Effect of Transplanting Plant Numbers per Hill on Heterosis in Hybrid Rice

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Abstract**—** *Hybrid rice is the primary cereal crop in Southern China, playing a crucial role in national food security. With a yield advantage of 15–20% over inbred varieties, agronomic practices. Planting density including inter-plant spacing and the number of transplanted plants per hill has a fundamental effect on rice production. However, the impact of transplanting plant numbers per hill on the expression of hybrid vigor remains unclear. This study evaluates the effects of different transplanting densities under sparse planting conditions on key physiological and yield-related traits in hybrid rice, its paternal lines, and inbred varieties. Results indicate that transplanting plant numbers per hill significantly influence heterosis, affecting key traits such as better-parent heterosis (BPH), plant height (PH), spikelets per panicle (SPP), seed setting rate (SSR), harvest index (HI), and overall yield. The optimal transplanting density for maximizing yield was 1–2 plants per hill for hybrid rice and 3–4 plants per hill for inbred varieties. These findings provide a theoretical foundation for breeding, high-yield cultivation, and the mechanized adoption of hybrid rice.*

Keywords**— *hybrid rice; heterosis; yield traits; transplanting density; restorer lines.***

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I. INTRODUCTION

Rice (*Oryza sativa* L.) is a staple food crop, with China contributing over one-fourth of global rice production. It provides essential energy and nutrition to approximately 65% of the Chinese population[1]. Hybrid rice has played a critical role in ensuring food security, yielding 15–20% more than inbred cultivars[2]. The best cultivation measures, including transplanting density, number of transplanted plants, and fertilization measures, can achieve the highest yield of hybrid rice.This yield advantage is primarily attributed to increased grain weight, biomass accumulation, and extended growth duration, which enables better utilization of environmental resources such as temperature, light, and heat[3-6]. With the widespread adoption of hybrid rice, optimizing cultivation practices is essential to fully exploit its yield potential. Among agronomic factors, planting density—including inter-plant spacing and the number of transplanted plants per hill—is a fundamental determinant of rice productivity[7]. Recent advancements in agricultural mechanization, alongside labor shortages, have made machine transplanting the preferred method due to its efficiency and control over spacing and transplanting density [8]. The number of seedlings per hill at transplanting is particularly influential, directly affecting rice growth and yield formation [9]. Thus, systematic evaluation of transplanting density is necessary to refine high-yield cultivation strategies for hybrid rice and inbred varieties.

Hybrid rice yield is strongly influenced by planting density, which modulates critical yield traits such as effective panicles per hill (EPN), spikelets per panicle (SPP), seed setting rate (SSR), and 1000-grain weight (KGW). Proper density management balances inter-plant competition and compensation, enhancing yield. Historically, inbred rice yield in China was increased in the 1960s through high-density planting to maximize panicle number per unit area. In contrast, the 1980s saw the adoption of sparse planting for large-panicle hybrid rice, which optimized plant architecture by reducing excessive tillering and increasing panicle size rather than panicle number [10, 11]. The number of seedlings per hill is a key factor in yield optimization. Under constant planting density, an increase in seedlings per hill initially enhances effective panicle formation but eventually reduces yield due to a decline in spikelets per panicle and increased competition[12]. Excessive seedling numbers per hill promote ineffective tillering, reducing panicle productivity and limiting yield gains [13]. Conversely, an appropriate seedling number per hill, coupled with optimal spacing, can improve population structure, minimize ineffective tillers, enhance tiller-to-panicle conversion rates, and optimize yield component relationships [14].

The yield potential of super high-yielding hybrid rice in China has risen from 10.5 t/ha to 15 t/ha [15]. Given the importance of transplanting practices, it is hypothesized that the number of plants per hill significantly affects the expression of heterosis in hybrid rice. Since farmers commonly adopt sparse planting densities, it is crucial to evaluate the impact of transplanting plant numbers per hill under these conditions. This study systematically compares key physiological and yield traits in different hybrid rice genotypes, their parental lines, and inbred varieties, clarifying the role of transplanting density in the expression of heterosis. The findings provide a theoretical basis for breeding, high-yield cultivation, and the mechanization of hybrid rice production, contributing to food security.

TABLE 1
MAIN RICE VARIETIES USED IN THE EXPERIMENT

Variety	Male steril line	Restore line	Super rice	Certification	Breeding unit
LYP9	P64s	R9311	1st	National approved 2001001	Hunan Hybrid Rice Research Center
YLY1	Y58s	R9311	2nd	National approved 2008001	Hunan Hybrid Rice Research Center
YLY2	Y58s	YH2	3rd	National approved 2013027	Hunan Hybrid Rice Research Center
YLY900	Y58s	R900	4th	National approved 2015034	Hunan Hybrid Rice Research Center
HHZ				National approved 2007018	Rice Research Institute, Guangdong
XWX17				National approved 2008035	Hunan Rice Research Institute

TABLE 2
MAIN SOIL PROPERTIES OF EXPERIMENTAL PADDY FIELD

Soil sample	Total N(g/kg)	Total N(g/kg)	Total N(g/kg)	pH	Organic matter (%)
1	1.75	0.93	9.93	5.7	2.92
2	1.53	0.79	8.14	6.0	2.89
3	1.17	0.63	10.69	5.8	1.99
4	1.91	0.78	10.13	6.5	3.75
5	1.91	0.73	10.98	6.4	3.94
6	1.74	0.91	10.39	6.4	3.52
Mean	1.67	0.80	10.04	6.13	3.17

TABLE 3
MAIN RICE VARIETIES ARRANGEMENTS AND GROWTH PERIOD IN THE EXPERIMENT

Year	Variety	Sowing date	Transplanting date	Heading date	Milk ripening date	Mature date	Whole growth period
2016	LYP9	2016/5/28	2016/6/22	2016/9/13	2016/9/15	2016/10/4	129
2016	YLY1	2016/5/28	2016/6/22	2016/9/13	2016/9/15	2016/10/4	129
2016	R9311	2016/5/28	2016/6/22	2016/9/13	2016/9/15	2016/10/4	129
2016	YLY2	2016/5/28	2016/6/22	2016/9/13	2016/9/15	2016/10/4	129
2016	YH2	2016/5/28	2016/6/22	2016/10/4	2016/10/5	2016/10/28	153
2016	YLY900	2016/5/28	2016/6/22	2016/9/13	2016/9/15	2016/10/4	129
2016	R900	2016/5/28	2016/6/22	2016/10/4	2016/10/5	2016/10/28	153
2016	HHZ	2016/5/28	2016/6/22	2016/8/29	2016/9/1	2016/9/25	120
2016	XWX17	2016/5/28	2016/6/22	2016/8/29	2016/9/1	2016/9/25	120

II. MATERIALS AND METHODS

2.1 Experimental sites and materials:

Field experiments were conducted at the Hunan Hybrid Rice Research Center experimental base (28°12′N, 112°59′E, altitude 73 m) in Changsha County, Hunan Province, China, during the 2015–2016 growing seasons under a subtropical climate. The primary experimental materials included super high-yielding hybrid rice varieties (LYP9, YLY1, YLY2, YLY900), restorer lines (R9311, YH2, R900), and inbred control varieties (HHZ and XWX17) (**Table A1 and 1**), all of which are widely cultivated in China. The experimental field had a high nitrogen content, with key soil properties summarized in **Table 2**. In 2015, the field was fertilized with 50 kg/ha of potassium fertilizer (KCl ≥40%, K_2O ≥22%) sourced from Canada and 200 kg/ha of compound fertilizer (N-P-K: 16%-16%-16%). In 2016, 375 kg/ha of compound fertilizer (N-P-K: 16%-16%-16%) was applied after transplanting. Field irrigation and management followed standard local farming practices.

2.2 Experimental design and sampling measurements:

The transplanting plot size was 19.8 cm × 26.4 cm. In 2015, each variety was transplanted with 1, 1, 2, or 4 plants per hill (PPH1-4), while in 2016, 1, 2, 3, or 4 plants per hill (PPH1-4) were used. Each plot covered an area of at least 30 m². A randomized complete block (RCB) design was implemented, with each variety treated as a separate factor and replicated three times. Details on sowing and transplanting dates, seedling numbers per hill, and maturity stages for each variety are provided in **Table 3**. Biomass accumulation was measured at different growth stages. Above-ground biomass was determined as the sum of the dry weight of leaves, stems, rachis, and filled, half-filled, and empty spikelets. Six hills per variety were sampled, and plant material was oven-dried at 70 °C for 48 hours until a constant weight was reached. The harvest index (HI) was calculated as the ratio of filled grain weight to total above-ground biomass [16]. Grain yield was assessed from more than 300 hills per plot, manually harvested, and adjusted to a standard moisture content. At maturity, 20 hills per variety were sampled for EPN and PH. Six hills per variety were examined for SPP, SSR, KGW, and HI. Panicles from each hill were hand-threshed, and filled grains were separated from unfilled grains by winnowing. SPP was calculated as the total number of grains divided by EPN, SSR as 100 × (total filled grains / total grains per hill), and KGW as 1000 × (total filled grain weight/number of filled grains per hill).

