BIODIVERSITAS
Volume 25, Number 10, October 2024
Pages: 3628-3636

ISSN: 1412-033X
E-ISSN: 2085-4722
DOI: 10.13057/biodiv/d251024

The potential of cold plasma technology for weed control in the pre-growth and post-growth phases

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Manuscript received: 10 July 2024. Revision accepted: 14 October 2024.

Abstract. *Bukhori A, Guntoro D, Sudradjat, Sugiarto AT. 2024. The potential of cold plasma technology for weed control in the pre-growth and post-growth phases. Biodiversitas 25: 3628-3636.* Efforts to reduce the use of herbicides can be made by using cold plasma technology. This technology produces heat energy through the emission of UV plasma light, generated by electrical energy. This research investigates the potential of various cold plasma treatments to inhibit germination, inhibit the growth of weed seeds in soil media, and suppress weed growth. The study was conducted at the Ecotoxicology Laboratory and Seed Propagation Laboratory, Institut Pertanian Bogor, Bogor, Indonesia, from March to September 2023. Three types of weeds used were *Asystasia gangetica* (L.) T.Anderson, *Cyperus rotundus* L., and *Eleusine indica* (L.) Gaertn. Three experiments were designed for this study. The first experiment tested cold plasma on weed seeds, the analysis was conducted using a single-factor completely randomized designed with varying doses of cold plasma and four replications. The second experiment tested cold plasma technology in soil media, the analysis was conducted using a single-factor completely randomized designed with various doses of cold plasma and seven replications. The third experiment tested cold plasma on the growth of each weed, the analysis was conducted using a single-factor randomized block design with various doses of cold plasma and four replications. The research shows that the application of cold plasma at a dose of 14 kV for 85 seconds can inhibit germination and weed growth in soil media of each type of weed *A. gangetica, C. rotundus,* and *E. indica.*

Keywords: *Asystasia gangetica*, *Cyperus rotundus*, *Eleusine indica*, weed germination, weed growth

Abbreviations: DAP: Days After Planting

INTRODUCTION

Weed control plays a vital role in managing agricultural land and plantations. Weeds compete with cultivated plants for essential resources such as air, light, and nutrients, significantly reducing crop yields (Abdulridha et al. 2023). One weed control technique involves the use of chemicals, specifically herbicides (Richard et al. 2023). Farmers commonly use herbicides to eliminate unwanted plants, which are closely associated with agricultural activities (Jin et al. 2023). Controlling weeds with herbicides is very popular and is the primary method for managing weeds, especially during the early phase of plant growth (Farmilo and Moxham 2023). Consequently, the demand for herbicides continues to increase.

The use of herbicides in Indonesia continues to rise due to their perceived practicality, speed, and cost-effectiveness. Between 2017 and 2021, herbicide usage increased sharply by 71.4%, from 1,037 tons to 3,634 tons, while the number of registered herbicide brands nationwide reached 2,145 (Indonesian Directorate of Fertilizers and Pesticides 2021). The increase in herbicide use in Indonesia occurs because workers prefer methods that are faster, more cost-effective, and more efficient in terms of time and energy (Hammami and Eslami 2024). This is proven by the use of herbicides for weed control, which can accelerate the control process and reduce labor costs compared to other control methods (Shekhawat et al. 2020).

Farmers' efforts to control weeds manually are considered inefficient and impractical. This method requires a long time, a lot of labor, and higher wage costs (Liu et al. 2023). On average, it takes two to three workers about 7 to 8 hours per hectare to control weeds in rice fields manually (Hamidah et al. 2015), and the labor wage for manual weed control is Rp 100,000.00 per workday for both male and female workers (Lestari et al. 2022).

The use of herbicides, while economically beneficial for farmers (Susha et al. 2018), is causing a significant negative impact on the environment and workforce health. These negative impacts, such as environmental pollution that can contaminate the surrounding water system (Ghazi et al. 2023), disrupt the physiological processes of animals, poison the sprayer (applicator), lead to weed resistance to herbicides (Rawat et al. 2023) groundwater contamination (Cabral et al. 2023) and loss of biodiversity (Mauser et al. 2024) are causes of concern. Farmers often suffer from dizziness, vomiting, and itchy skin when spraying herbicides, and in some cases, these symptoms can be fatal (Barnor et al. 2023). However, there is hope. By exploring alternative methods to reduce the use of herbicides, minimize the risk of environmental pollution, and prevent worker poisoning, we can pave the way for a more sustainable future. One such promising method is cold plasma, which offers potential benefits that we can look forward to.

Cold plasma is formed by using various types of energy that can ionize gas, such as electricity, heat, UV light, and electromagnetic radiation (visible light) (Misra 2015). When high energy is applied to a gas, it transforms into plasma. This plasma contains reactive compounds such as high-energy electrons, ionized molecules, and UV photons (Chen et al. 2019).

