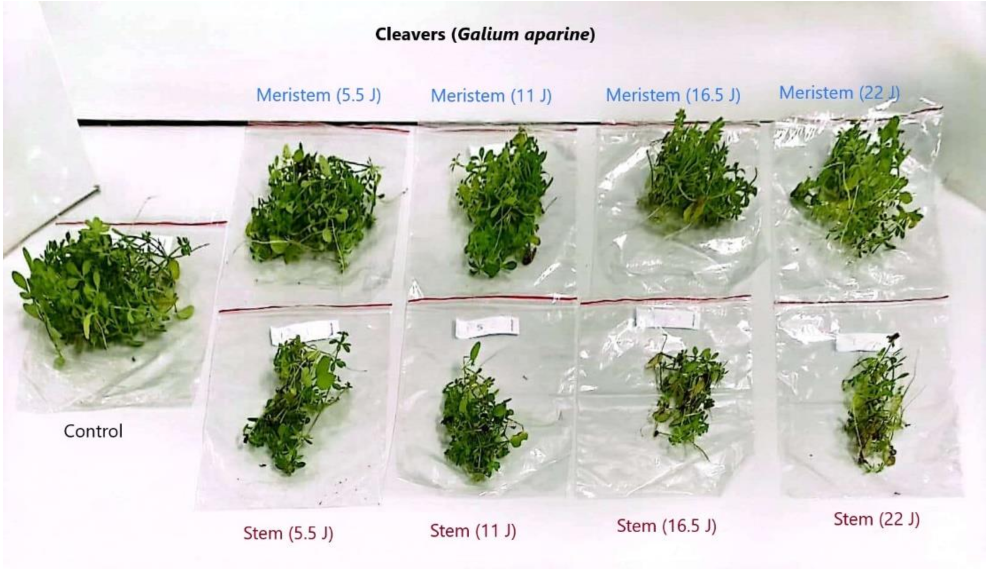

Figure 3. *Sample image of harvested plants after the experiments*

Data analysis

For each control and experimental groups, the dry mass increases, determined by measuring with a precision scale (±0.01 g), were assessed proportionally to the dry mass increase in the control groups on a percentage basis. The relationship between the applied energy amounts and the dry mass increases was examined through non-linear regression analysis.

Regression analyses were conducted using Minitab (V16) software, employing the log-logistic dose-response model and Gauss-Newton algorithm, as discussed in previous studies (Seefeld et al., 1995; Mathiassen et al., 2006). In *Equation 1,* instead of ED_{50}, representing the 50% effective dose in weeds, *Equation 2* was preferred, taking into account the ED_{90} value, indicating the dose that reduces the presence of weeds by 90% (Mathiassen et al., 2006). Subsequently, the ED_{90} value was separately calculated for the three plant species used in the experiments based on the applied tissue area.

$$G = \frac{D-C}{1+e^{[2b(log(ED_{50})-log(z)]}} + C \tag{Eq.1}$$

$$G = \frac{D-C}{1+e^{[2b(log(ED_{90})-1{,}099/b-log(z)]}} + C \tag{Eq.2}$$

where: G: Refers to the percentage value of the proportional decrease in plant dry mass development; D: Refers to the vertical axis values corresponding to the highest disagreements in the dose-response curve; C: Refers to the vertical axis values corresponding to the lowest disagreements in the dose-response curve; ED_{50}: The amount of energy (J) required for 50% of the maximum mass growth reduction expected in laser-treated plants; ED_{90}: The amount of energy (J) required for 90% of the maximum mass growth reduction expected in laser-treated plants; b: Refers to the slope of the dose-response curve around ED_{50} or ED_{90}; z: Refers to the amount of energy (Joule) applied.

Statistical analyses were conducted using Minitab (V16) software to assess the impact of treatments on plant development. Anova tests were applied to determine overall differences between groups, revealing a statistically significant at $p < 0.05$ and $p < 0.01$ levels. Subsequently, Tukey's tests were conducted to identify specific differences among groups.

Results and discussion

The results of the applications made to the plant stem for the weeds examined in the trials are shown in *Tables 4, 5* and *6.* For Clevers, the increase in plant dry mass three weeks after the application to the plant stem was determined as 1.04 g for the control group. For 5.50, 11.00, 16.50, and 22.00 J energy dose applications, these values were found 0.33, 0.19, 0.07 and 0.03 g, respectively. While the values obtained during application to the apical meristem were 0.91 g for 5.50 J, it could only be reduced to 0.44 g at 22.00 J energy dose. Plant stem targeting was successful in sun spurge trials, apical meritem results for this weed were not presented since the apical meristem could not be fully targeted in some trials due to plant physiology.