Heterosis was analyzed using high-parent heterosis (HPH) and standard heterosis (HCK), calculated as follows: $HPH = (F1-HP) / HP \times 100$, $HCK = (F1-CK) / CK \times 100$ where F1 represents the hybrid rice yield traits, HP denotes the best-performing parental restorer line, and CK represents the inbred control variety. All data, including biomass accumulation per hill (BPH), PH, EPN, SPP, SSR, KGW, HI, and yield, were subjected to analysis of variance (ANOVA) using SPSS 17.0. Mean comparisons among varieties were performed using the least significant difference (LSD) test at $P \leq 0.01$ or $P \leq 0.05$. Tables and figures were prepared using Microsoft Excel.

TABLE 4
DRY MATTER ACCUMULATION OF DIFFERENT RICE VARIETIES UNDER DIFFERENT TRANPLANTING PLANT NUMBERS PER HILL AT DIFFERENT STAGE IN 2016

2016- Variety	Tillering stage (Mean±SE)				Heading stage (Mean±SE)				Mature stage (Mean±SE)			
	PPH1	PPH2	3PPH3	PPH4	PPH1	PPH2	PPH3	PPH4	PPH1	PPH2	PPH3	PPH4
LYP9	34.39±5.43 Ab	26.3±2.26 ABCbc	27.08±7.47 Aa	32.07±8.54 ABabc	54.49±7.91 Aab	71.62±6.43 a	67.77±7.07 Aab	83.12±4.70 Ab	115.61±12.97 ABb	108.28±10.57 ABa	148.98±11.25 Bc	102.51±12.18 ABCabc
YLY1	33.06±5.63 Ab	33.55±4.37 BCc	31.98±7.52 ABa	39.79±6.55 ABCcd	78.34±6.88 Ac	70.2±8.69 a	71.02±7.62 Aab	79.85±3.65 Aab	126.93±8.26 Bb	106.66±6.76 ABa	90.98±7.81 Aa	130.5±15.36 BCcd
R9311	27.81±2.22 Aab	29.74±3.17 BCbc	30.97±3.82 ABa	28.25±8.12 Aa	48.96±8.03 Aa	60.09±3.92 a	70.8±12.89Aab	76.02±7.07Aab	97.48±8.33 ABab	95.55±11.58 Aa	92.22±7.67 Aa	139.24±14.12Cd
YLY2	30.91±3.43 Aab	26.55±4.06 ABCbc	36.93±7.85 ABb	39.04±9.37 ABCcd	76.45±4.72 Abc	73.3±8.08 a	76.76±5.16 Ab	68.01±11.51Aab	111.35±6.13 ABab	140.21±16.23 Bb	107.79±9.44 ABab	110.23±16.71 ABCabcd
YH2	19.85±2.95 Aa	14.85±2.95 Aa	41.27±7.84 Bb	40.77±7.59 BCcd	79.55±10.15Ac	67.13±10.67 a	51.62±7.90 Aa	72.57±6.00 Aab	112.51±14.74 ABab	86.22±10.41 Aa	111.33±19.79 ABab	95.16±12.93 ABCabc
YLY900	33.57±5.89Ab	35.73±2.7 Cc	36.04±5.96 ABb	37.89±7.27 ABCbc	59.9±10.05 Aabc	61.64±8.09 a	85.37±6.25 Ab	75.39±5.24 Aab	120.82±15.19 ABb	108.9±10.1 ABab	126.51±10.10 ABbc	125.22±7.92 BCbcd
R900	25.59±2.16 Aab	25.54±5.14 ABCbc	36.18±5.38 ABb	41.27±8.66 Cd	60.11±7.54 Aabc	63.92±6.21 a	64.45±5.5 Aab	67.5±6.88 Aab	104.37±9.16 ABab	106.33±16.63 ABa	104.71±10.42 Aab	86.02±5.56 ABa
HHZ	30.11±5 Aab	34.57±4.93 BCc	42.39±12.44 Bb	44.9±6.04 Cd	77.65±11.95 Abc	76.38±13.39 a	74.03±12.6 Aab	69.14±7.47Aab	100.05±10.18 ABab	88.59±5.16 Aa	97.36±9.86 Aab	74.74±12.98 Aa
XWX17	25.68±2.82 Aab	21.74±1.83 ABa	33.21±5.24 ABa	29.58±7.91 ABab	66.23±4.40 Aabc	66±4.28 a	81.11±3.65 Ab	62.55±4.37 Aa	84.4±9.56 Aa	90.3±4.61 Aa	88.89±11.59 Aa	91.97±10.98 ABCab

The mean of each main yield trait was compared among the different rice varieties (with 1,2,3,4 plants per hill). Within each column, trait differences among varieties are denoted by small letters (not significantly different; p≤0.05) or capital letters (not significantly different; p≤0.01) according to the least significant difference test (LSD). PPH1,2,3,4- 1,2.3,4 plants per hill

III. RESULTS

3.1 Significant heterosis in BPH and PH of hybrid rice:

Biomass accumulation per hill (BPH) is a key determinant of rice yield, varying among different rice varieties and increasing as growth progresses (**Table A2, Table 4**). The heterosis of BPH in hybrid rice was influenced by the number of plants per hill. At the tillering stage in 2015, under transplanting densities of 1, 1, 2, and 4 plants per hill, the high-parent heterosis (HBP%) for BPH ranged from -4.83% to 20.83%. Compared to the inbred control HHZ, the standard heterosis (HCK1%) ranged from -2.41% to 31.17%, while for XWX17 (HCK2%), it ranged from -13.77% to 10.9%. By the heading stage, the HBP% increased to 2.22%–15.27%, with HCK1% ranging from -8.09% to 14.87% and HCK2% from -1.58% to 36.51%. At maturity, HBP% declined to -13.75% to -1.88%, while HCK1% and HCK2% increased significantly, reaching 6.06%–52.2% and 28.15%–64.26%, respectively (**Table A3, Figure A1**).

A similar pattern was observed in 2016, where the effect of transplanting density on BPH heterosis remained evident. At the tillering stage, with 1, 2, 3, and 4 plants per hill, HBP% ranged from -1.44% to 18.96%. HCK1% (HHZ) remained negative (-19.05% to -1.85%), whereas HCK2% (XWX17) ranged from 3.33% to 31.42%. By the heading stage, the trends were consistent with those observed in 2015, with HBP% remaining within -1.44% to 18.96%, HCK1% at -19.05% to -1.85%, and HCK2% at 3.33% to 31.42%. At maturity, hybrid rice exhibited stronger heterosis, with HBP% increasing to 7.19%–22.5%, HCK1% (HHZ) to 18.62%–56.7%, and HCK2% (XWX17) to 27.34%–40.61% (**Table 5, Figure 1**). The BPH heterosis for hybrid rice are the foundation of yield. After heading, the starch stored in the stem is hydrolyzed and transferred to the grain.

For PH, heterosis was similarly influenced by transplanting density. In 2015, under 1, 1, 2, and 4 plants per hill, HBP% ranged from 2.55% to 6.34%, HCK1% (HHZ) from 13.18% to 16.03%, and HCK2% (XWX17) from 7.11% to 14.73% (**Table A4, Figure A2**). In 2016, under 1, 2, 3, and 4 plants per hill, HBP% increased to 5.04%–13.14%, while HCK1% (HHZ) ranged from 10.41% to 12.86%, and HCK2% (XWX17) from 0.64% to 10.21%. These results confirm that PH heterosis in hybrid rice remained positive (**Tables 6, 7, Figure 2**).

Overall, hybrid rice demonstrated lower BPH heterosis at the tillering stage but greater heterosis in mature growth stages. Hybrid and restorer lines consistently exhibited higher BPH than inbred varieties. The number of plants per hill had minimal impact on BPH at maturity, reinforcing that BPH heterosis in hybrid rice was significantly greater than that of restorer and inbred varieties. Similarly, transplanting density had little effect on PH across different varieties, although an increasing trend in PH was observed with higher transplanting densities. Notably, PH heterosis for HBP and HCK declined as transplanting density increased, suggesting that the number of plants per hill plays a role in shaping PH heterosis in hybrid rice. The BPH and PH become an important indicator of the strength of heterosis in hybrid rice. A small number of transplanted seedlings can also achieve the BPH and yield advantage of hybrid rice.

