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*Research Article*

# Determining granule size of *Cyperus rotundus* tuber-based bioherbicide for weed control in upland rice

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**ABSTRACT**

*The application of granular bioherbicides derived from purple nutsedge (Cyperus rotundus L.) tubers offers an environmentally friendly alternative for managing weed competition in upland rice cultivation. This study evaluated the efficacy of various granular bioherbicide forms and sizes (67.5 kg ha$^{-1}$) in suppressing weed growth and their impact on upland rice. A completely randomized design with twelve treatments was employed. Results showed that granular bioherbicides effectively controlled broadleaf weeds for up to four weeks without causing phytotoxicity to upland rice. Very small granular bioherbicides (spherical and cylindrical) were the most effective form to suppress weed growth of Alternanthera sessilis (L.) R.Br. ex DC., and Mimosa pudica L., and enhance upland rice growth and yield.*

**Keywords**: allelopathy; biological control; efficacy; pre-emergence; sustainable agriculture

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## INTRODUCTION

Upland rice cultivation poses several challenges, primarily weed infestations. Ridwan et al. (2022) noted that weed presence significantly reduces rice production. Weeds have been reported to decrease paddy rice productivity by 14.5-29.4% (Zarwazi et al., 2016) and upland rice by up to 96.9% (Prasetyo, 2023). Although synthetic herbicides provide rapid and effective weed control (Perkasa et al., 2016; Aditiya, 2021), continuous utilization is a detriment to crops, soil fertility, and the environment (Kesuma et al., 2015). Nalfin et al. (2018) documented herbicide toxicity in rice.

Utilizing bioherbicides from natural sources, such as purple nutsedge (*C. rotundus* L.), mitigates synthetic herbicide drawbacks. Purple nutsedge produces allelopathic compounds, including phenolics and sesquiterpenes, which inhibit seed germination of broadleaf weeds (Zohaib et al., 2016; Kusuma et al., 2017; Nuryana et al., 2019; Sulistiani et al., 2020). Research on purple nutsedge bioherbicide formulations has progressed systematically (Andhini & Chozin, 2016; Dewi et al., 2017; Kusuma et al., 2017; Arsa et al., 2020; Sulistiani et al., 2020). Although solution, powder, and granular formulations demonstrate efficacy, Sulistiani et al. (2020) recommend granular forms due to their ease of application and storage. However, optimal granular bioherbicide forms and sizes remain unknown. This study investigated the effectiveness of various granular bioherbicide forms and sizes, derived from purple nutsedge tubers (*C. rotundus* L.), in controlling weeds in upland rice cultivation and their impact on rice growth and yield.

## MATERIALS AND METHODS

### *Research design*

This research was conducted from October 2023 to February 2024 at the Sawah Baru Experimental Station, Department of Agronomy and Horticulture, IPB University, Bogor. Observations of weed analysis results were done at the Post-Harvest Laboratory, Department of Agronomy and Horticulture, IPB University.

The experiment used a completely randomized design with a single factor, which was weed control methods, including control (no weeding), manual weeding, bioherbicide of round/spherical-cylindrical combination of large, medium, small, and very small forms (Table 1), powder bioherbicide 67.5 kg $ha^{-1}$, and synthetic herbicide Oxyfluorfen 480 g $ha^{-1}$. The experiment consisted of 12 treatment combinations with three replications or 36 experimental units in the form of a plot of land measuring 3 m x 4 m.

Table 1. Specification of purple nutsedge bioherbicide.

| Granular bioherbicide category | 5-granule weight (g) | Diameter (mm) | Length (mm) |
|---|---|---|---|
| Large spherical | 1.10 ± 0.06 | 7.00 ± 0.12 | - |
| Medium spherical | 0.57 ± 0.02 | 5.06 ± 0.11 | - |
| Small spherical | 0.27 ± 0.02 | 4.00 ± 0.12 | - |
| Very small spherical | 0.04 ± 0.02 | 3.00 ± 0.07 | - |
| Large cylindrical | 2.29 ± 0.09 | 7.06 ± 0.15 | 12.14 ± 0.17 |
| Medium cylindrical | 1.33 ± 0.09 | 5.16 ± 0.17 | 10.01 ± 0.09 |
| Small cylindrical | 0.56 ± 0.05 | 4.04 ± 0.11 | 08.13 ± 0.13 |
| Very small cylindrical | 0.29 ± 0.03 | 3.04 ± 0.09 | 08.00 ± 0.10 |

