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Effect of Nano Urea and Post-emergence Herbicides on Growth Performance of Aerobic Rice (*Oryza sativa* L.)

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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Abstract

Growth and productivity of aerobic rice are often constrained by severe weed competition and inefficient nitrogen utilisation. Nitrogen nutrition is a key factor influencing crop growth, canopy development and biomass production. Adequate nitrogen supply supports crop growth and can enable the crop to compete effectively with weeds for available resources such as light, nutrients and moisture. The present study was conducted to evaluate the influence of nano urea and nano urea-herbicide mixtures on growth attributes of aerobic rice (*Oryza sativa* L.). A field experiment was carried out at the College of Agriculture, Vellayani, Kerala, during 2023-2025 using a randomised block design with fourteen treatments. The treatments included penoxsulam + cyhalofop-butyl, bispyribac sodium, and fenoxaprop-p-ethyl + ethoxysulfuron, each combined with nano urea at different concentrations (0.2, 0.1 and 0.05%), along with herbicide-alone treatments, weed-

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free check, and weedy check. The results revealed that integration of nano urea with post-emergence herbicides significantly improved growth parameters of rice compared to herbicide-alone treatments and the weedy check. Higher plant height, number of tillers, leaf area and total dry matter production were recorded in treatments receiving herbicide-nano urea combinations due to effective weed suppression and enhanced nitrogen availability. Among the treatments, penoxsulam + cyhalofop-butyl combined with 0.1 per cent nano urea produced superior growth attributes and was comparable with fenoxaprop-p-ethyl + ethoxysulfuron with 0.05 per cent nano urea. The improvement in crop growth due to reduced crop-weed competition and improved nutrient use efficiency associated with better weed management. The study indicates that the integration of nano urea with post-emergence herbicides can enhance the growth performance of aerobic rice, thereby contributing to improved crop productivity.

Keywords: Growth and growth attributes; post-emergence herbicides; nano urea; nitrogen use efficiency.

1. Introduction

The system of rice intensification was marked as a sustainable, low-cost alternative technique to conventional rice farming that may provide the chance to increase rice output with less external inputs in order to improve resource use efficiency. The major concern regarding the cultivation and sustainability of this crop in this region is its high water requirement. Puddling helps to create anaerobic conditions in the field, which suppresses the germination of weed seeds, which require aerobic environments (Brar et al., 2025). Aerobic rice cultivation is a water-saving technology in which rice is grown in non-flooded, unsaturated soil with supplemental irrigation when rainfall is insufficient (Bouman et al., 2012). Aerobic rice cultivation can save 50-70 per cent of water, boost water productivity by 64-80 per cent and can also lower methane emissions. The absence of standing water in aerobic rice fields creates favourable conditions for the emergence and growth of diverse weed flora, including grasses, sedges and broad-leaved weeds, which compete vigorously with the crop during the early growth stages (Chauhan & Johnson, 2011). Weed infestation is therefore considered one of the major constraints in aerobic rice systems.

Enhancing the sustainability of rice ecosystems while increasing production and reducing water and labor use is essential. Direct-seeded rice, a cost-effective and labor-saving alternative to traditional transplanting, has gained popularity. Unlike conventional methods, where seedlings are grown in nurseries and then transplanted into flooded fields, DSR involves sowing seeds directly into prepared fields. This approach offers advantages such as resource conservation, labor efficiency, and adaptability to various agroecosystems (Ashhar et al., 2025). Chemical weed management using post emergence herbicides has become an effective and widely adopted method for controlling weeds in aerobic rice. Herbicides such as bispyribac sodium, penoxsulam, cyhalofop butyl, fenoxaprop-p-ethyl and ethoxysulfuron are commonly used for their broad-spectrum activity against the diverse weed flora. Tank mix application of various herbicides with different modes of action is a solution to address this complex weed flora. Studies have shown that combinations such as fenoxaprop-p-ethyl + ethoxysulfuron and penoxsulam + cyhalofop-butyl effectively control dominant grassy weeds in direct-seeded rice (Chauhan & Abugho, 2012). Similarly, Lap et al., (2013) reported that application of penoxsulam + cyhalofop-butyl provided control over 90 per cent of major weeds in rice and also improved the crop performance.