The cold plasma working system involves the application of high heat energy from electricity, which produces Reactive Oxygen Species (ROS) that inhibit the systemic growth of seeds and plants (Ebadi et al. 2019). Cold plasma can inhibit seed germination, leading to seed deterioration (Shelar et al. 2022). Additionally, when cold plasma connected to a high-voltage source comes into contact with plants, plant tissues can experience damage due to the high-voltage flow and the heating effect of the electric current, ultimately causing plant death (Diprose and Benson 1984). Various cold plasma have been introduced in the agricultural sector, especially to extend the post-harvest life of strawberries, chilies, and nuts (Adhikari et al. 2020). However, this technology has not yet been applied to weed control. The use of cold plasma is expected to suppress weed growth, thereby reducing costs and labor. Therefore, research needs to be conducted to develop weed control techniques using cold plasma. The aim of this research determines the potential of cold plasma technology in controlling weeds in each phase of weed growth, including the pre-growth and post-growth phases. Application during the pre-growth phase is used to assess the effectiveness of cold plasma in inhibiting weed seed germination and weed growth in soil media, while the post-growth phase evaluates its effectiveness in reducing weed growth.

MATERIALS AND METHODS

Materials, tools, and experimental sites

The materials used in this research included weed seeds (*Asystasia gangetica* (L.) T.Anderson, *Cyperus rotundus* L., and *Eleusine indica* (L.) Gaertn.), filter paper, topsoil media, and plastic samples. The tools utilized were cold plasma (cold plasma generator), petri dishes, dropper pipettes, tweezers, and seedling trays. The research was conducted from March to September 2023 at the Ecotoxicology Laboratory, Seed Propagation Laboratory, and Cikabayan Experimental Garden (6°33'8.1" S and 106°42'56.4" E, 187 masl) in the Department of Agronomy and Horticulture, Faculty of Agriculture, Institut Pertanian Bogor, Dramaga, Bogor, Indonesia.

Experimental design and procedures

Testing cold plasma on each type of weed seed in the pre-growth phase

This study involved three types of weeds: *A. gangetica*, *C. rotundus*, and *E. indica*. The experimental design used was a completely randomized design with a single factor, which was the dose of plasma voltage and the duration of exposure. The treatments included P0 = Control, P1 = 140 kV for 75 seconds, P2 = 140 kV for 80 seconds, and P3 = 140 kV for 85 seconds. Each treatment was repeated four times, and each experimental unit consisted of 10 weed seeds.

The obtained weed seeds were by exploring the experimental garden at Cikabayan, Institut Pertanian Bogor. The weed seeds that have been obtained are then put into plastic samples according to the type of weed. Germination of weed seeds was carried out in petri dishes using filter paper media. The filter paper media was moistened with 25 drops of water using a 3 mL pipette. Weed seeds are arranged on filter paper media with a distance of 2.5 cm between weed seeds. Each petri dish was treated with cold plasma treatment according to the specified dose. Next, the petri dish was moved into a germinator cupboard at a temperature of 30°C. Maintenance was carried out every day by watering using a pipette with water whose volume was adjusted to the humidity of the filter paper.

The variables observed in the first experiment were the time of emergence of the sprouts (observed every day until the first sprout appeared), radicle length (measured using a ruler starting from the base of the growing stem to the longest root at 14 and 21 DAP), the percentage of weed germination (observation of the percentage weed germination was carried out at 14 and 21 DAP). The germination percentage is obtained using a formula:

$$\text{Germination percentage} = \frac{\text{Number of germinated seeds}}{\text{Total seeds sown}} \times 100\%$$

Testing cold plasma on topsoil media

Soil media sampling was carried out at the experimental garden Cikabayan, Institut Pertanian Bogor, specifically from the top layer of soil, with the assumption that it contains many weed seeds. The soil media was placed into 5 mm pots, with a hole made at the bottom and a soil thickness of approximately 5-7 cm. One by one, the pots containing soil media were treated with cold plasma treatment according to the specified dose. Next, the pot is placed on a tray filled with water at a height of one-third (⅓) of the pot. Observations were made daily, observing the types of weeds that appeared and counting the number of weeds in each treatment pot. Observations of the types of weeds that grew were carried out at 7, 14, and 21 DAP, and weeds that grew after 21 days of treatment were not counted and were considered not viable (unfit). The 21-day cut-off, a reliable method for assessing weed survival, refers to a common approach in the field (Espeland et al. 2010). The expected outcome of using cold plasma is its ability to inhibit the growth of all types of weeds in the soil medium used.