### *Preparation of bioherbicides*

Purple nutsedge tubers *C. rotundus* L. were collected from two locations, namely Cikabayan and Leuwikopo Experimental Stations, Department of Agronomy and Horticulture, IPB University. The tubers were cleaned with water and dried using an oven at 60 °C for three days. Then, it was mashed using a blender and filtered using a 60-mesh sieve. Granular bioherbicide was made at the IPB Feed Nutrition Laboratory using an animal feed pellet machine by mixing 67.5 kg $ha^{-1}$ of purple nutsedge flour and corn flour as carrier ingredients in a ratio of 1:10, and water as much as 50% of the total ingredients. The granular formulation was made in two forms (spherical and cylindrical) and four sizes (large, medium, small, and very small). After that, the granules were dried using an oven at a temperature of 80 °C for 24 hours.

### *Experimental treatment*

Soil tillage was carried out two times by using a tractor. The plots were made measuring 4 m x 3 m and were 0.5 m apart between the plots. Rice seeds of IPB 9G variety were soaked and ripened before planting. Rice planting uses a direct seed planting system with a 25cm x 25cm spacing with three seeds per planting hole (Ridwan et al., 2022). The application of bioherbicides and synthetic herbicides was carried out the same day after planting. Bioherbicide was broadcasted on the soil surface, and synthetic herbicide solutions were sprayed using a knapsack sprayer. Manual weeding was carried out at 3 and 6 weeks after planting (WAP). For optimum rice growth, it was applied of foliar silicate and potassium fertilizer (3 L $ha^{-1}$), PGPR biological fertilizers (83.5 kg $ha^{-1}$), cow manure (10 tons $ha^{-1}$), dolomite lime (1 tons $ha^{-1}$), and synthetic chemical fertilizers Urea, SP-36, and KCl of 250 kg $ha^{-1}$, 175 kg $ha^{-1}$, and 175 kg $ha^{-1}$, respectively.

Observations included weed vegetation, observation of rice plant toxicity, observation of rice growth, yield components, and rice productivity. Weed vegetation was observed before and after treatment at 2, 4, and 6 weeks after treatment (WAT). Weed vegetation was collected for SDR value using a quadrant measuring 0.5 m x 0.5 m (Ridwan et al., 2022). The weeds were dried using an oven at 105 °C for 24 hours.

Vegetative growth of rice was observed at 2, 4, 6, 8, and 10 WAP. The flowering stage was observed when 50% of the total population flowered. Rice traits including the number of productive tillers, the number of filled grains per panicle, the percentage of empty panicles, the weight of 1,000 grains, and the weight per plot were observed at harvest. Rice productivity was evaluated at harvest for dry unhusked rice, and harvest index. Rice plant toxicity was observed at 1, 2, and 3 WAT based on visual symptoms in plants followed Suwitra et al. (2016).

*Data analysis*

The data was analyzed using the Statistical Analysis System (SAS) application. Data analysis for weed control factors used the F test at α = 5%. Further testing used Duncan's Multiple Range Test (DMRT) at α = 5% to evaluate the difference between treatments.

## RESULTS AND DISCUSSION

*Changes in dominant weed species*

Twenty-four weed species were identified prior to tillage (Table 2). Vegetation analysis revealed dominant weeds belonging to the broadleaf group, specifically *Mimosa pudica, Alternanthera sessilis*, and *Commelina diffusa,* with respective SDR values of 16.08%, 14.76%, and 10.45%. Grassy weeds, specifically *Rottboellia exaltata* and *Digitaria adscendens*, followed with SDR values of 9.99% and 7.06%.

At four weeks after treatment (Table 2), vegetation analysis revealed that treatment with very small spherical bioherbicide granules was most effective at suppressing *M. pudica, A. sessillis*, and *C. diffusa* growth, yielding the lowest SDR values of 2.9%, 5.6%, and 4.0%, respectively, relative to other treatments. These findings support previous studies (Chairannisa & Chozin, 2018) reporting bioherbicide derived from *Cyperus rotundus* tubers effective for controlling broadleaf. Manual weeding also resulted in the absence of *C. diffussa, C. benghalensis, A. conyzoides*, and *C. rutidosperma* at 4 WAT.