Apart from weed management practices, crop competitiveness plays a crucial role in determining the extent of crop-weed interference. Nitrogen nutrition is a key factor influencing crop growth, canopy development and biomass production. Adequate nitrogen supply supports crop growth and can enable the crop to compete effectively with weeds for available resources such as light, nutrients and moisture (Shultana et al., 2016). Conventional nitrogen fertilisers exhibit lower nitrogen use efficiency due to losses through volatilisation, leaching and denitrification. Therefore, improving nitrogen use efficiency while sustaining crop productivity is an important challenge in crop production systems.

In recent years, nano fertilisers have been developed as an innovative approach to improve nutrient use efficiency and crop productivity. Nano urea, a liquid nitrogen fertiliser, has gained attention for its potential to deliver nitrogen more efficiently through targeted delivery and controlled nutrient release. Studies have demonstrated that the application of nano urea improves crop growth, yield attributes and nitrogen use efficiency in rice (Rathnayaka et al., 2018; Midde et al., 2022). Velmurugan et al., (2021) also reported that foliar application of nano urea increased rice yield and enhanced nitrogen use efficiency compared with conventional nitrogen fertilisation. Integration of nano fertilisers with other crop management practices may therefore enhance crop growth and improve resource use efficiency.

Despite the increasing interest in nano fertilisers, limited research has been conducted to evaluate the influence of nano urea when applied along with post-emergence herbicides in aerobic rice systems. Understanding the interaction between herbicide application and nano-nitrogen fertilisation is important for optimising weed management and improving crop growth under aerobic conditions. The present study was undertaken to evaluate the influence of nano urea combined with post-emergence herbicides on crop growth, herbicide performance and nutrient uptake in aerobic rice.

2. Materials and Methods

The study was carried out at the College of Agriculture, Vellayani, Kerala Agricultural University, Thrissur, Kerala, India, during the Rabi 2023. The experimental site is situated at 8°56′37.5″ N latitude and 76°37′37.8″ E longitude, at an altitude of 8 m above mean sea level. The region is characterised by a humid tropical climate with warm temperatures and high relative humidity. The experiment was laid out in a randomised complete block design with two replications and fourteen treatments. The rice variety Manuratna was used for the study, and the crop was established with a spacing of 15 cm x 10 cm in plots measuring 3 m x 2 m. Herbicides were applied as post-emergence spray at 15-20 days after sowing, and nano urea was applied along with the herbicide treatments at specified concentrations. Weed-free plots were maintained by two hand weeding at 20 and 40 days after sowing, while in other treatments, hand weeding was carried out at 40 days after sowing. All other agronomic practices were followed as per the Kerala Agricultural University Package of Practices recommendations (KAU, 2016). Observations on plant height, number of tillers per hill, leaf area per hill, flag leaf area, and total dry matter production were recorded following standard procedures. The details of the treatments of the experiment are given in Table 1. The data generated from the experiment were statistically analysed using the analysis of variance (ANOVA) technique for a randomised complete block design as described by Panse & Sukhatme (1954). The significance of treatment effects was tested using the F-test following the procedure outlined by Snedecor & Cochran (1967). Statistical analysis was carried out using the General R-based Analysis Platform Empowered by Statistics (GRAPES 1.0.0) software developed by Gopinath et al. (2021).