TABLE 5
HETEROSIS FOR DRY MATTER ACCUMULATION OF HYBRID RICE WITH DIFFERENT TRANSPLANTING PLANT NUMBERS PER HILL AT DIFFERENT STAGE IN 2016

Variety-transplanting number-date	Hybird rice （g/hill）			Restore line（g/hill）			HHZ（g/hill）			XW17 (BPH g/hill）			HBP（%）			HCK1 (%)			HCK2 (%)	
	Tillering stage	Heading stage	Mature stage	Tillering stage	Heading stage	Mature stage	Tillering stage	Heading stage	Mature stage	Tillering stage	Heading stage	Mature stage	Tillering stage	Heading stage	Mature stage	Tillering stage	Heading stage	Mature stage	Tillering stage	Heading stage
LYP9-PPH1-2016/8/18	34.39	54.59	115.61	27.81	48.96	97.48	30.11	77.65	100	25.68	66.23	84.4	23.66	11.50	18.60	14.21	-29.70	15.55	33.92	-17.58
YLY1-PPH1-2016/8/18	33.06	78.34	126.93	27.81	48.96	97.48	30.11	77.65	100	25.68	66.23	84.4	18.88	60.01	30.21	9.80	0.89	26.87	28.74	18.28
YLY2-PPH1-2016/8/18	30.91	76.45	111.35	19.85	79.55	112.51	30.11	77.65	100	25.68	66.23	84.4	55.72	-3.90	-1.03	2.66	-1.55	11.29	20.37	15.43
YLY900-PPH1-2016/8/18	19.85	59.9	120.82	25.59	60.11	104.37	30.11	77.65	100	25.68	66.23	84.4	-22.43	-0.35	15.76	-34.08	-22.86	20.76	-22.70	-9.56
Mean	29.55	67.32	118.68	25.27	59.40	102.96	30.11	77.65	100	25.68	66.23	84.4	18.96±16.04	16.82±14.77	15.89±6.45	-1.85±16.04	-13.3±7.64a	18.62±3.36a	15.08±12.9	1.65±8.95a
LYP9-PPH2-2016/8/18	26.3	71.62	108.28	29.74	60.09	95.55	34.57	76.38	88.59	21.74	66	90.3	-11.57	19.19	13.32	-23.92	-6.23	22.23	20.98	8.52
YLY1-PPH2-2016/8/18	33.55	70.2	106.66	29.74	60.09	95.55	34.57	76.38	88.59	21.74	66	90.3	12.81	16.82	11.63	-2.95	-8.09	20.40	54.32	6.36
YLY2-PPH2-2016/8/18	26.55	73.3	140.21	27.88	67.13	86.22	34.57	76.38	88.59	21.74	66	90.3	-4.77	9.19	62.62	-23.20	-4.03	58.27	22.13	11.06
YLY900-PPH2-2016/8/18	27.88	61.64	108.9	25.54	63.92	106.33	34.57	76.38	88.59	21.74	66	90.3	9.16	-3.57	2.42	-19.35	-19.30	22.93	28.24	-6.61
Mean	28.57	69.19	116.01	28.23	62.81	95.91	34.57	76.38	88.59	21.74	66.00	90.30	1.41±5.75	10.41±5.12	22.5±13.59	-17.36±5.75	-9.41±3.4a	30.95±9.12ab	31.42±7.8	4.83±3.93ab
LYP9-PPH3-2016/8/18	27.08	67.77	148.98	30.97	70.8	92.22	42.39	74.03	97.36	33.21	81.11	88.89	-12.56	-4.28	61.55	-36.12	-8.46	53.02	-18.46	-16.45
YLY1-PPH3-2016/8/18	31.98	71.02	90.98	30.97	70.8	92.22	42.39	74.03	97.36	33.21	81.11	88.89	3.26	0.31	-1.34	-24.56	-4.07	-6.55	-3.70	-12.44
YLY2-PPH3-2016/8/18	36.93	76.76	107.79	41.27	51.62	111.33	42.39	74.03	97.36	33.21	81.11	88.89	-10.52	48.70	-3.18	-12.88	3.69	10.71	11.20	-5.36
YLY900-PPH3-2016/8/18	41.27	85.37	126.51	36.18	64.45	104.71	42.39	74.03	97.36	33.21	81.11	88.89	14.07	32.46	20.82	-2.64	15.32	29.94	24.27	5.25
Mean	34.32	75.23	118.57	34.85	64.42	100.12	42.39	74.03	97.36	33.21	81.11	88.89	-1.44±6.25	19.3±12.76	19.46±15.05	3.33±7.24	1.62±5.21ab	21.78±12.81a	3.33±9.24	-7.25±4.76a
LYP9-PPH4-2016/8/18	32.07	83.12	102.51	28.25	76.02	139.24	44.9	69.14	74.74	29.58	62.55	91.97	13.52	9.34	-26.38	-28.57	20.22	37.16	8.42	32.89
YLY1-PPH4-2016/8/18	39.79	79.85	130.5	28.25	76.02	139.24	44.9	69.14	74.74	29.58	62.55	91.97	40.85	5.04	-6.28	-11.38	15.49	74.61	34.52	27.66
YLY2-PPH4-2016/8/18	39.04	68.01	110.23	40.77	72.57	95.16	44.9	69.14	74.74	29.58	62.55	91.97	-4.24	-6.28	15.84	-13.05	-1.63	47.48	31.98	8.73
YLY900-PPH4-2016/8/18	40.77	75.39	125.22	41.27	67.5	86.02	44.9	69.14	74.74	29.58	62.55	91.97	-1.21	11.69	45.57	-9.20	9.04	67.54	37.83	20.53
Mean	37.92	76.59	117.12	34.64	73.03	114.92	44.90	69.14	74.74	29.58	62.55	91.97	12.23±10.3	4.95±3.99	7.19±15.43	28.19±4.41	10.78±4.73b	56.7±8.68b	28.19±6.70	22.45±5.23b

TABLE 6

TRAITS OF DIFFERENT RICE VARIETIES WITH DIFFERENT TRANSPLANTING PLANT NUMBERS PER HILL IN 2016

2016-Variety	Plant height(cm)				Effective panicle number per hill (EPN)				Spikelets per panicle (SPP)			
	PPH1	PPH2	PPH3	PPH4	PPH1	1PPH2	PPH3	PPH4	PPH1	PPH2	PPH3	PPH4
LYP9	118.2±1.35De	116.73±3.92DEd	117.2±5.76DEFd	118.47±5.41CDEd	13.15±0.85Cc	13.95±0.94BCDbcd	14.8±0.68BCc	14.6±1.20BCDc	168.35±16.73BCb	130.62±5.01ABb	175.45±7.67Bb	174.54±4.42CDbc
YLY1	120.07±1.23De	118.47±5.82DEde	121.8±3.08Fe	119.07±5.48DEde	14.95±0.78Cc	14.4±0.93BCDcd	15.25±1.17Cc	15.3±0.82CDcd	199.42±8.73Cc	140.97±3.54Bb	152.81±4.7ABb	165.47±7.35CDbc
R9311	110.67±1.03Cd	113.53±4.52CDcd	113.33±4.43CDc	116.07±3.9CDcd	10.3±0.57Bb	11.7±1.10Bb	11.85±0.86Bb	12.35±0.59Bb	138.37±6.87Bb	124.8±6.19ABb	128.18±5.02ABab	130.23±10.34ABCab
YLY2	119.93±1.01De	121.93±5.51Ee	119.53±2.8Efde	122.53±4.29Ee	11.6±0.57BCbc	13.85±0.89BCDbcd	15.55±0.79Cc	13.8±0.75BCbc	146.03±9.55Bb	194.45±12.35Cd	138.67±23.49ABab	156.82±19.44BCDb
YH2	100.47±1.21Bb	108.07±8.18Bb	107.6±7.57Bb	107.53±5.34Bb	11.55±0.83BCbc	14.15±1.02BCDbcd	14±0.90BCbc	12.2±0.60Bb	155.79±10.5Bb	134.53±13.94ABb	148.36±18.82ABb	118.14±6.1ABa
Y900	110.27±1.14Cd	117.8±4.2DEde	112.47±3.52Cc	113.93±3.41Cc	10.15±0.62ABb	12.55±0.76BCbc	12.1±0.68Bb	13.9±0.81BCbc	210.93±12.15Cc	269.15±25.05Dd	253.03±10.55Cc	243.46±15.25Ed
R900	87.87±1.25Aa	86.53±11.92Aa	91.6±5.94Aa	88.33±7.58Aa	7.65±0.54Aa	4.8±0.37Aa	4.95±0.30Aa	4.65±0.47Aa	227.15±10.53Cc	146.16±7.13Bb	159.82±19.97Bb	194±10.62Dc
HHZ	103.33±1.06BCbc	105.2±4.23Bb	105±4.81Bb	107.33±3.22Bb	16.9±0.85Dd	15.1±1.02CDd	15.45±0.99Cc	17.2±0.84Dd	138.29±7.82Bb	136.26±10.57Bb	161.46±8.01Bb	141.9±9.25ABCab
XWX17	106.27±1.21Cc	111.87±4.16Cc	117±4.63CDEd	117.67±2.55CDd	14.95±0.48CDc	15.95±0.94Dd	16.1±0.88Cc	13.95±0.54BCbc	97.79±9.3Aa	91.16±3.71Aa	101.54±9.26Aa	111.63±4.97Aa

