Pol. J. Environ. Stud. Vol. XX, No. X (XXXX), 1-13
DOI: *10.15244/pjoes/192895* ONLINE PUBLICATION DATE:

Original Research

Impact of Different Cropping Methods Coupled with Nitrogen and Zinc on Growth Parameters and Total Yield in Rice

Sajjad Ahmad[1], Inamullah[2], Muhammad Yousaf Nadeem[3], Muhammad Yousaf[4], Zaid Khan[1], Hafeez ur Rahim[5], Muhammad Ayoub Khan[6], Manzer H. Siddiqui[7], Saud Alamri[7], Waqar Khan[8*]

[1]College of Natural Resources and Environment, South China Agricultural University, Guangzhou 510642, China
[2]The University of Agriculture Peshawar, Pakistan
[3]Key Laboratory of Crop Genetics and Physiology of Jiangsu Province, Key Laboratory of Crop Cultivation and Physiology of Jiangsu Province, College of Agriculture, Yangzhou University, Yangzhou 225009, China
[4]Centre for Animal Sciences and Fisheries University of Swat
[5]Department of Chemical, Pharmaceutical and Agricultural Sciences (DOCPAS), University of Ferrara, 44121 Ferrara, Italy
[6]State Key Laboratory of Crop Stress Adaptation and Improvement, Plant Germplasm Resources and Genetic Laboratory, School of Life Sciences, Henan University, Kaifeng, China
[7]Department of Botany and Microbiology, College of Science, King Saud University, Riyadh 11451, Saudi Arabia
[8]College of Horticulture, South China Agricultural University, Guangzhou 510642, China

Received: 14 May 2024
Accepted: 2 September 2024

Abstract

The rice transplantation method is still the predominant cultivation practice. However, with increasing water scarcity, high-cost production, and adverse effects on soil health and the surrounding environment, alternative crop production methods should be practiced for sustainable rice production. In the current study, we evaluated the transplantation and direct seeding rice cultivation methods under different nitrogen (N) and zinc (Zn) fertilization rates. We used four different input rates for both N (i.e., N0 = 0 kg ha^{-1}, N1 = 90 kg ha^{-1}, N2 = 120 kg ha^{-1}, and N3 = 150 kg ha^{-1}) and Zn (Zn0 = 0 kgha^{-1}, Zn1 = 5 kg ha^{-1}, Zn2 = 10 kg ha^{-1}, and Zn3 = 15 kg ha^{-1}). The results showed that the transplantation rice method coupling with N3 and Zn2 substantially improved yield and yield-related components compared to the direct seeded method and other fertilizer treatments. Considering weed density and non-productive tillers, the transplantation rice method coupled with N3 and Zn2 recorded lower weed density and non-productive tillers as compared to the direct seeded rice method coupled with nitrogen and zinc fertilization treatments. The transplantation method with N3 and Zn2 significantly improved leaf area index, leaf area duration, net assimilation rate, and photosynthetically active radiation in

*e-mail: waqar.khan399@gmail.com

comparison to other treatments applied. Furthermore, the transplantation rice method recorded higher economic returns compared to the direct seeded rice method. It was concluded from the findings of this study that the transplantation rice method, along with a suitable amount of N and Zn fertilizers, could enhance yield-related components, leading to higher production and substantially higher net income. While the transplantation method showed promising results, future research should explore ways to address the challenges of the direct seeding method, such as managing weed density and non-productive tillers, to make it a viable alternative for sustainable rice production.

Keywords: Rice, sowing methods, nitrogen, zinc, yield

Introduction

Rice (*Oryza sativa* L.) is the second most important cereal crop and is grown in more than 100 countries across the globe. Approximately, 3.5 billion people depend on rice for nourishment and as an income source globally, and it plays a key role in food security [1]. The low yield of rice might be due to traditional culturing techniques and mismanagement of agronomic factors, such as sowing methods and fertilizer application [2]. In the present world, water scarcity is the biggest threat that will affect rice cultivation in the near future, as rice consumes 2 to 3 times more water in comparison to other cereal crops [3]. One of the possible solutions to overcome this problem is the introduction of alternative practices for rice cropping.

Transplanting rice seedlings from nursery to puddled soil is the primary and traditional approach to rice cultivation. However, a significant quantity of water is required as it loses due to percolation and evaporation. Studies reported that the transplantation (TP) rice method requires 3000 to 5000 liters of water for the production of 1 kg of rice [4]. The transplantation rice method is also a major source of greenhouse gas emissions, causing global climate change [5]. Along with higher water usage and greenhouse gases, TP rice production also deteriorates soil physiochemical properties [6, 7]. Among the nutrient elements, nitrogen (N) plays a crucial role in the growth and development process of rice, leading to an increase in the total yield. The application of higher N fertilizer for getting the desired yield can cause a negative effect on the sustainability of the production and total cost. The high rate of N fertilizer not only affects yield and quality but also makes rice plants susceptible to lodging, insect pests, and disease attacks [8]. While applying N to rice, a valuable amount enters the surrounding environment, which pollutes both the surrounding atmosphere and water system.

Like N, zinc (Zn) has also a major role in the yield and quality of rice. Zn deficiency is common in flooded soils due to the formation of insoluble Zn-phosphate. Under anaerobic conditions, an increase in the organic acid concentration reduces the Zn uptake by the rice, which affects its development, yield, and quality [9]. The frequency of Zn deficiency in rice is higher as compared to other cereal crops, which results in nutritional disorders affecting more than 50% of the crop. The reduced Zn concentration in grains not only diminishes its bioavailability in humans but also contributes to Zn deficiency in the susceptible human population. Application of Zn to soil is a general strategy to address the Zn deficiency and improve Zn grain concentration [10]. Zn is also important for several physiological processes in plants, such as carbohydrate metabolism, nucleic acids, and auxins, as well as enzyme activation and protein synthesis. It is also important for gene expression, regulation, and reproductive development [9]. Our research aim is to modify the present cultivation and agronomic techniques to reduce production costs and to manage fertilizers in a better way.

To address the problem, efforts were made to shift transplantation rice cropping to direct seeded cropping (DS). The DS rice method is an eco-friendly production method that not only reduces the loss of resources, but also mitigates the emission of greenhouse gases from paddy fields. However, there is a dearth of studies on direct-seeded rice methods and their impact on yield, water scarcity, and economic stability. Therefore, we designed the current study to evaluate the effect of different cropping methods (TP and DS) coupled with the application of N and Zn fertilizers on the growth, yield, and economics of rice production.

Materials and Methods

Research Site and Weather Conditions

The two field trials with different sowing methods were conducted at Agricultural Research Institute (North) Mingora Swat during summer, located at 34°46’60”N latitude and 72°22’0”E longitude with an altitude of 905 meters above sea level. The experimental site has finely textured silt loam and well-drained soil. The soil analysis revealed that the soil has pH 8.1, EC 1.9 d S m^{-1}, organic matter 0.56%, total N 0.02%, available P 6.1 ppm, and available K 118 ppm. The research site has semi-arid subtropical climatic conditions with an average annual rainfall of about 800 mm. In combination with precipitation, the crop water requirements were achieved by supplying water through surface irrigation via water channels when needed.

Research Design and Management

In this study, we used 10 treatments with three replicates each, utilizing a randomized complete block design (RCBD). Two sowing methods were used, i.e., the TP rice method and the DS rice method. Additionally, different combinations of N fertilizer (0, 90, 120, and 150 kg ha^{-1}) and Zn levels (0, 5, 10, and 15 kg ha^{-1}) were also applied in both rice growing methods. Each plot consists of six rows (length = 4 m), while the row-to-row distance was 30 cm. The coarse variety SWATAI 2014 was used as a test variety. N was applied in the form of urea to the nursery, and the remaining N was applied in two equal splits, half at seedbed preparation and the remaining half at the tillering stage for both the TP and DS of rice. Zn (33%) was applied in the form of $ZnSO_4$ after 12 days of TP and DS of rice [10]. Five irrigations were applied in the DS rice cultivation, i.e., 1 day after sowing, at tillering (25), during panicle initiation (PI) (45), grain filling stage (65), and 20 days before harvesting. All the agronomic practices were carried out equally for all the trials throughout the life span of the crop.

