

PRODUCTIVITY AND PROFITABILITY OF SHORT DURATION MONSOON RICE UNDER VARYING RICE ESTABLISHMENT METHODS AND WEED MANAGEMENT PRACTICES

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Abstract

A field experiment was conducted at Bangladesh Agricultural University, Mymensingh during the *aman* season of 2024 to assess the effects of rice establishment methods and weed management practices on weed pressure, crop performance, and the economic profitability of Binadhan-7, a short-duration monsoon rice (*aman*) variety. Three establishment methods *viz.* (i) zero-till non-puddled transplanted (ZT-NPT) (ii) reduced-till non-puddled transplanted (RT-NPT) and (iii) puddled transplanted (PT) rice, and six weed management practices *viz.* (i) Season-long weedy (W₀), (ii) Season-long weed free (W₁), (iii) Two hand weeding at 30 and 45 days after transplanting (DAT) (W₂), (iv) Pre-emergence herbicide (Pretilachlor) + One hand weeding at 45 DAT (W₃), (v) Pre + post-emergence herbicide (Penoxsulam) (W₄), (vi) Post-emergence herbicide + One hand weeding at 45 DAT (W₅) were tested in a split-plot design with three replications. Twelve weed species belonging to seven families infested the experimental plots, with the highest weed density and dry weight recorded under ZT-NPT, particularly in season-long weedy plots (W₀). ZT-NPT produced the highest grain (4.65 t ha⁻¹), straw (7.74 t ha⁻¹), and biological yields (12.39 t ha⁻¹). Among weed management practices, season-long weed-free conditions (W₁) resulted in the highest grain yield, while integrated weed control performed comparably. The interaction of zero-till non-puddled transplanting with post-emergence herbicide followed by one hand weeding at 45 DAT produced the maximum grain yield (4.99 t ha⁻¹) and the highest economic return (BCR 2.55). In conclusion, combining conservation tillage with integrated weed management proved to be the most productive and economically viable strategy for sustainable *aman* rice production.

Keywords: Conservation tillage, integrated weed management, weed dynamics, economic return, rice establishment methods, benefit cost ratio

INTRODUCTION

Rice (*Oryza sativa* L.) is not merely a crop in Bangladesh; it is the lifeblood of the nation's food security and the cornerstone of daily sustenance. As the principal staple food, the crop dominates both agricultural landscapes and dietary patterns across the country (USDA, 2024). With an annual production of approximately 36.6 million metric tons, Bangladesh stands as the world's 3rd largest rice producer, surpassed only by China and India (USDA, 2024). Cultivation of rice in Bangladesh follows a unique seasonal rhythm, spanning three distinct growing periods: *aus* (summer), *aman* (monsoon), and *boro* (winter). Among these, the *aman* season, extending from July to November emerges as the most prominent, covering the largest cultivation area as a single crop (Sayeed and Yunus, 2018) and contributing about 37.90% of the country's total rice production (APCAS, 2016).

The most popular technique for establishing rice crops is transplanting in puddled soils (heavy tillage in ponded conditions) with ongoing flooding. Puddling requires significant amounts of water, time, and energy. Frequent puddling breaks down soil aggregates that leads to a compacted surface layer and a shallow plow pan (Bastola, 2020; Upasani and Barla, 2022). Non-puddled transplanted rice enables minimal or no soil disturbance, lowers tillage expenses, conserves water by eliminating puddling, may enhance profit and energy efficiency without sacrificing yield quality (Haque *et al.*, 2016; Chaki *et al.*,

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2021). In rice-based systems, conservation tillage has been demonstrated to enhance crop productivity and soil health (Sarker *et al.*, 2022). FAO (2016) states that conservation agriculture techniques, such as zero and reduced tillage, can improve resilience in rice production systems and lessen the effects of climate change. Tillage and crop establishment methods significantly influence rice yield (Saini *et al.*, 2023) and strongly affects soil biological properties such as soil microbial biomass carbon, dehydrogenase activity and microbial count as well as soil physical properties, including soil bulk density, soil penetration resistance, plant available water content, infiltration and hydraulic conductivity (Jiang *et al.*, 2021; Bhattacharya *et al.*, 2023; Tater and Vashisht, 2024). Several studies also revealed that tillage and crop establishment methods influence weed density and diversity in rice fields by altering weed seed banks and species composition (Punia *et al.*, 2016; Mishra *et al.*, 2022). Punia *et al.* (2016), reported reduced grain yield in rice planted under zero tillage or minimum tillage conditions due to more weed infestation. Effective weed management is critical in conservation tillage systems, particularly for non-puddled transplanted *aman* rice, where herbicides play a vital role in maintaining yields (Zander *et al.*, 2017). Although puddled transplanting provides effective weed control, maintaining flooded field conditions is labor-intensive, operationally cumbersome, costly, and time-consuming (Upasani and Barla, 2022).

However, the effectiveness of agricultural production is profoundly associated with weed infestation. Weed competition poses a significant risk to rice cultivation by intensifying interference for moisture, light, and nutrients, while also acting as alternative hosts for pests and diseases (Singh *et al.*, 2020), resulting in substantial yield losses (up to 79–83% under uncontrolled conditions) and diminished profitability. Yield losses due to inadequate weed management in Bangladesh have been reported to range from 4 to 22%, depending on the rice ecosystem. To enhance both economic returns and sustainable rice production, the adoption of cost-effective, integrated weed management strategies is essential. Timely and appropriate implementation of these techniques can substantially reduce yield losses, with the potential to increase national rice production by approximately 0.43 million tons by 2030 (Bhuiyan *et al.*, 2021).

Although rice establishment methods and weed management practices have been studied individually, limited research in Bangladesh has examined their combined effects on the productivity and profitability, particularly for short-duration *aman* rice varieties. Therefore, the present study aims to evaluate the effects of different rice establishment methods and weed management practices on weed pressure, crop performance, and economic profitability of Binadhan-7, a short duration *aman* rice variety.

MATERIALS AND METHOD

Experimental site and plant material

The experiment was conducted at the Old Brahmaputra Floodplain Agro-ecological Zone (AEZ-9) located at 24°43'09.0"N latitude and 90°25'42.1"E longitude with an altitude of 18 m above sea level. The soil was non-calcareous dark-grey floodplain soil, silty-loam in texture, moderately fertile, nearly neutral in pH (6.8), and low in organic matter (1.29%). The climate of the area is tropical with high temperature, humidity, and rainfall during the *khari*f season. The rice variety used was Binadhan-7, a short-duration, high-yielding transplanted *aman* rice developed by Bangladesh Institute of Nuclear Agriculture (BINA) with a crop duration of 110-120 days and average yield of 5.0 to 5.5 t ha⁻¹.