2016-Variety	Seed set rate (SSR)				1000 grains weight (KGW)				Harvest index (HI)			
	PPH1	PPH2	PPH3	PPH4	PPH1	PPH2	PPH3	PPH4	PPH1	PPH2	PPH3	PPH4
LYP9	92.76±0.67EFde	89.3±0.92CDd	94.38±0.77Cc	90.54±1.63Dd	30.71±0.26Cd	29.58±0.26CDEd	28.71±0.18Dd	26.59±0.23Cc	0.48±0.02BCc	0.39±0.02Cc	0.52±0.02Dd	0.56±0.02EFf
YLY1	96.88±0.31FE	94.85±1.05Dd	93.48±1.14Cc	91.85±1.38Dd	29.21±0.32Cc	28.95±0.20CDcd	26.06±0.79Cc	26.83±0.22Ccd	0.55±0.01Cd	0.52±0.01Dd	0.48±0.02CDcd	0.45±0.02Dd
R9311	82.91±3.07BCc	76.14±2.25BCc	60.88±3.96Aa	68.38±4.22Bb	32.98±0.33De	31.42±0.18Ee	31.66±0.30Ee	32.01±0.19De	0.41±0.02Bb	0.32±0.02BCb	0.3±0.02Bb	0.29±0.02Bb
YLY2	92.65±1.21EFde	94.94±0.98Dd	86.2±6.2BCc	91.16±0.84Dd	27.18±0.17Bc	28.78±0.32CDcd	27.81±0.16CDd	27.01±0.47Cd	0.56±0.00Cd	0.53±0.01Dd	0.54±0.01Dde	0.51±0.02Eef
YH2	70.16±2.96Aa	66.51±2.84Bb	81.11±2.81BCbc	83.7±0.78CDc	24.21±0.13ABab	24.82±0.28Bb	25.9±0.60Cc	28.2±0.37Cd	0.35±0.03ABa	0.28±0.02Bb	0.34±0.02BCb	0.35±0.01Cc
Y900	89.81±1.33DEd	90.4±1.27CDd	89.62±1.37Cc	92.72±0.96Dd	25.49±0.20Bb	23.33±0.15Bb	23.4±0.09Bb	23.23±0.12Bb	0.54±0.02Ccd	0.54±0.02Dd	0.57±0.01De	0.58±0.01Ff
R900	72.36±1.60Aab	45.44±6.89Aa	54.08±3.83Aa	42.06±2.49Aa	22.94±0.60Aa	20.48±1.47Aa	19.72±0.93Aa	15.49±0.99Aa	0.3±0.02Aa	0.16±0.4Aa	0.15±0.02Aa	0.11±0.01Aa
HHZ	84.26±0.59CDc	82.77±1.92Ccd	91.46±0.69Cc	83.78±1.84CDc	27.07±0.27Bc	27.51±0.11Cc	24.73±0.25BCbc	23.67±0.60Bb	0.52±0.01Ccd	0.51±0.02Dd	0.55±0.01Dde	0.54±0.02EFf
XWX17	76.73±1.76ABb	79.9±1.11Cc	75.11±1.87Bb	82.1±1.42Cc	30.7±1.13Cd	30.34±0.66DEde	30.93±0.40Ee	31.78±0.73De	0.46±0.04BCbc	0.48±0.01Dd	0.45±0.02Cc	0.49±0.01DEe

2016-Variety	Yield (t/ha)			
	PPH1	PPH2	PPH3	PPH4
LYP9	7976.89±814.68Bb	8872.7±255.81Dd	9935.5±1007.95EFe	8172.75±1818.77CDcd
YLY1	10622.28±183.14Cc	8381.65±148.71CDd	8781.04±446.98DEd	9026.08±1122.26DEd
R9311	6814.44±529.74Bb	7211.25±550.77Cc	5145.17±88.1Bb	4366.81±350.33Bb
YLY2	11137.38±288.89Cc	10215.94±455.02DEf	8493.25±277.56Dd	7777.85±1030.61Ccd
YH2	7028.11±512.07Bb	5595.4±301.87Bb	6921.27±592.71Cc	5960.41±870.83Cbc
Y900	10702.41±668.32Cc	11641.02±412.55Eg	11097.31±485.73Ff	10668.07±974.49Ed
R900	2777.67±297.41Aa	1976.42±213.67Aa	2564±423.93Aa	1976.42±790.49Aa
HHZ	9747.4±517.28Cc	10575.58±491.89Efg	10575.58±617.61Fef	9008.56±638.14DEd
XWX17	7095.45±332.45Bb	6804.2±185.8BCc	6799.17±342.31Cc	6810.72±211.97Cc

3.2 EPN and SPP advantages in hybrid rice under varying transplanting densities:

EPN is a key determinant of rice yield, showing significant variation among the studied varieties. In 2015, under transplanting densities of 1, 1, 2, and 4 plants per hill, the HBP for EPN in hybrid rice ranged from 35.93% to 43.29%. The HCK1 (HHZ) values ranged from -18.98% to 9.81%, while HCK2 (XW17) values ranged from -11.19% to -0.46% (**Table A5, Figure A2**). In 2016, with transplanting densities of 1, 2, 3, and 4 plants per hill, the HBP for EPN in hybrid rice increased significantly, ranging from 26.48% to 63.54%. The HCK1 (HHZ) values ranged from -26.26% to -6.63%, while HCK2 (XW17) values varied from -16.64% to 3.23% (**Tables 6, 7, Figure 2**). These results suggest that transplanting density influences EPN in hybrid rice, restorer lines, and inbred varieties. EPN increased significantly with higher transplanting densities, reaching its highest value at four plants per hill in 2015 and at two plants per hill in 2016 for the inbred variety XW17. The HBP for EPN remained positive, whereas the HCK for EPN was negative, although the trend was not pronounced.

SPP is another critical yield component, with substantial differences among the studied rice varieties. The restorer line R900 exhibited the highest SPP, while the inbred variety XW17 had the lowest. In 2015, under transplanting densities of 1, 1, 2, and 4 plants per hill, the HBP for SPP in hybrid rice ranged from 1.92% to 24.6%. The HCK1 (HHZ) values ranged from 8.65% to 36.72%, while HCK2 (XW17) values varied from 31.23% to 104.3% (**Table A5, Figure A2**). In 2016, with transplanting densities of 1, 2, 3, and 4 plants per hill, the HBP for SPP in hybrid rice increased to 13.1%–36.58%. The HCK1 (HHZ) values ranged from 11.48% to 34.89%, while HCK2 (XW17) values spanned from 65.79% to 101.62% (**Tables 6, 7, Figure 2**). These findings indicate that transplanting density influences SPP across different rice varieties. In 2015, SPP was highest at one plant per hill and lower at two and four plants per hill, a trend that persisted in 2016. The heterosis for SPP in hybrid rice was significant but declined as transplanting density increased.