Sampling and Data Collection

Different growth parameters like plant height, days to maturity, weed dry matter, harvest index (HI), straw yield, and hulling (%) were measured. For plant height measurement, 10 tillers were selected from each plot and measured from the base to the top of the plant, and then the average was calculated. Data relating days to physiological maturity was recorded when more than 50% of plants in every treatment became yellowish. Weed dry matter was recorded after drying the fresh in the sun. To calculate the HI, we calculated the ratio of paddy yield to biological yield, and then the HI was expressed in percentage. The straw yield of rice was computed by subtracting the paddy yield from the biological yield. Hulling (%) of rice was calculated by dividing the grain weight without hull (rice) by the grain weight with hull. Additionally, data on leaf area index (LAI), leaf area duration (LAD), crop growth rate (CGR), net assimilation rate (NAR), and photosynthetically active radiation (PAR) were also determined [11].

Economic and Statistical Analysis

Total expenditures like seeding costs, field preparation costs etc., were computed. After calculating the total operating costs and profits, the net profit was determined. The profitability of rice and income received in terms of increased grain yield were assessed according to the methodology explained by CIMMYT. Data collected was analyzed using Statistix 8.1. The means were compared at the 0.05 level of probability using the LSD test. Figures were generated using GraphPad Prism version 8.0 and R version 3.6.1.

Results

Growth Parameters

Data related to LAI, LAD, CGR, NAR, and PAR are presented in Table 1. Different sowing methods significantly affected the crop growth-related parameters. Among TP and DS, the TP rice crop attained the highest values of LAI, LAD, CGR, NAR, and PAR. The N fertilizer application also significantly affected the aforementioned parameters. N application at the rate of 150 kg ha^{-1} (N3) was observed to be more effective as compared to other N levels in relation to growth parameters. Similarly, Zn application also had a notable effect on growth attributes, and the results are presented in Table 1. Higher indices for growth-related parameters were observed in the case of Zn2 (10 kg ha^{-1}) and the minimum values were observed in Zn0, where no Zn was applied. The interactive effect between different sowing methods, N and Zn, was non-significant for LAD and CGR, while interaction between N and Zn levels in the case of LAI was significant.

Effects of different sowing methods and fertilizer treatments (N and Zn) on days to panicle initiation (PI) are displayed in Fig. 1(c, d). The statistical findings show that all the treatments used in the experiment recorded significant effects on the PI of the rice crop. An average of 60 days was noted to reach the PI stage in the TP rice method, which is comparatively higher than the DS rice (56 days). Among different N treatments, maximum days to PI (67 days) were observed for N3, followed by N2 (62 days) and N1 (55 days), while the N0 treatment depicted the least days to PI. Different Zn applications had a non-significant effect on the days to PI, as maximum days for PI (59 days) were observed in the Zn3 treatment, followed by Zn2 and Zn1, and minimum numbers (57 days) were obtained in the Zn0 treatment.

The result of the present study indicated that maximum days (111 days) to physiological maturity (PM) were observed in the rice grown under the TP method, while the least days (101 days) were recorded in the DS rice method (Fig. 1a, b). Within N applications, the highest days to PM (114 days) were recorded in N3, followed by N2 (110 days) and N1 (104 days) treatments. Considering Zn input rates, the greater number of days to PM was perceived with the application of Zn3, followed by Zn2 and Zn1, respectively. In both N and Zn treatments, the plots without application of N and Zn (N0 and Zn0) depicted the least time to attain PM.

Yield Related Attributes

Data related to yield parameters of rice grown in both TP and DS rice methods is presented in Fig. 2. We found that both the rice growing methods significantly affected plant height (Figs. 2 a and b). The results showed that maximum plant height was observed in the TP method as compared to the DS rice method. Plant height showed a positive response to different levels of

Table 1. Effect of different sowing methods, N and Zn levels on LAI, LAD, CGR, NAR and PAR of rice.

Treatments	LAI	LAD	CGR	NAR	PAR
N0	4.31 d	281.21 d	7.32 d	4.88 c	801 c
N1	5.41 c	295.32 c	10.81 c	5.11 b	875 b
N2	5.54 b	300.32 b	11.17 b	5.16 b	881 b
N3	5.57 a	307.11 a	11.82 a	5.36 a	905 a
Zn0	4.42 d	285.21 d	8.22 d	4.09 d	790 d
Zn1	5.38 c	293.31 c	10.57 c	5.03 c	814 c
Zn2	5.60 a	308.45 a	12.21 a	5.45 a	855 a
Zn3	5.50 b	303.68 b	11.17 b	5.21 b	840 ab
TPR	5.62 a	310.71 a	12.33 a	5.13 a	901 a
DSR	4.92 b	288.35 b	10.12 b	5.01 b	870 b
F-value significance					
SM x Nitrogen	ns	ns	ns	ns	ns
SM x Zn	ns	ns	ns	ns	ns
N x Zn	***	ns	ns	ns	ns
SM x Nitrogen x Zn	ns	ns	ns	ns	ns

Note: SM indicate different sowing methods. TPR: Transplantation rice method, DSR: Direct seeded rice method. N0, N1, N2 and N3 indicates different N levels and Zn0, Zn1, Zn2 and Zn3 represents different Zn levels. Different letters in a single column indicate significant difference between treatments at the 0.05 probability level. ns represent non-significant and *asterisks* indicate a significant difference at *$*P<0.05$, $**P<0.01$ and $***P<0.001$ level.*

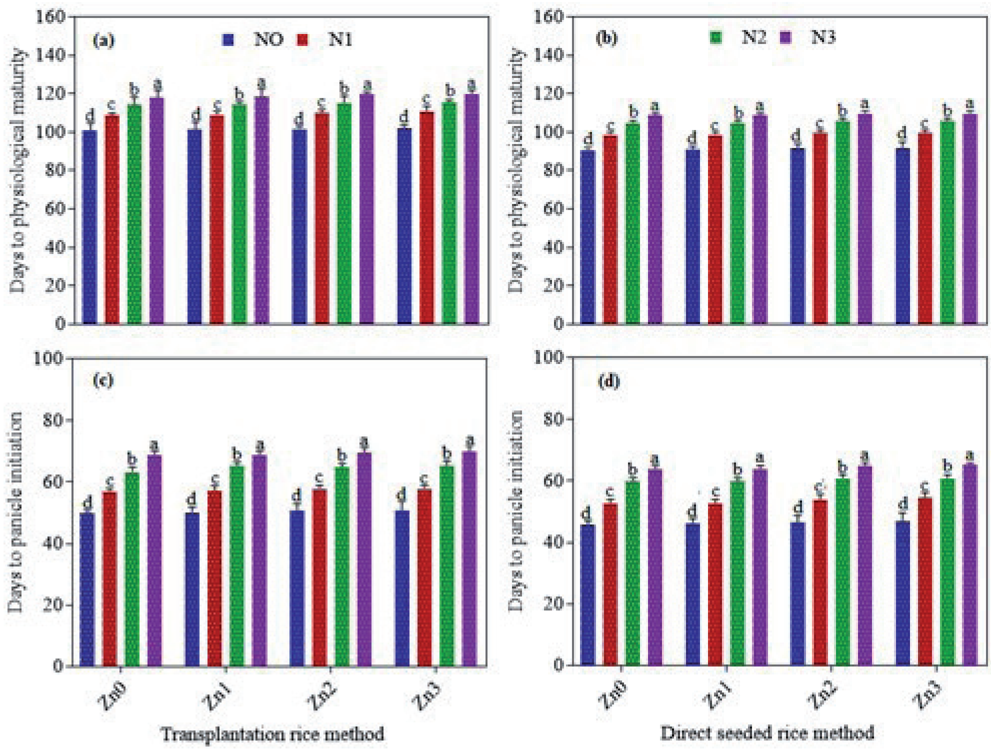

Fig. 1. Effect of different sowing methods, N and Zn levels on days to panicle initiation and physiological maturity. N0, N1, N2 and N3 indicate different N levels and Zn0, Zn1, Zn2 and Zn3 represent different Zn levels. The vertical bars represent the standard deviation of the means.