Experimental design and crop management

The experiment comprised three rice establishment methods *viz.*, (i) Zero-till non-puddled transplanted (ZT-NPT), (ii) Reduced-till non-puddled transplanted (RT-NPT), and (iii) Puddled Transplanted (PT), and six weed management practices *viz.*, (i) Season-long weedy (W₀), (ii) Season-long weed free (W₁),

(iii) Two hand weeding at 30 and 45 days after transplanting (DAT) (W_2), (iv) Pre-emergence herbicide (Pretilachlor) applied at 5 DAT + one hand weeding at 45 DAT (W_3), (v) Pre- at 5 DAT + post-emergence herbicide (Penoxsulam) at 15 DAT (W_4), (vi) Post-emergence herbicide at 15 DAT + one hand weeding at 45 DAT (W_5). The experiment was laid out in a Split-plot design with three replications, where the rice establishment methods were applied to main plots and weed management practices were in sub-plots. A total of 54 plots ($3 \times 6 \times 3$) were used with a plot size of $4.0 \text{ m} \times 2.5 \text{ m}$. A brief description of the herbicides used in the experiment along with their trade name, common name, selectivity, mode of application and their marketing company are shown in Table 1.

Table 1. Trade name, common name, selectivity, mode of application of herbicides and their marketing company

Trade name	Common name	Selectivity	Mode of application	Marketing company	Recommended dose
Superhit 500 EC	Pretilachlor	Grass and broadleaf	Pre-emergence	ACI Formulations Ltd.	@ 988 mL ha ⁻¹
Granite 240 SC	Penoxsulam	Grass, broadleaf and sedge	Post-emergence	Auto Crop Care Ltd.	@ 93.70 mL ha ⁻¹

Thirty-day-old seedlings were transplanted at spacing of $25 \text{ cm} \times 15 \text{ cm}$ with three seedlings hill⁻¹. Fertilizers were applied in the field as per recommendation of BINA *i.e.* 180 kg urea, 120 kg triple super phosphate, 70 kg muriate of potash, 6 kg of zinc sulphate and 55 kg gypsum ha⁻¹. Except urea all other fertilizers were applied as basal. On the other hand, urea was top dressed in three installments at 15, 30, and 45 DAT. Weed control and herbicide treatments were applied according to the experimental treatments.

Data collection procedure

Data on weed population were collected from each plot by using $0.5 \text{ m} \times 0.5 \text{ m}$ quadrat (placed in 3 places) as per method described by Cruz *et al.*, (1986). The weeds within the quadrat were counted at 30 DAT, 45 DAT, 60 DAT and accordingly weed density was expressed as no. m⁻². After counting the weed density, the weeds inside each quadrat were uprooted, cleaned, separated species-wise and dried first in the sun and then in an electric oven for 72 hours at a temperature 80°C. Then the dry weight of each species was taken by an electric balance and expressed in grams.

Five hills (excluding border hill) were randomly selected from each plot before harvest for recording necessary data on various plant characters and $2.0 \text{ m} \times 1.5 \text{ m}$ area of each plot harvested for grain and straw yields. The data on number of total tillers hill⁻¹, effective tillers hill⁻¹, grains panicle⁻¹, total spikelet's panicle⁻¹, panicle length and weight of 1000 grains (at 14% moisture content) were measured. After harvesting, grain yield (at 14% moisture content) and dried straw yield were recorded and converted to t ha⁻¹. Grain yield and straw yield are altogether regarded as biological yields. Harvest index of each plot was calculated by using the following formula:

$$\text{Harvest index (\%)} = \frac{\text{Grain Yield}}{\text{Biological Yield}} \times 100$$

Statistical analysis

The recorded data on various plant characters were statistically analyzed. The mean of all treatments was calculated and the analysis of variance for each of the characters under study was done with the help of Microsoft Excel, Statistics 10 software. The difference among treatment means were compared by Duncan's New Multiple Range Test (Gomez and Gomez, 1984).

RESULTS

Floristic composition of the weeds

The zero-till non-puddled transplanted field was infested by seven weed species belonging to two families, whereas the reduced-till non-puddled transplanted rice field recorded six weed species from three families. In contrast, the puddled transplanted field exhibited the highest weed diversity, with nine species belonging to seven families. Local name, scientific name, family, morphological type and life cycle of the weeds in the experimental plots are presented in the Table 2.

Table 2. Infesting weed species under different rice establishment methods

Sl. No	Local Name	Scientific Name	Family	Morphological Type	Life Cycle	Zero-till Non-puddled	Reduced-till Non-puddled	Puddled Transplanted
1	Shama	<i>Echinochloa crus-galli</i>	Poaceae	Grass	Annual	✓	✓	✓
2	Sabuj Nakful	<i>Cyperus difformis</i>	Cyperaceae	Sedge	Annual	✓	✓	✓
3	Joina	<i>Fimbristylis miliacea</i>	Cyperaceae	Sedge	Annual	✓	✓	✓
4	Khudey Shama	<i>Echinochloa colonum</i>	Poaceae	Grass	Annual	✓	✓	✓
5	Durba	<i>Cynodon dactylon</i>	Poaceae	Grass	Perennial	✓	✓	–
6	Mutha	<i>Cyperus rotundus</i>	Cyperaceae	Sedge	Perennial	✓	–	–
7	Chapra	<i>Scirpus juncoides</i>	Cyperaceae	Sedge	Annual	✓	–	–
8	Jheel Morich	<i>Sphenoclea zeylanica</i>	Sphenocleaceae	Broadleaf	Annual	–	✓	✓
9	Chanchi	<i>Alternanthera sessilis</i>	Amaranthaceae	Broadleaf	Perennial	–	–	✓
10	Pani Kochu	<i>Monochoria vaginalis</i>	Pontederiaceae	Broadleaf	Annual	–	–	✓
11	Pani Long	<i>Ludwigia octovalvis</i>	Onagraceae	Broadleaf	Perennial	–	–	✓
12	Halud Nakful	<i>Spilanthes iabadicensis</i>	Asteraceae	Broadleaf	Annual	–	–	✓

Weed density and dry weight

Effect of rice establishment methods on weed density and dry weight

Rice establishment methods significantly affected weed density at 30 and 45 DAT (Fig. 1), whereas weed dry weight did not differ significantly at these stages (Fig. 2). By 60 DAT, weed density showed no significant variation among establishment methods, however, weed dry weight differed significantly ($p < 0.05$). At 30 DAT, the highest weed density was recorded in ZT-NPT (21.44 m⁻²), followed by RT-

NPT (14.22 m^{-2}), while PT had the lowest weed density (11.22 m^{-2}). A similar trend was observed at 45 DAT. At 60 DAT, puddled tillage recorded the highest weed dry weight (9.03 g m^{-2}), statistically similar to zero tillage (8.79 g m^{-2}). In contrast, reduced tillage showed the lowest weed dry weight (2.67 g m^{-2}), which was significantly lower than both puddled and zero tillage.