The variables observed in the second experiment were the number of individual weed species (observations were made by looking at and recording the types of weeds that grew at 7, 14, and 21 DAP), the total number of weeds growing per pot (observations were made by counting the number of weeds that grew in each pot on the planting medium up to 21 DAP) and percentage of suppressing growing weeds (the percentage of weed suppression is obtained from the number of weeds growing at 21 DAP compared to the control treatment). The percentage of suppressing growing weeds can be calculated using the formula:

$$\%PP = \left(1 - \frac{JTP}{JTK}\right) \times 100\%$$

Where :
%PP : Percentage of suppression weed
JTP : Number of weeds that grow in the treatment
JTK : Number of weeds growing on the control

Testing cold plasma on the growth of each type of weed

This research involved three types of weeds: *A. gangetica, C. rotundus,* and *E. indica*. The experimental design used was a single-factor, randomized block design. Each treatment was repeated four times, with each experimental unit consisting of 10 weed seeds. Harvesting is done by cutting all plant parts at the exact ground level.

The obtained weed seeds were the experimental garden Cikabayan at Institut Pertanian Bogor. Weed seeds that have been obtained are then put into a plastic sample according to the type of weed. This experiment was carried out by growing weed seeds in soil media using a seeding tray (7 cm × 5 cm). One tray contains one type of weed consisting of 20 weed seeds. Weed seeds are planted by spreading them evenly over the soil medium. Maintenance is carried out daily by watering with an amount of water adjusted to the soil moisture conditions. Weeds are allowed to grow for a crucial period of approximately 55 days or until they reach maturity. Selection for weed growth is done by removing non-uniform plants and maintaining the number of live plant individuals at 10 per seedling tray. Next, each growing weed is treated with cold plasma technology according to the specified dose. The treatment was applied only once, on the 56 days after planting. The expected outcome is that the application of cold plasma can significantly suppress the growth of already established weeds.

Meanwhile, what was observed in the third experiment was the dry weight of the weeds (obtained by placing fresh weed parts in an envelope and then placing them in the oven at a temperature of 80°C for 48 hours) and the percentage of weed damage (observation of the percentage of damage was carried out at 21 DAP by harvesting plant biomass). The percentage of weed damage is obtained from the dry weight of weeds, which is converted into percent using a formula based on research by Guntoro and Fitri (2013):

$$\%KP = \left(1 - \frac{BSP}{BSK}\right) \times 100\%$$

Where :
%KP: Percentage of weed damage
BSK : Dry weight of fresh weed parts in the treatment
BSP : Dry weight of fresh weed parts in the control

Data analysis

The data obtained will be analyzed using Analysis of Variance (ANOVA); if there are significant differences, the data will be tested further using the Duncan Multiple Range Test (DMRT) at an α level of 5%; data processing with the help of Microsoft Excel and STAR IRRI.

RESULTS AND DISCUSSION

Testing cold plasma on each type of weed seed in the pre-growth phase

The time when the sprouts of each type of weed appear

Figure 1 shows that the application of cold plasma affects the emergence time of sprouts for each type of weed tested. At a cold plasma dose of 14 kV for 75 seconds, it was shown that the germination of each type of weed was delayed when compared to the control. The delay in weed germination increased with the increase in cold plasma dose. The highest germination delay was found at a dose of 14 kV for 85 seconds for each type of weed, *A. gangetica* 18.5 days, *C. rotundus* 14.3 days, and *E. indica* 18.3 days when compared to the control.

Delays in seed germination of each type of weed can be caused by heat energy produced from cold plasma UV rays, causing weed seeds to experience changes in physical properties, a decrease in the physiological quality of the seeds, not achieving good viability, and experiencing deterioration. Changes in physical properties, namely the weed seed coat burns, result in a change in the color of the seed coat on the top surface of the seed. Germination of weed seeds that have been applied with cold plasma does not achieve good viability for germination, and it will be disrupted. Deterioration includes disruption of the physical and physiological properties of seeds so that weed seed germination will experience setbacks and even erasable death. In line with the research by Li et al. (2021), tomato seeds did not germinate due to exposure to cold plasma UV light the high photon energy within the UV wavelength range has a significant direct impact on the photochemical reactions in seeds.

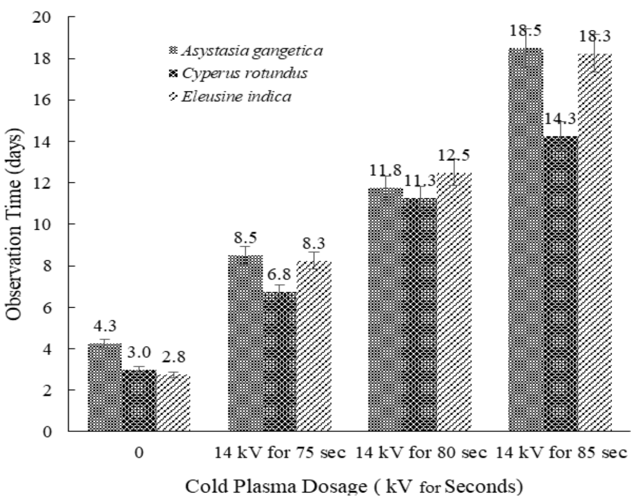

Figure 1. Effect of cold plasma on the time when the sprouts of each type of weed appear