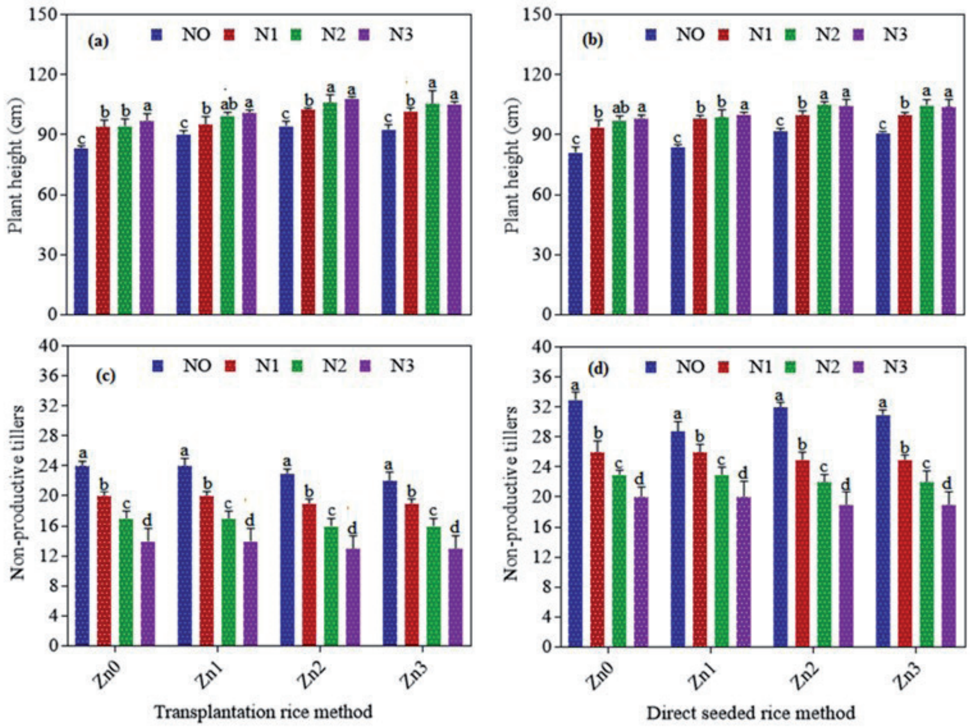

Fig. 2. Effect of different sowing methods, N and Zn levels on plant height and non-productive tillers. N0, N1, N2 and N3 indicates different N levels and Zn0, Zn1, Zn2 and Zn3 represent different Zn levels. The vertical bars represent the standard deviation of the means.

N fertilizer rates. Among N treatments, N3 recorded higher plant height, while the least was noted in the N0 treatment. However, considering Zn treatments, the maximum plant height was recorded in Zn2, followed by Zn1 and Zn3. A visible number of non-productive tillers were noted in the DS rice method in comparison to the TP rice method (Fig. 2c and d). N application to paddy reduced the number of non-productive tillers. We found that N0 treatment produced a higher number of non-productive tillers, while this number decreased from N1 to N3. Similarly, among Zn treatments, Zn0 produced higher non-productive tillers, while treatment Zn3 produced the least number of non-productive tillers.

The data related to panicles m^{-2} and grains panicle^{-1} is presented in Fig. 3. Investigation of the data showed that the sowing methods and N fertilizer levels had a significant effect on the rice panicle m^{-2}, while no significant differences were observed among Zn treatments (Fig 3a and b). The TP rice method produced a significantly higher panicle m^{-2} as compared to the DS rice method. Among N rates, maximum panicles m^{-2} (327) were observed in treatment N3, followed by N2 and N1, respectively. Considering Zn amendments, the maximum number of panicles m^{-2} was obtained in Zn3 treatment, followed by Zn2 and Zn1, respectively. While the lowest number of panicles m^{-2} (317) were recorded in treatment where no Zn was applied. All interactions were found non-significant. The results of the present study indicate that the number of grains panicle^{-1} was significantly affected by different sowing methods coupled with N and Zn levels (Figs. 3c and d). Maximum grains panicle^{-1} was recorded in the TP rice method, while DS observed a minimum number of grains panicle^{-1} (i.e., 120 grains). Among different N levels, N3 produced a higher number of grains panicle^{-1} (124) followed by N2 and N1 treatments. Whereas the N0 plot perceived the least number of grains panicle^{-1}, i.e., 118 grains. Among Zn treatments, higher grains panicle^{-1} (124) were noted with Zn2, followed by Zn3 (123) and Zn1 (121). The lower number of grains panicle^{-1} 118 was achieved in Zn0.

Fresh and Dry Biomass of Weeds

Our results depicted a significant effect of different sowing methods on weed density in rice crops, as DS rice production recorded higher weed fresh weight as compared to TP rice (Fig. 4a and b). Maximum weed fresh weight noted in direct-seeded rice was 445.4 g, while in the transplantation rice method, it was 198.5 g. The different N applications also showed a positive effect on weed fresh weight. A maximum weed fresh weight of 339.1 g was noted for N1 treatment, followed by N3 (332.6 g) and N2 (311.7 g), respectively. Considering different Zn treatments, no significant effect was observed on weed fresh weight. Among Zn treatments, the highest weed fresh weight of 329.8g was obtained from the Zn3 treatment, which was on par with Zn2 (325g) and Zn1 (320.9g). The lowest weed fresh weight of 312.1g was observed with no application of zinc.

Results obtained showed that weed dry weight was notably affected by the sowing methods and N levels. While Zn application levels showed no significant effect on weed dry weight (Fig. 4c and d). The weed dry weight of 148.5 g was significantly higher in the DS rice method as compared to the weed dry weight (66.2 g)