Table 1. Details of the treatments of the experiment

S. No	Treatment	Details of Treatment
1.	T_1	Penoxsulam + Cyhalofop-butyl (pre-mix) @ 135 g ha^{-1} + Nano urea @ 0.2%
2.	T_2	Penoxsulam + Cyhalofop-butyl (pre-mix) @ 135 g ha^{-1} + Nano urea @ 0.1%
3.	T_3	Penoxsulam + Cyhalofop-butyl (pre-mix) @ 135 g ha^{-1} + Nano urea @ 0.05%
4.	T_4	Bispyribac sodium @ 25 g ha^{-1} + Nano urea @ 0.2%
5.	T_5	Bispyribac sodium @ 25 g ha^{-1} + Nano urea @ 0.1%
6.	T_6	Bispyribac sodium @ 25 g ha^{-1} + Nano urea @ 0.05%
7.	T_7	Fenoxaprop-p-ethyl @ 60 g ha^{-1} + Ethoxysulfuron @ 15 g ha^{-1}(tank mix) + Nano urea @ 0.2%
8.	T_8	Fenoxaprop-p-ethyl @ 60 g ha^{-1} + Ethoxysulfuron @ 15 g ha^{-1} (tank mix) + Nano urea @ 0.1%
9.	T_9	Fenoxaprop-p-ethyl @ 60 g ha^{-1} + Ethoxysulfuron @ 15 g ha^{-1} (tank mix) + Nano urea @ 0.05%
10.	T_{10}	Penoxsulam + Cyhalofop-butyl (pre-mix) @ 135 g ha^{-1}
11.	T_{11}	Bispyribac sodium @ 25 g ha^{-1}
12.	T_{12}	Fenoxaprop-p-ethyl @ 60 g ha^{-1} + Ethoxysulfuron @ 15 g ha^{-1}(tank mix)
13.	T_{13}	Weed-free check
14.	T_{14}	Weedy check

3. Results and Discussion

3.1 Plant Height

The results on the effect of nano urea on plant height at active tillering, panicle initiation, and flowering stages were noted, analysed and presented in Table 2. At the active tillering stage, plant height ranged from 28.97 cm to

41.83 cm. Although the differences were statistically non-significant, a higher plant height was recorded in fenoxaprop-p-ethyl + ethoxysulfuron + 0.05 per cent nano urea (41.83 cm). At the panicle initiation stage, higher plant height (67.46 cm) was observed in the weed-free check, which was statistically similar to fenoxaprop-p-ethyl + ethoxysulfuron + 0.05 per cent nano urea (66.43 cm) and penoxsulam + cyhalofop-butyl + 0.1 per cent nano urea (64.52 cm). Among herbicide alone treatments, penoxsulam + cyhalofop-butyl recorded a higher plant height (52.81 cm), while a lower plant height (46.05 cm) was recorded in the weedy check. At the flowering stage, weedy check registered higher plant height (90.90 cm), which was comparable with the nano urea herbicide combinations penoxsulam + cyhalofop-butyl + 0.1 per cent nano urea (89.55 cm) and fenoxaprop-p-ethyl + ethoxysulfuron + 0.05 per cent nano urea (84.25 cm). Among the herbicide alone treatments, penoxsulam + cyhalofop-butyl registered higher plant height (76.91 cm), and was statistically similar to bispyribac sodium (73.06 cm) and fenoxaprop-p-ethyl + ethoxysulfuron (72.25 cm). Similar results of an increase in plant height by the application of penoxsulam + cyhalofop-butyl were observed by Yadav et al. (2018) and Patil et al. (2016). Raviteja et al. (2020) reported that effective weed management practices, such as hand weeding and the application of penoxsulam + cyhalofop-p-butyl, recorded higher plant height in rice. Post-emergence application of fenoxaprop-p-ethyl + ethoxysulfuron improved plant height in aerobic rice (Ramachandiran and Balasubramanian, 2012).

