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ASSESSMENT OF PLANT DENSITY AND INTERACTIONS WITH SOIL TYPES AND TRANSPLANTING METHODS IN RICE CULTIVATION

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ABSTRACT

Soil properties play a critical role in determining rice yield by influencing both belowground and aboveground parts of the plant, while also affecting optimal plant density. This study aimed to evaluate the effects of plant density and its interactions with two distinct soil types under manual and mechanical transplanting across two growing seasons of rice cultivation. A split-split plot arrangement was employed within a randomized complete block design with four replications. Two soil types with distinct properties (first soil type and second soil type) were considered as the main factor, planting methods (manual and mechanical transplanting) as the sub-factor, and plant densities (15.9, 20.8, and 27.8 plants m^{-2}) as the sub-sub-factor. Phenological traits, root characteristics, yield, and yield components were assessed. In 2022, at panicle initiation, the longest root length (23.93 cm) was observed at a density of 27.8 plants m^{-2}, while the highest root fresh weight (66.23 g) was recorded in the second soil type. At maturity, the second soil type with manual transplanting had the longest root length (22.43 cm) and, with a density of 15.9 plants m^{-2}, exhibited the highest fresh root weight (86.40 g). Regarding number of spikelets per panicle, in 2021, the highest values were observed in the first and second soil types at 27.8 and 15.9 plants m^{-2}, reaching 122.7 and 122.1 spikelets, respectively; in 2022, the second soil type with 27.8 plants m^{-2} recorded the highest value of 122.4 spikelets. The second soil type with 27.8 plants m^{-2} achieved the highest number of panicles, with values of 554.6 and 547.4 under mechanical and manual transplanting, respectively. Grain yield was indirectly influenced by yield components, being 8.7% higher in the second soil type compared to the first soil type (8048 kg ha^{-1}), peaking at 8687 kg ha^{-1} at a density of 27.8 plants m^{-2}. A density of 27.8 plants m^{-2} increased the number of spikelets per panicle in the first soil type, while it increased the number of panicles per m^{-2} in the second soil type. Accordingly, a density of 27.8 plants m^{-2} is recommended for both soil types.

Keywords: *Oryza sativa* L., planting method, planting spaces, soil characteristics.

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INTRODUCTION

Rice (*Oryza sativa* L.) is a globally important food crop (Peng et al., 2023). Global rice production in 2022/23 reached 513.7 million metric tons, marking a decrease compared to the previous year (USDA, 2023). Therefore, increasing yield and sustainable production of rice is essential for food security (Peng et al., 2023).

Deficiencies in the physical and chemical properties of soil affect plant growth and morphology (Mangosongo et al., 2019). For instance, soil pH determines alkalinity and chemical reactions between water and minerals (Imran et al., 2010). Soil texture also influences root penetration, as well as the movement of water and nutrients (Landon, 1991). Therefore, assessing soil conditions for rice cultivation based on these characteristics is essential (Safitri et al., 2021).

Rice planting can be performed on nursery beds or seedling trays, with seedlings transplanted either manually or mechanically (Ebrahimi et al., 2020). The mechanical method requires less land for the seedbed and offers high efficiency as it can cover a larger area in less time (Zhang and Gong, 2014). However, land scarcity and poor financial constraints pose significant barriers to the adoption of this technology (Saha et al., 2021). Furthermore, seedlings may be weak and susceptible to damage during transplantation (Xing et al., 2017).

Determining the optimal planting density for high-yield rice is crucial (Hu et al., 2020) and can help maximize crop yield (Afa et al., 2023). Plant density creates competition among plants (Pithaloka et al., 2015), which, when properly managed, allows for the efficient use of growth factors and increases yield (Kulig et al., 2019).

A study on loamy soil with 2.70-2.82% organic matter showed that increasing plant density in manual transplanting enhances rice grain yield (Yahyazadeh et al., 2023). Dou et al. (2021) examined various plant densities in mechanical transplanting on soil with 35.6 g kg^{-1} of organic matter, and found that reducing plant density decreases the number of panicles and grain yield per hectare.

Rice paddy soils in various rice-growing regions worldwide exhibit considerable variation in their physical and chemical properties, resulting in differences in their capacity to meet the requirements of plant populations. Since rice transplanting in these regions is carried out both manually and mechanically, with varying proportions, this study was designed based on two hypotheses: i) Soil properties, by influencing root characteristics and yield components, play a key role in determining optimal plant density; and ii) Optimal grain yield is influenced by soil properties and plant density. Therefore, this study aimed to evaluate the effects of plant density and its interactions with two distinct soil types under manual and mechanical transplanting of rice cultivation across two growing seasons. To achieve this, phenological traits, root characteristics, yield, and yield components were assessed.

MATERIALS AND METHODS

The experiment was conducted using a split-split plot arrangement within a randomized complete block design with four replications, across two growing seasons (2021 and 2022) at the Faculty of Agriculture and Natural Resources, Islamic Azad University, Qaemshahr Branch (36°29′N, 52°50′E; 29 m above sea level) in Mazandaran Province, along the Caspian Sea's coastal strip (Fig. 1).

Meteorological parameters of the experimental site, including average temperature, total precipitation, and total hours of sunlight, were measured for the rice-growing period in 2021 and 2022. The average temperatures for the months of May, June, July, and August in 2021 were recorded as 19.9°C, 26.0°C, 27.7°C, and 27.5°C, respectively. In 2022, the corresponding values were 20.5°C, 26.0°C, 29.3°C, and 29.6°C. The total precipitation for the same months in 2021 was 33.4 mm, 4.0 mm, 16.6 mm, and 39.2 mm, while in 2022, it amounted to 40.6 mm, 26.4 mm, 25.5 mm, and 27.9 mm, respectively. Additionally, the total hours of sunlight recorded were 182.5, 297.0, 255.5, and 134.7 hours in 2021, compared to 150.0, 219.5, 231.5, and 231.7 hours in 2022, respectively. The treatments consisted of two soil types with different physicochemical properties (first soil type and second soil type) as the main factor, planting methods (manual transplantation and mechanical transplantation) as the sub-factor, and plant densities (15.9, 20.8, and 27.8 plants m^{-2}, corresponding to spacings of 30 × 21 cm, 30 × 16 cm, and 30 × 12 cm, respectively) as the sub-sub-factor. The soil types corresponded to two fields located 400 meters apart, and their properties are detailed in Table 1.

During the experimental period (2021 and 2022), the fields were exclusively used for rice cultivation and remained fallow at other times. Soil chemical analysis was conducted only during the first year.

Shiroudi rice, the cultivar studied, is a high-yielding, late-maturing, and short-statured variety. This cultivar is known for its high yielding potential, good cooking quality, high

Fig. 1. Study area in Qaemshahr County, Mazandaran Province, Iran.

Table 1. Physicochemical properties of the studied soils (0 to 30 cm depth).

Soil properties	Unit	First soil type	Second soil type
Physical			
Sand	%	19.84	23.84
Silt	%	30.86	38.86
Clay	%	49.30	37.30
Soil texture	-	Clay	Clay Loam
Chemical			
pH	-	7.29	7.24
Electrical conductivity	d.S m^{-1}	1.70	1.60
Organic matter	%	2.63	3.31
Organic carbon	%	1.53	1.92
Available P	Mg kg^{-1}	30.45	27.93
Available K	Mg kg^{-1}	451.61	435.69

marketability, and resistantance to pests and diseases (Rice Research Institute of Iran, 2015). To prepare seedlings for manual transplanting, healthy seeds were first soaked in water for 24 hours and then in a 0.2% solution of the fungicide carboxin thiram for another 24 hours. This fungicide, commercially known as Vitavax, is used to control brown spot disease (*Cochliobolus miyabeanus*) and rice seedling blight (*Gibberella fujikuroi*). The disinfected seeds were kept in a warm room at 26°C for 72 h to germinate. The germinated seeds (2 to 3 mm) were then planted in a nursery that had been prepared a week in advance. The seedlings used for mechanical transplanting were obtained from the seedling bank on the scheduled date. The age of the seedlings was set at 30 days for manual transplanting and 25 days for mechanical transplanting. In mechanical transplanting, the seedlings need to be younger to prevent thick stems from causing issues during the transplanting process.

The experimental fields were cultivated with rice in 2020. Plowing, rotavating, leveling, and smoothing were carried out to prepare the seedbed. The fields were divided into four replications, with a two-meter gap between them. Each replication consisted of six plots (4 m × 5 m), separated by ridges 20 cm high and 50 cm wide. Transplanting was done on May 3 in both years, with each plot containing four seedlings. Manual transplanting was performed by laborers using marked wooden boards (400 cm long, with widths of 21, 16, and 12 cm). For mechanical transplanting, a four-row transplanter (Yanmar, made in Korea) with a planting depth of 4 cm was used. After transplanting, flooding was applied gradually.