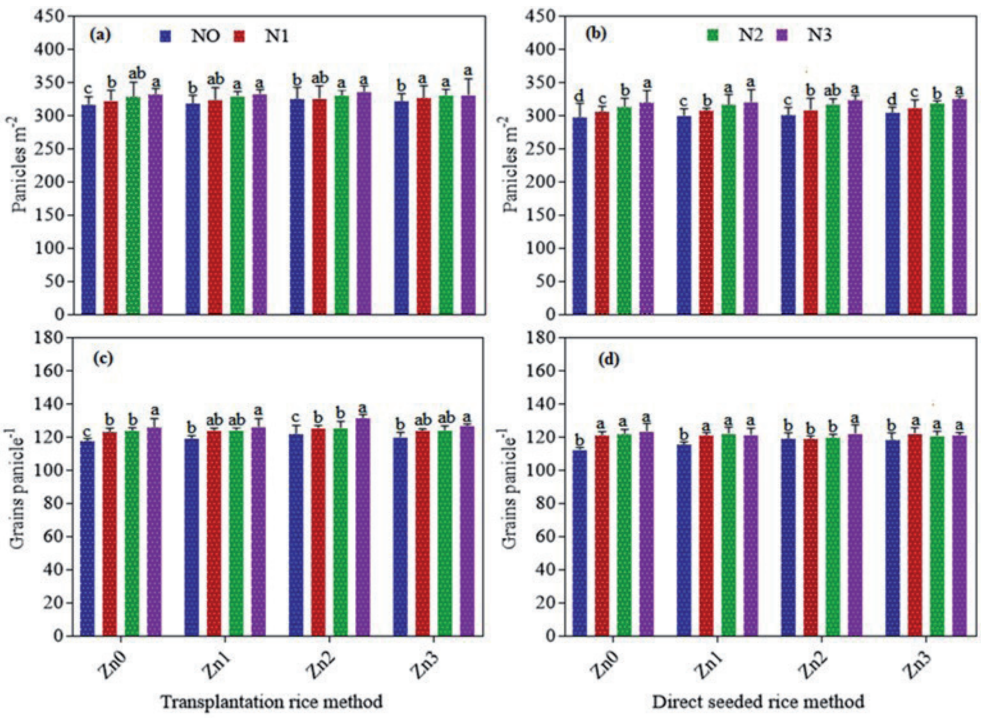

Fig. 3. Effect of different sowing methods, N and Zn levels on panicles m^{-2} and grains $panicle^{-1}$. N0, N1, N2 and N3 indicate different N levels and Zn0, Zn1, Zn2 and Zn3 represent different Zn levels. The vertical bars represent the standard deviation of the means.

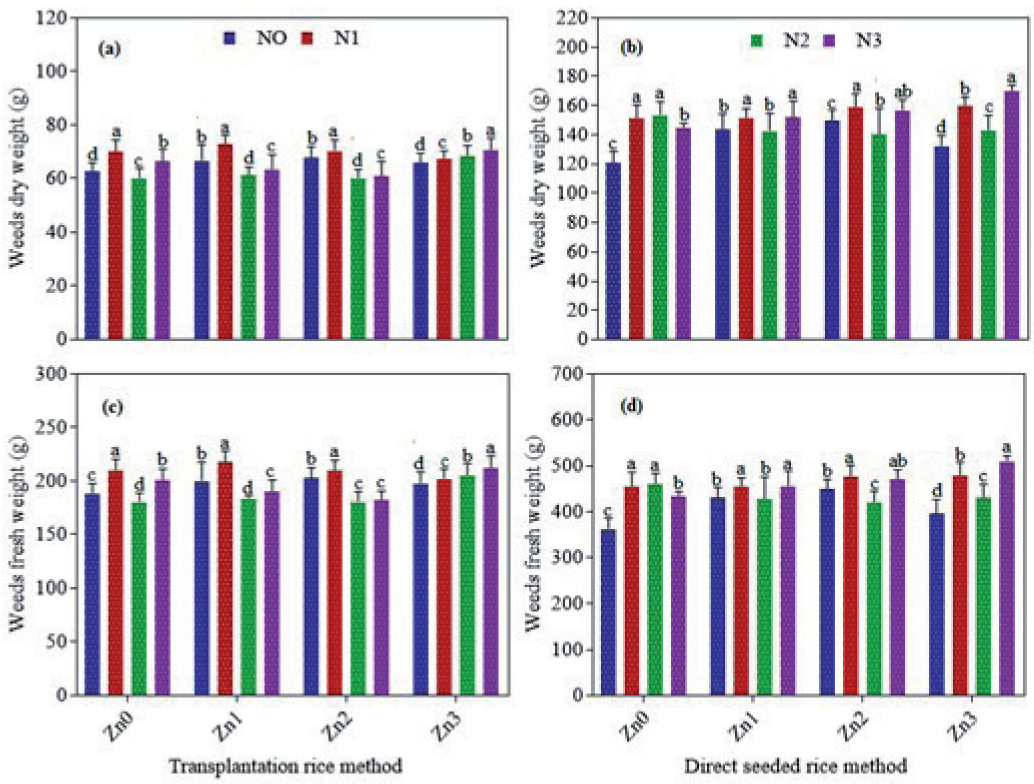

Fig. 4. Effect of different sowing methods, N and Zn levels on fresh and dry weight of weeds. N0, N1, N2 and N3 indicate different N levels and Zn0, Zn1, Zn2 and Zn3 represent different Zn levels. The vertical bars represent the standard deviation of the means.

in the TP rice cropping method. A maximum weed dry weight of 113g was noted with the application of N2 treatment, followed by 110.9g and 103g for N3 and N1 treatments. A minimum weed dry weight of 101.5 g was noted from no application of N. With Zn application, the highest weed dry weight of 109.9 g was obtained from Zn3 followed by 108.3g and 107g for Zn2 and Zn1, respectively. The lowest weed dry weight was observed with no zinc application.

Hulling Percentage and Biological Yield

The effect of different sowing techniques and N and Zn applications on the hulling percentage of rice is presented in Fig. 5(a and b). Investigation of the data indicated that hulling (%) was not significantly affected by the different sowing methods, while different N and Zn levels had a significant effect on the hulling (%) of rice. The hulling of 75.9% was recorded in the TP rice method, which is comparable to that of the DS rice method, i.e., 75.8%. Among various N applications, the maximum hulling of 77.6% was recorded for N3, followed by N2 (76.3%) and N1 (75.3%) treatments, respectively. The lowest hulling of 74.2% was shown with no application of N. In Zn treatments, Zn3 exhibited the maximum hulling % of 76.2% while Zn2 and Zn1 treatments showed 75.9% and 75.8%, respectively. The Zn0 treatment recorded a hulling % of 75.4%.

The biological yield of rice was significantly affected by the sowing methods, N fertilizer, and Zn application levels (Fig. 5c and d). A maximum biological yield of 15057 kg ha^{-1} was recorded in the TP rice method, which was significantly higher than the DS rice method's biological yield of 12113 kg ha^{-1}. Regarding N application, higher biological yield (15213 kg ha^{-1}) was observed in treatments with a higher N input rate N3, (150 kg ha^{-1}), which was followed by N2 and N1, where biological yield obtained was 14573 kg ha^{-1} and 13206 kg ha^{-1}, respectively. The least biological yield of 11347 kg ha^{-1} was revealed from treatment without N application. In the case of Zn input levels, the highest biological yield of 13954 kg ha^{-1} was perceived with the use of 10 kg Zn ha^{-1} (Zn2), followed by 15 kg Zn ha^{-1} (Zn3) and 5 kg Zn ha^{-1} (Zn1), where biological yield was 13823 kg ha^{-1} and 13499 kg ha^{-1}, respectively. The Zn0 treatment produced a minimum biological yield of 13062 kg ha^{-1}. All interactions, including SM x N, SM x Zn, and SM x N x Zn, were found non-significant except N x Zn. The interaction N x Zn indicates that at 0 kg N ha^{-1}, the biological yield was minimal no matter how much the Zn level was increased. Biological yield improved with the use of Zn up to 10 kg ha^{-1} but slightly declined at 15 kg Zn ha^{-1}. At 90 kg N ha^{-1}, an increase in biological yield was observed with an increase in Zn level up to 10 kg ha^{-1}, then a slight decrease was observed with 15 kg Zn ha^{-1}. However, with 120 kg N ha^{-1}, a slight increase was observed with an increase in Zn level. At 150 kg N ha^{-1}, a higher increase was noted in biological yield with the rise in Zn input up to 10 kg ha^{-1}, which slightly decreased at 15 kg Zn ha^{-1}.