3.2 Number of Tillers per Hill

Tillers per hill showed significant differences among treatments at active tillering, panicle initiation and flowering (Table 3). At the active tillering stage, the maximum number of tillers (15.92) was recorded in the weed-free check, which was significantly superior to all other treatments. Among the nano urea and herbicide combinations, fenoxaprop-p-ethyl + ethoxysulfuron + 0.05 per cent nano urea recorded a higher number of tillers per hill (14.29), which was on par with penoxsulam + cyhalofop-butyl + 0.1 per cent nano urea (14.16), fenoxaprop-p-ethyl + ethoxysulfuron + 0.1 per cent nano urea (13.18) and penoxsulam + cyhalofop-butyl + 0.05 per cent nano urea (12.91). The lowest tiller count (5.50) was observed in the weedy check. At the panicle initiation stage, the highest number of tillers per hill (17.16) was recorded in the weed-free check. Among nano urea herbicide combinations, fenoxaprop-p-ethyl + ethoxysulfuron + 0.05 per cent nano urea registered a higher number of tillers per hill (14.50), which was statistically similar to penoxsulam + cyhalofop-butyl + 0.1 per cent nano urea (14.41), fenoxaprop-p-ethyl + ethoxysulfuron + 0.1 per cent nano urea (13.27) and penoxsulam + cyhalofop-butyl + 0.05 per cent nano urea (13.25). The minimum number of tillers (7.08) was observed in the weedy check. At the flowering stage, weed-free check recorded a significantly higher number of tillers per hill (16.25). Among the nano urea herbicide combinations, fenoxaprop-p-ethyl + ethoxysulfuron + 0.05 per cent nano urea recorded the highest tillers per hill (13.25), which was statistically similar to penoxsulam + cyhalofop-butyl + 0.1 per cent nano urea (13.00), penoxsulam + cyhalofop-butyl + 0.05 per cent nano urea (12.50) and fenoxaprop-p-ethyl + ethoxysulfuron + 0.1 per cent nano urea (12.41) and the lowest number of tillers per hill (5.83) was registered in the weedy check. The increased tiller production can be attributed to the effective suppression of competing weeds, which minimised crop-weed competition for nutrients, light and moisture during the critical growth stages, thereby promoting better vegetative growth and tiller formation in rice. Hossain and Malik (2017) reported that the application of penoxsulam + cyhalofop-butyl resulted in a higher number of tillers in rice due to efficient control of complex weed flora. Increased tiller production could be attributed to the effective control of grassy and broad-leaved weeds, which minimised crop-weed competition for nutrients, light and moisture during the early stages of crop growth, thereby facilitating better vegetative growth and tiller development. Similar findings were reported by Bhullar et al. (2016), who observed that the tank mix application of fenoxaprop-p-ethyl with ethoxysulfuron effectively suppressed dominant weeds and improved crop growth attributes, including tiller production, in dry-seeded rice.

3.3 Leaf Area Per Hill

The data related to the effect of different treatments on leaf area per hill at different growth stages are presented in Table 4. The highest leaf area per hill at active tillering was recorded in the weed-free check (587.82 cm^2). Among the herbicide nano urea combinations higher leaf area (499.70 cm^2) was recorded in penoxsulam + cyhalofop-butyl + 0.1 per cent nano urea, at active tillering and was comparable with fenoxaprop-p-ethyl + ethoxysulfuron + 0.05 per cent nano urea (489.47 cm^2), penoxsulam + cyhalofop-butyl + 0.05 per cent nano urea (471.44 cm^2), fenoxaprop-p-ethyl + ethoxysulfuron + 0.1 per cent nano urea (438.52 cm^2), penoxsulam + cyhalofop-butyl + 0.2 per cent nano urea (431.62 cm^2) and bispyribac sodium + 0.1 per cent nano urea (426.40 cm^2) respectively. The lowest leaf area (237.44 cm^2) was recorded in the weedy check. At the panicle initiation stage, higher leaf area per hill (697.50 cm²) was observed in the weed-free check, and was comparable with penoxsulam + cyhalofop-butyl + 0.1 per cent nano urea (634.12 cm²). Weedy check recorded the lowest value (219.77 cm²).