Base fertilizers rates were determined according to the results of soil analysis (Table 1). For both soil types, 46 kg ha^{-1} of pure nitrogen from urea fertilizer (46% N) and 34.5 kg ha^{-1} of pure phosphorus from triple superphosphate fertilizer (46% P_2O_5) were applied. No potassium fertilizer was required. The fertilizers were calculated based on the area of each plot and applied manually. Phosphorus fertilizer was applied before transplanting, while nitrogen fertilizer was applied at the basal, panicle initiation, and full heading stages (Mobasser et al., 2005). To prevent the loss of water and urea fertilizer, the plots were covered with plastic sheets to a depth of 30 cm. Additionally, the water channels to the plots were blocked for 48 hours after fertilization to ensure complete absorption. Insects, weeds, and diseases were also controlled as needed.

Harvesting was conducted after physiological maturity on August 15 in both years. Sampling was performed by eliminating the edge effect in each plot. The number of days from transplanting to flowering and from flowering to physiological maturity were examined as phenological traits, determined based on the BBCH scale. Root characteristics were assessed at the early tillering stage, panicle initiation, and physiological maturity. For this purpose, five plants, along with the surrounding soil (20×20×30 cm), were removed from each plot and washed (Qi et al., 2012). Subsequently, root length and root fresh weight were measured (Mobasser et al., 2024). The number of panicles m^{-2} was determined by counting all the panicles in a 1 m^2 area of each plot. The total number of spikelets was calculated by averaging 20 panicles. The thousand-grain weight was determined by counting 10 samples of 100 grains each and weighing them. To calculate yield, all plants from the middle of each plot, covering an area of 4 m^2, were harvested and kept in an oven until they reached zero moisture. Subsequently, the grains were separated from the straw and weighed as grain yield and straw yield, expressed in kg ha^{-1}. The harvest index was calculated as the ratio of grain yield to biological yield (grain + straw) and expressed as a percentage. The moisture content of the grains at the time of measuring the thousand-grain weight and grain yield was 14% (Alipour Abookheili et al., 2024).

After the Bartlett test, the combined analysis of variance of the data was performed using SAS version 9.2 and MSTAT-C statistical software. Means were compared using Tukey's test at the 5% probability level. If the interaction effects between treatments were significant, the main effects were ignored. Tables and figures were drawn using Word 2007 and Excel 2007.

RESULTS AND DISCUSSION

Phenological traits

The number of days from transplanting to flowering and from flowering to maturity were significantly affected by the main effects of year ($F = 50.84$, $p < 0.0001$; $F = 9.10$, $p = 0.0041$, respectively), planting method ($F = 2583.31$, $p < 0.0001$; $F = 19.64$, $p < 0.0001$, respectively), and the interaction of year × soil type ($F = 86.94$, $p < 0.0001$; $F = 9.10$, $p = 0.0041$, respectively) at the 1% probability level. Furthermore, the number of days from transplanting to flowering was significantly influenced by the main effect of soil type ($F = 40.95$, $p < 0.0001$), as well as the interaction effects of soil type × planting method ($F = 22.60$, $p < 0.0001$) and year × soil type × planting method ($F = 10.83$, $p = 0.0019$) at the 1% probability level. The interaction effect of soil type × planting method also showed a statistically significant difference in the number of days from flowering to maturity ($F = 4.70$, $p = 0.0351$) at the 5% probability level (Table 2).

Fig. 2 shows that the minimum number of days from transplanting to flowering in 2021 was achieved in the first soil type with manual transplanting (52.08 days). In contrast, the maximum number of days in 2022 was observed in the same soil type with mechanical transplanting (68.50 days). The higher total precipitation and fewer sunlight hours in the early months of 2022, along with the delay in initial seedling establishment in mechanical transplanting, could explain this difference.

Table 3 indicates that the shortest period from flowering to maturity in 2022 was observed in the first soil type (41.33 days) and in the first soil type with manual transplanting (41.21 days). Meanwhile, the highest number of days were recorded for both the first and second soil types with mechanical transplanting, at 44.13 and 44.00 days, respectively.

Phenology plays a crucial role in the

Table 2. Combined analysis of variance for rice phenological traits (days from transplanting to flowering and flowering to maturity) and root characteristics (root length and root fresh weight) at tillering, panicle initiation, and maturity stages under the effects of soil type (ST), planting method (PM), plant density (PD), and their interactions.

				Root characteristics					
		Phenological traits		Root length			Root fresh weight		
SOV	df	Transplanting to flowering	Flowering to maturity	Tillering	Panicle initiation	Maturity	Tillering	Panicle initiation	Maturity
Year (y)	1	63.37500**	42.66667**	9.47527**	10.86760**	1.54534ns	5.84501ns	126.08750ns	74.44804ns
R(y)	6	1.65278	6.55556	1.27468	2.20562	4.99289	3.02525	195.81341	548.81117
ST (a)	1	51.04167**	16.66667ns	74.34240**	173.50504**	53.61070**	36.03460**	3607.13720**	2727.04120**
y × a	1	108.37500**	42.66667**	0.14107ns	5.85094*	0.00634ns	9.30264*	749.84260*	90.75370ns
error a	6	1.65278	6.55556	4.18223	6.07000	3.34078	0.97060	262.33189	176.74428
PM (b)	1	3220.16667**	92.04167**	156.06000**	91.26000**	70.58940**	96.00000**	311.04000ns	304.16640ns
y × b	1	1.50000ns	2.04167ns	0.00001ns	0.00003ns	0.00004ns	0.00001ns	0.00004ns	0.00003ns
a × b	1	28.16667**	22.04167*	0.54000ns	2.94000ns	8.21340*	3.84000ns	24.00001ns	82.14000ns
y × a × b	1	13.50000**	2.04167ns	0.00001ns	0.00004ns	0.00005ns	0.00001ns	0.00001ns	0.00006ns
error b	12	0.61111	1.15278	0.00002	0.00003	0.00005	0.00001	0.00001	0.00005
PD (c)	2	0.32292ns	0.94792ns	16.17945**	3.02471ns	18.12015**	4.45052ns	3219.57452**	5548.26760**
y × c	2	0.03125ns	0.51042ns	2.06887ns	11.89875**	1.89440ns	7.36069*	50.41807ns	73.63659ns
a × c	2	0.32292ns	0.94792ns	6.05855**	3.71521ns	13.55332**	2.86147ns	365.18102ns	508.58583*
y × a × c	2	0.03125ns	0.51042ns	11.94807**	0.76099ns	0.98765ns	0.09120ns	53.33232ns	13.38158ns
b × c	2	1.76042ns	1.76042ns	0.00001ns	0.00003ns	0.00003ns	0.00002ns	0.00002ns	0.00003ns
y × b × c	2	0.09375ns	0.19792ns	0.00002ns	0.00002ns	0.00004ns	0.00001ns	0.00003ns	0.00005ns
a × b × c	2	1.76042ns	1.76042ns	0.00001ns	0.00005ns	0.00004ns	0.00001ns	0.00001ns	0.00004ns
y × a × b × c	2	0.09375ns	0.19792ns	0.00001ns	0.00002ns	0.00003ns	0.00001ns	0.00002ns	0.00004ns
Total error	48	1.24653	4.68750	0.73142	1.42377	1.71940	1.53387	159.83968	124.56
CV (%)	-	1.84479	5.02529	4.63603	5.28075	6.38567	29.87594	22.51197	17.23

ns, **, *: Indicating non-significance and significance at probability levels of 1% and 5%, respectively.
Abbreviations: CV, coefficient of variation; df, degrees of freedom; R, replication; SOV, sources of variation.

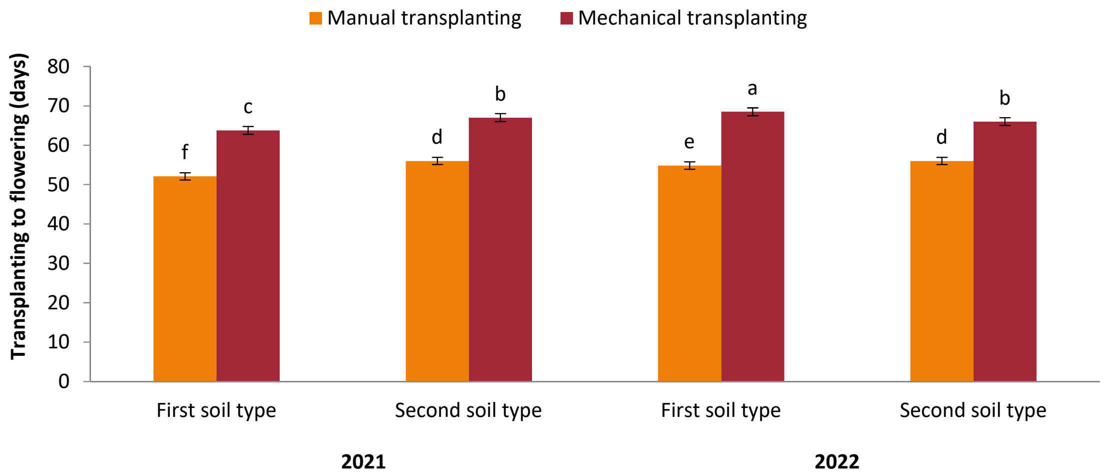

Fig. 2. Interaction effect of year, soil type, and planting method on the number of days from transplanting to flowering. Bars represent the mean of four replicates, with error bars indicating the standard error of the mean. Means with different letters are statistically different according to Tukey's test (P ≤ 0.05).