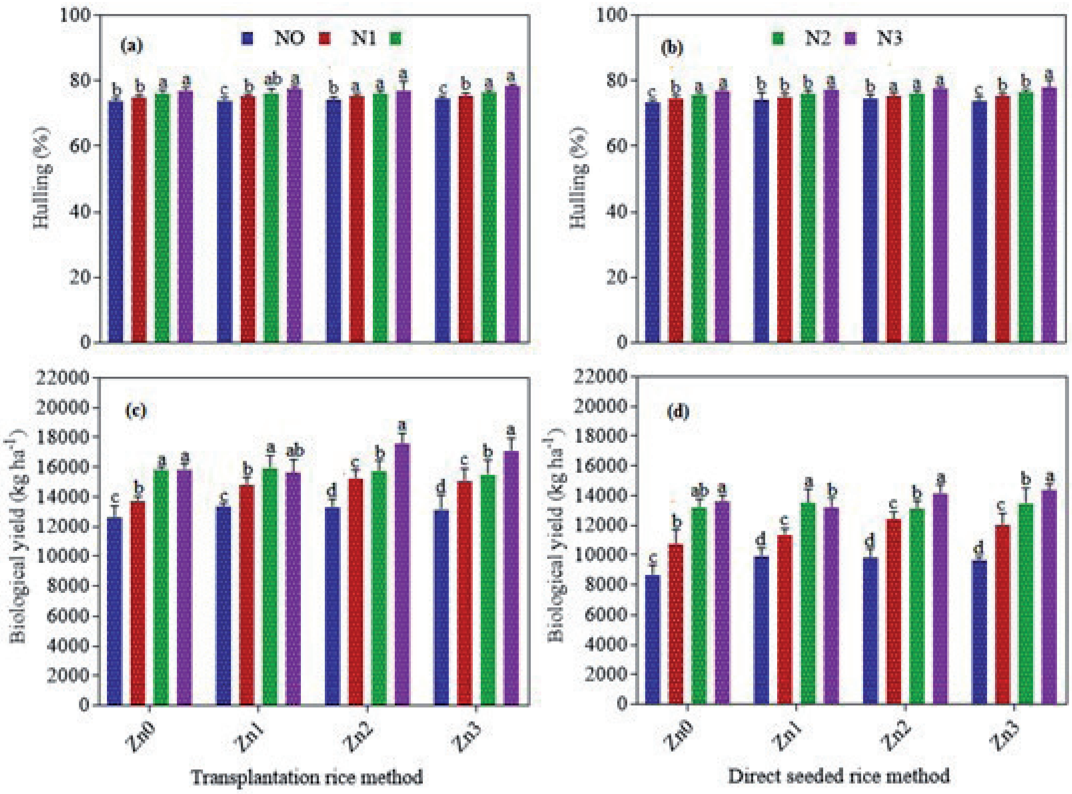

Fig. 5. Effect of different sowing methods, N and Zn levels on hulling % and biological yield of rice. N0, N1, N2 and N3 indicate different N levels and Zn0, Zn1, Zn2 and Zn3 represent different Zn levels. The vertical bars represent the standard deviation of the means.

Grain Yield

In the present study, the grain weight of the rice was significantly influenced by all the treatments (Table 2). The comparison of the two rice-growing methods showed that the TP rice recorded a higher 1000-grain weight as compared to the DS rice. Different N application rates also produced a significant effect on grain weight, as the maximum 1000-grain weight was noted in the N3 treatment and the minimum was observed for N0. Similarly, in Zn treatments, 1000-grain weight also varied with input rates; Zn2 produced the highest grain weight, followed by Zn3 and Zn1, while the minimum resulted from Zn0. Results of the current study showed that different sowing methods and N and Zn input levels considerably influenced the grain yield of rice (Table 2). The highest grain output of 4489 kg ha^{-1} was revealed by the transplantation rice method, while the direct seeded rice yielded 2741 kg ha^{-1}. Regarding the N application, the highest grain output of 4162 kg ha^{-1} was noted in the N3 treatment, followed by the N2 and N1 having grain yields of 3937 kg ha^{-1} and 3512 kg ha^{-1}, respectively. Within the Zn application treatments, the treatment Zn2 revealed the highest grain yield of 3757 kg ha^{-1}, followed by Zn3 and Zn1 treatments, which perceived grain yields of 3686 kg ha^{-1} and 3581 kg ha^{-1}, respectively. The Zn0 treatment produced the least grain yield of 3436 kg ha^{-1} among Zn input levels.

The results related to the straw yield of rice were also varied significantly among the different sowing methods and N and Zn application treatments. TP rice produced the highest straw yield of 10546 kg ha^{-1}, which was significantly higher than that of DS rice (9371 kg ha^{-1}). Comparing different N levels, the N3 treatment revealed the highest straw yield (11050 kg ha^{-1}) followed by N2 (10635 kg ha^{-1}) and N1 (9693 kg ha^{-1}), and the least (8456 kg ha^{-1}) was observed in the N0 treatment. Zn application also significantly influenced the straw yield of rice, as Zn2 produced a higher straw yield (10197 kg ha^{-1}) as compared to Z1 (9918 kg ha^{-1}), while less increase was noted in Zn3 (10137 kg ha^{-1}) as compared to Zn2. The Zn0 produced the least straw yield (9584 kg ha^{-1}) among Zn treatments. The results of the study indicate that HI was significantly affected by the sowing methods and N fertilizer input rates. While Zn application exhibited a non-significant effect on the HI of rice. HI of 29.9% was recorded in the TP rice method as compared to the 22.5% in the DS rice method. With the application of N, greater HI (27.2%) was obtained from the N3 plot, and the lowest (24.6%) was observed in treatment with no N application. Considering Zn application levels, Zn2 treatment showed the highest HI (26.5%) and the minimum (25.9%) was obtained in Zn0.

Table 2. Yield and yield components of rice in response to different sowing methods, N and Zn levels.

Treatments	Straw yield (kg ha^{-1})	HI (%)	1000 grain wt. (g)	Grain yield (kg ha^{-1})
N0	8457 c	24.6 c	19.7 d	2848 d
N1	9693 b	26.2 b	21.0 c	3513 c
N2	10635 a	26.8 ab	22.0 b	3937 b
N3	11050 a	27.2 a	22.6 a	4163 a
Zn0	9584 b	25.9	21.0 c	3436 d
Zn1	9918 ab	26.1	21.2 bc	3581 c
Zn2	10197 a	26.5	21.6 a	3757 a
Zn3	10137 a	26.3	21.5 ab	3686 b
TPR	10547 a	29.9 a	21.8 a	4489 a
DSR	9371 b	22.5 b	20.9 b	2742 b
F-value significance				
SM x N	ns	ns	ns	ns
SM x Zn	ns	ns	ns	ns
N x Zn	ns	ns	ns	***
SM x N x Zn	ns	ns	ns	ns

Note: SM indicated different sowing methods. TPR: Transplantation rice method, DSR: Direct seeded rice method. N0, N1, N2 and N3 indicate different N levels and Zn0, Zn1, Zn2 and Zn3 represent different Zn levels. Different letters in a single column indicate a significant difference between treatments at the 0.05 probability level. NS represents non-significant and asterisks indicate a significant difference at *$P<0.05$, **$P<0.01$ and ***$P<0.001$ level.

Economic Comparison

Economic analysis of the TP rice method and DS rice method is presented in Table 3. It showed that the total expenses in Pakistani rupees (Rs) for the experimental area of the TP rice were higher as compared to the DS rice. The total production costs per hectare for the TP rice method were greater as compared to the DS rice method. Whereas, the total income per hectare that comes from grain yield and straw yield was higher for TP rice compared to the direct seeded rice. Conclusively, the net income of the TP rice method was higher (Rs: 109,483) than the DS rice method (Rs: 96,945).

