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Effect of Shape and Size of Purple Nutsedge (*Cyperus rotundus* L.) Tuber Bioherbicide Granules on the Germination of Weed and Crop Seeds

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Abstract

The use of synthetic herbicides is an effective way to control weeds, but their widespread use has negative environmental impacts. A bioherbicide made from purple nutsedge tubers can be an alternative for weed control. Purple nutsedge's tuber contain allelopathy compounds that can inhibit the growth of other plants (weeds). This study aims to evaluate the response of various shapes and sizes of bioherbicide granules made from purple nutsedge's tuber in suppressing the germination of weed seeds and crop seeds. The experiment used a completely randomized design one factor and eleven treatments: control without herbicide treatment, synthetic herbicide active ingredient oxyfluorfen 240 g/L, purple nutsedge's tuber powder bioherbicide without carrier, very small round granule bioherbicide, small round granule, medium round granule, large round granule, very small cylindrical granule, small cylindrical granule, medium cylindrical granule, and large cylindrical granule. Each treatment was tested on four species: *Bidens pilosa* and *Cynodon dactylon* (weeds), cucumber, and rice (crops). The experimental results showed that the application of purple nutsedge's tuber-based bioherbicides exerts a noticeable influence on several germination parameters. The smaller the bioherbicide granule, the higher the germination inhibition rate. Very small, round-shaped granule bioherbicides showed greater effectiveness in suppressing seed sprout percentage, reducing growth rate, increasing the percentage of abnormal sprouts, and inhibiting plumula and radicle growth.

Keywords: α-cyperone, allelopathy, allelochemical, organic, sustainable agriculture

Introduction

The use of synthetic herbicides is currently considered an effective solution for controlling weeds, but prolonged use can have negative effects (Susanto & Pujisiswanto, 2023). Synthetic herbicides can lead to weed resistance (Bilkis et al., 2022; Evar et al., 2022). The active ingredients in herbicides leave residues in the soil, which can impact soil microorganisms (Sari et al., 2015), and these residues can be absorbed by plants during nutrient transport, potentially affecting human health if consumed over the long term (Kesuma et al., 2017). Efforts to lessen the adverse effects of synthetic herbicides should focus on alternative methods, such as plant-based herbicides (bioherbicides).

Bioherbicides are made from natural ingredients such as plant extracts and essential oils (Paiman et al., 2022). Bioherbicides can be developed from the allelopathic potential produced by plants (Motmainna et al., 2021). Allelopathy is a chemical compound released by plants that can inhibit or accelerate the growth of other plants (Hierro & Callaway, 2021; Kostina-Bednarz et al., 2023). Plants that contain

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allelopathic compounds include *Tetracera indica* (Pohan et al., 2023), *Euphorbia heterophylla*, *Bidens pilosa* (de Lima et al., 2022), *Acacia*, *Agropyron repens* L., *Imperata cylindrica* L., *Centaurea diffusa* L., and *Cyperus rotundus* L. (Djazuli, 2011). *Cyperus rotundus* has the potential to serve as a bioherbicide, inhibiting the germination of broadleaf weed seeds (Chozin et al., 2013).

The results of Gas Chromatography-Mass Spectrometry (GC-MS) analysis of *Cyperus rotundus* at various ages showed that extracts from the crown and tuber produced a type of phenolic compound, namely 2-furan methanol (Kusuma et al., 2017). Another compound contained in the purple nutsedge's tuber is sesquiterpene in the form of α-cyperone (Nuryana et al., 2019). According to Latif et al. (2017), sesquiterpene compounds and other metabolites related to monoterpenes in essential oils can exert phytotoxicity effects on other plants. Bioherbicides of purple nutsedge's tuber can suppress the germination of seeds of *Asystasia gangetica* and *Echinochloa crus-galli* (Sulistiani et al., 2020). In addition, the bioherbicide of purple nutsedge's tuber can also affect the growth speed and result in abnormal sprout growth (Arsa et al., 2020; Nabilah, 2020; Nuryana et al., 2019).