Table 3. Comparison of mean days from flowering to maturity (FTM) under the interaction effects of Year × Soil type and Soil type × Planting method.

Year × Soil type		FTM (days)	Soil type × Planting method		FTM (days)
	FST	44.00 a		MAT	41.21 c
2021	SST	43.50 ab	FST	MET	44.13 a
	FST	41.33 b		MAT	43.00 b
2022	SST	43.50 ab	SST	MET	44.00 a

Means with the same letters are not significantly different according to Tukey's test (P ≤ 0.05).
Abbreviations: FST; First soil type, SST; Second soil type. MAT, Manual transplanting; MET, Mechanical transplanting.

interception of radiation by the rice canopy (Katsura et al., 2008) and significantly affects grain yield (Guo et al., 2021; Guo et al., 2020; Katsura et al., 2008). In agreement with our findings, studies conducted by Mobasser et al. (2024; 2007) demonstrated that plant density does not significantly affect phenological traits. In their most recent study, the authors evaluated different plant densities in three types of soil with varying physical and chemical properties (fertile, semi-fertile, and infertile) and reported that the number of days from flowering to maturity was not influenced by soil type. However, the highest number of days from transplanting to tillering and the lowest number of days from tillering to flowering were observed in infertile soil (Mobasser et al., 2024). In contrast to our findings, Jiang et al. (2019) demonstrated that soil fertility levels do not significantly affect the growth period of different rice varieties. Regarding rice planting methods, our results are consistent with the finding of previous studies. Specifically, the growth stages in mechanical transplanting are delayed compared to manual transplanting (Liu et al., 2015; Huo et al., 2012). This delay may be attributed to the negative effects of mechanical transplanting on seedling roots, which take approximately 10 to 14 days to recover (Liu et al., 2015).

Root characteristics

The combined analysis of variance from the data in Table 2 indicated that root length at the tillering and panicle initiation stages was significantly affected by the main effect of the year (F = 12.95, p = 0.0008; F = 7.63, p = 0.0081, respectively) at the 1% probability level. Additionally, all root characteristics, including root length at the tillering, panicle initiation, and maturity stages, as well as root fresh weight at the same stages, showed significant differences under the main effect of soil type (F = 101.64, p < 0.0001; F = 121.86, p < 0.0001; F = 31.18, p < 0.0001; F = 23.49, p < 0.0001; F = 22.57, p < 0.0001; F = 21.89, p < 0.0001, respectively) at the 1% probability level. Root length at the tillering, panicle initiation, and maturity stages, as well as root fresh weight at the tillering stage, were significantly influenced by the main effect of planting method (F = 213.37, p < 0.0001; F = 64.10, p < 0.0001; F = 41.05, p < 0.0001; F = 62.59, p < 0.0001, respectively) at the 1% probability level. The root length at the panicle initiation stage under the interaction of year × soil type (F = 4.11, p = 0.0482), and at the maturity stage under the interaction of soil type × planting method (F = 4.78, p = 0.0338), showed a statistically significant difference at the 5% probability level. Root fresh weight at the tillering and panicle initiation stages was also significantly influenced by the interaction effect of year × soil type (F = 6.06, p = 0.0174; F = 4.69, p = 0.0353, respectively) at the 5% probability level. The main effect of plant density significantly influenced root length at the tillering and maturity stages (F = 22.12, p < 0.0001; F = 10.54, p = 0.0002, respectively), and root fresh weight at the panicle initiation and maturity stages (F = 20.14, p < 0.0001; F = 44.54, p < 0.0001, respectively) at the 1% probability level. Root length at the panicle initiation stage (F = 8.36, p = 0.0008) and root fresh weight at the tillering stage (F = 4.80, p = 0.0126) were significantly affected by the interaction effect of year × plant density at the 1% and 5% probability levels, respectively. Root length at the tillering and maturity stages (F = 8.28, p = 0.0008; F = 7.88, p = 0.0011, respectively) at the 1% probability level, and root fresh weight at the maturity stage (F = 4.08, p = 0.0230) at the 5% probability level, were significantly influenced by the interaction effect of soil type × plant density. Only root length at the tillering stage showed a significant difference under the interaction effect of year × soil type × plant density (F = 16.34, p < 0.0001) at the 1% probability level.

Table 4 shows that, at the tillering and panicle initiation stages, root length in mechanical transplanting was 2.55 cm and 1.95 cm shorter, respectively, compared to manual transplanting. At the tillering stage, root fresh weight in mechanical transplanting was 38.9% lower than in manual transplanting. Additionally, at the panicle initiation stage, the highest root fresh weight was observed at a density of 15.9 plants m^{-2} (67.54 g).

Fig. 3 shows that at the tillering stage, the maximum root length in 2021 was observed in the first soil type, with a density of 27.8 plants m^{-2} (20.59 cm). In 2022, the minimum root length was recorded in the second soil type, with densities of 20.8 and 15.9 plants m^{-2} (16.31 and 16.46 cm, respectively).

The two-way interaction effects presented in Table 5 indicate that, at the panicle initiation stage, the maximum root length was obtained in 2022 with the second soil type (24.52 cm). Additionally, at the same stage, the maximum root length in 2022 was observed with a density of 27.8 plants m^{-2} (23.93 cm). At the tillering and panicle initiation stages, the highest root fresh weight was obtained in 2021 with the first soil type (5.316 g) and in 2022 with the second soil type (66.23 g), respectively. Additionally, at the tillering stage, the minimum root fresh weight in 2022 was obtained at a density of 20.8 plants m^{-2} (3.010 g). At the maturity stage, the maximum root length was observed with the second soil type in manual transplanting (22.43 cm) and for the same soil type with a density of 15.9 plants m^{-2} (22.19 cm). At the same stage, the highest root fresh weight with the second soil type was achieved at a density of 15.9 plants m^{-2} (86.40 g).

In infertile soils, plants face soil compaction and nutrient deficiencies (Liu et al., 2021). Under these conditions, plants improve nutrient uptake by increasing root length and the root-to-shoot

Table 4. Comparison of mean root length (RL) and root fresh weight (RFW) in rice at the tillering (TI) and panicle initiation (PI) stages under the main effects of planting method and plant density (plant m^{-2}).

Treatment		RL/TI (cm)	RL/PI (cm)	RFW/TI (g)
	Manual transplanting	19.72 a	23.57 a	5.146 a
Planting method	Mechanical transplanting	17.17 b	21.62 b	3.146 b
				RFW/PI (g)
	15.9	-	-	67.54 a
	20.8	-	-	48.61 b
Plant density	27.8	-	-	52.33 b

Means with the same letters are not significantly different according to Tukey’s test (P ≤ 0.05).

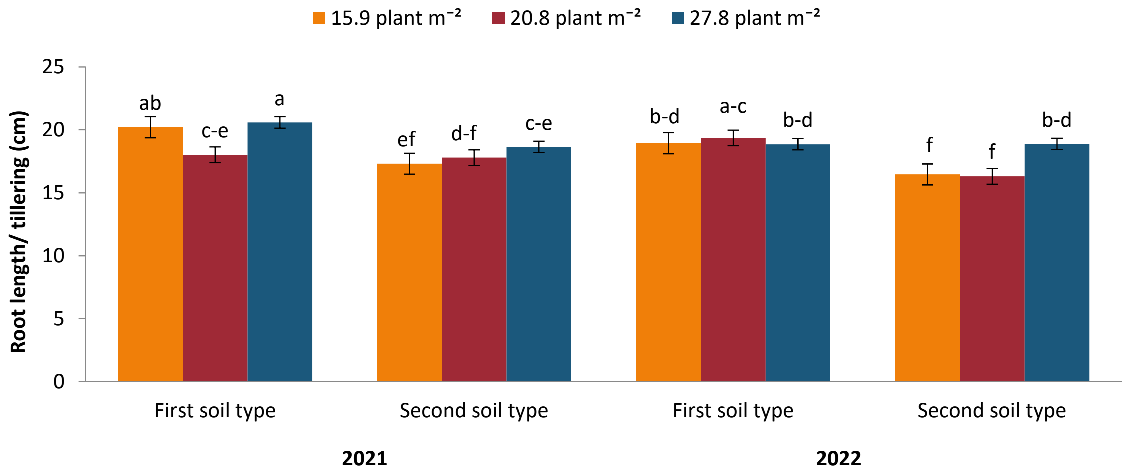

Fig. 3. Interaction effect of year, soil type, and plant density on root length (cm) at the tillering stage. Bars represent the mean of four replicates, with error bars indicating the standard error of the mean. Means with different letters are statistically different according to Tukey's test (P ≤ 0.05).