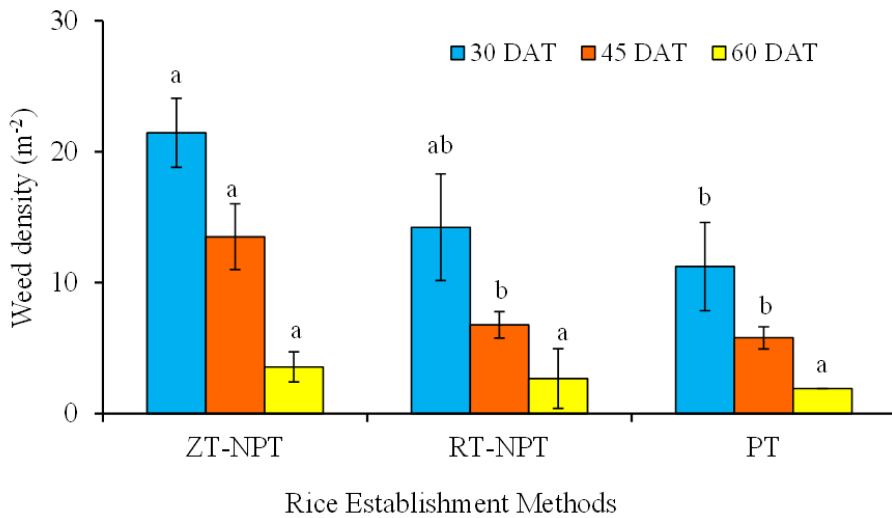


Fig. 1. Weed density m^{-2} in different rice establishment methods. Here, DAT= Days after transplanting, ZT-NPT= Zero-till non-puddled transplanted, RT-NPT = Reduced-till non-puddled transplanted, PT= Puddled tillage.

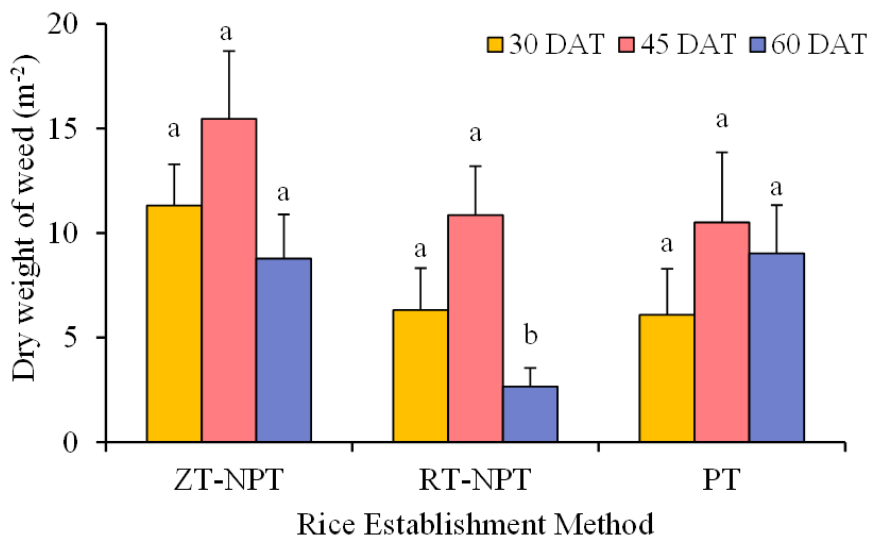


Fig. 2. Weed dry weight (g m^{-2}) in different rice establishment methods. Here, DAT= Days after transplanting, ZT-NPT= Zero-till non-puddled transplanted, RT-NPT = Reduced-till non-puddled transplanted, PT= Puddled tillage.

Effect of different weed management practices on weed density and dry weight

Weed management practices significantly influenced both weed density and weed dry weight throughout the crop growth period (Table 3). Season-long weedy plots (W_0) consistently showed the highest weed density (24.56–14.44 m^{-2}) and dry weight (17.26–33.59 $g m^{-2}$) from 30 to 60 DAT, indicating severe and persistent weed pressure. In contrast, season-long weed-free management (W_1) achieved complete suppression of weeds, with zero density and biomass at all stages. Two hand weeding (W_2) was less effective at early stages but successfully controlled weeds by 60 DAT. Integrated herbicide-based treatments (W_3 and W_4) substantially reduced both weed density and biomass from early stages onward, with W_4 achieving complete weed biomass suppression by 60 DAT and performing statistically similar to W_2 and W_3 .

Table 3. Effect of different weed management practices on weed density and dry weight at different days after transplanting of *aman* rice

Weed management practices	Weed density (no. m^{-2})			Weed dry weight ($g m^{-2}$)		
	Days after transplanting (DAT)					
	30	45	60	30	45	60
W_0	24.56±4.43 ^a	17±5.01 ^a	14.44±1.56 ^a	17.26±5.47 ^a	23.19±3.36 ^a	33.59±0 ^a
W_1	0±0 ^c	0±0 ^c	0±0 ^b	0±0 ^c	0±0 ^c	0±0 ^b
W_2	24.44±5.89 ^a	8.22±0.97 ^b	0±0 ^b	9.17±0.98 ^b	12.31±1.53 ^b	1.53±0 ^b
W_3	15.89±4.56 ^{ab}	10.44±4.7 ^b	0±0 ^b	9.78±1.61 ^b	14.65±0 ^{ab}	0±0 ^b
W_4	10.67±4.29 ^b	8.44±2.84 ^b	0±0 ^b	4.79±1.71 ^{bc}	9.67±0 ^b	0±0 ^b
W_5	18.22±1.56 ^{ab}	8±1.39 ^b	3.11±1.78 ^b	6.47±2.55 ^{bc}	13.84±5.84 ^{ab}	5.84±0 ^b
Level of significance	***	***	***	***	***	***
CV (%)	10.17	5.81	5.56	11.40	17.36	14.87

Means with the same letters or without letters within the same column do not differ significantly. *** = Significant at 0.1% level of probability, W_0 = Season-long weedy, W_1 = Season-long weed free, W_2 = Two hand weeding at 30 and 45 DAT, W_3 = Pre-emergence herbicide + one hand weeding at 45 DAT, W_4 = Pre + post emergence herbicide, W_5 = Post-emergence herbicide + one hand weeding at 45 DAT

Interaction effect of different rice establishment methods and weed management practices on weed density and dry weight

The interaction between rice establishment methods and weed management practices significantly influenced weed density at early stages, although differences were not significant by 60 DAT. Weed dry weight was significantly affected at 30, 45, and 60 DAT ($p < 0.05$) (Table 4). Zero-till non-puddled rice under season-long weedy conditions (ZT-NPT × W_0) consistently recorded the highest weed density (33.00, 27.00, and 16.00 m^{-2} at 30, 45, and 60 DAT, respectively) and weed dry weight (21.88, increasing to 42.07 $g m^{-2}$ by 60 DAT), indicating sustained weed pressure. In contrast, season-long weed-free treatments maintained zero weed density and biomass across all stages. Integrated herbicide-based practices, especially PT × W_4 , substantially reduced both weed density ($\approx 4 m^{-2}$ at 30 and 45 DAT) and weed biomass (1.73 $g m^{-2}$ at 30 DAT), demonstrating superior weed suppression. Although differences in weed density were not statistically significant by 60 DAT, season-long weedy plots continued to show relatively higher weed biomass, particularly under ZT-NPT and PT systems.