Table 2. Effect of nano urea combined with post-emergence herbicides on plant height, cm

Treatments	Plant height (cm)		
	Active Tillering	Panicle Initiation	Flowering
T_1-Penoxsulam+cyhalofop-butyl+0.2% nano urea	30.76 ± 11.10	57.14 ± 4.34^{cde}	78.48 ± 8.13^{bcd}
T_2-Penoxsulam + cyhalofop-butyl+ 0.1% nano urea	35.76 ± 8.71	64.52 ± 5.89^{ab}	89.55 ± 0.21^{a}
T_3-Penoxsulam +cyhalofop-butyl+0.05% nano urea	35.05 ± 5.74	58.49 ± 1.86^{bcd}	80.83 ± 9.43^{bc}
T_4-Bispyribac-sodium + 0.2% nano urea	33.79 ± 3.84	49.15 ± 2.19^{fgh}	69.27 ± 1.88^{e}
T_5-Bispyribac-sodium +0.1% nano urea	37.33 ± 0.16	54.84 ± 6.17^{cdef}	77.08 ± 7.80^{bcde}
T_6-Bispyribac-sodium+0.05% nano urea	34.90 ± 0.30	53.98 ± 6.97^{cdef}	71.00 ± 3.11^{de}
T_7-Fenoxaprop-p-ethyl+ ethoxysulfuron+0.2% nano urea	37.07 ± 0.19	55.33 ± 0.57^{cdef}	76.25 ± 0.77^{cde}
T_8-Fenoxaprop-p-ethyl+ethoxysulfuron+0.1% nano urea	38.99 ± 1.26	59.47 ± 1.61^{bc}	77.80 ± 1.76^{bc}
T_9-Fenoxaprop-p-ethyl +ethoxysulfuron +0.05% nano urea	41.83 ± 1.24	66.43 ± 4.07^{a}	84.25 ± 0.07^{ab}
T_{10}-Penoxsulam +cyhalofop-butyl	35.62 ± 1.20	52.81 ± 0.98^{defg}	76.91 ± 1.96^{bcd}
T_{11}-Bispyribac-sodium	32.74 ± 3.61	46.34 ± 3.38^{gh}	73.06 ± 0.90^{cde}
T_{12}-Fenoxaprop-p-ethyl +ethoxysulfuron	33.60 ± 0.51	51.46 ± 0.71^{efgh}	72.25 ± 4.17^{de}
T_{13}-Weed-free check	40.28 ± 1.73	67.46 ± 0.91^{a}	90.90 ± 1.40^{a}
T_{14}-Weedy check	28.97 ± 1.75	46.05 ± 6.44^{h}	60.45 ± 0.49^{f}
SEm (±)	2.877	2.177	2.616
CD (0.05)	NS	6.65	7.99

Table 3. Effect of nano urea combined with post-emergence herbicides on the number of tillers per hill

Treatments	Number of tillers per hill		
	Active Tillering	Panicle Initiation	Flowering
T_1-Penoxsulam+cyhalofop-butyl+0.2% nano urea	10.91±0.12^{de}	11.83±0.71^{de}	11.50±0.71^{c}
T_2-Penoxsulam + cyhalofop-butyl+ 0.1% nano urea	14.16±0.23^{b}	14.41±0.59^{bc}	13.00±0.23^{b}
T_3-Penoxsulam +cyhalofop-butyl+0.05% nano urea	12.91±0.12^{bc}	13.25±0.35^{bcd}	12.50±0.71^{c}
T_4-Bispyribac-sodium + 0.2% nano urea	8.50±0.94^{g}	9.16±1.65^{f}	8.41±0.83^{e}
T_5-Bispyribac-sodium +0.1% nano urea	10.59±0.59^{e}	10.75±0.59^{ef}	10.09±0.12^{d}
T_6-Bispyribac-sodium+0.05% nano urea	9.10±0.99^{fg}	9.41±0.59^{f}	9.58±0.59^{de}
T_7-Fenoxaprop-p-ethyl+ ethoxysulfuron+0.2% nano urea	12.08±0.35^{cd}	12.50±0.71^{cde}	11.58±0.82^{c}
T_8-Fenoxaprop-p-ethyl+ethoxysulfuron+0.1% nano urea	13.18±0.96^{bc}	13.27±0.84^{bcd}	12.41±0.83^{bc}
T_9-Fenoxaprop-p-ethyl +ethoxysulfuron +0.05% nano urea	14.29±0.87^{b}	14.50±0.71^{b}	13.25±1.06^{b}
T_{10}-Penoxsulam +cyhalofop-butyl	10.08±0.11^{ef}	11.50±0.71^{de}	11.66±0.23^{c}
T_{11}-Bispyribac-sodium	8.91±0.12^{fg}	9.34±0.47^{f}	9.17±0.71^{de}
T_{12}-Fenoxaprop-p-ethyl +ethoxysulfuron	11.35±0.92^{de}	11.91±1.53^{de}	11.59±0.59^{c}
T_{13}-Weed-free check	15.92±1.07^{a}	17.16±1.18^{a}	16.25±1.77^{a}
T_{14}-Weedy check	5.50±0.23^{h}	7.08±1.29^{g}	5.83±0.47^{f}
SEm (±)	0.481	0.651	0.404
CD (0.05)	1.47	1.99	1.24