Correlation Analysis

The mutual relationship between morphological indices, yield, and yield-related attributes of rice in TP (Fig. 6a) and DS rice systems (Fig. 6b) was investigated by performing Pearson correlation analysis. Results depict that weed density was negatively correlated with the grain yield of the rice. The TP rice system significantly improved the rice yield and its related components as compared to the DS rice method. The result of these positive correlation coefficients among the yield-related parameters and morphological indices suggested that the use of N along with Zn fertilizers in the TP rice system gives optimum yield and its related components.

Discussion

Plant height is one of the main vegetative growth parameters of rice, which represents the effect of different agronomic practices in rice fields (Fig. 1a, b). The current study reveals higher plant length in the TP rice method compared to the DS rice method, which was due to the better establishment of rice seedlings, proper plant-to-plant distance, nutrient availability, and optimum availability of water. These factors reduced the competition among plants and led to an increase in plant height in the TP rice method [12]. The different levels of N fertilizers also showed a significant effect on plant height in this study. The increase in plant height might be due to enhanced cell growth in rice plants due to N application. Similar results of an increase in plant height due to N application were also reported by [13]. The increase in plant height of the rice crop with Zn application is attributed to the sufficient Zn availability, which contributes to speeding up the activity of enzymes and the breakdown of auxin in the plant body [14].

In DS rice, the germination is generally depressed, and as a result, it affects crop establishment due to less root-soil contact to exploit the soil resources fully

Table 3. Economic comparison of transplanted rice vs direct seeded rice

Experimental Plot area	345.6 m^{-2}	345.6 m^{-2}
Activity	Transplanted rice	Direct seeded rice
Field preparation	2000	1500
Nursery cost	1000	…..
Seeding cost	……	1000
Transplantation cost	3000	…..
Weeding cost (manual)	250	250
Weedicides	600	1600
Irrigation cost	3600	1800
Total expenses experimental area	10450	5850
Total expenses in hectare (Rs.)	302372/--	169270/--
Rate of grains (Rs. kg^{-1})	80	80
Average grain yield (kg ha^{-1})	4489	2742
Grain yield income (Rs.)	359120/--	219360/--
Straw yield (kg ha^{-1})	10547	9371
Rate of straw (Rs. kg^{-1})	5	5
Straw yield income ha^{-1} (Rs.)	52735/--	46855/-
Total income ha^{-1} (Rs.)	411855/--	266215/--
Net income in hectare (Rs.)	109,483/--	96,945/--

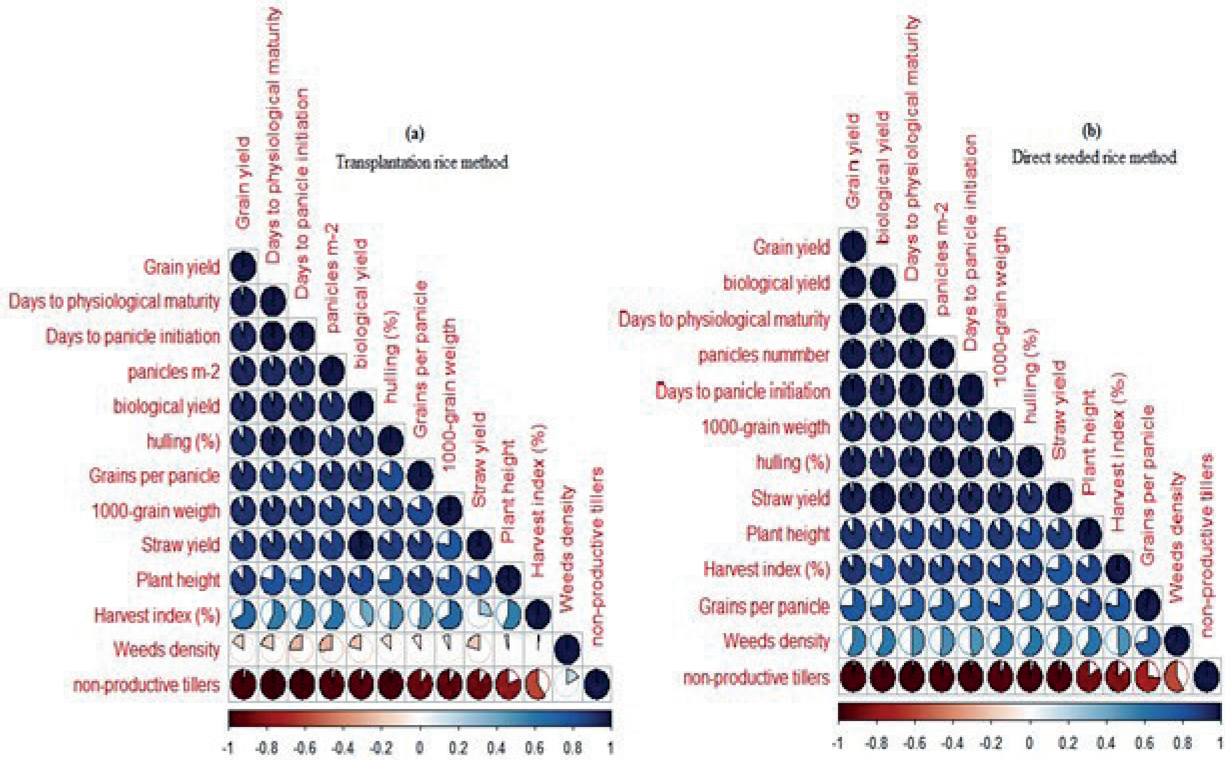

Fig. 6. Correlation coefficients between grain yield, yield-related components and morphological indices of rice in both sowing methods.

and ultimately lowers the productivity of the crop [15]. Similarly, a previous study reported that the TP rice method increases all growth and yield attributes over the DS rice method. The lower number of non-productive tillers in the N treatments may be attributed to the fact that when there were maximum plants m^{-2}, there would be more productive tillers [14]. Zn application treatments produced a lower number of non-productive tillers as it may enhance the accessibility and absorption of other vital nutrients, leading to improvement in the plant metabolic process, and finally, the crop growth and panicle-bearing capacity of the rice were increased.

Grains $panicle^{-1}$ is among the major components that determine the yield of the crop. The DS method recorded lower grains $panicle^{-1}$ due to the higher density of plants, increasing the competition among the plants for nutrient uptake [16]. Unlike this, TP rice production gives a high number of grains $panicle^{-1}$. The increase in N input rates increases grains $panicle^{-1}$ as the treatment receiving higher N rates had better N status of the plants during the panicle growth period and as a result, more grains $panicle^{-1}$ were obtained [17]. Higher grains $panicle^{-1}$ were observed with the input of 10 kg Zn ha^{-1} as it fulfills the soil Zn requirements and also increases the availability of other nutrients such as N and improves metabolic activities [18]. Panicles m^{-2} in the TP rice method were higher due to the greater quantity of productive tillers, while in DS rice, the number of productive tillers was less due to no proper plant-to-plant distance and higher weed density. Similar results were also reported by [19] while working on rice cultivation methods. The increase in panicles m^{-2} with an increase in the N rates shows that N takes active participation in different structural functions of the plants.

Weeds are one of the major problems of DS rice production that seriously affect the yield of rice. The main reason for higher weed infestation in the DS rice method is the absence of standing water that can suppress the weeds at the time of crop emergence and the absence of seedlings [20]. N is one of the most important components of crop-weed interaction. This is because some weeds consume more N than rice, thus reducing N uptake by rice crops [12]. The increase in weed density in lower N rate treatments as compared to higher N rates indicates that higher doses of N gave more advantages to rice crops as compared to weeds, and due to the suitable growth of the crop, the weeds were less responsive to N.