Table 4. Interaction effect of rice establishment methods and weed management practices on weed density and dry weight at different days after transplanting of *aman* rice

Interaction	Weed density (no. m ⁻²)			Weed dry weight (g m ⁻²)		
	Days after transplanting (DAT)			Days after transplanting (DAT)		
	30	45	60	30	45	60
ZT-NPT×W ₀	33±0.58 ^a	27±0.58 ^a	16±1.15 ^a	21.88±2.7 ^a	30.2±2.57 ^a	42.07±8.01 ^a
ZT-NPT×W ₁	0±0 ^{cd}	0±0 ^{de}	0±0 ^b	0±0 ^c	0±0 ^c	0±0 ^b
ZT-NPT×W ₂	30.67±1.76 ^a	10±1.15 ^{b-e}	0±0 ^b	9.43±0.59 ^{abc}	14.09±3.63 ^{abc}	0±0 ^b
ZT-NPT×W ₃	25±1.73 ^{ab}	19.33±7.33 ^{ab}	0±0 ^b	18.38±0.94 ^{ab}	17.85±6.04 ^{abc}	0±0 ^b
ZT-NPT×W ₄	18.67±1.76 ^{a-d}	14±2.31 ^{bc}	0±0 ^b	9.73±2.91 ^{abc}	17.26±5.01 ^{abc}	0±0 ^b
ZT-NPT×W ₅	21.33±9.96 ^{a-d}	10.67±3.71 ^{b-e}	5.33±0 ^{ab}	8.54±4.67 ^{abc}	13.37±2.2 ^{abc}	10.67±10.67 ^b
RT-NPT×W ₀	18±6.93 ^{a-d}	11.33±1.33 ^{b-e}	16±5.29 ^a	11.93±6.02 ^{abc}	16.85±1.37 ^{abc}	16±5.29 ^b
RT-NPT×W ₁	0±0 ^{cd}	0±0 ^{de}	0±0 ^b	0±0 ^c	0±0 ^c	0±0 ^b
RT-NPT×W ₂	30±5.03 ^a	8±1.15 ^{b-e}	0±0 ^b	11.13±1.47 ^{abc}	13.68±6.55 ^{abc}	0±0 ^b
RT-NPT×W ₃	11.33±0.67 ^{a-d}	8.67±1.76 ^{b-e}	0±0 ^b	4.82±1.21 ^{abc}	15.17±2.55 ^{abc}	0±0 ^b
RT-NPT×W ₄	9.33±5.46 ^{a-d}	6.67±0.67 ^{b-e}	0±0 ^b	2.91±1.48 ^{bc}	7.91±1.09 ^{bc}	0±0 ^b
RT-NPT×W ₅	16.67±6.36 ^{a-d}	6±1.15 ^{cde}	0±0 ^b	7.17±1.79 ^{abc}	11.58±2.45 ^{abc}	0±0 ^b
PT×W ₀	22.67±5.46 ^{abc}	12.67±1.76 ^{bcd}	11.33±0 ^{ab}	17.97±7.68 ^{ab}	22.52±5.2 ^{ab}	42.7±8.3 ^a
PT×W ₁	0±0 ^d	0±0 ^e	0±0 ^b	0±0 ^c	0±0 ^c	0±0 ^b
PT×W ₂	12.67±1.76 ^{a-d}	6.67±0.67 ^{b-e}	0±0 ^b	6.97±0.89 ^{abc}	9.17±1.2 ^{abc}	0±0 ^b
PT×W ₃	11.33±6.36 ^{a-d}	3.33±0.67 ^{cde}	0±0 ^b	6.15±2.68 ^{abc}	10.93±4.1 ^{abc}	0±0 ^b
PT×W ₄	4±2 ^{bcd}	4.67±1.33 ^{cde}	0±0 ^b	1.73±0.75 ^{bc}	3.84±0.96 ^{bc}	0±0 ^b
PT×W ₅	16.67±4.67 ^{a-d}	7.33±0.67 ^{b-e}	0±0 ^b	3.7±1.2 ^{bc}	16.57±8.62 ^{abc}	0±0 ^b
Level of significance	*	*	NS	*	*	*
CV (%)	23.66	12.70	13.24	9.74	12.79	17.98

Means with the same letters or without letters within the same column do not differ significantly * = Significant at 5% level of probability, NS = Non-significant, ZT-NPT= Zero-till non-puddled transplanted, RT-NPT = Reduced-till non-puddled transplanted, PT= Puddled tillage, W₀ = Season-long weedy, W₁ = Season-long weed free, W₂ = Two hand weeding at 30 and 45 DAT, W₃ = Pre-emergence herbicide + one hand weeding at 45 DAT, W₄ = Pre + post emergence herbicide, W₅ = Post-emergence herbicide + one hand weeding at 45 DAT

Yield attributes and yield of *aman* rice

Effect of rice establishment methods on the yield attributes and yield of aman rice

Rice establishment methods showed clear trends in influencing yield attributes of *aman* rice (Table 5). Zero-till non-puddled (ZT-NPT) consistently performed better for key yield-contributing traits, the highest number of effective tillers (10.33 hill⁻¹), and the maximum 1000-grain weight (27.69 g). In contrast, reduced-till non-puddled showed superiority in reproductive traits, recording the highest number of total spikelets (146.5 panicle⁻¹) and grains per panicle (129.42). Puddled tillage generally

exhibited lower values for most yield components, particularly spikelets and grains per panicle, although it produced a numerically higher harvest index (39.70%).

Table 5. Effect of rice establishment methods on the yield attributes and yield of *aman* rice

Rice establishment methods	No. of total tillers hill ⁻¹	No. of effective tillers hill ⁻¹	Panicle length (cm)	No. of total spikelets panicle ⁻¹	No. of grains panicle ⁻¹	1000- grain weight (g)	Harvest index (%)
Zero-till non-puddled	12.03	10.33±0.3 ^a	26.18	140.6±2.96 ^b	128.81±2.68 ^a	27.69±0.39 ^a	37.82
Reduced-till non-puddled	12.44	9.36±0.48 ^b	26.67	146.5±2.6 ^a	129.42±2.29 ^a	25.56±0.3 ^b	37.35
Puddled Tillage	11.61	9.27±0.26 ^b	25.42	135.47±2.92 ^c	120.72±2.97 ^b	25.61±0.36 ^b	39.70
Level of significance	NS	*	NS	*	**	**	NS
CV (%)	9.91	4.02	5.39	2.57	2.31	1.51	6.82

Means with the same letters or without letters within the same column do not differ significantly. * = Significant at 5% level of probability, ** = Significant at 1% level of probability, NS = Non-significant

Effect of weed management practices on the yield attributes and yield of *aman* rice

Weed management practices had a significant influence on most yield-contributing traits and the harvest index of *aman* rice (Table 6). As expected, the season-long weed-free treatment (W₁) recorded the highest values for total tillers per hill (13.93), effective tillers per hill (10.28), panicle length (28.30 cm), grains per panicle (134.96), 1000-grain weight (27.31 g), and harvest index (44.01%). Total spikelets panicle⁻¹ were highest in post-emergence herbicide combined with one hand weeding (W₅: 148.94), followed by pre-emergence herbicide plus one hand weeding (W₃: 146.58), while the lowest spikelet (126.86) and grain numbers (111.55) were observed in the pre- and post-emergence herbicide treatment (W₄). Season-long weedy plots (W₀) resulted in lower yield attributes, particularly harvest index (33.78%), indicating adverse effects of weed competition.