When the obtained data were evaluated collectively, the differences between both application doses and application areas were found to be statistically significant ($p < 0.05$). While the F statistical value of laser dose for Claver was determined as 125.68, this value was determined as $F = 983.07$ between Stem and Meristem ($p < 0.05$). In Small Scobus, the same F values were obtained as $F = 85.16$ for the application dose and $F = 2634.22$ for the application site, respectively ($p < 0.01$).

Table 4. *Measurement results obtained from Cleavers (Galium aparine) after three weeks of treatment*

Exposed tissue	Dose (J)	Dry mass (g)	Dry mass increase (g)
Control	0.00	1.24	1.04^{Aa}
Stem	5.50	0.53	0.33^{B}
Stem	11.00	0.39	0.19^{C}
Stem	16.50	0.27	0.07^{D}
Stem	22.00	0.23	0.03^{E}
Meristem	5.50	1.11	0.91^{a}
Meristem	11.00	0.89	0.69^{a}
Meristem	16.50	0.71	0.51^{a}
Meristem	22.00	0.64	1.44^{a}

The initial dry weed biomass average is 0.20 ± 0.03 g for Cleavers. Different letters (uppercase and lowercase) indicated statistically significant differences based on Tukey's test results

Table 5. *Measurement results obtained from small scabious (Scabiosa columbaria) after three weeks of treatment*

Exposed tissue	Dose (J)	Dry mass (g)	Dry mass increase (g)
Control	0.00	1.17	0.98 ^{Aa}
Stem	5.50	0.43	0.24 ^{B}
Stem	11.00	0.28	0.09 ^{C}
Stem	16.50	0.26	0.07 ^{C}
Stem	22.00	0.22	0.03 ^{D}
Meristem	5.50	1.12	0.93 ^{b}
Meristem	11.00	0.97	0.78 ^{c}
Meristem	16.50	0.84	0.65 ^{d}
Meristem	22.00	0.81	0.62 ^{d}

The initial dry weed biomass average is 0.19 ± 0.02 g for Small scabious. Different letters (uppercase and lowercase) indicated statistically significant differences based on Tukey’s test results

Table 6. *Measurement results obtained from sun spurge (Euphorbia helioscopia) after three weeks of treatment*

Exposed tissue	Dose (J)	Dry mass (g)	Dry mass increase (g)
Control	0.00	0.75	0.58 ^{A}
Stem	5.50	0.36	0.19 ^{B}
Stem	11.00	0.28	0.11 ^{C}
Stem	16.50	0.24	0.07 ^{D}
Stem	22.00	0.20	0.03 ^{E}

The initial dry weed biomass average is 0.17 ± 0.02 g for the sun spurge. Different letters (uppercase and lowercase) indicated statistically significant differences based on Tukey’s test results

Although the same dose of energy is applied to the apical meristem and stem of cleavers (*Galium aparine*) and small scabious (*Scabiosa columbaria*), the effectiveness of the application to the stem is higher in both species. This situation can be interpreted as follows: even if the apical meristem is sufficiently damaged, the plant can continue its development and increase its biomass owing to the presence of secondary meristems (*Fig. 4*).

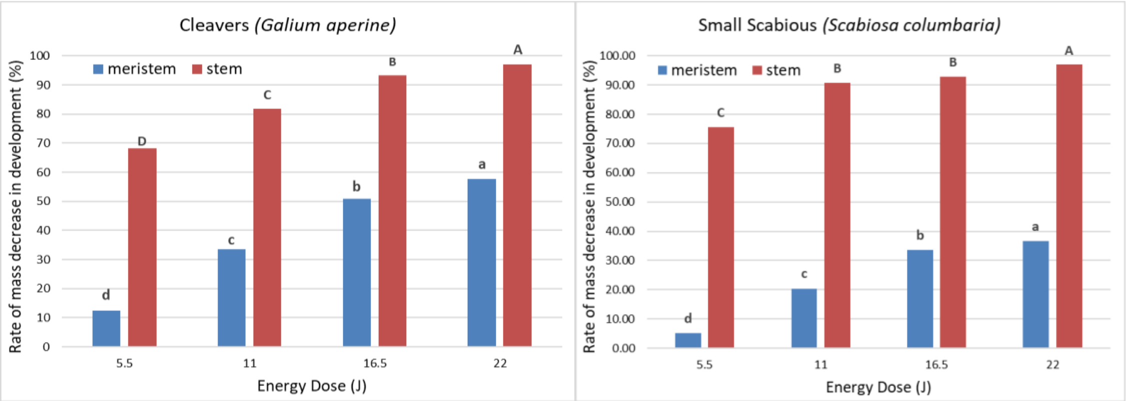

Figure 4. *Decreasing rates of mass growth of weeds at different laser energy doses. Different letters (uppercase and lowercase) indicated statistically significant differences based on Tukey’s test results*

