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Impact of laser radiation on seeds of *Berteroa incana* and *Setaria pumila* collected from habitats exposed to artificial light at night

Dariusz Zalewski[1], Anna Koszelnik-Leszek[1], Renata Kieloch[2*]

[1] Wrocław University of Environmental and Life Sciences, Plac Grunwaldzki 24 a, 50-375 Wroclaw, Poland
[2] Institute of Soil Science and Plant Cultivation – State Research Institute, Department of Weed Science, Orzechowa 61, 50-540 Wrocław, Poland
* Corresponding author's e-mail: r.kieloch@iung.wroclaw.pl

ABSTRACT

The aim of the controlled-environment experiment was to assess the effects of semiconductor laser light on the early growth stages of *Setaria pumila* and *Berteroa incana*, whose seeds had previously been exposed to direct artificial light at night (ALAN). The seeds were collected from two maize fields differing in nighttime light pollution: 1. a site in Siechnice (Wrocław County), located near the "Siechnice" horticultural complex emitting intense nocturnal illumination, 2. a control site in Jelcz-Laskowice (Oława County), situated ca. 12 km from the emission source. The collected seeds were subjected to presowing laser irradiation at three energy levels: three-fold, five-fold, and seven-fold of the base dose of 0.25 J·cm^{-2}, with an exposure time of 4.1 min. Non-irradiated seeds served as the control. The study proved that the root length of seedlings of both species originating from the ALAN-exposed site was significantly reduced compared with the plants from the light-pollution-free area. There were also differences in germination capacity of *Setaria pumila* seeds – those collected from the ALAN-exposed site germinated significantly weaker than those obtained from the ALAN-free location. Laser irradiation stimulated seedling growth; however, this response was more pronounced in plants originating from the environment without nocturnal artificial lighting.

Keywords: ALAN, light pollution, laser irradiation, plants, seeds germination, roots length.

INTRODUCTION

ALAN has become an increasingly significant environmental issue in recent decades, with far-reaching consequences for humans, animals, and plants (Kaushik et al., 2022). Disruption of the natural light–dark cycle affects fundamental physiological processes in organisms, leading, among others, to behavioural, metabolic, and developmental alterations (Bennie et al., 2016; Levy et al., 2024). In plants, light is a key environmental factor, serving both as the primary source of energy for photosynthesis and as a signal regulating numerous vital processes. Plants utilise a broad range of radiation (300–700 nm) (Głowacka, 2002), and specific wavelengths trigger distinct physiological responses, influencing germination, plant movements, growth rhythms, and reproductive processes. Due to photoperiodism, periods of darkness are also essential, as they enable critical transformations of light-sensitive photoreceptors (e.g., phytochromes) and coordinated expression of multiple genes involved in metabolism and stress responses.

One of the most frequently observed consequences of light pollution is the disruption of plant phenology. Intense nocturnal illumination may induce earlier budburst in trees and shrubs (Ffrench-Constant et al., 2016), delay the onset of dormancy, and influence the timing of autumn leaf senescence and abscission (Škvareninová et al., 2017). ALAN also disturbs the rhythmic opening and closing of stomata, which increases water loss and reduces the efficiency of resource management. A key concern is the interruption of the nocturnal recovery period, during which numerous repair mechanisms are activated and

protective proteins responsible for environmental stress responses are synthesised.

Increasing adverse environmental pressures have stimulated interest in methods enhancing plant stress tolerance. One such method is seed conditioning through laser irradiation, which, as a physical stimulus, modifies biochemical and physiological processes, affects enzymatic activity, increases antioxidant synthesis, and stimulates the expression of genes involved in the regeneration of tissues exposed to stress, e.g. water deficit (Dobrowolski and Różanowski, 1998; Dobrowolski, 2001; Szajsner et al., 2023). Numerous studies indicate that laser radiation can improve germination, enhance seedling emergence uniformity, as well as increase seedling vigour and yield in many plant species (Podleśny and Stochmal, 2005; Delibaltova and Ivanova, 2006; Szajsner, 2009; Hernandez et al., 2010).