Percentage of weed seed germination at 14 and 21 DAP

The application of cold plasma significantly reduced the germination of each type of weed at 7 and 14 days after treatment. Figures 2.A and 2.B show that the control treatment had the highest germination percentage value. At a dose of 14 kV for 75 seconds, a significant difference in the germination percentage compared to the control was shown. As the dose of cold plasma increased, the germination percentage of each type of weed tested decreased. At the observation time 14 DAP, it was shown that the percentage of germination of each type of weed had decreased, and there was no change in the percentage of germination at the observation time 21 DAP.

One consequence of this decrease in germination percentage is a decrease in seed hydrophilicity. Cold plasma was confirmed to significantly affect the hydrophilicity of each type of seed, resulting in a significant reduction in visible contact on the surface treated with plasma technology (Gao et al. 2019). Hydrophilicity is the ability of seeds to absorb water. In this experiment, weed seeds could not absorb water optimally on the filter paper medium. Hayashi et al. (2014) stated that significant inhibition of seed hydrophilicity occurred as the cold plasma dose increased.

The results showed that the application of cold plasma significantly affected the radicle length of each type of weed at 14 and 21 DAP. Table 1 shows that the control treatment exhibited the highest radicle length for each type of weed tested. The application of cold plasma at a dose of 14 kV for 75 seconds resulted in a reduction in radicle length for each type of weed compared to the control. At a dose of 14 kV for 85 seconds, the reduction in radicle length exceeded 50% at both observation times of 14 and 21 DAP. The radicle length was hampered because the weed seeds could not germinate normally due to the high electron bombardment from plasma heat energy. This is supported by Pérez-Pizá et al. (2020), who stated that cold plasma could affect seeds and inhibit root growth. As a result, the seeds' ability to explore the media and uptake water and nutrients will be disrupted. In addition, the inhibition of radicle length is caused by the presence of Reactive Oxygen Species (ROS) as promoters that interfere with cytokinin synthesis in the roots, which functions as root division (Tetelay 2003).

Twenty-one days after treatment, visual observation of several samples showed that several doses of cold plasma significantly inhibited the growth of root length of each type of weed when compared with the control treatment. The most visible symptom is a decrease in radicle growth at a dose of 14 kV for 85 seconds (Figure 3).

Table 1. Effect of cold plasma application on radicle length of each type of weed on days 14 and 21 after treatment

Plasma dosage (kV/D)	Radicle length (cm)					
	A. gangetica		*C. rotundus*		*E. indica*	
	14 DAP	21 DAP	14 DAP	21 DAP	14 DAP	21 DAP
0	1.28 a	1.50 a	1.03 a	1.30 a	0.90 a	1.28 a
14 kV for 75 sec	0.75 b	1.05 b	0.83 b	1.13 b	0.63 b	0.65 b
14 kV for 80 sec	0.60 b	0.76 c	0.45 c	0.68 c	0.38 c	0.60 b
14 kV for 85 sec	0.28 c	0.41 d	0.35 c	0.53 c	0.38 c	0.58 b

Note: Numbers followed by letters that are not the same in the column are declared significantly different based on the DMRT Test at the α level of 5%. DAP: Days After Planting

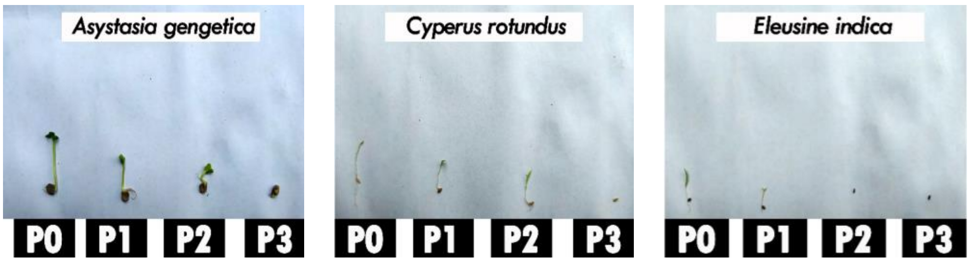

Figure 3. Effect of cold plasma technology on radicle length growth at 21 DAP. Note: P0: Control; P1: 14 kV for 75 sec; P2: 14 kV for 80 sec; P3: 14 kV for 85 sec