At the flowering stage, weed-free check continued to record higher leaf area (732.38 cm²), which was on par with penoxsulam + cyhalofop-butyl + 0.1 per cent nano urea (676.46 cm²) and fenoxaprop-p-ethyl + ethoxysulfuron + 0.05 per cent nano urea (671.75 cm²). Herbicide alone treatments, penoxsulam + cyhalofop-butyl, fenoxaprop-p-ethyl + ethoxysulfuron, recorded values of 512.29 cm² and 504.96 cm², respectively. The lowest leaf area (243.43 cm²) was observed in the weedy check. The higher leaf area per hill recorded under the treatments receiving penoxsulam + cyhalofop-butyl and fenoxaprop-p-ethyl + ethoxysulfuron in combination with nano urea could be due to the combined effect of effective weed suppression and improved nitrogen availability to the crop. Efficient control of weeds during the early growth stages reduces crop-weed competition for essential resources such as nutrients, light and moisture, thereby promoting better vegetative growth and leaf expansion in rice plants. Effective herbicide application enables the crop to utilize available nutrients more efficiently and develop a larger canopy, resulting in increased leaf area per hill. Similar findings were reported by Bhullar *et al*. (2016), who observed that tank-mix application of herbicides such as fenoxaprop-p-ethyl with ethoxysulfuron effectively controlled complex weed flora and improved crop growth attributes, including leaf area development in dry-seeded rice. Hossain and Malik (2017) also reported that the application of penoxsulam + cyhalofop-butyl provided effective weed control and significantly improved vegetative growth parameters in rice.

Foliar application of nano urea might have enhanced leaf area development through improved nitrogen use efficiency and nutrient assimilation in rice. Nitrogen plays an important role in chlorophyll synthesis, cell division and leaf expansion, which supports canopy development and increases photosynthetic surface area. Middle et al. (2022) reported that nano urea application significantly improved growth parameters such as plant height, tiller production and leaf area index in rice. Similarly, Bhargavi & Sundari (2023) observed higher leaf area and improved vegetative growth of rice with foliar application of nano urea.

3.4 Flag Leaf Area Per Hill

There was significant variation in flag leaf area per hill among the treatments, and the data are presented in Table 5. Weed-free check recorded the highest flag leaf area per hill (267.49 cm^2) compared to all other treatments. Among the herbicide and nano urea combinations, foliar application of nano urea @ 0.1 per cent along with (penoxsulam + cyhalofop-butyl) recorded a higher flag leaf area per hill (232.18 cm^2), which was comparable with fenoxaprop-p-ethyl + ethoxysulfuron + 0.05 per cent nano urea (226.66 cm^2). The increase in flag leaf area might be attributed to effective weed suppression in the treated plots, which reduced crop-weed competition for nutrients, moisture and light. The reduction in weeds created favourable growth conditions for the crop, resulting in improved vegetative growth and development with larger and more vigorous leaves that contributed to higher flag leaf area. Similar observations in cereals were given by Iqbal & Wright (1997) and Zare et al. (2016).