ALAN and laser radiation stimulate the same photoreceptor system in seeds. It therefore seems likely than ALAN can weaken, improve, or deregulate the effect of laser stimulation. There is a gap in the literature regarding the influence of both factors on the response of plants during germination and initial seedling development to the combined effects of artificial night light and laser radiation. In view of these considerations, the present laboratory experiment, conducted under controlled conditions, aimed to evaluate the effects of semiconductor laser light on the early growth stages of two weed species (*Setaria pumila* (Poir.) Roem. & Schult. and *Berteroa incana* (L.) DC.) occurred in maize field, whose seeds had previously been exposed to ALAN.

MATERIALS AND METHODS

Plant material

The research material consisted of the seeds of two weed species commonly associated with maize cultivation: yellow foxtail (*Setaria pumila* (Poir.) Roem. & Schult.) and hoary alyssum (*Berteroa incana* (L.) DC.). The seeds were collected from experimental fields of the Department of Weed Science in Wrocław (Institute of Soil science and Plant Cultivation – State Research Institute), located in Siechnice and Jelcz-Laskowice. In order to minimise the possible impact of the other factors than ALAN on the results obtained, the chosen experimental location (Siechnice and Jelcz-Laskowice) was characterised by similar soil and climatic conditions and the type of agrotechnical treatments carried out.

B. incana is a native species of ruderal character, preferring full sunlight and moderately warm habitats. *S. pumila* is an invasive ruderal therophyte occurring mainly in highly insolated and moderately warm sites (Zarzycki et al., 2002; Rutkowski, 2004).

Site characteristics and seed collection

The seeds of both species were obtained from two agricultural areas differing in the level of nocturnal light exposure:

Siechnice (Wrocław County) – an area located in the immediate vicinity of the "Siechnice" Horticultural Production enterprise. Seeds of both species were collected from a field situated approximately 150 m from a 24-ha greenhouse complex, which uses intensive plant illumination from October to March for about 18 hours per day. This practice produces a strong light glow, representing a local example of excessive artificial light at night. The soil at this site was classified as medium soil (sandy medium loam), slightly acidic in reaction, with high organic carbon content, medium levels of available potassium and phosphorus, and high magnesium availability.

Jelcz-Laskowice (Oława County) – a site located approximately 12 km from the greenhouse complex, treated as a control area without significant ALAN influence. The soil was a light loam with moderate humus content and slightly acidic reaction. Available potassium content was high, phosphorus content very high, and magnesium content moderate.

Laboratory experiment with laser radiation

A semiconductor laser (model CTL-1106MX) was used in the laboratory experiment. The seeds of *S. pumila* and *B. incana* were subjected to presowing laser light stimulation in three energy variants: D1 – three times the base dose, D2 – five times the base dose, and D3 – seven times the base dose. The base dose was 0.25 $J \cdot cm^{-2}$, with an exposure time of 4.1 min. Non-irradiated seeds served as the control (K).

On the first day after irradiation, 30 seeds per Petri dish filled with a standard control substrate were placed. The experiment was established according to complete randomisation design, and

each species–dose combination was conducted in triplicate. Plants were grown under controlled conditions (temperature 20/10 °C, photoperiod 14/10 h day/night) in a phytotron (Sanyo MLR-351H).

Statistical analysis

Data were analysed using Statistica 13.3 software. A two-factor analysis of variance (ANOVA) was applied, with habitat (two locations: Siechnice and Jelcz-Laskowice) and laser radiation dose (three levels: D1, D2, D3, plus the control variant) treated as fixed factors. The significance of main effects and interactions was assessed using the F-test. Differences between means were determined using Tukey's test at a significance level of $\alpha = 0.05$.