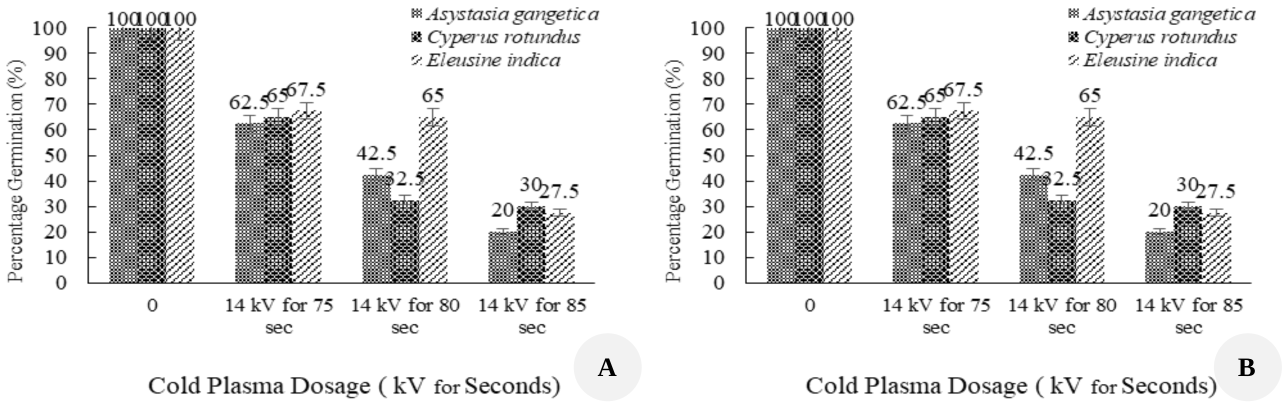

Figure 2. Effect of cold plasma on the germination percentage of each type of weed at: A.14 DAP; and B. 21 DAP

Testing cold plasma on topsoil media

Number of individual weed species growing in soil media in pots at 7, 14, and 21 DAP

Cold plasma has a significant effect on reducing the number of individual weed species growing in potted soil media (Table 2). The application of cold plasma with a dose of 14 kV for 75 seconds has shown a decrease in weed growth from all three types of weeds compared to the control at each observation time, namely 7, 14, and 21 days after treatment and increasing the dose of cold plasma; weed growth is decreasing, namely with a dose of 14 kV for 85 seconds has reached more than 50% decrease in the number of individuals of each type of test weed when compared to the control treatment. Weed propagules or seeds are unable to grow due to long-term high pressure, which can reduce water absorption and slow seed germination. The effect of cold plasma treatment with long-term high pressure can interfere with tomato seed germination (Prakash et al. 2023), inhibit safflower seed germination (Selcuk et al. 2018), inhibit corn and bean seed germination (Volin et al. 2000).

The total number of weeds that grew in the soil media in pots at 7, 14, and 21 DAP

Figure 4 shows that the application of cold plasma had a very significant effect on reducing the number of weeds growing in the soil media in pots compared to the control at 7, 14, and 21 DAP. The value of the number of weeds growing is obtained from the average total weeds growing per pot from each replication carried out. The highest number of growing weeds occurred in the control treatment at each observation time. At the recommended dose of 14 kV for 80 seconds, it reduced the number of weeds growing per pot at 7, 14, and 21 DAP, with suppression percentages of 56.4%, 54.3%, and 53.7%, respectively. This has shown a reduction in the number of weeds growing in the soil media by more than 50% when compared to the control.

The number of weeds growing in soil media is inhibited because cold plasma is capable of penetrating layers of soil media (Espeland et al. 2010). Heat energy that penetrates the soil will inhibit the germination of weed seed propagules in the soil. In line with research by Ochi et al. (2017), they stated that the application of cold plasma can inhibit the number of seed propagules in the soil and reduce the initial growth of weeds.

Percentage of weed suppression at 21 DAP compared with control

Meanwhile, the percentage value of weed suppression was obtained by calculating the average number of weeds growing at each observation time compared to the control treatment. Figure 5 shows that the control treatment began to differ significantly at a dose of 14 kV for 75 seconds, with a suppression percentage of 33.01%. As the dose of cold plasma technology increased, the percentage of suppression compared to the control also increased; specifically, the 14 kV for 85-second treatment showed a suppression of 70.96%. Increasing the plasma technology voltage dose inhibits the potential growth of weeds (Dhakal et al. 2014). The higher the cold plasma voltage, the more heat energy is produced, which can affect seeds and weeds (Jiafeng et al. 2014).