Research on the formulation of bioherbicides made from purple nutsedge's tuber has been systematically carried out (Andhini & Chozin, 2016; Arsa et al., 2020; Ridwan et al., 2022; Sulistiani et al., 2020). Various formulations, including solutions, flour, macerates, and granules, are effective at suppressing the germination of broadleaf weed seeds, but according to Sulistiani et al. (2020), granular bioherbicides are preferred because they are easier to apply and store. Bharti and Ibrahim (2020) stated that granular biopesticides are mostly used to apply products to soil to control weeds, nematodes, and soil-dwelling insects, or to deliver products to plants through roots. Once applied, granules release their active ingredient slowly.

The effectiveness of bioherbicide granules in inhibiting plant seed germination is suspected to depend on the granule surface area in direct contact with the soil. The particle size of granular formulations plays a critical role in determining the contact surface area exposed to the soil solution. Smaller granules present a higher surface-area-to-volume ratio, thereby increasing the total area in direct contact with the soil or moisture film around them. This enhanced contact facilitates more rapid infiltration of water, dissolution of active allelochemicals, and subsequent diffusion or release into the surrounding soil matrix. In support of this, controlled-release studies show that smaller particles exhibit faster release rates of active ingredients than larger particles (Gámiz et al., 2021; Ren et al., 2022). Moreover, the increased local concentration of allelochemicals (due to faster release and greater contact interface) is likely to increase inhibition of seed germination by elevating local exposure of seeds to suppressive concentrations. According to Bailey et al. (2009), smaller granules provided broader coverage and faster biopesticide release, resulting in greater efficacy of *P. macrostoma* compared to larger granules. Hence, granule size should be considered a key parameter in the design of granular bioherbicide formulations to optimize release kinetics and allelochemical inhibition efficacy. In addition, information on the effective shape and size is necessary to design the granulator, or the bioherbicide granule-making machine.

Materials and Methods

Materials

The materials used are purple nutsedge tubers (*Cyperus rotundus* L.), *Bidens pilosa* seeds, *Cynodon dactylon* seeds, rice seeds of the 'Inpari 32' variety, cucumber seeds of the 'Ethana F1' variety, corn flour, bran, sterilized soil, and a synthetic herbicide containing the active ingredient oxyfluorfen at 240 g/L.

Statistical Analysis

The experimental design used is a completely randomized design with a single

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factor. The experimental treatment consisted of 11 treatments, namely control without herbicide treatment (P0), the synthetic herbicide of active ingredient oxyfluorfen 240 g/L, bioherbicide of purple nutsedge's tuber flour without carriers, bioherbicide of very small round granules, small round granules (P4), medium round granules, large round granules, very small cylindrical granules, small cylindrical granules, medium cylindrical granules, and large cylindrical granules. The bioherbicide dose is 67.5 kg of purple nutsedge tuber flour per ha. The shapes and sizes of bioherbicides, along with their speciation, are shown in Figure 1 and Table 1. Each treatment was repeated three times, yielding 33 experimental units per tested plant. The tested plants used were *Biden pilosa*, *Cynodon dactylon*, cucumber variety 'Ethana F1', and rice variety 'Inpari 32'.

Experimental Procedure

Purple nutsedge tubers (*Cyperus rotundus* L.) were collected from Leuwikopo and Cikabayan Experimental Field, Department of Agronomy and Horticulture, Faculty of Agriculture, IPB University. The purple nutsedge tubers were obtained, cleaned, and dried using an oven for 2-3 days at 60 °C. The purple nutsedge tubers were then mashed and filtered to obtain purple nutsedge tuber powder. Bioherbicide granules are manufactured using a pelleter machine. The formulation of bioherbicide granules is made by mixing purple nutsedge tuber powder and carrier (corn flour and bran) in a ratio of 1:5:5. The results of mixing purple nutsedge tuber powder and carrier are formed into two shapes, namely round and cylindrical, as well as four sizes: large, medium, small, and very small (Figure 1).

Weed seeds (*Biden pilosa*, and *Cynodon dactylon*), rice seeds of the 'Inpari 32' variety, and cucumber seeds of the 'Ethana F1' variety were

Table 1

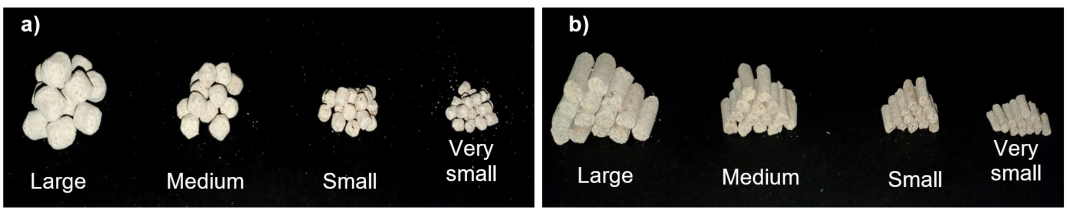
Specification of Bioherbicide Granules of Various Shapes and Sizes