RESULTS

In each experimental combination, 30 seeds were used for both plant species tested. The assessment of the germination capacity of the *B. incana* seeds revealed no significant differences in the percentage of germinating seeds depending on the seed collection location, and no stimulation of germination was observed as a result of the application of laser light. In each trial, germination capacity was high, ranging from 68.1% to 91.1% (Table 1). However, analysis of variance revealed a significant effect of the origin of the *S. pumila* seeds. For this species, the seeds from Siechnice had a lower germination rate, with an average of 43.6%, while seeds from the other location germinated at 75% (Table 1). No significant differences in germination percentage were found for the laser light doses used, and the interaction between the doses used and the origin of the seeds was also insignificant (Table 2).

The analysis of variance revealed significant differences in mean root length for both studied species depending on seed origin (habitat), the applied laser radiation dose, as well as the interaction between these factors. In contrast, no significant differences or interactions were found for shoot length, allowing the assumption of equal means for this trait. The overall mean root lengths of yellow foxtail (*S. pumila*) and hoary alyssum (*B. incana*) were significantly higher in the plants originating from the seeds collected in Jelcz-Laskowice compared with those from Siechnice (Table 3). In *B. incana*, the mean root length was 2.27 cm for thr plants from Siechnice and 3.18 cm for the plants from Jelcz-Laskowice. For *S. pumila*, these values were 1.77 cm and 2.51 cm, respectively.

Application of laser radiation had a significant effect on root length, and the response varied between species (Table 4). In *B. incana*, the stimulation was highly visible. Control seeds produced a mean root length of 0.50 cm, whereas the exposure to dose D2 increased the mean to 4.09 cm. Strong stimulatory effects were also observed for doses D1 – 3.29 cm and D3 – 3.34 cm. *S. pumila* responded to the laser treatment to a lesser extent than *B. incana*. A significant increase in root length was observed only after the application of dose D1 – 3.74 cm), while the mean root length in the control treatment was 1.39 cm.

Table 1. Germination capacity of *Berteroa incana* seeds

Habitat	K	D1	D2	D3	Mean
Jelcz-Laskowice	78.9%	78.9%	85.6%	91.1%	83.6% a
Siechnice	68.9%	86.7%	81.1%	86.7%	80.8% a
Mean	73.9%	82.8%	83.3%	88.9%	82.2%

Note: K, D1, D2, D3 – doses of laser light (see Materials and methods). Means marked with different letters within a column are significantly different according to Tukey's HSD test at $\alpha = 0.05$.

Table 2. Germination capacity of *Setaria pumila* seeds

Habitat	K	D1	D2	D3	Mean
Jelcz-Laskowice	68.9%	73.3%	92.2%	65.6%	75.0% a
Siechnice	33.3%	36.7%	41.1%	63.3%	43.6% b
Mean	51.1%	55.0%	66.7%	64.4%	59.3%

Note: K, D1, D2, D3 – doses of laser light (see Materials and methods). Means marked with different letters within a column are significantly different according to Tukey's HSD test at $\alpha = 0.05$.

Table 3. Mean root lengths of the studied species (*Setaria pumila* and *Berteroa incana*) depending on the habitat of seed origin

Habitat	Root length (cm)	
	Berteroa incana	*Setaria pumila*
Jelcz-Laskowice	3.18 a	2.51 a
Siechnice	2.27 b	1.77 b

Note: Means marked with different letters within a column are significantly different according to Tukey's HSD test at $\alpha = 0.05$.

Table 4. Mean root lengths of the studied species (*Setaria pumila* and *Berteroa incana*) depending on the applied laser light dose

Laser irradiation dose	Root length (cm)	
	Berteroa incana	*Setaria pumila*
K	0.50 c	1.39 bc
D1	3.29 b	3.74 a
D2	4.09 a	2.26 b
D3	3.34 b	1.18 c

Note: K, D1, D2, D3 – doses of laser light (see materials and methods). Means marked with different letters within a column are significantly different according to Tukey's HSD test at $\alpha = 0.05$.