In the regression analysis based on the log-logistic dose-response model, it was concluded that plant development could not be completely stopped with the maximum dose applied to the meristem in both plants. In the regression analysis, it was calculated that with the maximum dose applied to the apical meristem, plant development could be reduced by up to 72.18% in the cleavers and by up to 41.64% in the small scabious. This supports the thesis that laser application to the weed from the apical meristem region cannot have a sufficient effect at stages beyond the cotyledon period (Mathiassen et al., 2006). However, it has been observed that the effectiveness of laser application targeting the plant stem in more advanced development stages is quite high.

As shown in *Figure 5*, the application of diode laser to the apical meristem of cleavers demonstrates on the dose-response curve that plant development can be inhibited by a maximum of 72.18%. In the regression analysis, the energy dose corresponding to the 90% effectiveness level of the dose-response curve was determined as 31.25 J.

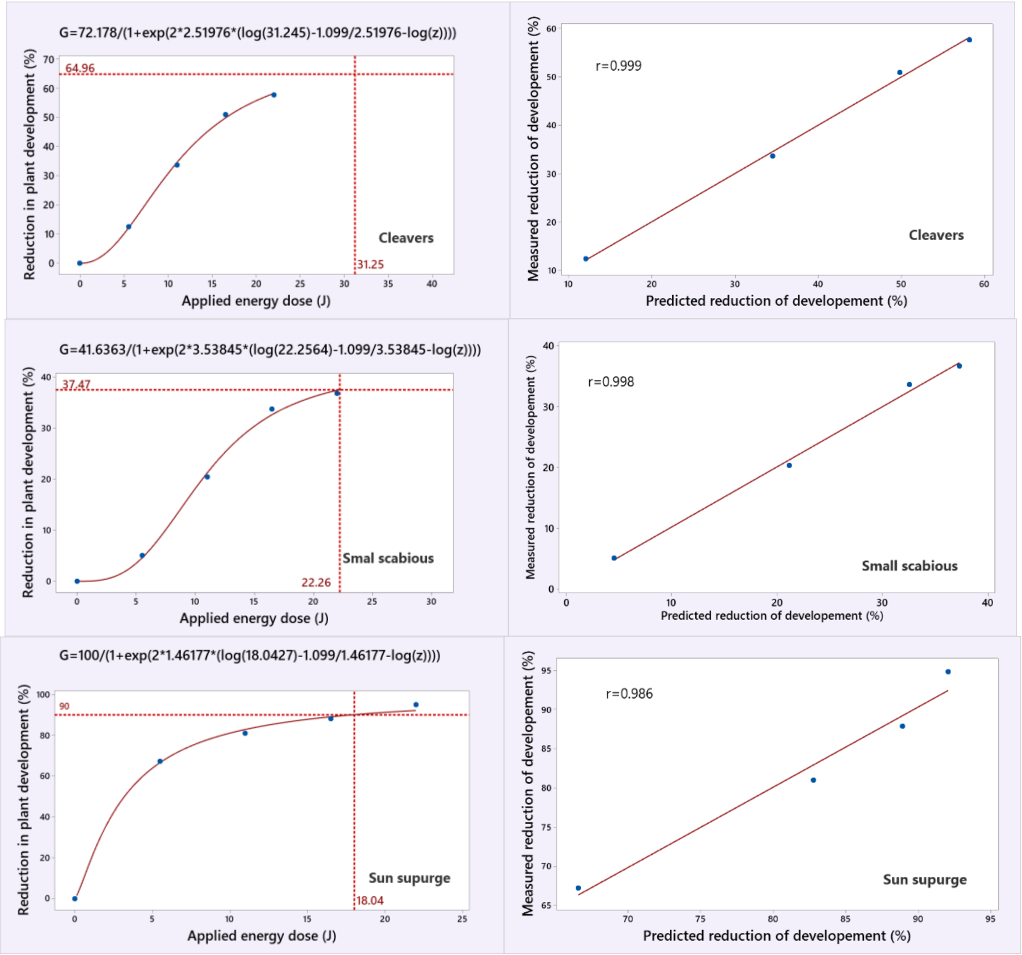

Figure 5. *Mathematical relationship between reductions in plant development and applied energy doses in apical meristem applications*

This dose represents the amount needed for a 90% reduction from the maximum inhibition rate of 72.18% in plant growth. In other words, it is predicted that plant development will decrease by 64.96% as a result of applying 31.25 J of energy to the

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plant apical meristem. For small scabious, it is observed that plant development can be inhibited by a maximum of 41.64% on the dose-response curve as a result of the application to the apical meristem. In the regression analysis, the energy dose corresponding to the 90% effectiveness level of the dose-response curve was determined as 22.26 J; it is expected that plant growth will decrease by 37.47% as a result of applying 22.26 J of energy to the plant apical meristem.