Table 5. Comparison of mean root length (RL) and root fresh weight (RFW) at the tillering (TI), panicle initiation (PI), and maturity (MA) stages under two-way interaction effects composed of year, soil type, planting method, and plant density (plant m^{-2}).

Year	Soil type	RL/PI (cm)	RFW/TI (g)	RFW/PI (g)	Soil type	Planting method	RL/MA (cm)
	FST	21.16 b	5.316 a	51.68 ab		MAT	20.35 b
2021	SST	23.36 ab	3.468 b	58.35 ab	FST	MET	19.22 d
	FST	21.34 b	4.200 b	48.38 b		MAT	22.43 a
2022	SST	24.52 a	3.597 b	66.23 a	SST	MET	20.13 c

Year	Plant density	RL/PI (cm)	RFW/TI (g)	Soil type	Plant density	RL/MA (cm)	RFW/MA (g)
	15.9	22.65 b	4.695 a		15.9	20.51 bc	73.18 b
	20.8	22.16 b	4.518 a		20.8	19.04 d	58.53 c
2021	27.8	21.97 b	3.964 ab	FST	27.8	19.82 cd	46.64 d
	15.9	22.19 b	4.323 a		15.9	22.19 a	86.40 a
	20.8	22.67 ab	3.010 b		20.8	21.73 ab	60.25 c
2022	27.8	23.93 a	4.363 a	SST	27.8	19.93 cd	63.68 bc

Means with the same letters are not significantly different according to Tukey's test (P ≤ 0.05).
Abbreviations: FST; First soil type, SST; Second soil type. MAT, Manual transplanting; MET, Mechanical transplanting.

ratio (White et al., 2013). However, in fertile soils, plants tend to increase root diameter and reduce root length (Wang et al., 2018). Deng et al. (2020) reported that increasing plant density, especially under low nitrogen conditions, increases root length. Additionally, Chen et al. (2021) demonstrated that root length and root biomass increase at various growth stages with higher plant density and increased nitrogen. Mobasser et al. (2024) examined the effects of three different plant densities (15.2, 19.6, and 27.8 plants m^{-2}) and soil types (fertile, semi-fertile, and infertile) on root morphological traits at different growth stages, and reported that: (1) At the tillering stage, the longest root length in 2022 was observed in infertile soil with high density; (2) At the same stage, the highest root fresh weight was found in infertile soil, and the lowest in fertile soil; (3)

At the panicle initiation stage, the longest root length in 2023 was recorded with high density; (4) At the same stage, root length in fertile soil was greater than in infertile soil; (5) At the panicle initiation and flowering stages, root fresh weight was higher in fertile soil than in infertile soil; (6) At the same stages, the highest root fresh weight was observed at low density; and (7) At the flowering stage, the maximum root length in fertile soil was obtained with low and medium densities (Mobasser et al., 2024).

Yield components

The number of panicles m^{-2} ($F = 6.67$, $p = 0.0129$) at the 5% probability level and the thousand-grain weight ($F = 10.51$, $p = 0.0022$) at the 1% probability level were significantly affected by the main effect of the year. The main effects of soil type and planting method on the number of panicles m^{-2} ($F = 17.22$, $p = 0.0001$; $F = 10.36$, $p = 0.0023$, respectively), the total number of spikelets per panicle ($F = 20.07$, $p < 0.0001$; $F = 94.56$, $p < 0.0001$, respectively), and the thousand-grain weight ($F = 10.91$, $p = 0.0018$; $F = 92.39$, $p < 0.0001$, respectively) showed statistically significant differences at the 1% probability level. The thousand-grain weight was significantly affected at the 5% probability level by the interactions of year × planting method ($F = 4.26$, $p = 0.0443$), soil type × planting method ($F = 5.98$, $p = 0.0182$), and year × soil type × planting method ($F = 4.34$, $p = 0.0425$). The interaction of soil type × planting method significantly affected the number of panicles m^{-2} ($F = 4.30$, $p = 0.0435$) and the total number of spikelets per panicle ($F = 14.05$, $p = 0.0005$) at the 5% and 1% probability levels, respectively. The total number of spikelets per panicle was significantly affected by the main effect of plant density ($F = 9.91$, $p = 0.0002$) at the 1% probability level. Furthermore, statistically significant differences at the 5% probability level were observed under the interaction effects of soil type × plant density ($F = 3.41$, $p = 0.0411$), planting method × plant density ($F = 3.67$, $p = 0.0328$), and soil type × planting method × plant density ($F = 3.71$, $p = 0.0318$). The number of panicles m^{-2} was significantly affected at the 1% probability level under the same interactions ($F = 24.85$, $p < 0.0001$; $F = 5.99$, $p = 0.0048$; $F = 5.85$, $p = 0.0053$, respectively). The total number of spikelets per panicle was significantly affected by the interaction effect of year × soil type × plant density ($F = 3.39$, $p = 0.0420$) at the 5% probability level (Table 6).

Table 7 shows that the number of panicles m^{-2} in 2022 was 15.5 panicles more than in 2021. According to the results of the three-way interactions, the highest thousand-grain weight in 2021 and 2022 was obtained with the first type of soil in mechanical transplanting (28.11 and 28.16 g, respectively). The lowest thousand-grain weight was observed only in 2021 with the same soil in manual transplanting (26.65 g) (Fig. 4).

The thousand-grain weight is a genetic trait that varies depending on the cultivar. However, a reduction in thousand-grain weight is observed under stress conditions such as poor soil fertility (Jiang et al., 2019; Tanzi et al., 2013). Conversely, an increase in thousand-grain weight is influenced by yield components such as the number of panicles m^{-2}, the total number of spikelets per panicle, and the percentage of filled spikelets (Zhou et al., 2023; Wafa and Kakar, 2022; Chen et al., 2022).

The maximum total number of spikelets per panicle in 2021 was observed with the first soil type and a density of 27.8 plants m^{-2} (122.7 spikelets) and with the second soil type and a density of 15.9 plants m^{-2} (122.1 spikelets). Similar results were obtained in 2022 with the second soil type and a density of 27.8 plants m^{-2} (122.4 spikelets) (Fig. 5).

The highest number of panicles m^{-2} in the second type of soil was obtained with mechanical transplanting and a density of 27.8 plants m^{-2} (554.6 panicles), and with manual transplanting at the same plant density (547.4 panicles). The lowest number of panicles m^{-2} and the highest total number of spikelets per panicle (427.0 panicles and 134.1 spikelets, respectively) were obtained with manual transplanting in the first type of soil at the same plant density (Fig. 6 and 7). Under these conditions, where an increase in one yield component is accompanied by a decrease in another, no change in grain yield is observed. This suggests that grain yield was not affected by the mentioned interaction.

Wang et al. (2014) examined different plant densities in two types of soil and showed that the highest number of panicles m^{-2} was obtained at the highest plant density. Additionally, the authors reported that, in less fertile soil, the lowest number of spikelets per panicle was observed at the highest plant density. In a similar experiment, Mobasser et al. (2024) investigated different plant densities in three types of soil, reporting that: (1) the highest number of panicles m^{-2} in 2023 was obtained in fertile soil with high density; (2) the highest number of spikelets per panicle was obtained at low density, which was not statistically different from high density; and (3) the highest thousand-grain weight was recorded in the fertile soil. Ebrahimi et al. (2020) demonstrated that the number of grains per panicle and the thousand-grain weight did not differ statistically between mechanical and manual transplanting. However, the number

Table 6. Combined analysis of variance for yield components (number of panicles m^{-2}, total spikelets per panicle, and thousand-grain weight), as well as grain yield, straw yield, and harvest index in rice under the effects of soil type (ST), planting method (PM), plant density (PD), and their interactions.