Figures 1 and 2 present the root length response of the two studied weed species, taking into account the effects of both factors: habitat and laser light dose. A comparison of mean root lengths in *S. pumila* shows a significant increase in root length at both locations after the application of the lowest dose, D1 (Figure 1). The seeds collected in Siechnice reached a root length of 3.66 cm following D1 treatment, whereas the control value was 1.22 cm. In the seeds collected in Jelcz-Laskowice, the D1 treatment caused noticeable stimulation, with seedlings reaching 3.81 cm compared to 1.55 cm in the unexposed control.

A different response pattern was observed for material originating from Jelcz-Laskowice, where a highly strong reaction to dose D2 was recorded. Roots of the plants treated with D2 reached 3.46 cm, whereas those from Siechnice obtained only 1.06 cm, indicating inhibition (Figure 1). When analysing the response of *S. pumila*, it becomes apparent that dose D2 exerts the strongest effect compared with the responses of the seeds from both habitats. While no significant differences were detected among mean root lengths in the control, D1, or D3 treatments for either location, only after applying D2 were the roots of plants originating from Jelcz-Laskowice markedly longer (Figure 1).

A comparison of mean root lengths obtained from the seeds collected at the studied locations confirms the beneficial effect of laser radiation on *B. incana*. A very strong response was observed in the seeds collected in Jelcz-Laskowice, where the highest stimulation occurred following the application of dose D2. In this treatment, root length increased to 4.92 cm, whereas the seedlings from the control treatment reached only 0.49 cm on average. The remaining doses also exhibited stimulatory effects (Figure 2).

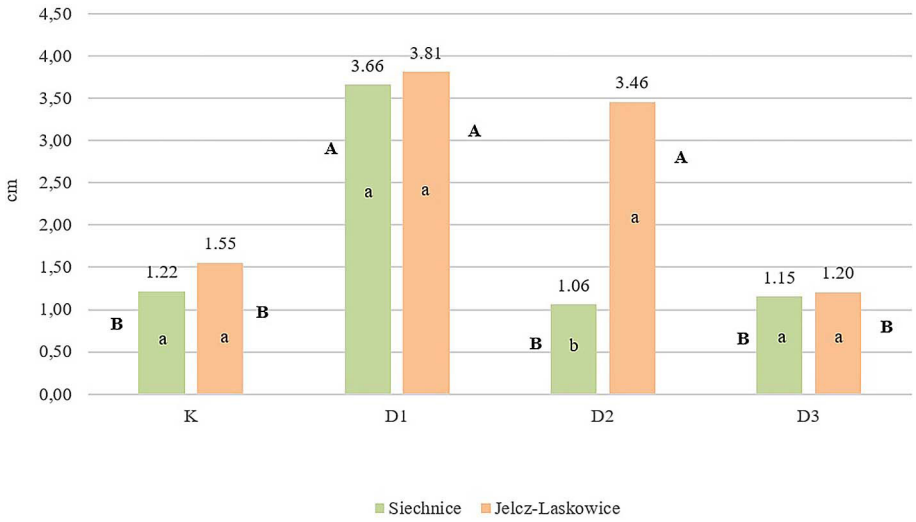

Figure 1. The length of *Setaria pumila* seedling roots depending on the seed origin and the laser irradiation dose. Different lowercase letters indicate significant differences between habitats within a given laser dose; different uppercase letters indicate significant differences among laser doses within a given habitat ($\alpha = 0.05$)

A similar response pattern was observed in the plants originating from the seeds collected in Siechnice, although the effect was less pronounced. Control seedlings showed a mean root length of 0.50 cm, while those treated with dose D2 reached 3.54 cm, corresponding to a stimulation of 608%. Significant effects were also observed for doses D1 and D3 (Figure 2). The response to the applied stimulating factor depended on the habitat from which the seeds were collected. A stronger reaction to laser radiation was observed in the *B. incana* seeds originating from Jelcz-Laskowice. Mean root lengths were significantly higher in the plants derived from seeds collected at this location compared with those from Siechnice. This pattern was evident for each laser dose, whereas in the control treatments, root lengths did not differ between the two habitats (Figure 2).