Bioherbicide granules	Weight of 5 grains (g)	Diameter (mm)	Length (mm)
Very small round	0.04 ± 0.02	3.00 ± 0.07	-
Small round	0.27 ± 0.02	4.00 ± 0.12	-
Medium round	0.57 ± 0.02	5.06 ± 0.11	-
Large round	1.10 ± 0.06	7.00 ± 0.12	-
Very small cylinder	0.29 ± 0.03	3.04 ± 0.09	8.00 ± 0.10
Small cylinder	0.56 ± 0.05	4.04 ± 0.11	8.13 ± 0.13
Medium cylinder	1.33 ± 0.09	5.16 ± 0.17	10.01 ± 0.09
Large cylinder	2.29 ± 0.09	7.06 ± 0.15	12.14 ± 0.17

Note. Values are the average ± standard deviation.

Figure 1

Bioherbicide Granular Round (a) and Cylindrical Shapes (b)



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planted as many as 50 seeds on trays measuring 40 cm x 30 cm x 12 cm that had been filled with sterile soil. Bioherbicides of purple nutsedge tuber granules of various shapes and sizes are applied by spreading them evenly on the soil surface immediately after planting with a dose of 67.5 kg of purple nutsedge tuber powder per ha (total granule weight). The dose of 67.5 kg/ha of purple nutsedge tuber powder was selected based on a previous field experiment (Ridwan et al., 2022; Sulistiani et al., 2020). Application of herbicide active ingredient oxyfluorfen 240 g/L by spraying it on the soil surface with a spray volume of 500 L/ha, 3 days before planting.

Observations and measurements were conducted for 30 days; the parameters included the percentage of final germination, the number of normal and abnormal sprouts, the growth rate, and measurements of the plumula and radicle.

Data Analysis

All data were analyzed using the F-test in SAS (Statistical Analysis System). If the treatment had a real effect, further tests were carried out using the Duncan's multiple range test (DMRT) at the α = 5% level to assess differences between treatments.

Results and Discussion

Percentage of Germination

Purple nutsedge tuber bioherbicide significantly suppresses the germination of both broadleaf and grassy weeds (Table 2). All bioherbicide treatments significantly suppressed the germination of *Biden pilosa* weed seeds compared to the control. The average germination percentage in the bioherbicide treatment ranged from 55.33% to 77.33%, which was significantly lower than the control (90.00%). The lowest percentage of granular bioherbicide treatment was found in the very small cylindrical and very small round granular bioherbicide treatments, at 56.67% and 57.33%, respectively. Similarly, in the germination of *Cynodon dactylon* weeds, the lowest percentage of granular bioherbicide

Table 2

Percentage of Germination of Biden pilosa, Cynodon dactylon, Cucumber, and Rice at Various Treatments at 30 Days After Planting (DAP)

Treatments	Germination percentage (%)			
	Weeds		Crops	
	Biden Pilosa	*Cynodon dactylon*	Cucumber	Rice
Control	90.00a	85.33a	98.00	74.00a
Synthetic herbicide oxyifluorfen 240 g/L	54.67d	52.00e	98.00	46.67bc
Purple nutsedge's tuber powder bioherbicide	55.33d	64.67d	95.33	53.33bc
Very small round granule bioherbicide	57.33cd	64.67d	95.33	56.00b
Small round granule bioherbicide	68.00bcd	73.33bcd	96.00	58.00b
Medium round granule bioherbicide	66.00bcd	76.00abc	97.33	58.67b
Large round granule bioherbicide	64.00cd	78.67ab	96.00	58.00b
Very small cylindrical granule bioherbicide	56.67cd	67.33cd	96.67	54.67bc
Small cylindrical granule bioherbicide	62.00cd	72.67bcd	98.00	58.00b
Medium cylindrical granule bioherbicide	69.33bc	76.00abc	97.33	57.33b
Large cylindrical granule bioherbicide	77.33b	77.33ab	97.33	61.33b

Note. Values followed by the same letter in the same column do not differ significantly based on the DMRT (Duncan's multiple range test) at the level of α = 5%.