Interaction effect of rice establishment methods and weed management practices on the yield attributes and yield of *aman* rice

The interaction between rice establishment methods and weed management practices significantly affected the number of effective tillers hill⁻¹, total spikelets panicle⁻¹, and grains panicle⁻¹ (p < 0.001), whereas total tillers hill⁻¹, panicle length, 1000-grain weight, and harvest index remained statistically unaffected (Table 7). The highest number of effective tillers hill⁻¹ was recorded under ZT-NPT × W₃ (11.84) and PT × W₁ (11.40), while the lowest value was observed in PT × W₀ (7.40). Total spikelets panicle⁻¹ peaked in RT-NPT × W₃ (173.5) and RT-NPT × W₁ (172.5), whereas the minimum was recorded in PT × W₀ (120.5). Similarly, the maximum number of grains panicle⁻¹ was obtained under RT-NPT × W₁ (143.33) and PT × W₅ (142.33), in contrast to the lowest value under ZT-NPT × W₄ (104.67). Across all establishment methods, season-long weedy plots (W₀) consistently produced lower values of effective tillers and panicle traits, while weed-free (W₁) and integrated weed management practices (W₃ and W₅) maintained superior yield-contributing attributes.

Table 6. Effect of weed management practices on the yield attributes and yield of *aman* rice

Weed management practices	No. of total tillers hill ⁻¹	No. of effective tillers hill ⁻¹	Panicle length (cm)	No. of total spikelets panicle ⁻¹	No. of grains panicle ⁻¹	1000-grain weight (g)	Harvest index (%)
W ₀	11.53±0.4 8 ^b	9.51±0.3 ^a b	25.85±0.9 4 ^{ab}	141.33±1.9 ^a b	127.56±1.5 3 ^{bc}	26.03±0.2 3 ^b	33.78±1.9 ^b
W ₁	13.93±0.4 5 ^a	10.28±0.2 2 ^a	28.3±0.84 ^a	144.32±1.6 7 ^{ab}	134.96±2.3 6 ^a	27.31±0.7 2 ^a	44.01±2.8 1 ^a
W ₂	12.06±0.2 7 ^b	9.51±0.5 ^a b	25.6±0.8 ^{ab}	137.1±3.21 b	122.8±2.7 ^c	26.36±0.2 ab	37.15±2.1 1 ^{ab}
W ₃	11.51±0.3 5 ^b	9.92±0.36 ab	25.95±1.0 5 ^{ab}	146.58±3.3 ^a	127.07±3.3 7 ^{bc}	26.02±0.2 5 ^b	38.56±3.7 4 ^{ab}
W ₄	11.72±0.3 5 ^b	9.65±0.33 ab	24.43±1.3 7 ^b	126.86±3.0 ^c	111.55±2.7 2 ^d	25.89±0.3 8 ^b	38.25±2.1 3 ^{ab}
W ₅	11.41±0.2 6 ^b	9.02±0.36 b	26.38±0.9 8 ^{ab}	148.94±3.8 4 ^a	133.95±3.2 ^a b	26.11±0.3 1 ^b	37.97±1.9 7 ^{ab}
Level of sig.	***	*	**	***	***	**	**
CV (%)	5.75	7.80	7.49	4.11	3.96	2.90	13.40

Means with the same letters or without letters within the same column do not differ significantly. * = Significant at 5% level of probability, ** = Significant at 1% level of probability, *** = Significant at 0.1% level of probability, NS = Non-significant, W₀ = Season-long weedy, W₁ = Season-long weed free, W₂ = Two hand weeding at 30 and 45 DAT, W₃ = Pre-emergence herbicide + one hand weeding at 45 DAT, W₄ = Pre + post emergence herbicide, W₅ = Post-emergence herbicide + one hand weeding at 45 DAT. Level of Sig. = Level of Significance.

Grain, straw and biological yields

Effect of rice establishment methods on grain, straw and biological yields

Rice establishment methods had a significant influence on grain, straw, and biological yields (Fig. 3). Among the treatments, zero-till non-puddled resulted in the highest grain yield (4.65 t ha⁻¹), straw yield (7.74 t ha⁻¹), and biological yield (12.39 t ha⁻¹), followed by puddled and reduced-till non-puddled. Reduced-till non-puddled showed the lowest values across all yield parameters, with grain, straw, and biological yields recorded at 3.15, 5.22, and 8.37 t ha⁻¹, respectively. Puddled-till non-puddled was intermediate, with a grain yield of 4.07 t ha⁻¹ and biological yield of 10.36 t ha⁻¹.

Effect of different weed management practices on grain, straw and biological yields

Weed management had a significant effect on grain yield but not on straw or biological yield (Fig. 4). The highest grain yield (4.51 t ha⁻¹) was recorded in the season-long weed-free treatment (W₁), which was significantly higher than the weedy check (W₀: 3.44 t ha⁻¹). Other treatments such as two hand weeding (W₂: 4.00 t ha⁻¹), post-emergence herbicide with one hand weeding (W₅: 4.06 t ha⁻¹), and pre- and post-emergence herbicide (W₄: 3.87 t ha⁻¹) produced intermediate yields without significant differences among them.