DISCUSSION

In recent years, ALAN has become an increasingly recognised environmental problem. This phenomenon, generated primarily in highly urbanised areas, affects living organisms, including plants. ALAN disrupts naturally occurring dark periods, which play a crucial role in regulating plant physiological processes such as photoperiodism or hormonal balance. As noted by Czaja and Kołton (2022), artificial night-time lighting affects not only vegetation typical of urban environments but also extra-urban plant communities, including meadows, pastures, forests, and agricultural fields. This is due to the wave nature of light, which allows it to disperse over considerable distances. Light pollution in peri-urban zones may result not only from expanding urban infrastructure but also from horticultural activities that involve intensive plant illumination throughout the year, particularly during periods of shortened day length. Under such conditions, bright light glows are formed and become visible over long distances, providing an additional source of artificial night-time light and affecting plant growth in the vicinity of greenhouse complexes (Czaja and Kołton, 2022).

Plants have evolved precise mechanisms that allow them to adjust their growth and development to natural light conditions. One of the key factors regulating plant functioning is the photoperiod, and disruptions caused by light pollution may lead to alterations in physiological processes. As reported by Abuelsoud et al. (2020), the exposure to artificial light at night can disturb oxidative balance, causing changes in hydrogen peroxide levels and in components of the antioxidant system in plants. Disturbances in light perception, such as shortened or extended dark periods, may significantly affect plant metabolism. Studies by Frank et al. (2022) confirm that an unnaturally prolonged photoperiod can modify hormonal regulation, including changes in auxin and cytokinin levels. Since these hormones control numerous developmental processes, from

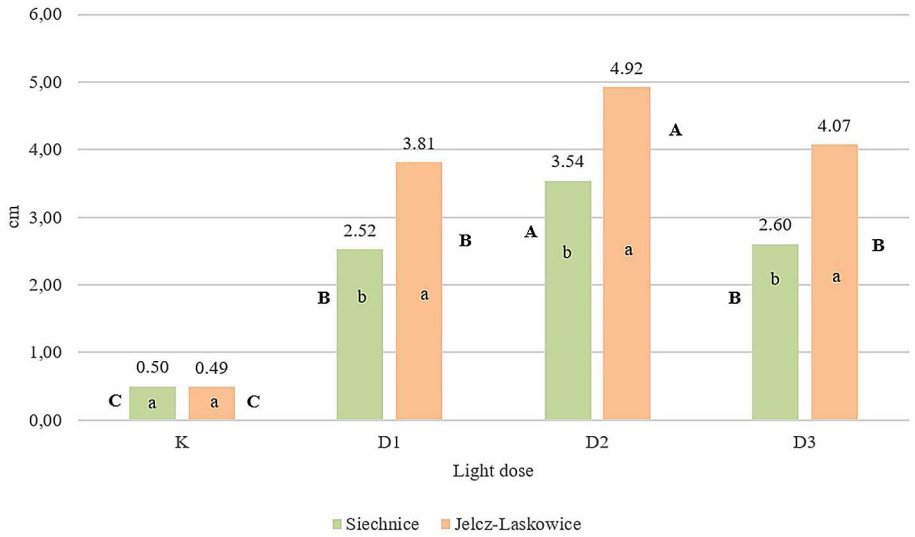

Figure 2. The length of Berteroa incana seedling roots depending on the seed origin and the laser irradiation dose. Different lowercase letters indicate significant differences between habitats within a given laser dose; different uppercase letters indicate significant differences among laser doses within a given habitat ($\alpha = 0.05$)

germination and shoot elongation to senescence, such disruptions may lead to abnormal growth and adaptive changes in the plants exposed to artificial light at night. The results of the present study showed the detrimental effect of ALAN on the germination and initial growth of *B. incana* and *S. pumila*. The variation in response to artificial light at night reflects the inherent species-specific traits. Root of both species seedlings originating from the ALAN-exposed site were shorter than from the ALAN-free location. However, a harmful impact on germination capacity was only observed for *S. pumila*.