		Yield Components					
SOV	df	NPPM^2	TSPP	TGW	GY	SY	HI
Year (y)	1	5758.72*	222.47^{ns}	2.04**	341174.26^{ns}	9483436.80*	11.71^{ns}
R(y)	6	2764.61	154.14	0.04	953759.08	2332193.80	6.07
ST (a)	1	14878.99**	1246.47**	2.12**	14181131.34**	218536402.60**	475.66**
y × a	1	0.13^{ns}	244.99^{ns}	0.43^{ns}	152721.26^{ns}	12018303.00*	27.36^{ns}
error a	6	2183.35	93.15	0.21	250235.47	3360734.30	6.94
PM (b)	1	8948.45**	5873.13**	17.91**	481241.76^{ns}	12977898.00**	105.57**
y × b	1	802.32^{ns}	42.35^{ns}	0.83*	9420.84^{ns}	114885.80^{ns}	0.11^{ns}
a × b	1	3714.46*	872.54**	1.16*	71122.59^{ns}	1617983.00^{ns}	0.57^{ns}
y × a × b	1	831.14^{ns}	76.58^{ns}	0.84*	10395.84^{ns}	4551.30^{ns}	0.17^{ns}
error b	12	1132.78	85.91	0.05	28082.07	41538.90	0.72
PD (c)	2	1487.68^{ns}	615.55**	0.21^{ns}	1816280.67**	17349110.00**	25.00^{ns}
y × c	2	558.58^{ns}	33.73^{ns}	0.08^{ns}	464274.54^{ns}	19130952.00**	104.40**
a × c	2	21467.20**	211.96*	0.16^{ns}	732406.50^{ns}	14706754.60**	31.52*
y × a × c	2	197.96^{ns}	210.48*	0.11^{ns}	387795.54^{ns}	21593155.80**	104.49**
b × c	2	5175.70**	228.19*	0.12^{ns}	1115.17^{ns}	83779.20^{ns}	1.31^{ns}
y × b × c	2	933.82^{ns}	53.12^{ns}	0.24^{ns}	286360.13^{ns}	82599.50^{ns}	1.55^{ns}
a × b × c	2	5053.65**	230.40*	0.12^{ns}	769.50^{ns}	293940.80^{ns}	1.21^{ns}
y × a × b × c	2	947.61^{ns}	67.60^{ns}	0.24^{ns}	290730.87^{ns}	408756.50^{ns}	1.63^{ns}
Total error	48	863.89	62.11	0.19	319881.96	1752627.80	9.49
CV (%)	-	5.76	6.93	1.60	6.71	12.61	6.84

ns, **, *: Indicating non-significance and significance at probability levels of 1% and 5%, respectively.
Abbreviations: CV, coefficient of variation; df, degrees of freedom; R, replication; SOV, sources of variation; NPPM^2, Number of panicles per m^2; TSPP, Total spikelets per panicle; TGW, Thousand-grain weight; GY, grain yield; SY, straw yield; HI, harvest index.

of panicles m^{-2} was 8.1% higher in mechanical transplanting. These findings are consistent with our results but contradict those of Liu et al. (2015). Wang et al. (2014) also found a higher number of panicles m^{-2} in mechanical transplanting, while manual transplanting resulted in the lowest number of panicles m^{-2} and the highest number of spikelets per panicle, which was consistent with our results. Additionally, in the first year of the experiment, the thousand-grain weight was higher in some varieties with manual transplanting. Zhu et al. (2023) also observed a significant effect of planting method on rice yield components.

Grain yield, straw yield, and harvest index

The combined analysis of variance showed that only straw yield was significantly affected by the main effect of the year ($F = 5.41$, $p = 0.0243$) at the 5% probability level. Grain yield, straw yield, and harvest index were significantly influenced by the main effect of soil type ($F = 44.33$, $p <$

Table 7. Comparison of mean number of panicles m^{-2}, grain yield, straw yield, and harvest index in rice under the main effects of year, soil type, planting method, and plant density (plants m^{-2}).

Treatment		Number of panicles m^{-2}	Grain yield (kg ha^{-1})	Straw yield (kg ha^{-1})	Harvest index (%)
	2021	502.6 b	-	-	-
Year	2022	518.1 a	-	-	-
	FST	-	8,048 b	-	-
Soil type	SST	-	8,817 a	-	-
	MAT	-	-	10,866 a	43.97 b
Planting method	MET	-	-	10,130 b	46.07 a
	15.9	-	8,215 b	-	-
	20.8	-	8,396 b	-	-
Plant density	27.8	-	8,687 a	-	-

Means with the same letters are not significantly different according to Tukey's test (P ≤ 0.05).
Abbreviations: FST; First soil type, SST; Second soil type. MAT, Manual transplanting; MET, Mechanical transplanting.

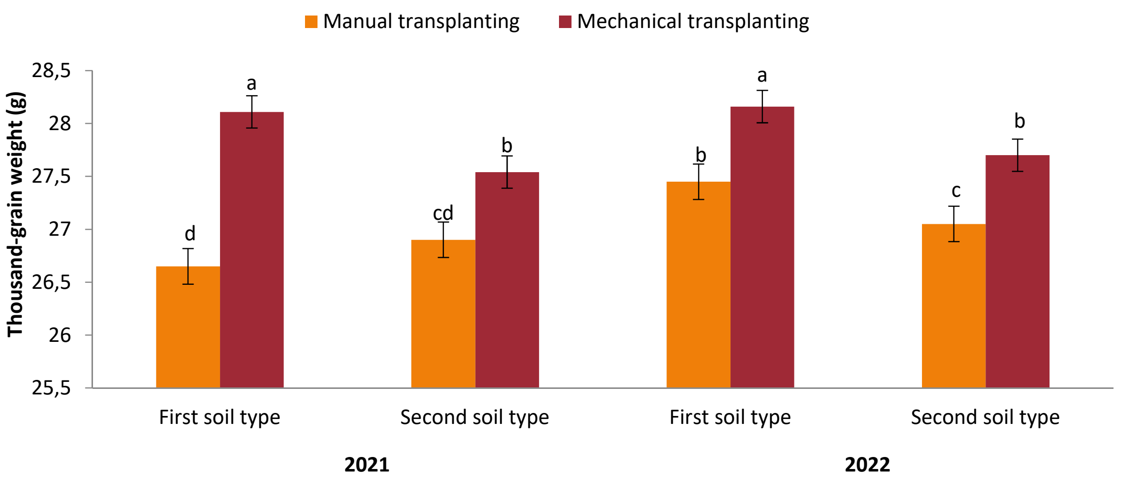

Fig. 4. Interaction effect of year, soil type, and planting method on thousand-grain weight (g). Bars represent the mean of four replicates, with error bars indicating the standard error of the mean. Means with different letters are statistically different according to Tukey's test (P ≤ 0.05).

0.0001; F = 124.69, p < 0.0001; F = 50.14, p < 0.0001, respectively) at the 1% probability level. The grain yield (F = 5.68, p = 0.0061) and harvest index (F = 11.13, p = 0.0016) were significantly affected, respectively, by the main effects of plant density and planting method at the 1% probability level. Similarly, straw yield under the main effects of planting method and plant density (F = 7.40, p = 0.0090; F = 9.90, p = 0.0003, respectively) showed a statistically significant difference at the 1% probability level. Furthermore, straw yield was significantly affected by the interaction effect of year × soil type (F = 6.86, p = 0.0118) at the 5% probability level. Straw yield and harvest index showed statistically significant differences under the interaction effects of year × plant density (F = 10.92, p = 0.0001; F = 11.01, p = 0.0001, respectively) and year × soil type × plant density (F = 12.32, p < 0.0001; F = 11.02, p = 0.0001, respectively) at the 1% probability level. Additionally, the interaction effect of soil type × plant density was significant for straw yield (F = 8.39, p = 0.0007) at the 1% probability level, and for harvest index (F = 3.32, p = 0.0445) at the 5% probability level (Table 6).

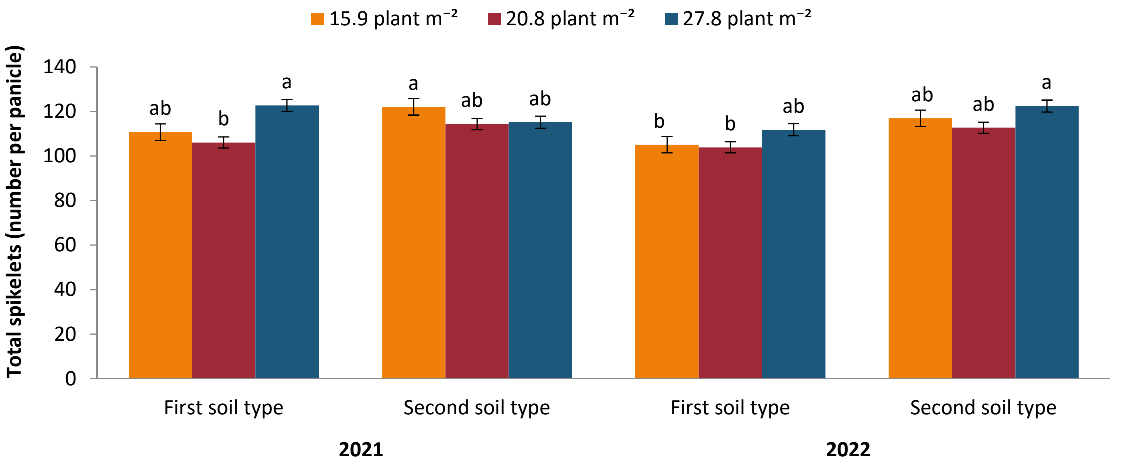

Fig. 5. Interaction effect of year, soil type, and plant density on total spikelets (number per panicle). Bars represent the mean of four replicates, with error bars indicating the standard error of the mean. Means with different letters are statistically different according to Tukey's test (P ≤ 0.05).