Table 7. Interaction effect of rice establishment methods and weed management practices on the yield attributes and yield of *aman* rice

Interaction	No. of total tillers hill ⁻¹	No. of effective tillers hill ⁻¹	Panicle length (cm)	No. of total spikelets panicle ⁻¹	No. of grains panicle ⁻¹	1000-grain weight (g)	Harvest index (%)
ZT-NPT×W ₀	10.80	10.44±0.19 ^{a-e}	26.55	146±2.23 ^{b-d}	118.67	27.51	34.26
ZT-NPT×W ₁	11.60	10.15±0.02 ^{a-e}	27.91	133.95±0.95 ^{d-f}	119.67	28.51	40.60
ZT-NPT×W ₂	12.93	11.26±0.63 ^{a-c}	25.47	137.81±1.27 ^{c-f}	109.00	28.01	34.80
ZT-NPT×W ₃	12.40	11.84±0.5 ^a	26.19	138.92±5.09 ^{c-e}	126.00	27.44	39.33
ZT-NPT×W ₄	11.33	9.26±0.12 ^{b-f}	22.96	124.58±3.87 ^{ef}	104.67	27.10	42.15
ZT-NPT×W ₅	10.53	9.04±0.33 ^{c-f}	27.98	162.31±4.31 ^{ab}	125.00	27.59	35.77
RT-NPT×W ₀	11.53	10.7±0.4 ^{a-d}	26.33	157.5±0.29 ^{ab}	134.33	25.10	32.28
RT-NPT×W ₁	12.73	9.3±0.17 ^{b-f}	28.67	172.5±1.44 ^a	143.33	26.80	45.31
RT-NPT×W ₂	10.67	8.67±0.77 ^{d-f}	25.33	120±3.46 ^f	118.33	25.40	37.93
RT-NPT×W ₃	11.00	8.53±0.24 ^{d-f}	28.00	173.5±0.87 ^a	140.67	25.37	32.94
RT-NPT×W ₄	13.07	10.6±0.81 ^{a-e}	26.00	133.5±3.75 ^{d-f}	126.33	25.24	36.37
RT-NPT×W ₅	10.07	8.33±0.47 ^{ef}	25.67	122±5.77 ^{ef}	122.67	25.47	39.24
PT×W ₀	9.67	7.4±0.3 ^f	24.67	120.5±3.18 ^f	122.33	25.49	34.80
PT×W ₁	12.93	11.4±0.46 ^{ab}	28.33	126.5±2.6 ^{ef}	111.33	26.63	46.11
PT×W ₂	11.73	8.6±0.12 ^{d-f}	26.00	153.5±4.91 ^{bc}	130.67	25.67	38.74
PT×W ₃	11.47	9.4±0.35 ^{b-f}	23.67	127.33±3.93 ^{ef}	112.67	25.26	43.41
PT×W ₄	13.07	9.1±0.06 ^{b-f}	24.33	122.5±1.44 ^{ef}	124.33	25.33	36.23
PT×W ₅	10.80	9.7±0.29 ^{a-f}	25.50	162.5±1.44 ^{ab}	142.33	25.27	38.90
Level of significance	NS	***	NS	***	***	NS	NS
CV (%)	3.09	2.26	6.18	17.85	15.28	2.29	15.40

Means with the same letters or without letters within the same column do not differ significantly, * = Significant at 5% level of probability, ** = Significant at 1% level of probability, *** = Significant at 0.1% level of probability, NS = Non-significant, ZT-NPT= Zero-till non-puddled, RT-NPT=Reduced-till non-puddled, PT= Puddled Tillage, W₀= Season long weedy, W₁= Season-long weed free, W₂= Two hand weeding at 30 and 45 DAT, W₃= Pre-emergence herbicide + one hand weeding at 45 DAT, W₄= Pre + post emergence herbicide, W₅= Post-emergence herbicide + one hand weeding at 45 DAT

Interaction effect of rice establishment method and weed management practices on grain, straw and biological yields

The interaction between crop establishment methods and weed management practices significantly influenced grain, straw, and biological yields (Fig. 5). The highest grain yield (4.99 t ha⁻¹) was obtained under both ZT-NPT×W₁ and ZT-NPT×W₅, followed by ZT-NPT×W₂ (4.65 t ha⁻¹) and PT×W₁ (4.58 t ha⁻¹). In contrast, RT-NPT×W₀ produced the lowest grain yield (2.25 t ha⁻¹), reflecting severe yield reduction due to uncontrolled weed infestation. Straw and biological yields exhibited trends similar to grain yield. The maximum straw yield (8.99 t ha⁻¹) was recorded in ZT-NPT×W₅, followed by ZT-NPT×W₂ (8.61 t ha⁻¹) and ZT-NPT×W₀ (8.53 t ha⁻¹), whereas the minimum straw yield (4.65 t ha⁻¹)

was observed in RT-NPT×W₀. Likewise, the highest biological yield (13.97 t ha⁻¹) occurred in ZT-NPT×W₅, while the lowest (6.91 t ha⁻¹) was recorded under RT-NPT×W₀.

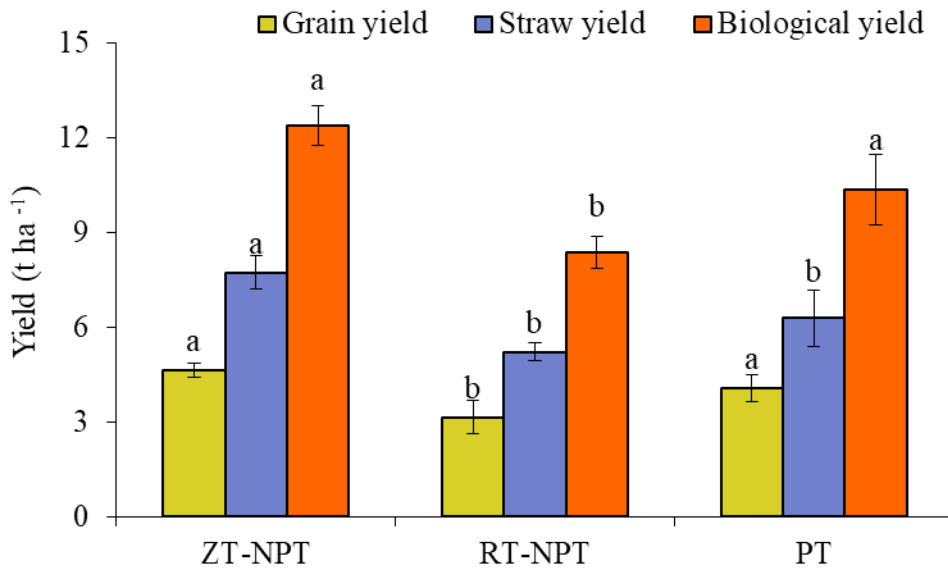


Fig. 3. Effect of rice establishment methods on grain, straw and biological yields of short duration *aman* rice. Here, DAT= Days after transplanting, ZT-NPT= Zero-till non-puddled transplanted, RT-NPT = Reduced-till non-puddled transplanted, PT= Puddled tillage.