As sessile organisms, plants cannot avoid unfavourable conditions and have therefore evolved complex mechanisms that minimise the effects of environmental stress. These mechanisms are largely coordinated by the internal biological clock, which synchronises physiological processes with prevailing environmental conditions, particularly with the daily light–dark cycle and seasonal changes in photoperiod. As noted by Xu et al. (2022), disturbances in the photoperiod can significantly reduce the ability of plants to cope with both biotic and abiotic stress.

A naturally reduced photoperiod serves as a signal for plants to enter dormancy, which is essential for enhancing their frost tolerance. Disruption of this process through nighttime exposure to ALAN may limit the ability of plants to acclimate to low temperatures, thereby reducing their cold hardiness (Roeber et al., 2022). Moreover, the duration of light within the daily cycle affects the efficiency of defence mechanisms related to the resistance against pathogenic microorganisms. It has been demonstrated that photoperiod disruption can weaken the immune response of plants, increasing their susceptibility to biotic stress (Roeber et al., 2022).

The present research investigated the combined effect of artificial light at night and laser radiation on seed germination and initial growth of seedlings of two species. The effect of ALAN on maternal plants which affect plant physiology and consequently seeds properties were considered. Regarding the sensitivity to laser radiation of seeds produced by plants exposed to ALAN, it was assumed that artificial light at night can act in three ways on seeds. Firstly, artificial light at night can make seeds more susceptible to laser radiation. The second possible way is no influence on seed reaction to laser radiation, because plants received sufficient light for germination. The third way ALAN affects the seed quality is due to the stress it causes on the mother plant. Anthropogenic light sources (e.g., illumination in greenhouses) emit radiation that partially overlaps with the absorption maxima of plant photoreceptors (Longcore et al,. 2004; Gaston et al., 2013; Davies et al., 2014), which make plants exposed to prolonged ALAN less sensitive to additional light stimuli. Consequently, the response of such plants to stimulation with laser radiation may be weaker compared with individuals developing under conditions free from nocturnal light pollution. This argumentation is in accordance with the results of this research, especially in the case of the effect of ALAN and laser radiation on the length of seedlings roots. The study conducted by Zhou et al. (2023) demonstrated that the impact of ALAN is smaller in species that prefer full illumination compared with shade-tolerant plants. Both species analysed in the present study are light-demanding, which may partially explain the limited magnitude of changes induced by nocturnal light pollution. Conversely, the stronger response of *B. incana* to the applied laser light doses – expressed as greater root elongation compared with *S. pumila* – may result from differences in their life forms, namely hemicryptophyte versus therophyte. Variations in life-history strategies can determine species-specific sensitivity to environmental stimuli, including light-driven stimulation.

It is a well-known fact that environmental conditions, especially water, temperature, and light determine seed germination. The investigated plant species grown under similar climate-soil condition, to minimise the effect of light and habitat conditions overlap. Understanding the influence of individual environmental factors in combination with ALAN and laser stimulation requires thorough research under controlled conditions.

CONCLUSIONS

The study proved that ALAN affected the germination capacity of *Setaria pumila* and root length of *Setaria pumila* and *Berteroa incana*. Laser irradiation stimulated seedling growth; however, this response was more pronounced in the plants originating from the environment without nocturnal artificial lighting.

Research on the effects of ALAN on plants is challenging and often yields ambiguous results

due to the complex interplay of environmental factors that influence plant growth and development. Nevertheless, this issue warrants particular attention, as the loss of natural dark periods clearly affects plant physiology, circadian regulation, metabolism, and adaptive capacity. From the perspective of environmental biology and plant ecology, understanding the consequences of ALAN is essential not only for ecosystem protection but also for agricultural practice and the planning of suburban and urban spaces.

Plants constitute a fundamental component of terrestrial ecosystems and the basis of Earth's trophic networks. Therefore, understanding the effects of artificial light at night on plants has not only theoretical significance but also practical relevance in both ecological and agricultural contexts.

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