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germination was observed with very small round-size bioherbicides (64.67%) and very small cylinders (67.33%), which were lower and significantly different from the control (85.33%).

These results strengthen the research of Sulistiani et al. (2020), which stated that the bioherbicide of purple nutsedge tuber powder is effective in suppressing the germination of weed seeds of the broadleaf weed (*Asystasia gangetica*) and grass weed (*Echinocloa cruss-galli*) by more than 50%. The low germination of weed seeds is suspected to be due to allelopathic compounds in the tubers, including sesquiterpene and phenol compounds. According to Nuryana et al. (2019), sesquiterpene compounds in purple nutsedge tuber, namely α-cyperone, can inhibit germination in lettuce and rice seeds. In addition, the presence of phenol compounds in purple nutsedge tubers can also affect germination.

The effects of purple nutsedge tuber bioherbicide on the germination of cucumber and rice seeds are not as good as suppressing the germination of weeds (*Biden pilosa* and *Cynodon dactylon*). This is thought to be because the plant seeds in this study were planted 1-2 cm deeper than the weed seeds, which were located at the soil surface. At a certain depth, the pre-emergence herbicide spectrum cannot reach the vegetative parts or plant seeds (Parminder & Jhala, 2016), thus providing a lower effect.

Abnormal Sprouts

The percentage of abnormal sprouts of *Biden pilosa* in the bioherbicide treatment of purple nutsedge's tuber powder (6.67%), very small round granule (7.33%), and very small cylindrical granule (8.00%), was higher and significantly different from the control (1.33%) (Table 3). A similar pattern was also shown in the percentage of abnormal sprouts of the weed *Cynodon dactylon*. The bioherbicide treatment of purple nutsedge's tuber powder (9.33%), very small round granule (9.33%), and very small cylindrical granule (7.33%) had greater values and were significantly different compared to the control (1.33%). Nuryana et al. (2019) reported that allelopathic compounds in purple nutsedge's tuber can cause sprouts to grow abnormally, such as curved, circular shapes, stunted radicle and plumule growth, and can result in stagnant growth.

Table 3 shows that bioherbicide treatment of purple nutsedge tubers reduces the incidence of abnormal cucumber sprouts. The percentage of abnormal cucumber sprouts in the bioherbicide treatment of purple nutsedge's tuber powder, very small round granule, and very small cylindrical granule, respectively, was 16.00%, 18.67%, and 17.33%, higher and significantly different compared to the control (4.00%). The highest percentage of abnormal sprouts was observed in the synthetic herbicide treatment (64.00%), which was significantly higher than in the control. Weed control with the herbicide oxyfluorfen can cause severe poisoning and reduce the germination percentage in cucumber plants (Kadmana, 2020). In rice, the application of bioherbicides did not significantly increase the incidence of abnormal sprouts. As with cucumbers, the highest rate of abnormal rice sprouts was observed with the synthetic herbicide oxyfluorfen at 240 g/L, namely 17.33%. The performance of normal and abnormal sprouts from the tested plants is shown in Figure 2.

Growth Speed

The growth rate of *Biden pilosa* weed sprouts in all bioherbicide treatments was slower than that of the control. Among the granule bioherbicide treatments, the lowest seedling growth rate for this weed was observed with very small granule bioherbicides, both round and cylindrical, namely 1.67%/etmal and 1.62%/etmal (Table 4). Bioherbicide treatment significantly inhibited the growth rate of *Cynodon dactylon* seedlings. The lowest growth rate was observed in the powder bioherbicide treatment (1.84%/etmal) and in very small round grains (1.89%/etmal), both of which were slower and significantly different from the control (2.80%/etmal). Phenolic compounds in sedge tubers can inhibit germination. Phenolic compounds can affect cell membrane permeability, thereby inhibiting imbibition in seeds and resulting in a

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Table 3

Percentage of Abnormal Sprouts of Biden pilosa, Cynodon dactylon, Cucumber, and Rice at Various Treatments at the Age of 30 Days After Planting (DAP)