3.3 Strong heterosis for SSR but negative effects on KGW across transplanting densities:

SSR is another essential yield-related trait, displaying significant variation among the studied rice varieties. In 2015, under transplanting densities of 1, 1, 2, and 4 plants per hill, the HBP for SSR in hybrid rice ranged from 2.89% to 5.43%. The HCK1 (HHZ) values ranged from -3.68% to 2.14%, while HCK2 (XW17) values varied from 1.59% to 10.14% (**Table A5, Figure A2**). In 2016, with transplanting densities of 1, 2, 3, and 4 plants per hill, the HBP for SSR in hybrid rice increased substantially, reaching 21.23%–49.02%. The HCK1 (HHZ) values ranged from -0.59% to 11.6%, while HCK2 (XW17) values varied from 11.53% to 21.24% (**Tables 6, 7, Figure 2**). The SSR of hybrid rice and the inbred variety HHZ was significantly higher than that of other varieties. While transplanting density had a limited impact on SSR in hybrid rice and inbred varieties, it significantly influenced restorer lines. As transplanting density increased, SSR exhibited a decreasing trend. The heterosis for SSR in hybrid rice was evident in 2015 and 2016, demonstrating a clear effect of transplanting density on this trait.

KGW, another critical yield component, exhibited considerable variation across rice varieties. The restorer line R900 had the smallest KGW, while 9311 had the highest. In 2015, under transplanting densities of 1, 1, 2, and 4 plants per hill, the HBP for KGW in hybrid rice ranged from -11.59% to -6.61%. The HCK1 (HHZ) values were between 4.71% and 9.54%, while HCK2 (XW17) values ranged from -17.16% to -14.06% (**Table A5, Figure A2**). In 2016, with transplanting densities of 1, 2, 3, and 4 plants per hill, the HBP for KGW in hybrid rice further declined from -25.09% to -14.23%. The HCK1 (HHZ) values ranged from -2.04% to 3.42%, while HCK2 (XW17) values varied between -24.54% and -10.39% (**Tables 6, 7, Figure 2**). These results suggest that the KGW of hybrid rice, restorer lines, and inbred varieties remained relatively high, with transplanting density exerting minimal influence. The HBP for KGW in hybrid rice showed a consistent negative trend in 2015 and 2016, whereas HCK1 (HHZ) exhibited a positive advantage, and HCK2 (XW17) displayed a negative advantage. As transplanting density increased, both HBP and HCK for KGW in hybrid rice exhibited a downward trend.

TABLE 7
HETEROSIS FOR TRAITS OF HYBRID RICE UNDER DIFFERENT TRANSPLANTING PLANT NUMBERS PER HILL IN 2016

2016-variety	**Hybird rice（PH）**	**Restore line（PH）**	**HHZ（PH）**	**XW17(PH）**	**HBP（%）**	**HCK1 (%)**	**HCK2 (%)**
LYP9-PPH1	118.2	110.67	103.33	106.27	6.8	10.39	11.23
YLY1-PPH1-	120.07	110.67	103.33	106.27	8.49	9.62	12.99
YLY2-PPH1-	119.93	100.47	103.33	106.27	19.37	19.37	12.85
YLY900-PPH1	110.27	87.87	103.33	106.27	25.49	6.72	3.76
Mean	117.12	102.42	103.33	106.27	15.04±4.46	11.53±2.73	10.21±2.19b
LYP9-PPH2	116.73	115.53	105.2	111.87	1.04	10.96	4.34
YLY1-PPH2-	118.47	115.53	105.2	111.87	2.55	12.61	5.9
YLY2-PPH2-	121.93	108.07	105.2	111.87	12.83	15.9	8.99
YLY900-PPH2	117.8	86.53	105.2	111.87	36.14	11.98	5.3
Mean	118.73	106.42	105.2	111.87	13.14±8.10	12.86±1.07	6.13±1.01b
LYP9-PPH3	117.2	113.33	105	117	3.42	11.62	0.17
YLY1-PPH3-	121.8	113.33	105	117	7.47	16	4.1
YLY2-PPH3-	119.53	107.6	105	117	11.09	13.84	2.16
YLY900-PPH	112.47	91.6	105	117	22.78	7.11	-3.87
Mean	117.75	106.47	105	117	11.19±4.17	12.14±1.90	0.64±1.70a
LYP9-PPH4	118.47	116.07	107.33	117.67	2.07	10.38	0.68
YLY1-PPH4-	119.07	116.07	107.33	117.67	2.59	10.94	1.19
YLY2-PPH4-	122.53	107.53	107.33	117.67	13.95	14.16	4.13
YLY900-PPH4	113.93	88.33	107.33	117.67	28.98	6.15	-3.18
Mean	118.5	107	107.33	117.67	11.90±6.32	10.41±1.65	0.71±1.50a
2016-variety	**Hybird rice（EPN）**	**Restore line（EPN）**	**HHZ （EPN）**	**XW17（EPN）**	**HBP（%）**	**HCK1 (%)**	**HCK2 (%)**
LYP9-PPH1	13.15	10.3	16.9	14.95	27.67	-22.19	-12.04
YLY1-PPH1-	14.95	10.3	16.9	14.95	45.15	-11.54	0
YLY2-PPH1-	11.6	11.55	16.9	14.95	0.43	-31.36	-22.41
YLY900-PPH1	10.15	7.65	16.9	14.95	32.68	-39.94	-32.11
Mean	12.46	9.95	16.9	14.95	26.48±9.43	-26.26±3.05a	--16.64±6.9a

LYP9-PPH2	13.95	11.7	15.1	15.95	19.23	-7.62	-12.54
YLY1-PPH2-	14.4	11.7	15.1	15.95	23.08	-4.64	-9.72
YLY2-PPH2-	13.85	14.15	15.1	15.95	-2.12	-8.28	-13.17
YLY900-PPH2	12.55	4.8	15.1	15.95	161.46	-16.89	-21.32
Mean	13.69	10.59	15.1	15.95	50.41±37.43	-9.35±2.63b	-14.18±2.49a
LYP9-PPH3	14.8	11.85	15.45	16.1	24.89	-4.21	-8.07
YLY1-PPH3-	15.25	11.85	15.45	16.1	28.69	-1.29	-5.28
YLY2-PPH3-	15.55	14	15.45	16.1	11.07	0.65	-3.42
YLY900-PPH	12.1	4.95	15.45	16.1	144.44	-21.68	-24.84
Mean	14.43	10.66	15.45	16.1	52.28±30.95	-6.63±5.11b	-10.40±4.91ab
LYP9-PPH4	14.6	12.35	17.2	13.95	18.22	-15.12	4.66
YLY1-PPH4-	15.3	12.35	17.2	13.95	23.89	-11.05	9.68
YLY2-PPH4-	13.8	12.2	17.2	13.95	13.11	-19.77	-1.08
YLY900-PPH4	13.9	4.65	17.2	13.95	198.92	-19.19	-0.36
Mean	14.4	10.39	17.2	13.95	63.54±45.18	-16.28±2.03ab	3.23±2.50b
2016-variety	**Hybird rice (GNP)**	**Restore line (GNP)**	**HHZ (GNP)**	**XW17 (GNP)**	**HBP（%）**	**HCK1 (%)**	**HCK2 (%)**
LYP9-PPH1	168.35	138.37	138.29	97.79	21.67	21.74	72.15
YLY1-PPH1-	199.42	138.37	138.29	97.79	44.12	44.2	103.93
YLY2-PPH1-	146.03	155.79	138.29	97.79	-6.26	5.6	49.33
YLY900-PPH1	210.93	227.15	138.29	97.79	-7.14	52.53	115.7
Mean	181.18	164.92	138.29	97.79	13.10±12.32	31.02±10.68	85.28±15.11
LYP9-PPH2	130.62	124.8	136.26	91.16	4.66	-4.14	43.29
YLY1-PPH2-	140.97	124.8	136.26	91.16	12.96	3.46	54.64
YLY2-PPH2-	194.45	134.53	136.26	91.16	44.54	42.71	113.31
YLY900-PPH2	269.15	146.16	136.26	91.16	84.15	97.53	195.25
Mean	183.8	132.57	136.26	91.16	36.58±18.03	34.89±23.27	101.62±34.78
LYP9-PPH3	175.45	128.18	161.46	101.54	36.88	8.66	72.79
YLY1-PPH3-	152.81	128.18	161.46	101.54	19.22	-5.36	50.49
YLY2-PPH3-	138.67	148.36	161.46	101.54	-6.53	-14.11	36.57
YLY900-PPH3	253.03	159.82	161.46	101.54	58.32	56.71	149.19
Mean	179.99	141.14	161.46	101.54	26.97±13.73	11.48±15.79	77.26±25.11