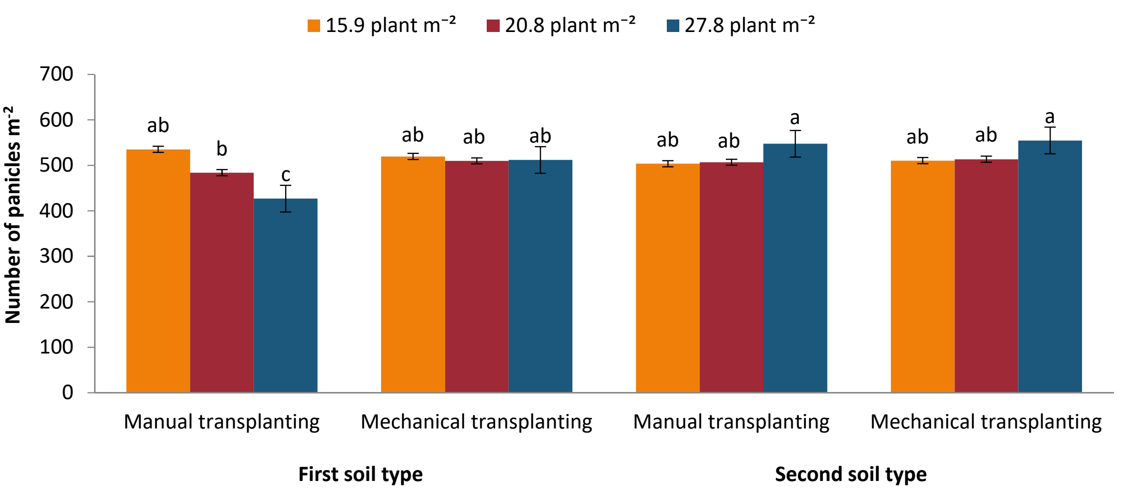

Fig. 6. Interaction effect of soil type, planting method, and plant density on the number of panicles m^{-2}. Bars represent the mean of four replicates, with error bars indicating the standard error of the mean. Means with different letters are statistically different according to Tukey's test (P ≤ 0.05).

The results presented in Table 7 show that grain yield in the second soil type was 8.7% higher than in the first soil type. Straw yield in manual transplanting was 6.8% higher than in mechanical transplanting, whereas the harvest index in mechanical transplanting was 2.1% higher than in manual transplanting. Grain yield increased by 5.4% with an increase in plant density up to 27.8 plants m^{-2}. The highest straw yield and the lowest harvest index in 2021 were obtained with the second soil type and a density of 20.8 plants m^{-2} (15039 kg ha^{-1} and 37.00%, respectively) (Fig. 8 and 9).

Recent research indicates that the highest rice yields are observed in soils rich in organic matter and essential elements such as nitrogen, phosphorus, and potassium (Peng et al., 2023). Additionally, Kheyri et al. (2018) demonstrated that increasing the availability of nutrients improves rice grain yield. Additionally, other researchers have demonstrated that increasing plant density leads to higher grain yield (Alipour Abookheili and Mobasser, 2021; Alipour Abookheili et al., 2020). In fields with fertile soil,

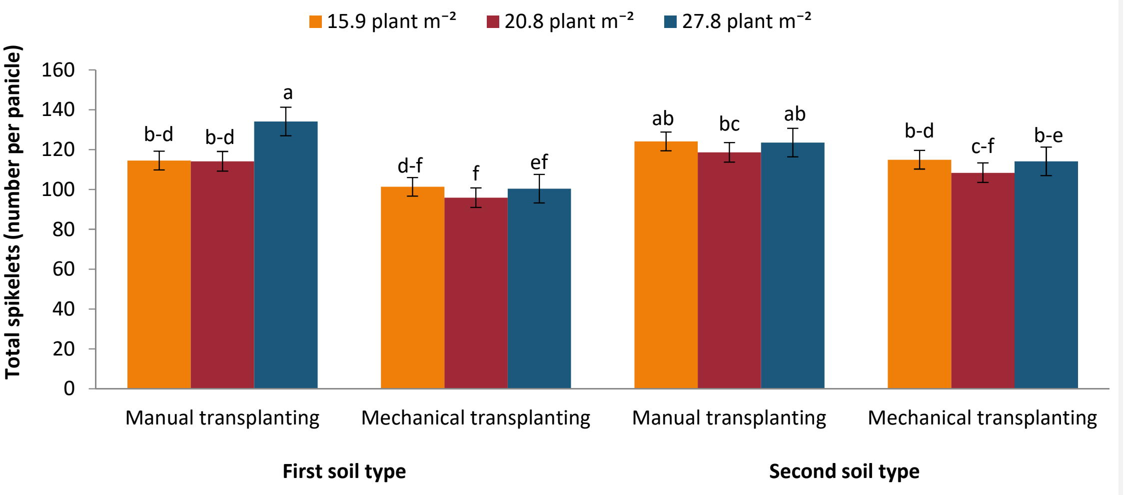

Fig. 7. Interaction effect of soil type, planting method, and plant density on total spikelets (number per panicle). Bars represent the mean of four replicates, with error bars indicating the standard error of the mean. Means with different letters are statistically different according to Tukey's test ($P \leq 0.05$).

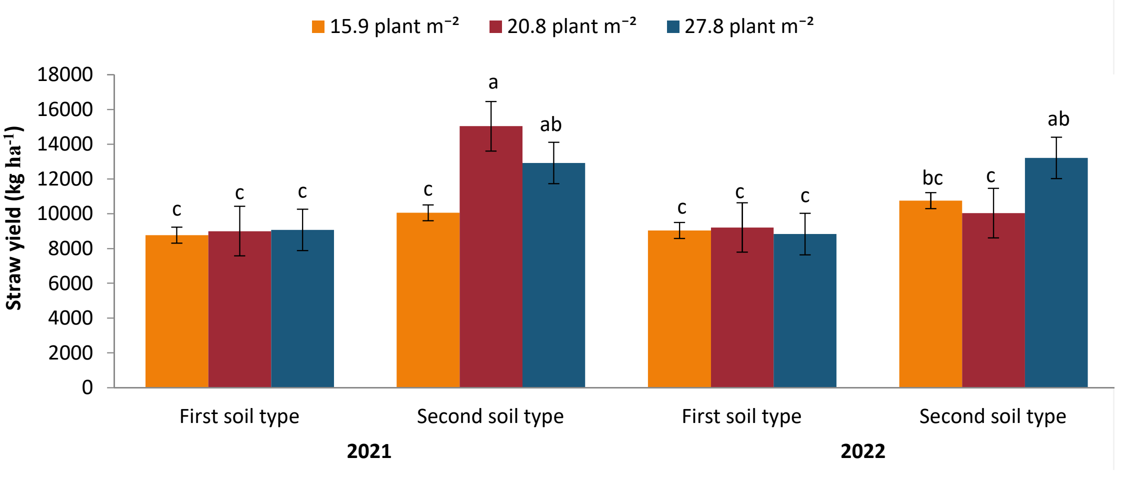

Fig. 8. Interaction effect of year, soil type, and plant density on straw yield (kg ha^{-1}). Bars represent the mean of four replicates, with error bars indicating the standard error of the mean. Means with different letters are statistically different according to Tukey's test ($P \leq 0.05$).

the highest grain yield was achieved from high plant density due to a greater number of panicles and spikelets per unit area (Zhu et al., 2023; Yang et al., 2021). Furthermore, in a more recent study conducted by Mobasser et al. (2024), the highest grain yield was observed in fertile soil with high density, while the lowest grain yield was recorded in infertile soil with high and medium densities.

Andrew Bebeley et al. (2021) reported that improved physical and chemical properties of farm soils increase straw yield and harvest index. Mobasser et al. (2024) also reported that, over two years of study, increased soil fertility and improved soil properties led to higher straw yield, while the harvest index decreased. They observed the highest straw yield and the lowest harvest index in fertile soil with medium density in 2022. Ebrahimi et al. (2020) found no significant differences in grain yield and biological yield between mechanical and manual transplanting; however, the harvest index was 2.1% higher with mechanical transplanting. Other studies have indicated that the planting method significantly influences biomass accumulation and the harvest

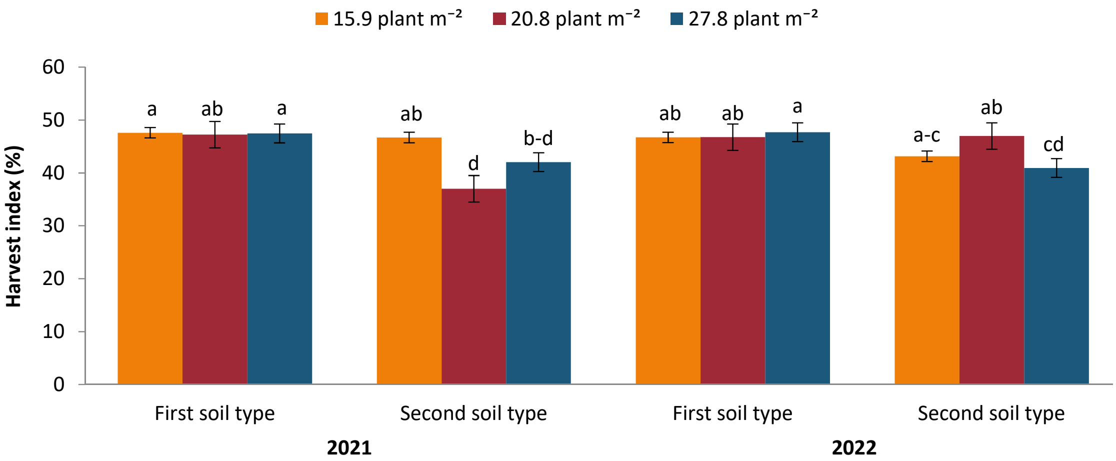

Fig. 9. Interaction effect of year, soil type, and plant density on harvest index (%). Bars represent the mean of four replicates, with error bars indicating the standard error of the mean. Means with different letters are statistically different according to Tukey's test (P ≤ 0.05).

index (Zhu et al., 2023). Additionally, planting method had a significant impact on total dry weight, but its effect on the harvest index was non-significant (Zaraei et al., 2018).