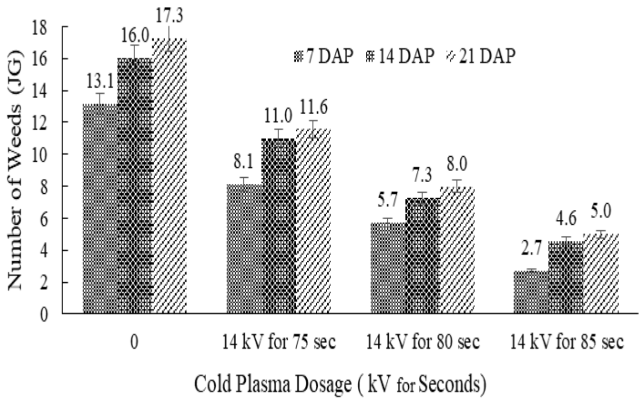

Figure 4. Effect of cold plasma on the total number of weeds growing in potted soil media at 7, 14, and 21 DAP

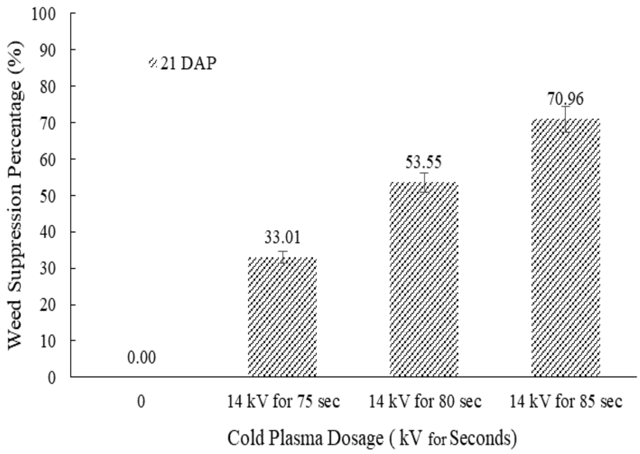

Figure 5. Effect of cold plasma on the percentage of weed suppression 21 DAP compared to control

Table 2. Effect of cold plasma on the number of individual weed species growing in soil media in pots at 7, 14, and 21 days after treatment

Plasma dosage (kV/D)	Number of individual weed species growing (JISG)								
	Ageratum conyzoides			*Cyperus kyllingia*			*Hedyotis corymbosa*		
	7 DAP	**14 DAP**	**21 DAP**	**7 DAP**	**14 DAP**	**21 DAP**	**7 DAP**	**14 DAP**	**21 DAP**
0	41 a	47 a	52 a	30 a	39 a	42 a	21 a	26 a	27 a
14 kV for 75 sec	26 b	38 b	42 b	19 b	25 b	25 b	12 b	14 b	14 b
14 kV for 80 sec	18 c	25 c	26 c	13 c	16 c	17 bc	9 b	10 b	13 b
14 kV for 85 sec	11 d	18 d	20 c	6 d	11 d	12 c	2 c	3 c	3 c

Note: Numbers followed by letters that are not the same in the column are declared significantly different based on the DMRT Test at the α level of 5%. DAP: Days After Planting

Figure 6 shows the effect of the application of cold plasma on weed growth in potted soil 21 days after treatment. The application of various doses of cold plasma affects weed growth. Visual observations at a dose of 14 kV for 75 seconds showed a reduction in weed growth compared to the control, as did doses of 14 kV for 80 seconds and 14 kV for 85 seconds compared to the control.

Testing cold plasma on the growth of each type of weed

Damage percentage and fresh dry weight of each type of weed

Table 3 shows that the application of cold plasma affects the percentage of weed damage and the dry weight of the weed species. The percentage value of weed damage was obtained by calculating the dry weight of fresh weeds that survived the cold plasma treatment compared to the control treatment. In the control treatment, there was no damage to the weed leaves of any type. Cold plasma treatment with a dose of 14 kV for 75 seconds caused damage to *A. gangetica, C. rotundus,* and *E. indica* weeds by 24.94%, 17.27%, and 19.68%, respectively, compared to the control. As the dose increased, weed damage also increased. The cold plasma dose of 14 kV for 85 seconds showed the highest percentage of weed damage for each type of weed. This is caused by the UV light produced by cold plasma; the heat energy scorches the top of the leaves (Seol et al. 2017), resulting in yellowing, abnormal growth, tissue death, and chlorosis. The effect of applying cold plasma expands and widens the damage to the leaves (Zhang et al. 2014).

Cold plasma treatment has a significant effect on reducing the dry weight of weeds. The three types of weeds tested showed the highest dry weight of weeds, namely in the control treatment. Application of cold plasma with a dose of 14 kV for 75 seconds can reduce the dry weight of *A. gangetica, C. rotundus,* and *E. indica* weeds by 1.02 g/pot, 0.81 g/pot, and 0.66 g/pot, respectively, compared to control. The higher the dose of cold plasma, the lower the dry weight of the weeds. In line with the research by Dobrin et al. (2015), early wheat plants experienced growth problems due to plasma treatment, such as damage to leaf organs, which disrupted the plant growth process. This reduction in growth rate leads to significant damage and even death of the weeds, resulting in a decreased dry weight of fresh weeds.