The rice grown under the DS rice method takes fewer days to PI than the rice grown under the TP rice method, which might be due to the earlier stand establishment of rice plants [21]. The longer time for PI may also be caused by the removal of tillers from the mother hill and their subsequent transplantation [2]. The delayed days for PI receiving higher N doses might be due to the longer vegetative growth period, as shown by plant height, which hindered the panicle from coming out and also the maturity [22]. The Zn application to rice fields increases the uptake of N by the crop and thus affects the growth period yield of the crop. The maximum days to PM noted in the TP rice might be due to the enhanced growth period [23]. Rice crops grown under DS matured

8 to 10 days earlier than rice grown under the TP method. The results obtained from this study confirm the fact that the maximum supply of N delays PM by promoting vigorous vegetative growth of the plant [24]. Zn was the only micronutrient that was significantly correlated with the pH of the rhizosphere. Due to the higher availability of Zn in the soil rhizosphere, it decreases the soil pH and increases N absorption, thus resulting in crop PM [25].

An increase in the hulling % could be attributed to N and Zn levels, which enhanced grain filling, and as a result, hull thickness was decreased. The present research outcomes are in line with the results of [26], who reported a marked increase in the hulling and milling % by the use of N. Biological yield was higher in the TP due to shallow roots and heavy weed infestation. The increase in biological yield due to Zn application indicates the need for Zn application to rice plants. The Zn application is co-related with all growth parameters as well as photosynthesis and production of fully filled grains up to a certain rate, as beyond that rate it will negatively affect the crop yield [27].

We found higher LAI in the TP rice system due to the better seedling establishment with an extensive root system. This allows the rice plants to have a higher leaf area in comparison to DS rice in which plants start growing from zero [28]. Proper application of N and Zn to rice fields enhances the chlorophyll content, which encourages leaf growth and expansion. The well-established seedlings in the TP rice system maintain their leaves for a longer period of time, resulting in a higher LAD compared to the DS rice method [29]. Zn application enhances the uptake of N, P, and K, which are essential for leaf growth and function, leading to healthier and longer-lasting leaves with an extended LAD [30].

CGR is a measure of the increase in crop biomass over time. The higher CGR in TP rice was due to the initial growth and established root system of the seedlings [22]. Both N and Zn also play a pivotal role in CGR as they designate more assets for the development and advancement of rice plants. The NAR and PAR of the TP rice method are higher than those of the DS approach. This is mostly attributable to the benefits of transferring young rice seedlings from nurseries to the main field [31]. Rice seedlings that have been transplanted can access available resources more effectively because of the reduced competition caused by the spaced-out planting, which raises NAR and PAR [32]. Additionally, more effective weed management prior to transplantation enables the rice to make the best use of its new environment, resulting in increased growth and photosynthetic activity.

To achieve proper plant growth, more area is required around them to capture more nutrients and absorb more solar radiation for better photosynthesis [33]. Previous research studies reported that the TP rice method gave higher straw yield as compared to the direct seeded rice method due to better growth establishment of rice [34, 35]. The increased straw yield at a higher N rate is the result of the maximum availability of N to plants. The higher HI in the TP rice method determines the partitioning of photo assimilates to the grain. The optimum plant spacing and row-to-row distance between plants improves the uptake of nutrients from the soil, as well as the ability to harvest the most sunlight and create the ideal environment for each plant to translocate its maximum assimilates towards the grain, increasing grain yield and HI of rice, whereas, in the DS rice, there is maximum competition for nutrients as a result of the lack of a proper plant spacing [36].

Grain weight is an essential yield component and has a major contribution to rice yield. In TP, the 1000-grain weight was higher due to the minimum competition among the plants for nutrients, which is attributed to the optimum plant spacing in the TP rice cultivation as compared to the DS rice production [37]. The increase in grain weight at higher N rates is primarily due to improvements in chlorophyll contents in leaves, which led to improved photosynthetic activity. Economic comparison is also an important aspect that determines the interest of the farmer in growing the crop. Economic analysis reveals that the cost of production for the TP system was higher as compared to the DS system. The main cause of high-cost production in TP rice cultivation is the shortage of labor at peak times, and as a result, the production costs increase due to expensive labor. The expenditures were also high for raising the nursery, its uprooting, transportation, and transplantation, while for DS rice, only two men were required for two hours to sow in the same area.

Conclusions

The findings of the current study indicated that the DS cultivation system in rice recorded lower yield and yield-related components as compared to the TP rice cultivation. Higher weed infestation, non-productive tillers, and earlier PI and PM led to a decrease in yield and yield-related components. Considering N application, N3 treatments noted maximum yield and yield-related attributes. In comparison, the higher weed density was recorded in N2 treatments. Regarding Zn application, Zn2 treatments gave higher yield while Zn3 recorded higher panicles m^{-2}, weed infestation, days to PI, PM, and non-productive tillers. To achieve a comparable yield with the TP rice method, an integrated set of management technologies should be used to reduce major constraints of the DS rice method. In light of the impending worldwide water shortage and labor deficit, our findings suggest DS rice as a feasible alternative planting strategy. Nevertheless, further work has to be implement suitable management techniques and breeding advances.

Funding

This study was supported by the Researchers Supporting Project number (RSP2025R347), King Saud University, Riyadh, Saudi Arabia.