CONCLUSIONS

The results obtained in this study revealed that the longest root length was observed at the tillering stage in the first soil type with high plant density (27.8 plants m^{-2}) in 2021. This likely contributed to an increase in the number of spikelets per panicle. Notably, this treatment (the first soil type with high plant density) also significantly affected the number of spikelets per panicle in 2022. The first soil type, with a higher clay content and likely improved water and nutrient retention, combined with higher levels of phosphorus and potassium, facilitated root growth. High plant density, by increasing competition for soil resources, further intensified this growth.

Additionally, in 2021, the second soil type with low plant density (15.9 plants m^{-2}), exhibited the highest number of spikelets per panicle. This was likely associated with increased root length and root fresh weight at the maturation stage. The second soil type, characterized by a lower clay content, higher silt content, and likely improved aeration, along with higher levels of organic carbon, facilitated deeper and more extensive root growth. Low plant density, by reducing competition for soil resources, further supported root development and spread.

Notably, the second type of soil, with high plant density, demonstrated the highest number of panicles m^{-2} in both manual and mechanical transplanting methods. It also recorded the highest number of spikelets per panicle in 2022. High plant density increased the number of stems (tillers) per m^{-2} and, under the favorable conditions of the second soil type, including high levels of organic matter, enhanced both the number and length of panicles.

Upon further investigation, no clear relationship was observed between yield components and grain yield under the influence of the experimental treatments. However, grain yield significantly increased in the second soil type, likely due to the positive effects of this soil on root characteristics. Additionally, higher plant density resulted in a significant improvement in grain yield, which could be attributed to enhanced soil resource utilization.

In general, grain yield varies with variations in its components. In this study, grain yield was indirectly influenced by these components. The results showed that, in the first soil type, a density of 27.8 plants m^{-2} produced the highest number of spikelets per panicle, whereas the same density in the second soil type resulted in the highest number of panicles m^{-2}. Accordingly, a plant density of 27.8 plants m^{-2} is recommended for both soil types.

Author Contributions

Ebrahim Rezaei, Morteza Sam Daliri, and Hamid Reza Mobasser actively contributed to the bibliographic review and the methodology development. The results were discussed by Hamid Reza Mobasser, Amir Abbas Mousavi Mirkolaei, and Morteza Moballeghi. Lastly, Morteza Sam Daliri and Hamid Reza Mobasser reviewed and approved the final version of the article.

LITERATURE CITED

Afa, L.O., A. Ansi, Z. Zulfikar, M. Muhidin, and A. Al Qadri. 2023. The Growth and Yield of Local Upland Rice (*Oryza sativa* L.) Wakawondu Cultivar in Various Plant Populations and Balanced Fertilization. Buletin Penelitian Sosial Ekonomi Pertanian Fakultas Pertanian Universitas Haluoleo 24(2): 88–98. https://doi.org/10.37149/bpsosek.v24i2.288

Alipour Abookheili, F., and H.R. Mobasser. 2021. Effect of planting density on growth characteristics and grain yield increase in successive cultivations of two rice cultivars. Agrosystems, Geosciences & Environment 4(4): e20213. https://doi.org/10.1002/agg2.20213

Alipour Abookheili, F., Gh. Noormohammadi, H. Madani, H. Heidari Sharifabad, and H.R. Mobasser. 2020. Effect of Nitrogen Splitting and Plant Density on Yield and Grain Yield Components of Two Rice Genotypes (*Oryza sativa* L.). Iranian Journal of Field Crops Research 17(4): 631-645.

Alipour Abookheili, F., Gh. Noormohammadi, H. Madani, H. Heidari Sharifabad, and H.R. Mobasser. 2024. Effects of plant density and nitrogen splitting on grain yield and nitrogen uptake in rice re-cropping. Journal of Plant Nutrition 47(13): 2070-2084. https://doi.org/10.1080/01904167.2024.2327591

Andrew Bebeley, H., P. Tongor Mabey, and P. Emmanuel Norman. 2021. Effects of Biochar, Plant Density and Spacing on Growth and Yield of Rice in a Tropical Inland Valley Swamp. International Journal of Applied Agricultural Sciences 7(2): 77-83. https://doi.org/10.11648/j.ijaas.20210702.11

Chen, J., X. Zhu, J. Xie, G. Deng, T. Tu, X. Guan, Z. Yang, S. Huang, X. Chen, C. Qiu, Y. Qian, C. Shao, M. Xu, and C. Peng. 2021. Reducing nitrogen application with dense planting increases nitrogen use efficiency by maintaining root growth in a double-rice cropping system. The Crop Journal 9(4): 805–815. https://doi.org/10.1016/j.cj.2020.09.006

Chen, Y., Y. Liu, S. Dong, J. Liu, Y. Wang, S. Hussain, H. Wei, Z. Huo, K. Xu, and Q. Dai. 2022. Response of Rice Yield and Grain Quality to Combined Nitrogen Application Rate and Planting Density in Saline Area. Agriculture 12(11): 1788. https://doi.org/10.3390/agriculture12111788

Deng, J., X. Feng, D. Wang, J. Lu, H. Chong, C. Shang, K. Liu, L. Huang, X. Tian, and Y. Zhang. 2020. Root morphological traits and distribution in direct-seeded rice under dense planting with reduced nitrogen. PLoS ONE 15(9): e0238362. https://doi.org/10.1371/journal.pone.0238362

Dou, Z., Y. Li, H. Guo, L. Chen, J. Jiang, Y. Zhou, Q. Xu, Z. Xing, H. Gao, and H. Zhang. 2021. Effects of Mechanically Transplanting Methods and Planting Densities on Yield and Quality of Nanjing 2728 under Rice-Crayfish Continuous Production System. Agronomy 11(13): 488. https://doi.org/10.3390/agronomy11030488

Ebrahimi, M., M. Majidian, and M.R. Alizadeh. 2020. Effect of tillage and planting methods on soil physical properties, grain yield and milling recovery of rice (*Oryza sativa* L. cv. Hashemi). Iranian Journal of Crop Sciences 22(1): 66-80.

Guo, Y., W. Wu, Y. Liu, Z. Wu, X. Geng, Y. Zhang, C.R. Bryant, and Y. Fu. 2020. Impacts of Climate and Phenology on the Yields of Early Mature Rice in China. Sustainability 12(23): 10133. https://doi.org/10.3390/su122310133

Guo, Y., Y. Fu, F. Hao, X. Zhang, W. Wu, X. Jin, C. Robin Bryant, and J. Senthilnath. 2021. Integrated phenology and climate in rice yields prediction using machine learning methods. Ecological Indicators 120: 106935. https://doi.org/10.1016/j.ecolind.2020.106935

Hu, Q., W. Jiang, S. Qiu, Z. Xing, Y. Hu, B. Guo, G. Liu, H. Gao, H. Zhang, and H. Wei. 2020. Effect of wide-narrow row arrangement in mechanical pot-seedling transplanting and plant density on yield formation and grain quality of japonica rice. Journal of Integrative Agriculture 19(5): 1197-1214. https://doi.org/10.1016/S2095-3119(19)62800-5

Huo, Z.Y., J. Li, H.C. Zhang, Q.G. Dai, K. Xu, H.Y. Wei, and J.L. Gong. 2012. Characterization of Nitrogen Uptake and Utilization in Rice under Different Planting Methods[J]. Acta Agronomica Sinica 38(10): 1908-1919.

Imran, M., A. Khan, A. Hassan, F. Kanwal, M. Liviu, M. Amir, and M.A. Iqbal. 2010. Evaluation of physico-chemical characteristics of soil samples collected from Harrapa-Sahiwal (Pakistan). Asian Journal of Chemistry 22(6): 4823-4830.