Table 4. Effect of nano urea combined with post-emergence herbicides on leaf area per hill, cm^2

Treatments	Leaf area per hill (cm^2)		
	Active Tillering	Panicle Initiation	Flowering
T_1-Penoxsulam+cyhalofop-butyl+0.2% nano urea	431.62± 0.61^{bcde}	498.08±6.06^{cd}	543.31±28.48^{c}
T_2-Penoxsulam + cyhalofop-butyl+ 0.1% nano urea	499.70± 10.08^{b}	634.12±68.18^{ab}	676.46±63.97^{ab}
T_3-Penoxsulam +cyhalofop-butyl+0.05% nano urea	471.44± 11.80^{bc}	552.64±31.95^{c}	634.50±63.45^{b}
T_4-Bispyribac-sodium + 0.2% nano urea	379.92± 56.15^{de}	450.03±79.88^{de}	463.16±71.46^{d}
T_5-Bispyribac-sodium +0.1% nano urea	426.40± 15.26^{bcde}	515.20±12.69^{cd}	544.89±25.31^{c}
T_6-Bispyribac-sodium+0.05% nano urea	389.40± 44.40^{de}	454.23±63.64^{de}	487.60±16.46^{cd}
T_7-Fenoxaprop-p-ethyl+ ethoxysulfuron+0.2% nano urea	376.22± 66.07^{de}	452.79±46.54^{de}	511.67±28.89^{cd}
T_8-Fenoxaprop-p-ethyl+ethoxysulfuron+0.1% nano urea	438.52± 22.08^{bcd}	502.39±7.04^{cd}	532.23±29.74^{c}
T_9-Fenoxaprop-p-ethyl +ethoxysulfuron +0.05% nano urea	489.47± 5.18^{b}	625.21±68.84^{b}	671.75±65.96^{ab}
T_{10}-Penoxsulam +cyhalofop-butyl	410.36±7.33^{cde}	481.58±10.44^{d}	512.29±0.57^{cd}
T_{11}-Bispyribac-sodium	362.25±66.20^{e}	407.92±39.19^{e}	455.31±59.89^{d}
T_{12}-Fenoxaprop-p-ethyl +ethoxysulfuron	370.36±67.96^{d}	467.12±7.07^{de}	504.96±6.69^{cd}
T_{13}-Weed-free check	587.82± 19.26^{a}	697.50±2.62^{a}	732.38±33.58^{a}
T_{14}-Weedy check	237.44± 48.46^{f}	219.77±7.91^{f}	243.43±9.23^{e}
SEm (±)	24.488	22.325	21.875
CD (0.05)	74.81	68.21	66.83

3.5 Total Dry Matter Production

The data on total dry matter production at the harvest stage as influenced by different treatments are presented in Table 6. Significant difference in total dry matter production was observed due to treatments at the harvest stage. Among the herbicide + nano urea combinations, penoxsulam + cyhalofop-butyl + 0.1 per cent nano urea resulted in higher total dry matter production (6215.50 kg ha^{-1}), which was statistically on par with weed-free check (6183.00 kg ha^{-1}), fenoxaprop-p-ethyl + ethoxysulfuron + 0.05 per cent nano urea (6191.00 kg ha^{-1}) and fenoxaprop-p-ethyl + ethoxysulfuron + 0.1 per cent nano urea (5462.00 kg ha^{-1}). Among herbicide alone treatments, penoxsulam + cyhalofop-butyl recorded higher dry matter production (4477.00 kg ha^{-1}) and was statistically comparable with fenoxaprop-p-ethyl + ethoxysulfuron (4463.00 kg ha^{-1}) and bispyribac sodium (4083.50 kg ha^{-1}), whereas the weedy check showed the lowest dry matter production (2493.00 kg ha^{-1}). The increased total dry matter production observed with the application of post-emergence herbicides such as penoxsulam + cyhalofop-butyl and fenoxaprop-p-ethyl + ethoxysulfuron, in combination with nano urea, could be attributed to efficient weed suppression during the critical period of crop weed competition.