LYP9-PPH4	174.54	130.23	141.9	111.63	34.02	23	56.36
YLY1-PPH4-	165.47	130.23	141.9	111.63	27.06	16.61	48.23
YLY2-PPH4-	156.82	118.14	141.9	111.63	32.74	10.51	40.48
YLY900-PPH4	243.46	194	141.9	111.63	25.49	71.57	118.1
Mean	185.07	143.15	141.9	111.63	29.83±2.09	30.42±13.95	65.79±17.73
2016-variety	**Hybird rice (SSR %)**	**Restore line (SSR %)**	**HHZ (SSR %)**	**XW17 (SSR)**	**HBP（%）**	**HCK1 (%)**	**HCK2 (%)**
LYP9-PPH1	92.76	82.91	84.26	76.73	11.88	10.09	20.89
YLY1-PPH1-	96.88	82.91	84.26	76.73	16.85	14.98	26.26
YLY2-PPH1-	92.65	70.16	84.26	76.73	32.06	9.96	20.75
YLY900-PPH1	89.81	72.36	84.26	76.73	24.12	6.59	17.05
Mean	93.03	77.09	84.26	76.73	21.23±4.4	10.4±1.73b	21.24±1.9c
LYP9-PPH2	89.3	76.14	82.77	79.9	17.28	7.89	11.76
YLY1-PPH2-	94.85	76.14	82.77	79.9	24.57	14.59	18.71
YLY2-PPH2-	94.94	66.51	82.77	79.9	42.75	14.7	18.82
YLY900-PPH2	90.4	45.44	82.77	79.9	98.94	9.22	13.14
Mean	92.37	66.06	82.77	79.9	45.89±18.48	11.6±1.78b	15.61±1.84ab
LYP9-PPH3	94.38	60.88	91.46	75.11	55.03	3.19	25.66
YLY1-PPH3-	93.48	60.88	91.46	75.11	53.55	2.21	24.46
YLY2-PPH3-	86.2	81.11	91.46	75.11	6.28	-5.75	14.77
YLY900-PPH3	89.62	54.08	91.46	75.11	65.72	-2.01	19.32
Mean	90.92	64.24	91.46	75.11	45.14±13.24	-0.59±2.06a	21.05±2.51c
LYP9-PPH4	90.54	68.38	83.78	82.1	32.41	8.07	10.28
YLY1-PPH4-	91.85	68.38	83.78	82.1	34.32	9.63	11.88
YLY2-PPH4-	91.16	83.7	83.78	82.1	8.91	8.81	11.04
YLY900-PPH4	92.72	42.06	83.78	82.1	120.45	10.67	12.94
Mean	91.57	65.63	83.78	82.1	49.92±24.5	9.3±0.56b	11.53±0.57b
2016-variety	**Hybird rice (KGW)**	**Restore line (KGW)**	**HHZ (KGW)**	**XW17 (KGW g)**	**HBP（%）**	**HCK1 (%)**	**HCK2 (%)**
LYP9-PPH1	30.71	32.98	27.07	30.7	-6.88	13.45	0.03
YLY1-PPH1-	29.21	32.98	27.07	30.7	-11.43	7.91	-4.85
YLY2-PPH1-	27.18	32.98	27.07	30.7	-17.59	0.41	-11.47
YLY900-PPH1	22.94	32.98	27.07	30.7	-30.44	-15.26	-25.28

Mean	27.51	32.98	27.07	30.7	-16.59±5.11	1.63±6.23	-10.39±2.75
LYP9-PPH2	29.58	31.42	27.51	30.34	-5.86	7.52	-2.5
YLY1-PPH2-	28.95	31.42	27.51	30.34	-7.86	5.23	-4.58
YLY2-PPH2-	28.78	31.42	27.51	30.34	-8.4	4.62	-5.14
YLY900-PPH2	20.48	31.42	27.51	30.34	-34.82	-25.55	-32.5
Mean	26.95	31.42	27.51	30.34	-14.23±6.88	-2.04±7.86	-11.18±7.13
LYP9-PPH3	28.71	31.66	24.73	30.93	-9.32	16.09	-7.18
YLY1-PPH3-	26.06	31.66	24.73	30.93	-17.69	5.38	-15.75
YLY2-PPH3-	27.81	31.66	24.73	30.93	-12.16	12.45	-10.09
YLY900-PPH3	19.72	31.66	24.73	30.93	-37.71	-20.26	-36.24
Mean	25.58	31.66	24.73	30.93	-19.22±6.40	3.42±8.2	-17.31±6.55
LYP9-PPH4	26.59	32.01	23.67	31.78	-16.93	12.34	-16.33
YLY1-PPH4-	26.83	32.01	23.67	31.78	-16.18	13.35	-15.58
YLY2-PPH4-	27.01	32.01	23.67	31.78	-15.62	14.11	-15.01
YLY900-PPH4	15.49	32.01	23.67	31.78	-51.61	-34.56	-51.26
Mean	23.98	32.01	23.67	31.78	-25.09±8.85	1.31±11.96	-24.54±8.91
2016-variety	**Hybird rice (HI)**	**Restore line (HI)**	**HHZ (HI)**	**XW17 (HI)**	**HBP (%)**	**HCK1(%)**	**HCK2 (%)**
LYP9-PPH1	0.48	0.41	0.52	0.46	17.07	-7.69	4.35
YLY1-PPH1-	0.55	0.41	0.52	0.46	34.15	5.77	19.57
YLY2-PPH1-	0.56	0.35	0.52	0.46	60	7.69	21.74
YLY900-PPH1	0.54	0.3	0.52	0.46	80	3.85	17.39
Mean	0.53	0.37	0.52	0.46	47.8±13.89	2.4±3.46	15.76±3.91
LYP9-PPH2	0.39	0.32	0.51	0.48	21.88	-23.53	-18.75
YLY1-PPH2-	0.52	0.32	0.51	0.48	62.5	1.96	8.33
YLY2-PPH2-	0.53	0.28	0.51	0.48	89.29	3.92	10.42
YLY900-PPH2	0.54	0.16	0.51	0.48	237.5	5.88	12.5
Mean	0.5	0.27	0.51	0.48	102.79±46.99	-2.94±6.91	3.13±7.34
LYP9-PPH3	0.52	0.3	0.55	0.45	73.33	-5.45	15.56
YLY1-PPH3-	0.48	0.3	0.55	0.45	60	-12.73	6.67
YLY2-PPH3-	0.54	0.34	0.55	0.45	58.82	-1.82	20
YLY900-PPH3	0.57	0.15	0.55	0.45	280	3.64	26.67

Mean	0.53	0.27	0.55	0.45	118.04±54.09	-4.09±3.43	17.22±4.19
LYP9-PPH4	0.56	0.29	0.54	0.49	93.1	3.7	14.29
YLY1-PPH4-	0.45	0.29	0.54	0.49	55.17	-16.67	-8.16
YLY2-PPH4-	0.51	0.35	0.54	0.49	45.71	-5.56	4.08
YLY900-PPH4	0.58	0.11	0.54	0.49	427.27	7.41	18.37
Mean	0.53	0.26	0.54	0.49	155.32±91.23	-2.78±5.37	7.14±5.92