Jiang, S.C., J.M. Wang, H.W. Lou, Y.M. Xie, D.H. Feng, L. Zhou, L. Shi, H. Chen, Y.Y. Xu, M. Wang, and D.Y. Xing. (2019). Effect of meteorology and soil fertility on direct-seeded rice (*Oryza sativa* L.) performance in Central China. Applied Ecology and Environmental Research 17(5): 12397-12406. http://dx.doi.org/10.15666/aeer/1705_1239712406

Katsura, K., S. Maeda, I. Lubis, T. Horie, W. Cao, and T. Shiraiwa. 2008. The high yield of irrigated rice in Yunnan, China—'A cross-location analysis'. Field Crops Research 107(1): 1–11. https://doi.org/10.1016/j.fcr.2007.12.007

Kheyri, N., H. Ajam Norouzi, H.R. Mobasser, and B. Torabi. 2018. Effect of different resources and methods of silicon and zinc application on agronomic traits, nutrient uptake and grain yield of rice (*Oryza sativa* L.). Applied Ecology and Environmental Research 16(5): 5781-5798. http://dx.doi.org/10.15666/aeer/1605_57815798

Kulig, B., E. Gacek, R. Wojciechowski, A. Oleksy, M. Kołodziejczyk, W. Szewczyk, and A. Klimek-Kopyra. 2019. Biomass yield and energy efficiency of willow depend on the cultivar, harvesting frequency, and planting density. Plant, Soil and Environment 65(8): 377–386. https://doi.org/10.17221/594/2018-PSE

Landon, J.R. 1991. Booker tropical soil manual: a handbook for soil survey and agricultural land evaluation in the tropics and subtropics. (New York and London: Routledge Taylor & Francis Group). https://doi.org/10.4324/9781315846842

Liu, B., H. Li, H. Li, A. Zhang, and Z. Rengel. 2021. Long-term biochar application promotes rice productivity by regulating root dynamic development and reducing nitrogen leaching. GCB Bioenergy 13(1): 257–268. https://doi.org/10.1111/gcbb.12766

Liu, Q., X. Wu, J. Ma, B. Chen, and C. Xin. 2015. Effects of delaying transplanting on agronomic traits and grain yield of rice under mechanical-transplantation pattern. PLoS ONE 10(4): e0123330. https://doi.org/10.1371/journal.pone.0123330

Mangosongo, H.M., H.V. Lyaruu, and E.E. Mneney. 2019. Assessment of Soil Physico-Chemical Properties in Selected Natural Habitats of The Wild Rice (*Oryza Longistaminata*) and their Effects on the Species Morphological Characters. Huria: Journal of the Open University of Tanzania 26(1): 12-29.

Mobasser, H.R., G. Noormohamadi, V.M. Fallah, F. Darvish, and S. Majidi. 2005. Effects of nitrogen rates and splitting on grain yield of rice (*Oryza sativa* L.) Var.Tarom Hashemi. Journal of Agricultural Science 11(3): 109–120.

Mobasser, H.R., M. Mohseni Delarestaghi, A. Khorgami, D. Barari Tari, and H. Pourkalhor. 2007. Effect of Planting density on agronomical characteristics of rice (*Oryza Sativa* L.) varieties in north of Iran. Pakistan Journal of Biological Sciences 10(18): 3205–3209.

Mobasser, H.R., S.A. Sadeghi, and F. Alipour Abookheili. 2024. The determination of desired plant density in soils with different fertility in a region for mechanized rice cultivation. Agronomy Journal 116(5): 2217-2228. https://doi.org/10.1002/agj2.21631

Peng, G., T. Zhang, X-Y. Lei, X-W. Cui, Y-X. Lu, P-F. Fan, S-P. Long, J. Huang, J-S. Gao, Z-H. Zhang, and H-M. Zhang. 2023. Improvement of soil fertility and rice yield after long-term application of cow manure combined with inorganic fertilizers. Journal of Integrative Agriculture 22(7): 2221–2232. https://doi.org/10.1016/j.jia.2023.02.037

Pithaloka, S.A., S. Sunyoto, M. Kamal, and K.F. Hidayat. 2015. Pengaruh Kerapatan Tanaman Terhadap Pertumbuhan Dan Hasil Beberapa Varietas Sorgum (*Sorghum bicolor* (L.) Moench). Jurnal Agrotek Tropika 3(1): 56-63. http://dx.doi.org/10.23960/jat.v3i1.1948

Qi, W.Z., H.H. Liu, P. Liu, S.T. Dong, B.Q. Zhao, H.B. So, G. Li, H.D. Liu, J.W. Zhang, and B. Zhao (2012). Morphological and physiological characteristics of corn (*Zea mays* L.) roots from cultivars with different yield potentials. European Journal of Agronomy 38: 54-63. https://doi.org/10.1016/j.eja.2011.12.003

Rice Research Institute of Iran. 2015. Transformation in the country's rice production through the introduction of high-yielding varieties. Rice Research Institute of Iran. Rasht, Gilan Province, Iran.

Safitri, D.E., A. Ahmad, and M. Nathan. 2021. Study of soil management in rice fields in Bantimurung District Maros Regency. IOP Conference Series: Earth and Environmental Science 807: 042008.

Saha, R., P.S. Patra, and A.S. Ahmed. 2021. Impact of Mechanical Transplanting on Rice Productivity and Profitability-Review. International Journal of Economic Plants 8(4): 226–230. https://ojs.pphouse.org/index.php/IJEP/article/view/4700

Tanzi, B.N., M.S.A. Arifin, M.A. Mondol, A.K. Hasan, and M. A. Wadud. 2013. Effect of tree leaf biomass on soil fertility and yield of rice. Journal of Agroforestry and Environment 7(1): 129-133.

USDA. 2023. World agricultural production (WAP 10-23). Foreign Agricultural Service, United States Department of Agriculture. https://downloads.usda.library.cornell.edu/usda-esmis/files/5q47rn72z/tm70pd08x/n5840d235/production.pdf

Wafa, I.K., and K. Kakar. 2022. Effects of Different Planting Densities and Planting Spaces on the Growth and Yield Attributes of Rice under Irrigated Condition. Nangarhar University International Journal of Biosciences 1(1): 6–12. https://doi.org/10.70436/nuijb.v1i01.3

Wang, D., S. Chen, Z. Wang, C. Ji, C. Xu, X. Zhang, and B. Singh Chauhan. 2014. Optimizing Hill Seeding Density for High-Yielding Hybrid Rice in a Single Rice Cropping System in South China. PLoS ONE 9(10): e109417. https://doi.org/10.1371/journal.pone.0109417

Wang, Y., T. Zhang, R. Wang, and Y. Zhao. 2018. Recent advances in auxin research in rice and their implications for crop improvement. Journal of Experimental Botany 69(2): 255–263. https://doi.org/10.1093/jxb/erx228

White, P.J., T.S. George, P.J. Gregory, A.G. Bengough, P.D. Hallett, and B.M. McKenzie. 2013. Matching roots to their environment. Annals of Botany 112(2): 207–222. https://doi.org/10.1093/aob/mct123

Xing, Z.P., Y.J. Hu, H.J. Qian, W.W. Cao, B.W. Guo, H.Y. Wei, K. Xu, Z.Y. Huo, G.S. Zhou, Q.G. Dai, and H.C. Zhang. 2017. Comparison of yield traits in rice among three mechanized planting methods in a rice-wheat rotation system. Journal of Integrative Agriculture 16(7): 1451–1466. https://doi.org/10.1016/S2095-3119(16)61562-9

Yahyazadeh, S., H.R. Mobasser, E. Rahimi Petroudi, and A. Daneshmand. 2023. Effect of Nitrogen Fertilizer and Plant Density on Growth Characteristics, Yield Components and Grain Yield of Rice. Journal of Crop Production and Processing 13(1): 1-14.

Yang, G., X. Wang, F. Nabi, H. Wang, C. Zhao, Y. Peng, J. Ma, and Y. Hu. 2021. Optimizing Planting density and Impact of panicle types on grain yield and microclimatic response index of hybrid rice (*Oryza sativa* L.). International Journal of Plant Production 15: 447–457. https://doi.org/10.1007/s42106-021-00150-8

Zaraei, Zh., H. Heidari, I. Nosratti, and M. Khoramivafa. 2018. Comparison of Direct Seeding and Transplanting Systems in Maize (*Zea Mays* L.) Under The Usual and Early Planting Dates. Journal of Plant Productions (Scientific Journal of Agriculture), 41(1): 97-108. https://doi.org/10.22055/ppd.2018.13553

Zhang, H.C., and J.L. Gong. 2014. Research status and development discussion on high-yield agronomy of mechanized planting rice in China. Scientia Agricultura Sinica 47(7): 1273–1289. https://doi.org/10.3864/j.issn.0578-1752.2014.07.004

Zhou, W., L. Yan, Z. Fu, H. Guo, W. Zhang, W. Liu, Y. Ye, and P. Long. 2023. Increasing Planting Density and Reducing N Application Improves Yield and Grain Filling at Two Sowing Dates in Double-Cropping Rice Systems. Plants 12(12): 2298. https://doi.org/10.3390/plants12122298

Zhu, H., X. Lu, K. Zhang, Z. Xing, H. Wei, Q. Hu, and H. Zhang. 2023. Optimum Basic Seedling Density and Yield and Quality Characteristics of Unmanned Aerial Seeding Rice. Agronomy 13(8): 1980. https://doi.org/10.3390/agronomy13081980