*Rottboellia exaltata* was identified as a dominant weed before treatment and maintained its dominance across all treatments at 4 WAT. This species is challenging to control due to its aggressive invasive traits. According to Tjitrosoedirdjo et al. (2016), *R. exaltata* exhibits aggressive growth, reaching 3 m in height, with hairy stems, large seeds, and high adaptability. Vegetation analysis at 4 WAT revealed that *R. exaltata* was not effectively controlled by purple nutsedge tuber bioherbicides. These findings support previous statement that *C. rotundus* bioherbicide is ineffective in suppressing grassy weed germination (Sulistiani et al., 2020).

*Total dry weight of weeds*

The application of bioherbicides was effective in suppressing total weed growth at 4 WAT (Table 3). The average total weed weight in the bioherbicide treatment tuber of purple nutsedge ranged from 34.42-54.78 g. The lowest weed weight in the bioherbicide treatment was small (37.86 g) and very small (34.42 g) round granular, as well as small cylindrical forms (37.07 g), which was significantly different from the control (75.85 g). The finding indicated that smaller granules were more effective compared to larger forms. Of all the treatments tested, the manual weeding treatment had the lowest dry weight of weeds (0.57 g). The critical period of rice plants occurs at 3 WAP or 21-28 days after planting (DAP) (Hutagaul et al., 2018). Weed control during critical periods will provide a growing environment free of weeds which favors plant growth (Srinithan et al., 2021).

Table 3 shows the effect of purple nutsedge tuber bioherbicide on weed growth. Application of this bioherbicide suppressed weed growth by 27.78-54.62%. These results demonstrated the effectiveness of purple nutsedge tuber bioherbicide in suppressing weed growth. The phenolic compounds and sesquiterpenes present in purple nutsedge tubers contribute to inhibiting weed seed germination, showing potential for development as pre-emergence bioherbicides (Kusuma et al., 2017; Nuryana et al., 2019; Arsa et al., 2020).

Table 2. Summed dominance ratio (SDR) of identified weed species before and after bioherbicide treatments.