It was observed that plant growth could be completely halted by applying a sufficient dose of laser to the stem area of all three tested weeds. In the study, if the dry mass measured at the time of weed application did not increase after 3 weeks following the laser application, it was considered that the weed was 100% controlled. The study demonstrated that the ED_{90} values, representing the energy dose expected to reduce plant growth by 90% compared to the control group, were achieved.

In the non-linear regression conducted for the values obtained from the application to the stems of cleavers, small scabious, and sun spurge; it was determined that plant development can be completely halted, requiring the application of 14.42 J, 11.04 J, and 18.04 J of energy to impede the development of the plants by 90%, respectively (*Fig. 6*).

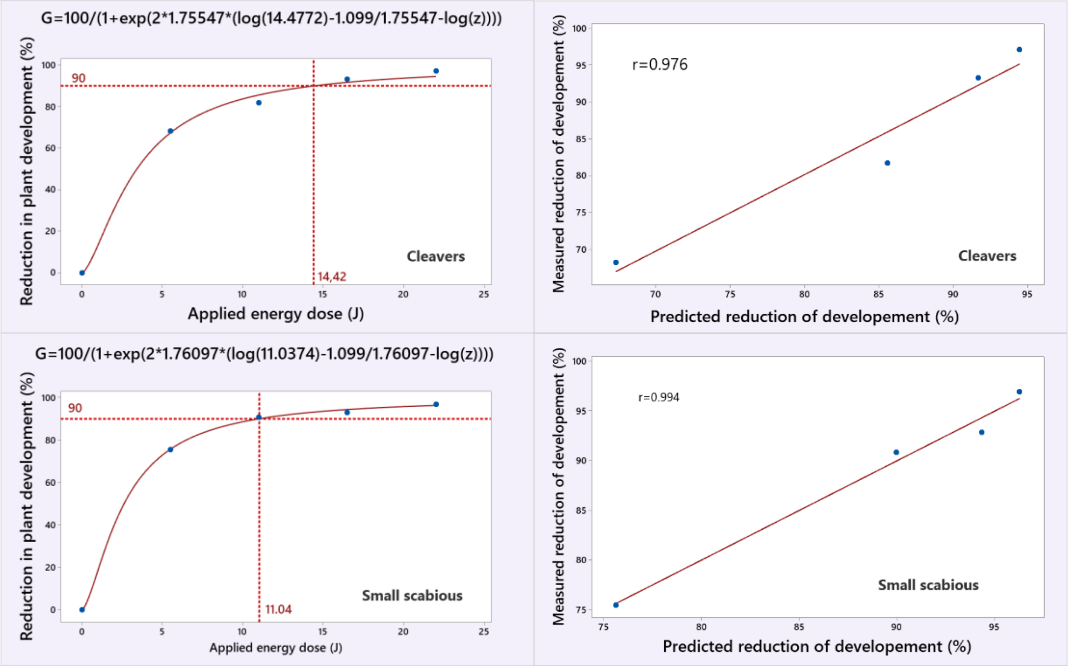

***Figure 6.** Mathematical relationship between reductions in plant development and applied energy doses in stem applications*

The extent to which the energy delivered to the plant via laser is absorbed is influenced by numerous parameters, including the wavelength of laser beams, application time, beam diameter, color of the area in the plant where the laser is directed, and liquid content (Mathiassen et al., 2006). Additionally, the degree of damage caused by the transmitted energy is expected to vary based on the structural characteristics of the plant, its developmental stage, and the biological function of the targeted region. Consequently, the outcomes of laser application are anticipated to differ for each plant species, each developmental stage, and each distinct region where the application is performed. According to the findings of the study, it was demonstrated that applying the laser module with a power of 5500 mW, emitting light at a wavelength of 450 nm to the stems of cleavers in the 10-12 leaf stage, small scabious in the 4-6 leaf stage, and sun spurge plants in the 10-12 leaf stage yielded effective results.