Visual observations 21 DAP showed that applying cold plasma technology at various doses damaged weed leaves, thereby disrupting weed growth. At a dose of 14 kV for 85 seconds, weed damage due to cold plasma application was more than 50% in the three types of weed tested compared to the control; symptoms of leaf damage due to the application of cold plasma (Figure 7).

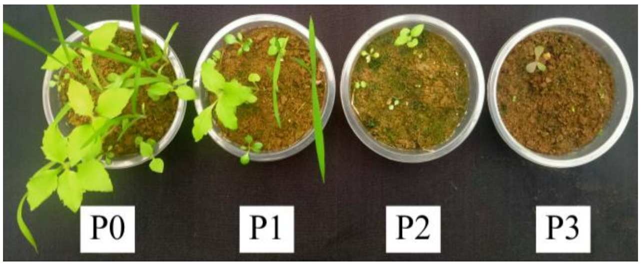

Figure 6. The effect of cold plasma on soil media in pots. Note: P0: Control; P1: 14 kV for 75 sec; P2: 14 kV for 80 sec; P3: 14 kV for 85 sec

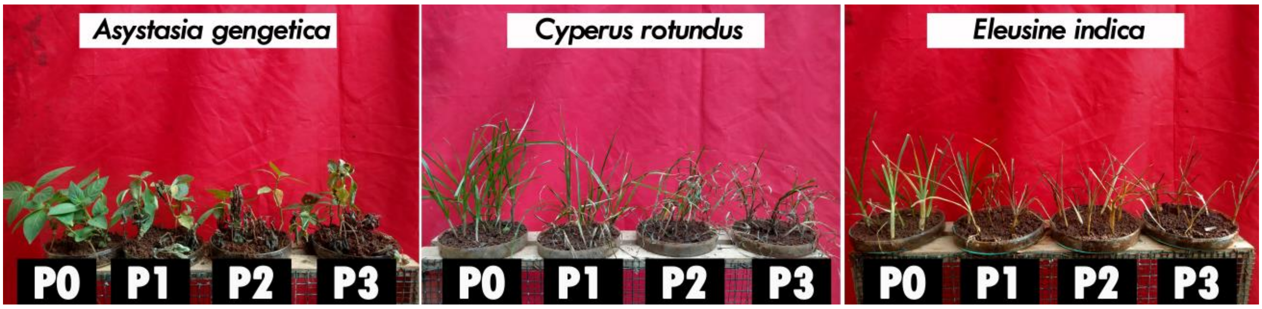

Figure 7. Effect of cold plasma on each type of weed plant. Note: P0: Control; P1: 14 kV for 75 sec; P2: 14 kV for 80 sec; P3: 14 kV for 85 sec

Table 3. Effect of cold plasma on the percentage of damage and dry weight of each type of weed

Plasma dosage (kV/D)	Weed damage percentage (%)			Weed dry weight (gram/pots)		
	Asystasia gangetica	*Cyperus rotundus*	*Eleusine indica*	*Asystasia gangetica*	*Cyperus rotundus*	*Eleusine indica*
0	0.00 d	0.00 d	0.00 d	1.36 a	0.98 a	0.82 a
14 kV for 75 sec	24.94 c	17.27 c	19.68 c	1.02 b	0.81 b	0.66 b
14 kV for 80 sec	41.08 b	47.72 b	32.82 b	0.80 c	0.52 c	0.55 b
14 kV for 85 sec	60.65 a	67.70 a	76.22 a	0.53 d	0.32 d	0.19 c

Note: Numbers followed by letters that are not the same in the column are declared significantly different based on the DMRT test at the α level of 5%

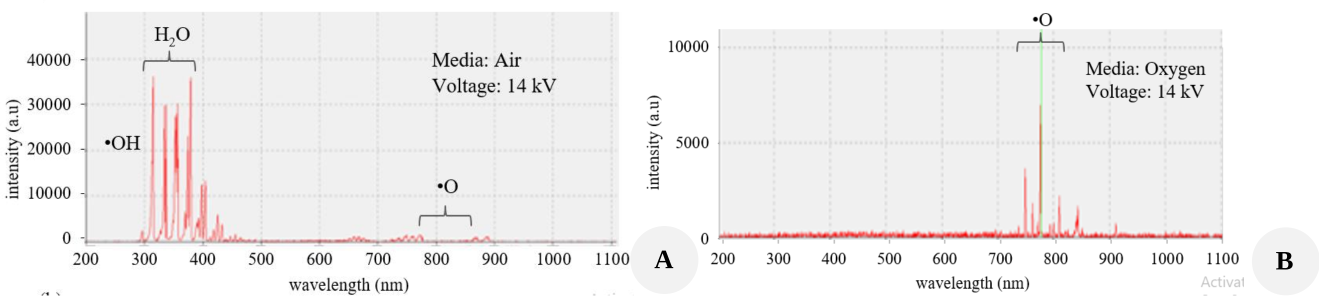

Figure 8. A. Water spectrum analysis; B. Oxygen spectrum analysis

The formation of Reactive Oxygen Species (ROS) occurs when oxygen molecules are not properly formed, leading to potential damage to plant cells or tissues due to their reactivity (Xu et al. 2022). Cold plasma generates reactive oxygen species such as nitrogen monoxide, nitrogen dioxide, hydroxyl radicals, hydrogen peroxide, and oxygen, which can inhibit seed germination and plant growth (Wojtyla et al. 2016).