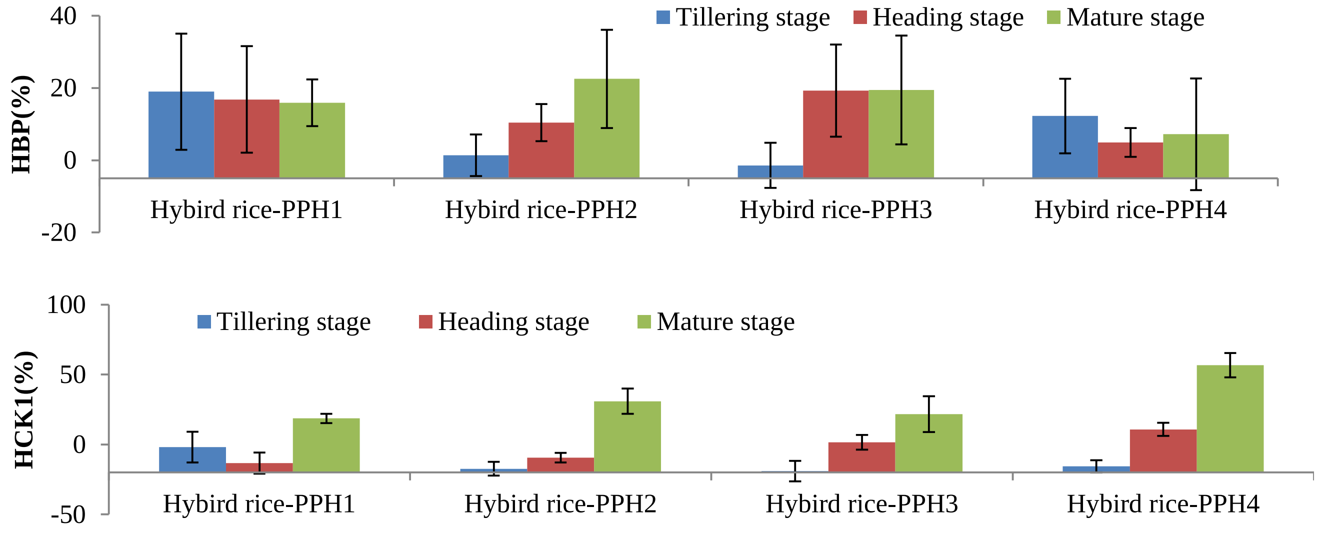
2016-variety	**Hybird rice (Yield)**	**Restore line(Yield)**	**HHZ(Yield)**	**XW17 (Yield)**	**HBP(%)**	**HCK1(%)**	**HCK2 (%)**
LYP9-PPH1	7976.89	6814.44	9747.4	7095.45	17.06	-18.16	12.42
YLY1-PPH1-	10622.28	6814.44	9747.4	7095.45	55.88	8.98	49.71
YLY2-PPH1-	11137.38	7028.11	9747.4	7095.45	58.47	14.26	56.97
YLY900-PPH1	10702.41	6814.44	9747.4	7095.45	57.05	9.8	50.83
Mean	10109.74	6867.86	9747.4	7095.45	47.12±61.15	3.72±7.39	42.48±10.15
LYP9-PPH2	8872.7	7211.25	10575.58	6804.2	23.04	-16.1	30.4
YLY1-PPH2-	8381.65	7211.25	10575.58	6804.2	16.23	-20.75	23.18
YLY2-PPH2-	10215.94	5595.4	10575.58	6804.2	82.58	-3.4	50.14
YLY900-PPH2	11641.02	7211.25	10575.58	6804.2	61.43	10.07	71.09
Mean	9777.83	6807.29	10575.58	6804.2	45.82±113.08	-7.54±6.92	43.7±5.1
LYP9-PPH3	9935.5	5145.17	10575.58	6799.17	93.1	-6.05	46.13
YLY1-PPH3-	8781.04	5145.17	10575.58	6799.17	70.67	-16.97	29.15
YLY2-PPH3-	8493.25	6921.27	10575.58	6799.17	22.71	-19.69	24.92
YLY900-PPH3	11097.31	5145.17	10575.58	6799.17	115.68	4.93	63.22
Mean	9576.78	5589.2	10575.58	6799.17	75.54±69.23	-9.44±5.63	40.85±8.75
LYP9-PPH4	8172.75	4366.81	9008.56	6810.72	87.16	-9.28	20
YLY1-PPH4-	9026.08	4366.81	9008.56	6810.72	106.7	0.19	32.53
YLY2-PPH4-	7777.85	5960.41	9008.56	6810.72	30.49	-13.66	14.2
YLY900-PPH4	10668.07	4366.81	9008.56	6810.72	144.3	18.42	56.64
Mean	8911.19	4765.21	9008.56	6810.72	92.16±92.67	-1.08±7.11	30.84±9.41

PPH1,2,3,4- 1,2.3,4 plants per hill

3.4 Hybrid rice demonstrates a noticeable HI and Yield advantage across transplanting densities:

HI is a critical yield trait, varying significantly among different rice varieties. Hybrid rice and the inbred variety HHZ exhibited relatively high HI values, whereas restorer lines had consistently low HI. In 2015, under transplanting densities of 1, 1, 2, and 4 plants per hill, the HBP for HI in hybrid rice ranged from 19.79% to 24.75%. The HCK1 (HHZ) values ranged from -12.07% to -8.19%, while HCK2 (XW17) varied from -3.77% to 2.04% (**Table A5, Figure A2**). In 2016, with transplanting densities of 1, 2, 3, and 4 plants per hill, the HBP for HI in hybrid rice increased significantly, ranging from 47.8% to 155.32%. The HCK1 (HHZ) values ranged from -4.09% to 2.4%, while HCK2 (XW17) ranged from 3.13% to 17.22% (**Tables 6, 7, Figure 2**). These results indicate that hybrid rice and HHZ maintain relatively high HI values, with transplanting density having minimal influence across different varieties. The HBP for HI in hybrid rice exhibited strong positive heterosis in both years. Notably, in 2016, HBP for HI increased with the number of transplanted plants. While HCK2 (XW17) displayed positive heterosis, HCK1 (HHZ) exhibited negative heterosis. Overall, transplanting density had a limited impact on HBP for HI in hybrid rice.

Rice yield, a comprehensive expression of multiple yield-contributing traits, varied significantly across the studied varieties. Hybrid rice and the inbred variety HHZ exhibited relatively high yields, while restorer lines had consistently low yields. In 2015, under transplanting densities of 1, 1, 2, and 4 plants per hill, the HBP for hybrid rice yield ranged from 39.64% to 58.2%. The HCK1 (HHZ) values ranged from -19.6% to 8.89%, while HCK2 (XW17) ranged from 23.17% to 41.49% (**Table A5, Figure A2**). In 2016, with transplanting densities of 1, 2, 3, and 4 plants per hill, the HBP for hybrid rice yield increased further, reaching 45.82%–92.16%. The HCK1 (HHZ) values ranged from -9.44% to 3.72%, while HCK2 (XW17) ranged from 30.84% to 42.48% (**Tables 6, 7, Figure 2**). These findings indicate that transplanting density significantly influenced yield. Hybrid rice achieved relatively high yields at 1 and 2 plants per hill, but yields declined as transplanting density increased. In contrast, the inbred varieties HHZ and XW17 showed higher yields at 2 and 3 plants per hill. The maximum yield of HHZ, recorded at 9551.5 kg ha^{-1} with 4 plants per hill in 2015, suggests that increasing transplanting density can enhance inbred rice yield to some extent. The HBP for hybrid rice yield demonstrated significant positive heterosis in both years. While HCK2 (XW17) also exhibited positive heterosis, HCK1 (HHZ) showed negative heterosis. The effect of transplanting density on yield heterosis was more pronounced in 2015, whereas in 2016, yield heterosis increased with higher transplanting densities.



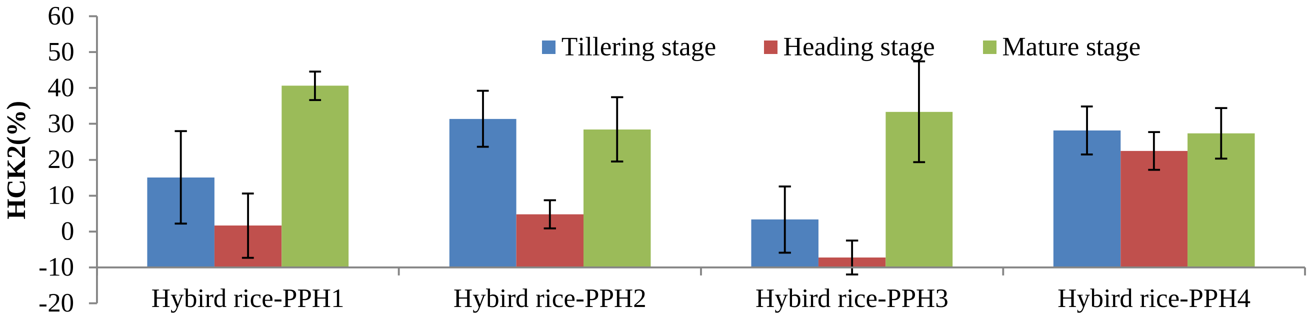


FIGURE 1: Heterosis for dry matter accumulation in hybrid rice under different transplanting densities at various growth stages in 2016, HBP: High-parent heterosis, HCK: Standard heterosis, PPH1,2,3,4: 1,2,3,4 plants per hill. Within each column, different letters indicate statistically significant differences: lowercase letters (p ≤ 0.05) and uppercase letters (p ≤ 0.01), as determined by the least significant difference (LSD) test.