Acknowledgment

The authors would like to extend their sincere appreciation to the Researchers Supporting Project number (RSP2025R347), King Saud University, Riyadh, Saudi Arabia. The authors also thanks to Management of Agricultural Research Institute, Mingora Swat, Pakistan for providing land and Equipment's for the Trials.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. FAROOQ M., RASHID A., NADEEM F., STUERZ S., ASCH F., BELL R.W., SIDDIQUE K.H. Boron nutrition of rice in different production systems. A review. Agronomy for Sustainable Development, **38**, 1, **2018**.
2. GAUTAM P., LAL B., NAYAK A., RAJA R., PANDA B., TRIPATHI R., SHAHID M., KUMAR U., BAIG M., CHATTERJEE D. Inter-relationship between intercepted radiation and rice yield influenced by transplanting time, method, and variety. International journal of biometeorology, **63**, 337, **2019**.
3. HOSSEN M., HOSSAIN M., HAQUE M., BELL R. Transplanting into non-puddled soils with a small-scale mechanical transplanter reduced fuel, labour and irrigation water requirements for rice (*Oryza sativa* L.) establishment and increased yield. Field Crops Research, **225**, 141, **2018**.
4. SURENDRAN U., RAJA P., JAYAKUMAR M., SUBRAMONIAM S.R. Use of efficient water saving techniques for production of rice in India under climate change scenario: A critical review. Journal of Cleaner Production, **309**, 127272, **2021**.
5. DATTA A., ULLAH H., FERDOUS Z. Water management in rice. Rice production worldwide, 255, **2017**.
6. MISHRA M., WUNGRAMPHA S., KUMAR G., SINGLA-PAREEK S.L., PAREEK A. How do rice seedlings of landrace Pokkali survive in saline fields after transplantation? Physiology, biochemistry, and photosynthesis. Photosynthesis Research, **150**, 117, **2021**.
7. AHMAD S., NADEEM M.Y., GAO S., LI Q., TAO W., LI W., DING Y., LI G. Mitigating Ammonia Volatilization without Compromising Yield and Quality of Rice through the Application of Controlled-Release, Phosphorus-Blended Fertilizers. Agronomy, **13** (2), 448, **2023**.
8. NADEEM M.Y., ZHANG J., ZHOU Y., AHMAD S., DING Y., LI G. Quantifying the Impact of Reduced Nitrogen Rates on Grain Yield and Nitrogen Use Efficiency in the Wheat and Rice Rotation System of the Yangtze River Region. Agronomy, **12** (4), 920, **2022**.
9. JAKSOMSAK P., TUIWONG P., RERKASEM B., GUILD G., PALMER L., STANGOULIS J. The impact of foliar applied zinc fertilizer on zinc and phytate accumulation in dorsal and ventral grain sections of four Thai rice varieties with different grain zinc. Journal of Cereal Science, **79**, 6, **2018**.
10. HASNAIN Z., KHAN S., NASRULLAH F., MEHMOOD K., IBRAR D., BASHIR S., BAKHSH A., AZIZ I., RAIS A., FAROOQ N. Impact of different levels of zinc and nitrogen on growth, productivity, and quality of aromatic rice cultivated under various irrigation regimes in two districts of Pakistan. Frontiers in Plant Science, **13**, 951565, **2022**.
11. ISHFAQ M., AKBAR N., ANJUM S.A., ANWAR-IJL-HAQ M. Growth, yield and water productivity of dry direct seeded rice and transplanted aromatic rice under different irrigation management regimes. Journal of Integrative Agriculture, **19** (11), 2656, **2020**.
12. AWAN T.H., CRUZ P.C.S., AHMED S., CHAUHAN B.S. Effect of nitrogen application, rice planting density, and water regime on the morphological plasticity and biomass partitioning of Chinese sprangletop (Leptochloa chinensis). Weed science, **63** (2), 448, **2015**.
13. HAMOUD Y.A., SHAGHALEH H., GUO X., ZHANG K. pH-responsive/sustained release nitrogen fertilizer hydrogel improves yield, nitrogen metabolism, and nitrogen use efficiency of rice under alternative wetting and moderate drying irrigation. Environmental and Experimental Botany, **211**, 105376, **2023**.
14. HASSAN M.U., AAMER M., HATTHA M.U., HAIYING T., SHAHZAD B., BARBANTI L., NAWAZ M., RASHEED A., AFZAL A., LIU Y. The critical role of zinc in plants facing the drought stress. Agriculture, **10** (9), 396, **2020**.
15. LESKOVAR D.I., OTHMAN Y.A. Direct Seeding and transplanting influence root dynamics, morpho-physiology, yield, and head quality of globe artichoke. Plants, **10** (5), 899, **2021**.
16. ZIA R., NAWAZ M.S., SIDDIQUE M.J., HAKIM S., IMRAN A. Plant survival under drought stress: Implications, adaptive responses, and integrated rhizosphere management strategy for stress mitigation. Microbiological research, **242**, 126626, **2021**.
17. MASUM S., ALI M., MANDAL M., CHOWDHURY I., PARVEEN K. The effect of nitrogen and zinc application on yield and some agronomic characters of rice cv. BRRI dhan33. International Journal of Sciences Basic and Applied Research, **4** (8), 2256, **2013**.
18. KUMAR V., SINGH M., RAGHUVANSHI N. Study on integrated nutrient management on crop growth indices in unpuddled transplanted rice (*Oryza sativa* L.). The Pharma Innovation Journal, **10**, 680, **2021**.
19. LIU H., HUSSAIN S., ZHENG M., PENG S., HUANG J., CUI K., NIE L. Dry direct-seeded rice as an alternative to transplanted-flooded rice in Central China. Agronomy for Sustainable Development, **35**, 285, **2015**.
20. MATLOOB A., KHALIQ A., CHAUHAN B.S. Weeds of direct-seeded rice in Asia: problems and opportunities. Advances in agronomy, **130**, 291, **2015**.
21. KUMHAR B.L., CHAVAN V.G., RAJEMAHADIK V., KANADE V., DHOPAVKAR R., AMETA H., TILEKAR R. Effect of different rice establishment methods on growth, yield and different varieties during kharif season. International Journal of Plant, Animal and Environmental Sciences, **6**, 127, **2016**.

22. CLERGET B., BUENO C., DOMINGO A.J., LAYAOEN H.L., VIAL L. Leaf emergence, tillering, plant growth, and yield in response to plant density in a high-yielding aerobic rice crop. Field Crops Research, **199**, 52, **2016**.
23. LIU Q., ZHOU X., LI J., XIN C. Effects of seedling age and cultivation density on agronomic characteristics and grain yield of mechanically transplanted rice. Scientific reports, **7** (1), 1, **2017**.
24. ABERA T., ADINEW A. Effect of blended NPS fertilizer supplemented with nitrogen on yield components and yield of maize (*Zea mays* L.) in Kachabirra district, Kembata Tambaro zone, southern Ethiopia. International Journal of Research in Agricultural Sciences, **7** (3), 2348, **2020**.
25. SOLANKI M. The Zn as a vital micronutrient in plants. Journal of microbiology, biotechnology and food sciences, **11** (3), e4026, **2021**.
26. SAHA S., CHAKRABORTY M., PADHAN D., SAHA B., MURMU S., BATABYAL K., SETH A., HAZRA G., MANDAL B., BELL R. Agronomic biofortification of zinc in rice: Influence of cultivars and zinc application methods on grain yield and zinc bioavailability. Field Crops Research, **210**, 52, **2017**.
27. MUSTAFA A., ATHAR F., KHAN I., CHATTHA M.U., NAWAZ M., SHAH A.N., MAHMOOD A., BATOOL M., ASLAM M.T., JAREMKO M. Improving crop productivity and nitrogen use efficiency using sulfur and zinc-coated urea: A review. Frontiers in plant science, **13**, 942384, **2022**.
28. SUBEDI P., SAH S.K., MARAHATTHA S., YADAV D.R. Effects of need-based nitrogen management and varieties on growth and yield of dry direct seeded rice. Pertanika Journal of Tropical Agricultural Science, **42** (2), **2019**.
29. JABRAN K., ULLAH E., AKBAR N. Mulching Improves Crop Growth, Grain Length, Head Rice and Milling Recovery of Basmati Rice Grown in Water-saving Production Systems. International Journal of Agriculture & Biology, **17** (5), **2015**.
30. WANG L., LUO Y.C., WANG H., ZOU Y.B., YAO H.Q., ULLAH S., LI Z.Q. Azure-winged magpies fail to understand the principle of mirror imaging. Behavioural Processes, **177**, 8, **2020**.
31. FAGERIA N.K. Nitrogen management in crop production. CRC press, **2014**.
32. CHANDARAK N., SOMJINDA P., PHONCHAROEN P., BANTERNG P., TARATIMA W., THEERAKULPISUT P., DONGSANSUK A. Booting heat stress alters leaf photosynthesis, growth rate, phenology and yield in rice. Plant Stress, **10**, 100226, **2023**.
33. JANSSEN P.J., LAMBREVA M.D., PLUMERÉ N., BARTOLUCCI C., ANTONACCI A., BUONASERA K., FRESE R.N., SCOGNAMIGLIO V., REA G. Photosynthesis at the forefront of a sustainable life. Frontiers in chemistry, **2**, 36, **2014**.
34. XU L., LI X., WANG X., XIONG D., WANG F. Comparing the grain yields of direct-seeded and transplanted rice: A meta-analysis. Agronomy, **9** (11), 767, **2019**.
35. XU L., CHEN H., ZHOU Y., ZHANG J., NADEEM M.Y., MIAO C., YOU J., LI W., JIANG Y., DING Y., LI G. Long-term straw returning improved soil nitrogen sequestration by accelerating the accumulation of amino acid nitrogen. Agriculture, Ecosystems & Environment, **362**, 108846, **2024**.
36. DHITAL G., MARAHATTA S., KARKI T.B., BASNET K.B. Response of different levels of nitrogen and plant population to grain yield of winter hybrid maize in Chitwan Valley, Agronomy Journal of Nepal, **6**, **2022**.
37. PATTANAYAK S., JENA S., DAS P., ROUL P.K., MAITRA S., SHANKAR T., SAIRAM M., SWAIN D.K., PRAMANICK B., GABER A. Crop establishment methods and weed management practices influence the productivity and profitability of Kharif rice (*Oryza sativa* L.) in a hot-humid summer climatic conditions. Paddy and Water Environment, **21** (4), 447, **2023**.