| Species | BT (%) | SDR at 4 WAT (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | P0 | P1 | P2 | P3 | P4 | P5 | P6 | P7 | P8 | P9 | P10 | P11 |
| Broadleaf | | | | | | | | | | | | | |
| *Mimosa pudica* L. | 16.1 | 4.9 | 11.4 | 3.9 | 3.8 | 2.6 | 2.9 | 4.0 | 3.3 | 4.4 | 4.0 | 5.0 | 7.2 |
| *Alternanthera sessilis* (L.) R.Br. ex DC. | 14.8 | 9.5 | 7.7 | 6.9 | 7.1 | 8.6 | 5.6 | 7.9 | 6.9 | 6.1 | 6.2 | 6.2 | 10.8 |
| *Commelina diffusa* Burm.f. | 10.4 | 4.0 | - | 6.9 | 5.4 | 5.1 | 4.0 | 6.5 | 2.9 | 3.3 | 5.2 | 6.8 | - |
| *Sida rhombifolia* L. | 4.8 | 3.6 | 2.1 | 3.9 | 3.2 | 2.0 | 6.5 | 4.3 | 4.6 | 4.8 | 6.0 | 5.6 | - |
| *Mimosa invisa* Mart. ex Colla | 4.8 | 2.1 | 1.4 | 2.0 | 3.5 | 6.4 | 5.1 | 4.6 | 5.1 | 4.0 | 4.5 | 3.9 | - |
| *Synedrella nodiflora* (L.) Gaertn. | 3.4 | 4.9 | 6.4 | 4.4 | 5.0 | 5.1 | 5.6 | 4.7 | 4.1 | 5.0 | 4.7 | 5.1 | 11.7 |
| *Commelina benghalensis* L. | 3.2 | 6.5 | - | 3.2 | 6.6 | 5.1 | 9.6 | 2.9 | 7.1 | 4.9 | 1.3 | 4.9 | 4.0 |
| *Celosia argentea* L. | 3.1 | 10.8 | 8.1 | 4.4 | 2.8 | 3.5 | 4.7 | 1.2 | 3.7 | 6.0 | 10.0 | 2.8 | - |
| *Calopogonium mucunoides* Desv. | 2.7 | 3.8 | 9.0 | 6.4 | 3.3 | 3.3 | 2.3 | 4.3 | 3.4 | 4.9 | 3.9 | 4.6 | 22.6 |
| *Ageratum conyzoides* L. | 2.6 | - | - | - | - | - | - | - | - | - | - | - | - |
| *Cleome rutidosperma* DC. | 2.4 | 6.3 | - | 4.7 | 5.1 | 6.0 | 5.8 | 6.1 | 4.0 | 5.1 | 4.5 | 3.8 | 3.7 |
| Grasses | | | | | | | | | | | | | |
| *Rottboellia exaltata* | 10.0 | 20.6 | 13.4 | 22.9 | 26.3 | 28.4 | 26.4 | 30.2 | 28.6 | 25.4 | 20.4 | 31.0 | 14.0 |
| *Digitaria adscendens* (L). L.f. | 7.1 | 4.2 | 5.7 | 9.4 | 6.2 | 5.0 | 6.6 | 7.1 | 5.8 | 4.9 | 8.5 | 6.3 | - |
| *Cynodon dactylon* | 4.1 | 0.9 | 6.5 | 3.5 | 1.3 | 1.2 | - | - | 1.5 | 3.4 | 3.2 | 1.3 | 2.5 |
| Sedges | | | | | | | | | | | | | |
| *Cyperus rotundus* (L.) Pers. | 2.4 | 4.9 | 11.9 | 7.9 | 10.9 | 2.3 | 7.0 | 4.8 | 5.6 | 8.8 | 9.5 | 6.9 | 10.2 |
| Others (9) | 8.3 | 13.0 | 16.5 | 9.6 | 9.5 | 15.4 | 8.0 | 11.3 | 13.9 | 8.8 | 8.0 | 5.8 | 8.0 |

*Note:* Rice plant conditions in various weed control treatments at 4 WAT (week after treatment); P0 (no weeding), P1 (manual weeding), P2 (large spherical bioherbicide), P3 (medium spherical bioherbicide), P4 (small spherical bioherbicide), P5 (very small spherical bioherbicide), P6 (large cylindrical bioherbicide), P7 (medium cylindrical bioherbicide), P8 (small cylindrical bioherbicide), P9 (very small cylindrical bioherbicide), P1 (powder bioherbicide 67.5 kg ha$^{-1}$), P10 (synthetic herbicide Oxyfluorfen 480 g ha$^{-1}$), BT (before treatment)

*Dry weight of dominant weeds*

*Rottboellia exaltata* was identified as a dominant grassy weed in the experimental field (Table 2). However, bioherbicide derived from purple nutsedge tubers failed to suppress *R. exaltata* growth at 4 weeks after treatment (WAT) (Table 4). Only manual weeding and synthetic herbicide treatments showed significantly lower weed dry weights (0.15 g and 7.12 g, respectively) compared to the control (28.98 g). These findings support previous studies indicating limited efficacy of purple nutsedge tuber-based bioherbicides against grassy weeds (Nuryana et al., 2019; Arsa et al., 2020; Sulistiani et al., 2020). Notably, observations at 4 WAT revealed a reduction in weed growth in smaller granule-size treatments. Specifically, small spherical bioherbicide granules caused lower weed weights (20.23 g per quadrant) compared to larger sizes (24.30 g per quadrant), with similar trends observed for cylindrical forms.

At 4 WAT, the growth of *A*. sessilis was suppressed after bioherbicide treatment (Table 4). The average dry weight of *A. sessilis* weeds treated with purple nutsedge tuber-based bioherbicide ranged from 2.18-3.18 g, significantly lower than the control (5.47 g). Among granular bioherbicide treatments, the smallest spherical (2.18 g) and cylindrical (2.41 g) formulations resulted in the lowest weed weights, statistically comparable to the smaller powder formulation (2.81 g). This finding supports Trisnaliani et al. (2017), who reported that smaller bioherbicide granules increase surface area, enhancing soil contact and efficacy.