Treatments	Abnormal sprout (%)			
	Weeds		Crops	
	Biden Pilosa	*Cynodon dactylon*	Cucumber	Rice
Control	1.33c	1.33e	4.00d	1.33bc
Synthetic herbicide oxyfluorfen 240 g/L	37.33a	32.00a	64.00a	17.33a
Purple nutsedge's tuber powder bioherbicide	6.67b	9.33b	16.00b	5.33b
Very small round granule bioherbicide	7.33b	9.33bc	18.67b	5.33b
Small round granule bioherbicide	2.67bc	8.00cde	10.00c	1.33bc
Medium round granule bioherbicide	4.00bc	3.33cde	8.00cd	0.00c
Large round granule bioherbicide	2.67bc	2.67cde	8.00cd	2.67bc
Very small cylindrical granule bioherbicide	8.00b	7.33bcd	17.33b	4.00bc
Small cylindrical granule bioherbicide	2.67bc	4.00bcde	6.00cd	2.67bc
Medium cylindrical granule bioherbicide	3.33bc	2.00de	8.67c	0.00c
Large cylindrical granule bioherbicide	3.33bc	2.67cde	8.67c	0.00c

Note. Values followed by the same letter in the same column do not differ significantly based on the DMRT (Duncan's multiple range test) at the level of α = 5%.

Figure 2

Comparative Morphology of Normal and Abnormal Seedlings Following Exposure to Cyperus rotundus Tuber Bioherbicide at 7 Days After Planting

Note. (a) Normal sprouts of *Biden pilosa*, (b) abnormal sprouts of *Biden pilosa*, (c) normal sprouts of *Cynodon dactylon*, (d) abnormal sprouts of *Cynodon dactylon*, (e) normal sprouts of cucumber, (f) abnormal sprouts of cucumber, (g) normal rice sprouts, (h) abnormal sprouts of rice.

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low imbibition rate. A low imbibition rate delays germination, so the germination percentage will be lower (Mahayaning et al., 2015).

The results of the variance analysis showed that the growth rate of *Biden pilosa* weed sprouts in all bioherbicide treatments was slower than that of the control. Among the granule bioherbicide treatments, the lowest seedling growth rate for this weed was observed with very small granular bioherbicides, both round and cylindrical, namely 1.67%/etmal and 1.62%/etmal (Table 4). Bioherbicide treatment significantly inhibited the growth rate of *Cynodon dactylon* seedlings. The lowest growth rate was observed in the flour bioherbicide treatment (1.84%/etmal) and very small round grains (1.89%/etmal), which were slower and significantly different from the control (2.80%/etmal). Phenolic compounds in purple nutsedge tubers can inhibit germination. Phenolic compounds can affect cell membrane permeability, thereby inhibiting imbibition in seeds and resulting in a low imbibition rate. A low imbibition rate delays germination, so the germination percentage will be lower (Mahayaning et al., 2015).

Table 4 shows that the growth rate of cucumbers in the bioherbicide treatment of purple nutsedge's tuber powder, very small round granules, and very small cylinder granules, was lower and significantly different compared to the control (3.11%/etmal). The percentage of growth speed of the bioherbicide treatment of purple nutsedge's tuber powder, very small round granule, and very small cylinder granule, respectively, was 2.64%/etmal; 2.56 %/etmal; and 2.64%/etmal. Table 4 also shows that the growth rate of rice sprouts is slower and significantly lower than the control (2.43%/etmal), but not significantly different between the bioherbicide treatments. The lowest growth rate of rice sprouts was observed in the synthetic herbicide oxyfluorfen treatment, 0.98%/etmal (Table 4). The herbicide oxyfluorfen can cause plant death by rapidly degrading cell membranes (Perkasa, 2020).

Table 4

Growth Speed of Biden pilosa, Cynodon dactylon, Cucumber, and Rice at Various Treatments at the Age of 30 Days After Planting (DAP)

Treatments	Growth speed (%/etmal)			
	Weeds		Crops	
	Biden Pilosa	*Cynodon dactylon*	Cucumber	Rice
Control	2.95a	2.80a	3.11a	2.43a
Synthetic herbicide oxyfluorfen 240 g/L	0.58e	0.66e	1.13d	0.98d
Purple nutsedge's tuber powder bioherbicide	1.62d	1.84d	2.64c	1.60c
Very small round granule bioherbicide	1.67d	1.89d	2.56c	1.69bc
Small round granule bioherbicide	2.18bc	2.33bc	2.87b	1.89bc
Medium round granule bioherbicide	2.07bcd	2.42b	2.97ab	1.96bc
Large round granule bioherbicide	2.05bcd	2.53ab	2.93ab	1.85bc
Very small cylindrical granule bioherbicide	1.62d	2.00cd	2.64c	1.69bc
Small cylindrical granule bioherbicide	1.98cd	2.29bc	3.00ab	1.85bc
Medium cylindrical granule bioherbicide	2.20bc	2.47ab	3.02ab	1.91bc
Large cylindrical granule bioherbicide	2.47bc	2.49ab	2.96ab	2.04b