The results clearly demonstrate the impact of laser energy doses on weed control. For cleavers, an increase in dry mass three weeks after stem application was observed to be 1.04 g for the control group. For the energy doses of 5.50, 11.00, 16.50, and 22.00 J, these values were found to be 0.33, 0.19, 0.07, and 0.03 g, respectively. These results indicate the effectiveness of laser technology in weed control. In the applications targeting the apical meristem, dry mass values were 0.91 g for 5.50 J and 0.44 g for 22.00 J. However, due to plant physiology, targeting the apical meristem was challenging in some trials, and thus apical meristem results for sun spurge were not presented.

Despite applying the same energy dose to the apical meristem and stem of cleavers (*Galium aparine*) and small scabious (*Scabiosa columbaria*), the effectiveness of stem application was higher in both species. This can be attributed to the plants' ability to continue development and increase biomass due to the presence of secondary meristems, even if the apical meristem is sufficiently damaged.

Regression analysis based on the log-logistic dose-response model concluded that plant development could not be completely stopped with the maximum dose applied to the meristem in both plants. The analysis showed that plant development could be reduced by up to 72.18% in cleavers and by up to 41.64% in small scabious with the maximum dose applied to the apical meristem. These findings support the thesis that laser application targeting the apical meristem beyond the cotyledon stage cannot have a sufficient effect (Mathiassen et al., 2006). However, it was observed that the effectiveness of laser application targeting the plant stem in more advanced developmental stages is quite high.

Each alternative technology has its own set of advantages and limitations. For instance, chemical herbicides are widely used due to their effectiveness and ease of application, but their environmental impact and the risk of developing herbicide-resistant weed species are significant drawbacks. Mechanical weeding is environmentally friendly and effective for certain weed types but can be labor-intensive and potentially harmful to soil structure (Brucien et al., 2022; Ozpinar and Ozpinar, 2011). Thermal methods, such as flaming, are effective in controlling weeds without chemicals, but they require significant energy inputs and can be less selective, potentially harming crops (Pérez et al., 2014). One of the significant advantages of laser technology is its ability to precisely target critical regions like the plant stem and meristem. This increases energy efficiency and effectively halts the growth of undesirable plant species. Additionally, laser applications leave no chemical residues, making them an essential alternative for organic and environmentally friendly farming practices.

Conclusion

In this study, a diode laser emitting light at a wavelength of 450 nm was utilized to target the plant stems of cleavers (*Galium aparine*) at the 10-12 leaf stage, scabious (*Scabiosa columbaria*) at the 4-6 leaf stage, and sun spurge (*Euphorbia helioscopia*) at the 10-12 leaf stage. The effectiveness of the application in controlling these weeds was demonstrated. The ED_{90} values, representing the energy dose required to reduce plant growth by 90% in stem applications, were determined as 14.42 J for cleavers, 11.04 J for scabious, and 18.04 J for sun spurge. The most efficient effect was observed when applied to the stem of scabious.

Consistent with previous suggestions by Mathiassen et al. (2006), who indicated the effectiveness of laser application to the apical meristem in the cotyledon period, it was found that this approach alone might not suffice to halt plant development in later stages. Lower effects were observed in applications targeting the apical meristem of cleavers at the 10-12 leaf stage and scabious at the 4-6 leaf stage. This suggests that, despite damage to the apical meristem beyond the cotyledon period, the plant can continue developing owing to other meristems.

For laser applications on weeds in advanced developmental stages, it was revealed that targeting the plant stem is a more energy-efficient and effective alternative compared to the apical meristem. Further studies are required to assess the efficacy of laser application to the plant stem for various weeds and developmental stages, diversifying with different laser types and wavelengths.

The practical implementation of laser weed control necessitates the design of systems employing computer vision to detect weeds (Wang et al., 2019), conduct separate evaluations for cultivated areas, autonomously target plants from various angles, and apply necessary energy doses from the most effective points following a multi-factor assessment. Therefore, additional research is warranted to detect tissues such as meristem and stem using computer vision and machine learning, allowing for laser targeting from various angles and the design of autonomous systems for this purpose. The design and use of laser-based weed control machines entail challenges such as unfavorable weather conditions, uneven field surfaces, and variations in the physical characteristics of weeds (Tran et al., 2023). Additionally, there are concerns about the potential for theft and sabotage of such devices, as well as the potential harm they may pose to humans and animals (Tran et al., 2023). Consequently, measures should be taken in the designs to mitigate the stated challenges and concerns as much as possible.

Future studies should aim to combine laser-based weed control technologies with self-operating robotic systems that utilize sophisticated machine vision and AI. Such an integration would improve the accuracy and effectiveness of weed management, offering a scalable solution for diverse agricultural environments. Furthermore, investigating various wavelengths and types of lasers could enhance the technology’s performance and energy efficiency.

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