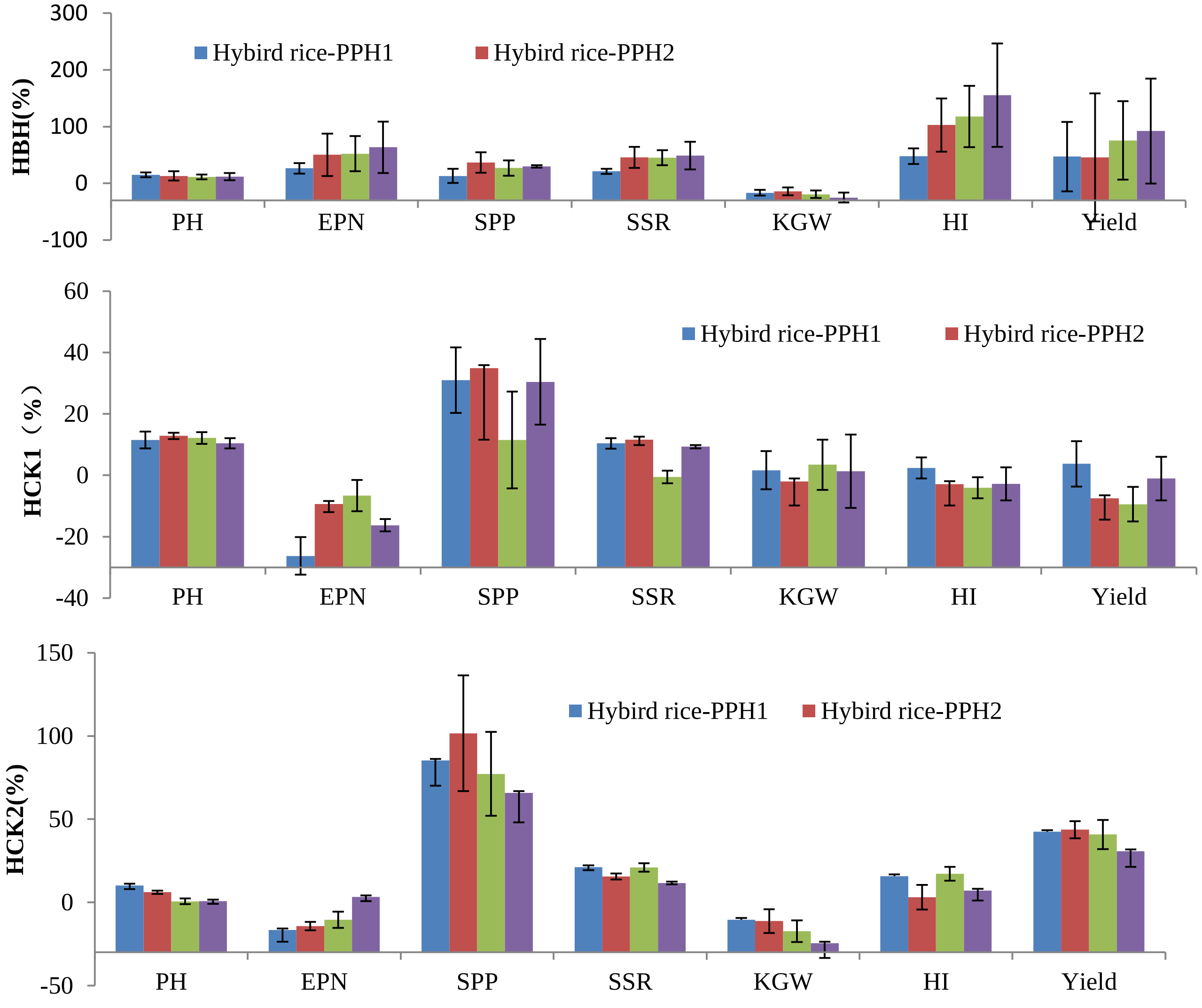


FIGURE 2. Heterosis for agronomic traits of hybrid rice under different transplanting densities in 2016, PPH1,2,3,4: 1,2,3,4 plants per hill, PH: Plant height, EPN: effective panicle number per hill, SPP: spikelets per panicle, SSR: seed setting rate, KGW: 1000-grain weigh, HI: Harvest index

IV. DISCUSSION

4.1 Influence of transplanting density on rice yield:

This study demonstrated that hybrid rice varieties achieved optimal yields with 1–2 plants per hill, while inbred varieties performed best with 3–4 plants per hill under a transplanting spacing of 19.8 cm × 26.4 cm. These findings provide a theoretical foundation for breeding strategies, high-yield cultivation, and the large-scale adoption of hybrid rice. Previous studies have reported similar results; for example, when two-line hybrid rice JLY534 was transplanted at 18 cm × 30 cm with 1–6 plants per hill, yields were highest with 1–2 plants per hill, with significant effects on EPN, SPP, SSR, and KGW [17]. Under a 30 cm × 12.6 cm transplanting specification, yields of both hybrid and inbred varieties initially increased with transplanting density before declining, with the optimal number per hill being 3–4 for hybrid rice and 4–5 for inbred rice [18].

Hybrid rice achieved its highest yield when planted with two seedlings per hill at a spacing of 30 cm × 25 cm × 16.67 cm (2.25×10^5 hills ha^{-1}), suggesting that this configuration is most suitable. Transplanting experiments under different fertilizer conditions revealed that high yields were achieved with 3–5 plants per hill at 25 cm × 17 cm (2.35×10^5 hills ha^{-1})[19]. Consistent with these findings, our results indicate that super hybrid rice yields declined as the number of transplanted plants per hill increased. Inbred variety HHZ exhibited peak yields when transplanted with four plants per hill in 2015 and with two or three plants per hill in 2016. While hybrid rice displayed clear yield advantages over restorer lines and inbred varieties, no consistent pattern emerged regarding its response to transplanting density.

4.2 Effects of transplanting density on dry matter accumulation, EPN, SPP, and SSR:

Our study revealed that transplanting density significantly affected BPH, PH, SPP, SSR, HI, and yield in hybrid rice. Hybrid varieties thrived under optimal planting densities but showed reduced lodging resistance under high-density conditions [20]. *Indica* hybrid rice, which typically exhibits high tillering potential, benefits from an appropriate number of transplants per hill, optimizing tiller utilization and balancing individual and population growth dynamics [21]. When transplanting density exceeded five plants per hill, the effective tiller percentage declined sharply, with 2–4 plants per hill identified as optimal [22, 23].

As transplanting density increased, the leaf area index and dry matter accumulation rose during the tillering stage but declined at maturity. The most efficient light use and biomass production occurred with 2–3 plants per hill; beyond this threshold, further increases in seedling numbers provided no additional benefit [14]. High-yielding hybrid rice is characterized by large panicles and significant above-ground dry matter accumulation, which supports sustained productivity [24, 25]. Transplanting experiments confirmed that 3–5 plants per hill at 25 cm × 17 cm (2.35×10^4 hills ha^{-1}) produced high yields across fertilizer conditions [19].

Direct-seeding experiments showed that reducing the sowing rate of hybrid rice from 240 grains m^{-2} to 60 grains m^{-2} did not affect yield, whereas inbred varieties suffered yield losses due to insufficient tillering and reduced panicle formation[26]. Studies on *Japonica* hybrid rice III You 98 indicated that planting density strongly influenced yield, while PH, panicle length, and KGW remained relatively stable. Close spacing and transplanting two seedlings per hill were optimal for maximizing yield [27]. Machine transplanting trials at 30 cm × 12 cm found that increasing planting density boosted effective panicle numbers but reduced sink capacity per hill. Although SPP decreased, transplanting at 30 and 35 days of seedling age improved yield, whereas seedling age of 25 days had minimal impact on yield under increased planting density[28].

Our findings demonstrated that the advantages of hybrid rice in dry matter accumulation and effective panicle number declined as transplanting density increased. Additionally, HCK for SPP decreased with higher planting densities, mirroring trends observed in SSR. These results suggest that effective panicle number and SPP are key contributors to hybrid rice yield. Moreover, lodging risks increased significantly when the number of transplanted plants per hill exceeded 3–4, underscoring the importance of optimized spacing to balance yield potential and structural stability. With the development of direct seeding machine and rice seeding transplanter, controlling the amount of seeds, density, and number of transplanted seedlings has become an important challenge and a key control technology, this result is of great significance for improving yield.

V. CONCLUSION

Under the spatial planting arrangement of 19.8 cm × 26.4 cm, super hybrid rice demonstrated significant advantages in dry matter accumulation, PH, SPP, SSR, HI, and overall yield. EPN showed a moderate advantage, whereas KGW exhibited a slight disadvantage. For optimal yield without compromising seed quantity, transplanting 1–2 plants per hill is recommended for hybrid rice, while 3–4 plants per hill are suitable for inbred rice. The investigation of biological and yield traits of hybrid rice, restorer lines and conventional varieties under the same cultivation conditions can early determine the strength and weakness of heterosis of hybrid rice.

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