Note. Values followed by the same letter in the same column do not differ significantly based on the DMRT (Duncan's multiple range test) test at the level of α = 5%.

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Plumula Length

Bioherbicide applications significantly suppressed the length of the *Biden pilosa* plumula, but did not show a significant difference between treatments. Table 5 shows that the shortest plumula was observed in the synthetic herbicide oxyfluorfen 240 g/L treatment, at 3.75 cm. Table 5 shows that bioherbicide treatment has a real effect on the length of *Cynodon dactylon* plumula. The treatment of very small (4.47 cm) and very small cylindrical (4.55 cm) granule bioherbicide suppressed plumula growth more than the control (6.55 cm) and larger granular bioherbicide treatment.

The application of bioherbicides also significantly affected cucumber plumula length. All bioherbicide treatments and synthetic herbicides significantly inhibited the growth of the cucumber sprout plumula. Table 5 also shows that the shortest cucumber plumula length was observed in the synthetic herbicide treatment with oxyfluorfen at 240 g/L, which was 8.61 cm. The length of the cucumber plumula treated with very small round granules (8.81 cm) and very small cylinders (8.72 cm) was shorter and significantly different from the control (11.24 cm). This result supports the findings of Nabilah (2020), who reported that the application of purple nutsedge tuber bioherbicide can inhibit the length of the plumula and radicle of cucumbers. The treatment of bioherbicides on rice did not significantly inhibit the growth of plumula in rice germination, except for the very small size of bioherbicides. The length of rice plumula in the treatment of very small round grain and very small cylinders was 20.11 cm and 20.37 cm, respectively, which were shorter than the control (22.45 cm).

Radicle Length

The results of the variance analysis show that bioherbicide application significantly suppresses radicle growth in *Biden pilosa*. The treatment of very small granules is more effective at suppressing radicle growth than larger granular bioherbicides. The radicle length of *Biden pilosa* in the treatment of bioherbicide

Table 5

Plumula Length of Biden pilosa, Cynodon dactylon, Cucumber, and Rice at Various Treatments at the Age of 28 Days After Planting (DAP)

Treatments	Plumula length (cm)			
	Weeds		Crops	
	Biden Pilosa	*Cynodon dactylon*	Cucumber	Rice
Control	5.03a	6.55a	11.24a	22.45a
Synthetic herbicide oxyfluorfen 240 g/L	3.75d	4.23f	8.61c	17.23d
Purple nutsedge’s tuber powder bioherbicide	3.78cd	4.45ef	8.68c	20.51abc
Very small round granule bioherbicide	3.78cd	4.47ef	8.81c	20.11c
Small round granule bioherbicide	4.01bcd	4.62def	9.31b	21.06abc
Medium round granule bioherbicide	4.29bc	5.15bc	9.63b	20.97abc
Large round granule bioherbicide	4.17bcd	6.06bc	9.71b	21.62abc
Very small cylindrical granule bioherbicide	3.85cd	4.55ef	8.72c	20.37bc
Small cylindrical granule bioherbicide	3.91cd	4.76cde	9.65b	21.52abc
Medium cylindrical granule bioherbicide	4.01bcd	4.97bcd	9.74b	21.98abc
Large cylindrical granule bioherbicide	4.44b	5.18b	9.81b	22.28ab

Note. Values followed by the same letter in the same column do not differ significantly based on the DMRT (Duncan’s multiple range test) at the level of α = 5%.