Very small, spherical-granule bioherbicides demonstrated superior efficacy in suppressing *M. pudica* weed's weight (2.18 g) compared to larger formulations (Table 4). Similarly, cylindrical bioherbicides (2.41 g) exhibited the same pattern. The allelopathic compounds in these bioherbicide granules are gradually released onto the soil surface, inhibiting weed growth (Bharti & Ibrahim, 2020).

Table 3. Total dry weed weight under various weed control treatments at 4 WAT.

| Treatment | Total weed dry weight (g per quadrant) | |
|---|---|---|
| | 4 WAT | Weed suppression (%) |
| No weeding (control) | 75.85a | 0.00 |
| Manual weeding | 0.57d | 99.25 |
| Large spherical bioherbicide | 54.78ab | 27.78 |
| Medium spherical bioherbicide | 52.08abc | 31.34 |
| Small spherical bioherbicide | 37.86bc | 50.09 |
| Very small spherical bioherbicide | 34.42bc | 54.62 |
| Large cylindrical bioherbicide | 51.13ab | 32.59 |
| Medium cylindrical bioherbicide | 51.85abc | 31.64 |
| Small cylindrical bioherbicide | 44.61abc | 41.19 |
| Very small cylindrical bioherbicide | 37.07bc | 51.13 |
| Powder bioherbicide 67.5 kg $ha^{-1}$ | 53.68abc | 29.23 |
| Synthetic herbicide oxifluorfen 480 g $ha^{-1}$ | 27.40c | 63.88 |

*Note*: Numbers followed by the same letter in the same column were not significantly different in the DMRT test α = 5%, WAT (week after treatment).

Table 4. Dry weight of dominant weeds *R. exaltata*, *A. sessilis*, and *M. pudica* under various treatments at 4 WAT.

| Treatment | Total weed dry weight (g per quadrant) | | |
|---|---|---|---|
| | *R. exaltata* | *A. sessilis* | *M. pudica* |
| No weeding (control) | 28.98a | 2.30a | 5.47a |
| Manual weeding | 0.15c | 0.09e | 0.04e |
| Large spherical bioherbicide | 24.30ab | 0.39b | 3.18b |
| Medium spherical bioherbicide | 25.85ab | 0.38b | 2.97bc |
| Small spherical bioherbicide | 20.23ab | 0.37b | 2.97bc |
| Very small spherical bioherbicide | 17.84ab | 0.31cd | 2.18d |
| Large cylindrical bioherbicide | 30.43a | 0.39b | 3.17b |
| Medium cylindrical bioherbicide | 29.76a | 0.37b | 3.29b |
| Small cylindrical bioherbicide | 23.47ab | 0.38b | 2.92bc |
| Very small cylindrical bioherbicide | 14.69ab | 0.34bc | 2.41cd |
| Powder bioherbicide 67.5 kg $ha^{-1}$ | 33.95a | 0.35bc | 2.81cd |
| Synthetic herbicide Oxifluorfen 480 g $ha^{-1}$ | 7.12bc | 0.27d | 2.04d |

*Note*: Numbers followed by the same letter in the same column were not significantly different in the DMRT test α = 5%, WAT (week after treatment).

*Rice toxicity and growth*

Table 3 shows that oxyfluorfen's synthetic herbicide significantly suppressed weed growth in upland rice fields. However, the results of observations at 1, 2, and 3 WAT showed that the treatment of the synthetic herbicide oxyfluorfen caused symptoms of phytotoxicity in rice plants. The symptoms of toxicity are characterized by leaf yellowing/bleaching, wilting, and desiccation. By using the scoring method from Suwitra et al. (2016), the toxicity score in rice ranged from 2-4 (average 2.98) at 3 WAT after synthetic herbicide treatment. According to Nalfin et al. (2018), a toxicity score of 3-4 causes plant death. In the present experiment, no toxicity was found in rice plants after bioherbicide treatments.

Table 5 shows the average plant height and number of tillers at 10 WAP and at the flowering stage of upland rice under various weed control treatments. Overall, weed control treatments substantially affected upland rice growth. The average plant height in purple nutsedge tuber bioherbicide treatments ranged from 78.67-96.55 cm, surpassing the control (71.19 cm). Notably, very small, spherical (96.55 cm), and cylindrical (89.34 cm) bioherbicide formulations able to suppress weed growth resulted in the highest rice growth rates. The percentage of weed suppression in the two treatments was 54.62 and 51.13%, respectively (Table 4).