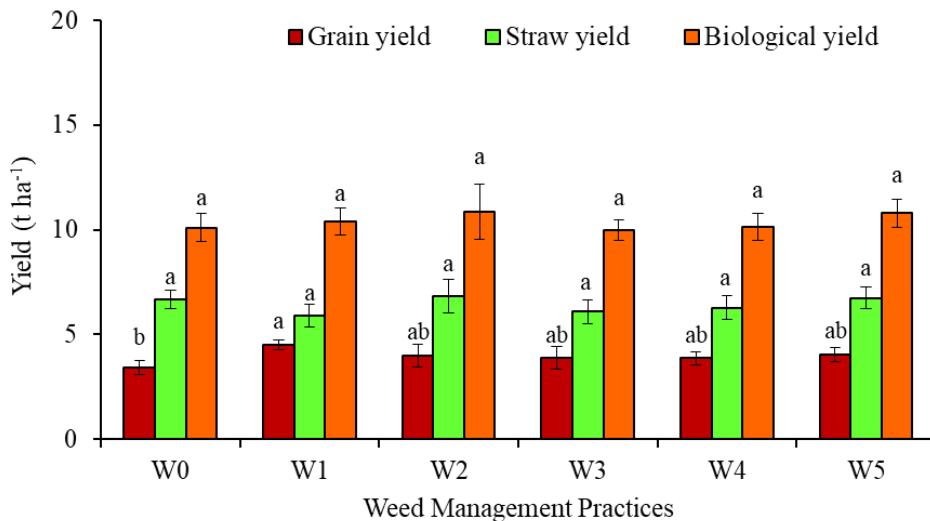


Fig. 4. Effect of weed management practices on grain, straw and biological yields of short duration *aman* rice. Here, W₀ = Season-long weedy, W₁ = Season-long weed free, W₂ = Two hand weeding at 30 and 45 DAT, W₃ = Pre-emergence herbicide + one hand weeding at 45 DAT, W₄ = Pre + post emergence herbicide, W₅ = Post-emergence herbicide + one hand weeding at 45 DAT.

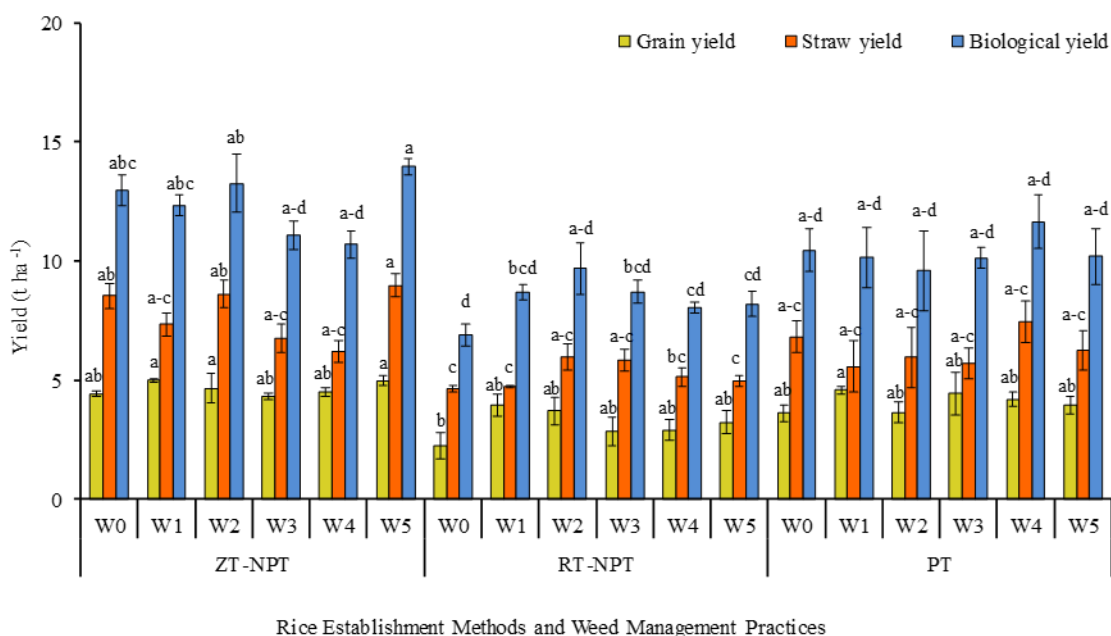


Fig. 5. Interaction effect of rice establishment methods and weed management practices on grain, straw and biological yields of short duration *aman* rice. Here, W₀ = Season-long weedy, W₁ = Season-long weed free, W₂ = Two hand weeding at 30 and 45 DAT, W₃ = Pre-emergence herbicide + one hand weeding at 45 DAT, W₄ = Pre + post emergence herbicide, W₅ = Post-emergence herbicide + one hand weeding at 45 DAT.

Economic benefit

Economic analysis revealed clear differences among treatments in terms of cost of cultivation, returns, and benefit–cost ratio (BCR), largely driven by variations in grain yield (Table 8). Zero-till non-puddled transplanting (ZT-NPT) combined with effective weed management provided the highest economic advantage. The most profitable treatment was ZT-NPT with post-emergence herbicide followed by one hand weeding, which recorded the highest gross return (Tk. 187,125 ha⁻¹), net return (Tk. 113,770 ha⁻¹), and BCR (2.55). In contrast, reduced-till non-puddled transplanting (RT-NPT) was the least profitable, particularly under season-long weedy conditions, resulting in the lowest gross return (Tk. 84,375 ha⁻¹), net return (Tk. 11,988 ha⁻¹), and BCR (1.17). Puddled transplanting (PT) showed moderate profitability, with higher production costs under season-long weed-free conditions (W₁) but improved net return and BCR under integrated weed management (W₃).

DISCUSSION

In rice cultivation, weed infestation is a major constraint to achieving optimal yield and quality, while also increasing production costs. The typically moist and flooded conditions of rice fields provide a conducive environment for the rapid emergence and proliferation of diverse weed species (Ali *et al.*, 2024). In this study, a total of 12 weed species belonging to seven families were identified. Among them, shama (*Echinochloa crus-galli*), sabuj nakful (*Cyperus difformis*), joina (*Fimbristylis miliacea*), and khudey shama (*Echinochloa colonum*) were commonly observed across different rice establishment plots. Onna *et al.* (2026), documented the occurrence of 14 weed species belonging to eight families in transplanted *aman* rice from the same experimental region, including shama

(*Echinochloa crus-galli*), panikachu (*Monochoria vaginalis*), sabuj nakphul (*Cyperus difformis*), chaise (*Fimbristylis dichotoma*), joina (*Fimbristylis miliacea*), and panilong (*Ludwigia hyssopifolia*), are in common among others.