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of very small round granules (4.38 cm) and very small cylinders (4.60 cm), was shorter and significantly different from the treatment of medium round, large round, medium cylinder, and large cylinder (Table 6). Bioherbicide applications also showed similar effectiveness on the growth of *Cynodon dactylon* radicles. Treatment with smaller granules suppresses radicle growth more than treatment with larger granules. The radicle length in the treatment of large round (4.11 cm) and large cylindrical (4.38 cm) granule bioherbicides was longer and significantly different than the treatment of very small round granules (3.75 cm). Nuryana et al. (2019) reported that sesquiterpene compounds in purple nutsedge tubers can cause plumula and radicle growth to be shorter. In addition to sesquiterpene compounds, phenol compounds are also thought to affect radicle growth. Denaxa et al. (2022) explained that phenolic compounds can inhibit plant root elongation, cell membrane division, and plant growth and development

Table 6 shows that bioherbicide application significantly affects cucumber radicle length. The shortest radicle was observed in the treatment with the synthetic herbicide oxyfluorfen at 240 g/L, which was 9.58 cm. Among bioherbicide treatments, smaller granules are more effective at suppressing cucumber radicle growth than larger granules. In length, the radicle in the treatment of very small round and small round grains is 9.66 cm and 9.71 cm. Similar effectiveness is also shown in the treatment of very small and small cylindrical granules. Table 6 also shows that bioherbicide treatment significantly affects rice radicle growth. The length of plumula in the treatment of medium-round, large-round, medium-cylinder, and large-cylinder granule bioherbicides was 9.49 cm, 9.67 cm, 9.54 cm, and 9.59 cm, respectively, with no significant difference compared to the control (10.25 cm). The smaller the particle size, the greater the surface area and the greater the particle's contact with the contact plane.

In conclusion, purple nutsedge (*Cyperus rotundus* L.) tuber–based bioherbicides are particularly highly effective in suppressing weed seed germination and early seedling growth

Table 6

Radicle Length of Biden pilosa, Cynodon dactylon, Cucumber, and Rice at Various Treatments at the Age of 28 Days After Planting (DAP)

Treatments	Radicle length (cm)			
	Weeds		Crops	
	Biden Pilosa	*Cynodon dactylon*	Cucumber	Rice
Control	6.68a	5.38a	11.09a	10.25a
Synthetic herbicide oxyfluorfen 240 g/L	4.11d	3.54e	9.58e	8.99b
Purple nutsedge's tuber powder bioherbicide	4.27d	3.75de	9.62de	9.03b
Very small round granule bioherbicide	4.38d	3.75de	9.66cde	9.27b
Small round granule bioherbicide	4.61cd	3.79cde	9.71cde	9.33b
Medium round granule bioherbicide	5.39b	3.95cd	9.95b	9.49ab
Large round granule bioherbicide	5.53b	4.11bc	9.81bcd	9.67ab
Very small cylindrical granule bioherbicide	4.60cd	3.77cde	9.64de	9.23b
Small cylindrical granule bioherbicide	5.17bc	3.89cd	9.69cde	9.40b
Medium cylindrical granule bioherbicide	5.58b	4.07bcd	9.82bcd	9.54ab
Large cylindrical granule bioherbicide	5.53b	4.38b	9.87bc	9.59ab

Note. Values followed by the same letter in the same column do not differ significantly based on the DMRT (Duncan's multiple range test) at the level of α = 5%.

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when formulated as very small granules, while showing relatively lower inhibitory effects on crop seeds. It seems that the effectiveness of very small granules is associated with their larger surface area, which enhances contact with the soil environment and promotes greater release of allelopathic compounds. These findings provide a scientific basis for developing granular bioherbicide formulations as an environmentally friendly alternative to synthetic herbicides in pre-emergence weed management. Moreover, because purple nutsedge is a globally distributed weed species and allelopathy-based weed control principles are widely applicable, the results of this study are relevant beyond local conditions and may benefit international researchers working on sustainable weed management, bioherbicide development, and agroecological farming systems in different cropping environments.

Conclusions

This study establishes that the bio-efficacy of *Cyperus rotundus* tuber-derived bioherbicides is primarily governed by their physical formulation. Finer granule geometries-regardless of being spherical or cylindrical-exerted a more profound inhibitory effect on seed germination kinetics, as well as the allometric development of the plumule and radicle in both target and non-target species. This heightened bioactivity is driven by the superior specific surface area of smaller granules, which accelerates the leaching and bio-availability of allelochemicals within the soil matrix. Consequently, optimizing the surface-to-volume ratio of the carrier represents a strategic imperative for maximizing the herbicidal potential of *C. rotundus* extracts in sustainable weed management systems.

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