All weed control treatments significantly increased the total number of rice tillers (Table 5). The average tillers number of rice plots treated with purple nutsedge tuber bioherbicide ranged from 7.3-7.7 tillers, substantially higher than the control (4.9 tillers). No significant differences were observed among granular bioherbicide treatments regarding tiller numbers.

Weed affected flowering time in upland rice (Table 5). Unweeded rice plots had the longest flowering period (90.33 days) compared to manual weeding (77.67 days). Except for the smallest granules, bioherbicide form and size showed no significant differences (83.33-86.80 days). It is likely that smaller granular bioherbicides favored rice flowering. Weed-free environments benefit plants by providing competition-free space for optimizing growth (Srinithan et al., 2021).

Table 5. Average plant height, total number of tillers, and rice flowering time under various weed control treatments at 10 WAP.

| Treatment | PH (cm) | TNT | FT (days) |
|---|---|---|---|
| No weeding (control) | 71.19d | 4.9d | 90.33a |
| Manual weeding | 107.57a | 10.7a | 77.67d |
| Large spherical bioherbicide | 78.67cd | 7.5b | 86.80ab |
| Medium spherical bioherbicide | 82.32bcd | 7.5b | 84.67ab |
| Small spherical bioherbicide | 83.69bcd | 7.5b | 83.33bc |
| Very small spherical bioherbicide | 96.55ab | 7.7b | 78.87d |
| Large cylindrical bioherbicide | 79.76cd | 7.3b | 86.80ab |
| Medium cylindrical bioherbicide | 82.67bcd | 7.4b | 85.13ab |
| Small cylindrical granular bioherbicide | 83.02bcd | 7.5b | 83.60bc |
| Very small cylindrical bioherbicide | 89.34bc | 7.5b | 79.40d |
| Powder bioherbicide 67.5 kg $ha^{-1}$ | 88.80bc | 7.4b | 80.33cd |
| Synthetic herbicide oxifluorfen 480 g $ha^{-1}$ | 90.48bc | 6.9c | 84.00bc |

*Note*: Numbers followed by the same letter in the same column were not significantly different in the DMRT test α = 5%, PH (plant height), TNT (total number of tillers), and FT (flowering time).

*Rice yield*

Environmental factors and weed presence significantly impact upland rice yield components. Table 6 demonstrates that weed control treatments substantially affect productive tillers, grains per panicle, empty grain percentage, and 1000-grain weight of upland rice. The control plot showed significantly lower productive tillers (3.00) compared to manual weeding (9.2). Bioherbicide-based weed control significantly increased productive tillers. Among bioherbicide treatments, very small, spherical (6.1) and cylindrical (5.7) granules yielded the highest number of productive tillers.

Manual weeding significantly increased the number of grains per panicle, producing 279.2 grains, the highest among the control and other treatments. Bioherbicide treatments showed varying results, with grains per panicle ranging from 85.1 to 177.8. The most effective treatments were very small spherical and cylindrical bioherbicides, averaging 177.8 and 124.9 grains per panicle, respectively.

Upland rice plots unweeding had significantly higher empty grain percentages (71.3%) compared to manual weeding plots (29.3%). No significant differences were observed among other weed control treatments regarding empty grain percentages. Bioherbicide treatments demonstrated lower empty grain percentages (44.3-56.9%) compared to the control. Manual weeding significantly increased 1,000-grain weight (24.9 g), differing substantially from other treatments (16.3-19.6 g). Weed disrupts plant growth, affecting the number of tillers and total biomass (Zarwazi et al., 2016).