Table 8. Cost effectiveness of different rice establishment methods under different weed management practices

Rice establishment methods	Weed management practices	Total variable cost (Tk. ha ⁻¹)	Herbicides and pesticides cost (Tk. ha ⁻¹)	Labor for cost (Tk. ha ⁻¹)	Total cost (Tk. ha ⁻¹)	Gross return (Tk. ha ⁻¹)	Net return (Tk. ha ⁻¹)	Benefit Cost Ratio
Zero-till non-puddled	W ₀	65800	0	0	65800	166125	100325	2.52
	W ₁	65800	0	16500	82300	187125	104825	2.27
	W ₂	65800	0	11000	76800	174375	97575	2.27
	W ₃	65800	1358	6600	73758	162750	88992	2.21
	W ₄	65800	2314	2200	70314	169125	98811	2.41
	W ₅	65800	955	6600	73355	187125	113770	2.55
Reduced-till non-puddled	W ₀	72387	0	0	72387	84375	11988	1.17
	W ₁	72387	0	16500	88887	148125	59238	1.67
	W ₂	72387	0	11000	83387	139125	55738	1.67
	W ₃	72387	1358	6600	80345	106875	26530	1.33
	W ₄	72387	2314	2200	76901	109125	32224	1.42
	W ₅	72387	955	6600	79942	121500	41558	1.52
Puddled Tillage	W ₀	88011	0	0	88011	136125	48114	1.55
	W ₁	88011	0	16500	104511	171750	67239	1.64
	W ₂	88011	0	11000	99011	136500	37489	1.38
	W ₃	88011	1358	6600	95969	166500	70531	1.73
	W ₄	88011	2314	2200	92525	157125	64600	1.70
	W ₅	88011	955	6600	95566	147750	52184	1.55

W₀ = Season-long weedy, W₁ = Season-long weed free, W₂ = Two hand weeding at 30 and 45 DAT, W₃ = Pre-emergence herbicide + one hand weeding at 45 DAT, W₄ = Pre + post emergence herbicide, W₅ = Post-emergence herbicide + one hand weeding at 45 DAT

Haque *et al.* (2020) reported that *Paspalum scrobiculatum*, *Echinochloa crus-galli*, *Leersia hexandra*, *Oxalis europae*, *Monochoria vaginalis*, *Ludwigia hyssopifolia*, *Cyperus difformis*, *Scirpus juncooides* and *Fimbristylis diphylla* were the major weeds found in the T. aman rice field in the same location. In this study, zero tillage non puddled transplanted rice plots recorded the highest weed density and dry weight at different DATs (Fig. 1 and 2). Minimal soil disturbance in ZT-NPT keep weed seeds near the soil surface, where they can germinate easily. The absence of puddling and early flooding also reduces natural weed suppression, allowing weeds to emerge more rapidly. Rao *et al.* (2017), emphasized that weed flora and biomass are strongly influenced by the method of rice establishment, with zero tillage systems often supporting more weed growth due to reduced soil disturbance. Chauhan *et al.* (2015) reported that the highest total weed density (225-256 m⁻²) was recorded in direct seeded rice (DSR)

while the lowest (102-129 m⁻²) in puddled transplanted rice. Previous studies have reported that season-long weed-free management results in the lowest weed density and biomass in rice, while integrated approaches combining herbicides with hand weeding are also highly effective in suppressing weeds (Rastogi *et al.* 2025). Consistent with these findings, the current study demonstrated that integrated weed management under reduced and puddled tillage systems provided the most consistent and effective weed control. Similarly, Netam *et al.* (2018) observed that transplanted rice had the lowest total weed density and dry matter at 60 DAS/T, and that a combination of chemical and manual weeding achieved the minimum weed population and biomass along with the highest weed control efficiency, thereby independently supporting our results.

In contrast, under both main and interaction effects, non-puddled tillage systems, particularly zero- and reduced-tillage, exhibited significantly higher yield-determining attributes than puddled tillage, as reflected by greater numbers of effective tillers hill⁻¹ (11.84 in ZT-NPT × W₃), higher spikelets panicle⁻¹ (173.5 in RT-NPT × W₃), increased grains panicle⁻¹ (143.33 in RT-NPT × W₁), and higher 1000-grain weight (28.51 g in ZT-NPT × W₁). Higher tiller numbers may be associated with slightly greater surface soil compaction under conservation tillage systems, as moderate soil firmness improves root–soil contact, reduces percolation losses, and creates a more stable soil physical environment conducive to tiller initiation and survival. Soil compaction at 0–20 cm depth showed a strong positive correlation with the number of rice tillers (Bui *et al.*, 2022). The greater grain count under zero and reduced tillage may result from improved soil physical conditions and nutrient availability, which enhance spikelet fertility and grain filling. Our result is also consistent with the findings of Bhatt *et al.* (2020), who observed improved grain development in conservation tillage systems due to better soil health and crop vigor. The lack of statistical significance in total tillers, panicle length, and harvest index suggests that tillering response may be more strongly influenced by other agronomic factors, such as cultivar, seed rate, and nutrient management, rather than tillage practices alone. Higher weed pressure intensifies competition for light, nutrients, and moisture, which adversely affects crop growth and development. Consequently, growth parameters such as plant height, dry matter accumulation, and leaf area index, as well as physiological traits including crop growth rate, relative growth rate, net assimilation rate, chlorophyll content, and leaf thickness, are markedly reduced under heavy weed infestation (Korav *et al.*, 2018). The superior yield attributes and yield observed under the season-long weed-free treatment, followed by integrated weed management practices, can be attributed to lower weed infestation, as reflected by reduced weed density and dry weight. The interaction effect of rice establishment methods and weed management practices suggests that combining effective weed control with suitable rice establishment methods improves sink formation through enhanced tillering and grain set, whereas poor weed management consistently limits yield-contributing traits, regardless of tillage practice. Maintaining weed-free conditions during the critical period up to 40–45 DAT is particularly important to minimize yield loss (Bhuiyan *et al.*, 2021). Finally, the higher yield and economic return obtained under zero-till non-puddled rice in combination with integrated or weed-free management can be attributed to a greater number of effective tillers and improved yield-contributing characters. These advantages are likely the result of reduced crop–weed competition and enhanced availability and efficient utilization of nutrients during the critical tillering and panicle development stages. Several studies have shown that microbial activity varies significantly across different crop establishment and weed management practices. Although herbicide application initially reduces microbial activity, unpuddled transplanted conditions subsequently exhibit higher microbial populations and enzyme activities, while zero tillage records the highest availability of N, P, K, and S (Alam *et al.*, 2014; Pattanayak *et al.*, 2022). Despite the fact that zero tillage alone may reduce rice yield and profitability (Saini *et al.*, 2022), this tillage system, when combined with effective weed control, can maintain or enhance yields in rice systems (Gathala *et al.* 2015). Abbas *et al.* (2018) emphasized the importance of integrating manual and chemical weed management to improve weed suppression and crop productivity, especially under resource-conserving tillage systems.

CONCLUSION

This study demonstrates that both rice establishment methods and weed management practices play a crucial role in regulating weed pressure, crop yield, and profitability in transplanted *aman* rice. Although zero-till non-puddled transplanting showed higher weed density, it consistently produced superior grain, straw, and biological yields. The combination of zero-till non-puddled transplanting with post-emergence herbicide followed by one hand weeding at 45 DAT proved to be the most productive and economically viable option, delivering the highest grain yield and benefit–cost ratio. Integrating conservation tillage with efficient weed management offers a practical and profitable strategy for sustainable *aman* rice production. However, this study conducted in a single season and location, limits the broader applicability of the results across diverse agro-ecological zones. Long-term multi locational studies are needed to evaluate the sustainability of conservation tillage and integrated weed management.

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