Table 5. Effect of nano urea combined with post-emergence herbicides on flag leaf area per hill, cm^2

Treatments	Flag leaf area per hill
T_1-Penoxsulam+cyhalofop-butyl+0.2% nano urea	179.22±13.07^{cd}
T_2-Penoxsulam + cyhalofop-butyl+ 0.1% nano urea	232.18± 6.34^{b}
T_3-Penoxsulam +cyhalofop-butyl+0.05% nano urea	179.26± 9.17^{cd}
T_4-Bispyribac-sodium + 0.2% nano urea	158.30± 7.70^{e}
T_5-Bispyribac-sodium +0.1% nano urea	194.17±11.00^{c}
T_6-Bispyribac-sodium+0.05% nano urea	169.23± 8.63^{de}
T_7-Fenoxaprop-p-ethyl+ ethoxysulfuron+0.2% nano urea	168.42± 1.15^{de}
T_8-Fenoxaprop-p-ethyl+ethoxysulfuron+0.1% nano urea	181.33± 8.61^{cd}
T_9-Fenoxaprop-p-ethyl +ethoxysulfuron +0.05% nano urea	226.66±20.31^{b}
T_{10}-Penoxsulam +cyhalofop-butyl	162.45± 1.15^{de}
T_{11}-Bispyribac-sodium	152.74± 9.39^{e}
T_{12}-Fenoxaprop-p-ethyl +ethoxysulfuron	161.56± 2.10^{de}
T_{13}-Weed-free check	267.49± 1.87^{a}
T_{14}-Weedy check	69.02±13.76^{f}
SEm (±)	6.708
CD (0.05)	20.49

Table 6. Effect of nano urea combined with post-emergence herbicides on total dry matter production, kg ha^{-1}

Treatments	Total Dry Matter Production
T_1-Penoxsulam+cyhalofop-butyl+0.2% nano urea	5039.50±75.66^{bc}
T_2-Penoxsulam + cyhalofop-butyl+ 0.1% nano urea	6215.50±149.20^{a}
T_3-Penoxsulam +cyhalofop-butyl+0.05% nano urea	5329.50±208.60^{b}
T_4-Bispyribac-sodium + 0.2% nano urea	4806.50±803.98^{bcd}
T_5-Bispyribac-sodium +0.1% nano urea	5177.50±439.11^{bc}
T_6-Bispyribac-sodium+0.05% nano urea	4715.00±165.46^{bcd}
T_7-Fenoxaprop-p-ethyl+ ethoxysulfuron+0.2% nano urea	5245.50±198.70^{bc}
T_8-Fenoxaprop-p-ethyl+ethoxysulfuron+0.1% nano urea	5462.00±366.28^{ab}
T_9-Fenoxaprop-p-ethyl +ethoxysulfuron +0.05% nano urea	6191.00±151.32^{a}
T_{10}-Penoxsulam +cyhalofop-butyl	4477.00±374.77^{cd}
T_{11}-Bispyribac-sodium	4083.50±51.62^{d}
T_{12}-Fenoxaprop-p-ethyl +ethoxysulfuron	4463.00±246.07^{cd}
T_{13}-Weed-free check	6183.00±233.35^{a}
T_{14}-Weedy check	2493.00±685.89^{e}
SEm (±)	259.259
CD (0.05)	792.09

Similar findings were reported by Patil et al. (2016), who observed higher dry matter accumulation in rice with the application of penoxsulam + cyhalofop-butyl due to improved weed control efficiency. Likewise, Rao et al. (2021) reported increased crop biomass with fenoxaprop-p-ethyl + ethoxysulfuron due to effective suppression of dominant weeds in direct-seeded rice. In addition, foliar application of nano urea might have enhanced dry matter production through improved nitrogen use efficiency, increased photosynthetic activity and better nutrient assimilation in rice plants, as reported by Namasharma et al. (2023).

4. Conclusion

It can be concluded that the treatment combination penoxsulam + cyhalofop butyl, combined with nano urea @ 0.1 per cent, recorded higher growth attributes of aerobic rice such as plant height, number of tillers per hill, leaf area, flag leaf area and total dry matter production, which was also found statistically at par with fenoxaprop-p-ethyl + ethoxysulfuron combined with nano urea @ 0.05 per cent.

Disclaimer (Artificial Intelligence)

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

Competing Interests

Authors have declared that no competing interests exist.

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