Table 6. The average number of productive tillers, the number of grains per panicle, the percentage of empty grains, and the weight of 1,000 rice grains under various weed control treatments.

| Treatment | NPT | NGP | PEG (%) | Weight 1,000 grain (g) |
|---|---|---|---|---|
| No weeding (control) | 3.0g | 75.9d | 71.3a | 16.3d |
| Manual weeding | 9.2a | 279.2a | 29.3c | 24.9a |
| Large spherical bioherbicide | 4.1f | 87.7d | 56.7b | 18.6bc |
| Medium spherical bioherbicide | 4.1f | 110.4d | 53.0b | 18.5bcd |
| Small spherical bioherbicide | 5.3bcd | 115.0d | 51.5b | 19.0bc |
| Very small spherical bioherbicide | 6.1b | 177.8bc | 44.8b | 19.6b |
| Large cylindrical bioherbicide | 4.3ef | 108.6d | 57.2ab | 17.8bcd |
| Medium cylindrical bioherbicide | 4.5def | 96.3d | 46.6b | 16.7cd |
| Small cylindrical bioherbicide | 5.1cde | 130.3d | 49.0b | 18.7bc |
| Very small cylindrical bioherbicide | 5.7bc | 134.1cd | 44.5b | 19.2bc |
| Powder bioherbicide 67.5 kg ha$^{-1}$ | 4.9def | 96.9cd | 53.8b | 17.9bcd |
| Synthetic herbicide oxifluorfen 480 g ha$^{-1}$ | 4.07f | 209.50b | 54.10b | 18.42bcd |

*Note*: Numbers followed by the same letter in the same column were not significantly different in the DMRT test α=5%, NPT (number of productive tillers), NGP (number of grains per panicle), and PEG (percentage of empty grain).

Weed significantly impeded upland rice production (Table 7). Unweeding plots produced 0.38 kg of harvested dry grain (HDG), while clean weeding plots by manual produced 5.13 kg HDG (92.5% reduction in HDG by weed presence). The average HDG yield from purple nutsedge bioherbicide treatments ranged from 0.56-1.61 kg per plot. Very small round (1.61 kg per plot) and cylindrical (1.58 kg per plot) bioherbicides demonstrated superior performance compared to the control (0.38 kg per plot). Similarly, unhusked dry grain (GDG) showed that the smaller size of purple nutsedge tuber bioherbicide significantly enhanced rice harvest index and productivity (Table 7). The average harvest index ranged from 0.13-0.27% across bioherbicide treatments. Notably, very small spherical (0.27%) and cylindrical (0.21%) granules yielded the highest indices, substantially surpassing the control (0.08%).

Table 7. The average dry grain harvest, unhusked dry grain, and harvest index of rice under various weed control treatments.

| Treatment | HDG (kg) | UDG (kg) | HI |
|---|---|---|---|
| No weeding (control) | 0.38f | 0.26f | 0.08f |
| Manual weeding | 5.13a | 4.32a | 0.45a |
| Large spherical bioherbicide | 0.56ef | 0.42ef | 0.13ef |
| Medium spherical bioherbicide | 0.69def | 0.73def | 0.14ef |
| Small spherical bioherbicide | 0.94cde | 0.90cde | 0.17cde |
| Very small spherical bioherbicide | 1.84b | 1.42b | 0.27b |
| Large cylindrical bioherbicide | 0.77def | 0.58def | 0.17cde |
| Medium cylindrical bioherbicide | 0.84def | 0.64def | 0.17cde |
| Small cylindrical granular bioherbicide | 1.03def | 0.80cde | 0.18cde |
| Very small cylindrical bioherbicide | 1.58bc | 1.24bc | 0.21cd |
| Powder bioherbicide 67.5 kg ha$^{-1}$ | 0.69ef | 0.53ef | 0.16de |
| Synthetic herbicide Oxifluorfen 480 g ha$^{-1}$ | 1.40bcd | 1.08bcd | 0.23bc |

*Note*: Numbers followed by the same letter in the same column were not significantly different in the DMRT test α = 5%, HDG (harvest dry grain), UDG (unhusked dry grain), and HI (harvest index).

## CONCLUSIONS

Bioherbicides with very small granules demonstrated superior efficacy in suppressing total weed growth and specific weed species compared to larger, spherical, or cylindrical granules. These bioherbicides effectively controlled broadleaf weeds *A. sessilis* and *M. pudica* but exhibited limited efficacy against *R. exaltata* (grass). Moreover, purple nutsedge tuber-based bioherbicides did not induce toxicity in upland rice.

Compared to the control (no weeding), bioherbicide application enhanced upland rice growth, yield components, and overall production, particularly with very small granules.

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