Reactive oxygen species produced by cold plasma effectively demonstrate that hydroxyl radical emissions originate from the dissociation of water and oxygen molecules exposed to high plasma voltage and the UV photolysis process (Pei et al. 2013). Reactive oxygen species can cause damage to plants, interfering with metabolic functions such as photosynthesis and respiration, affecting the efficiency of nutrient and energy use (Mandal et al. 2022), altering plant tissue structure, leading to necrosis or decay, which can impact productivity (Sachdev et al. 2021), and inhibiting seed germination by damaging seed embryos and disrupting the early growth process (Bartosz 2019). The dissociation of water and oxygen molecules produces hydroxyl radical emissions at a voltage of 14 kV, analyzed using an oscilloscope and spectrometer connected to the cold plasma panel, as shown in Figure 8.

Figure 8.A shows that a plasma voltage of 14 kV produces an intensity value ranging from 200 to 900 nm, resulting in hydroxyl radical emissions at 309 nm and nitrogen dioxide emissions in the wavelength range of 310-410 nm. Figure 8.B displays oxygen radical emissions in the range of 777-840 nm. In line with Attri et al. (2015), the intensity wavelength from 200 to 900 nm can disrupt the function and structure of seed membranes, affecting plant growth.

Reactive oxygen species play a crucial role in plants and can significantly affect plant growth. They can inhibit plant growth or damage plant genes (Chen et al. 2024). The higher the plasma voltage, the greater the production of reactive oxygen species (Hu et al. 2023). Elevated levels of reactive oxygen species, such as superoxide, hydroxyl ions, and hydrogen peroxide, can be toxic to plants (Dezest et al. 2017), and plants can suffer damage if reactive oxygen species are released too rapidly (Gunes et al. 2021). An increase in the reactive oxygen species released into seeds or plants accelerates germination inhibition and interferes with plant growth (Choudhury et al. 2016). At lower plasma voltages, reactive oxygen species such as nitrogen monoxide and hydrogen peroxide do not act as destroyers of plants but rather as signals indicating potential plant damage (Dolezalova and Lukes 2015).

Cold plasma technology is not yet widely utilized in agriculture, particularly as a weed control tool, and this experiment represents an early stage in its application. Weed control aims to restrict weed growth to minimize competition with primary crops (Umiyati and Widayat 2017). Traditionally, farmers rely on chemical methods to control weeds, which can pose environmental risks. In contrast, cold plasma technology has been shown not to have a negative impact on the surrounding environment (Pankaj et al. 2018). Cold plasma technology has the potential to reduce herbicide use for weed control, especially during the post-emergence phase. However, significant optimization is necessary before this technology can be scaled up for widespread use. One potential application of cold plasma technology in future weed control efforts involves integrating it with agricultural machinery, such as tractors. During soil tilling operations, weeds emerging above the ground could be exposed to UV light and heat energy from cold plasma technology, thereby hindering the growth of weed seeds before they can establish themselves.

These findings demonstrate that cold plasma technology is a promising and effective method for weed management, particularly in the pre-growth phase, offering a non-chemical approach to suppressing weed growth. Using the recommended dose of 14 kV for 85 seconds can slow down the germination time of each type of weed, reduce the percentage of weed germination, inhibit the radicle length of each type of weed, and inhibit the growth of weeds in soil media. This is evidenced by the decrease in the number of individuals growing for each type of weed (*Ageratum conyzoides* L., *Cyperus kyllingia* Endl., and *Hedyotis corymbosa* (L.) Lam.) compared to the control. The treatment significantly reduced the total number of weeds per pot at each observation time. It suppressed weed growth by 71.00% compared to the control, which can increase the percentage of weed damage in each type of weed: *A. gangetica* by 60.65%, *C. rotundus* by 67.70%, and *E. indica* by 76.22%. Additionally, the treatment effectively reduced the dry weight of each weed species: *A. gangetica* by 0.53 grams/pot, *C. rotundus* by 0.32 grams/pot, and *E. indica* by 0.19 grams/pot. From the three experiments conducted, cold plasma effectively inhibits and suppresses weed growth in all observations, making it a viable method to suppress weed growth, particularly in the pre-growth phase.

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