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Optimum Basic Seedling Density and Yield and Quality Characteristics of Unmanned Aerial Seeding Rice

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Abstract: Unmanned aerial seeding (UAS) is an efficient unmanned rice planting method with broad application prospects. But its optimum basic seedling number and yield and quality characteristics remain unclear. Field experiments were conducted to compare UAS, unmanned dry direct seeding (UDDS), and unmanned carpet transplanting (UCT) methods using inbred *japonica* rice variety Nanjing 5718. The UAS method was subdivided into four planting density treatments (UAS105, UAS150, UAS195, and UAS240 = 105, 150, 195, and 240 seedlings/m^2, respectively). The results showed that increasing the basic seedling density first increased the yield but then it decreased, and UAS195 produced a significantly higher yield. On the other hand, the grain processing, appearance, and taste quality deteriorated with improved nutritional quality. Among the three planting methods, UAS (UAS195) yielded less than UCT due to there being fewer spikelets per panicle, a lower grain-filling rate, and less photosynthetic activity after heading. However, UAS (UAS195) produced more yields than UDDS by having more panicles, more spikelets per panicle, and more biomass accumulation. Both UAS195 and UDDS had poorer grain processing, appearance, and nutritional quality than UCT, but increased amylose content and taste values. Therefore, UAS195 could be an alternative planting method for inbred *japonica* rice with coordinated yield, quality, and production efficiency.

Keywords: mechanized planting; unmanned aerial seeding; basic seedling; yield; quality

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1. Introduction

Rice (*Oryza sativa* L.) plays an extremely important role as the staple food in China, since more than 60% of Chinese people rely on it as a part of their daily diet [1]. But because of the huge economic gap between urban and rural areas and among industrial structures, fewer people are entering rice production, creating a severe labor shortage. Mechanized operations could compensate for this by increasing the efficiency of rice production [2]. However, the mechanized planting rate of rice in China is only 53.89%, far behind the mechanized tillage rate and mechanized harvesting rate (98.84% and 93.43%, respectively). As a result, mechanized rice planting has become a major limiting factor. At present, mechanized rice planting in China mainly relies on ground machinery, and operational efficiency can still hardly meet the requirements of rice production [3]. As well, how to further improve the efficiency of rice planting has become an important issue. Apart from unmanned upgrading to existing ground-based agricultural machinery [4], unmanned aerial seeding (UAS) might be an alternative and high-efficiency planting method. UAS is a direct seeding method with agricultural drones as the platform, and it has the unique advantage of low support requirements and all-terrain operation [5,6]. Moreover, the method has a major advantage in terms of labor cost and operational efficiency: it could improve work efficiency that is more than twice that of ground-based direct seeders and

over four times that of rice carpet transplanters, and save labor cost by about 70% or more [7,8]. Therefore, the UAS planting method has broad application prospects.

In China, the UAS method is always combined with wet direct seeding, as the latter provides moist and soft soil that promotes seed water uptake and germination [9]. But research on the production characteristics of this method is currently lacking in the industry, with more emphasis being placed on comparing and summarizing traditional planting methods. Previous studies show that wet direct seeding has more vigorous aboveground growth and more roots than dry direct seeding, which could lead to an obvious yield increase [10]. At the same time, it could improve the taste quality without reducing the other rice qualities much [11]. However, wet direct seeding can easily cause seeds to enter a state of hypoxia stress [9]. Encountering high temperatures and plum rain weather tends to result in seed rot and seedling rot, leading to a low seedling emergence rate and a potential risk of safe heading [11]. Compared with transplant rice, direct seeding rice makes tiller occurrence earlier and more frequent, and achieves more effective panicles due to the absence of transplant damage [12]. Conversely, it also results in a low percentage of productive tillers and intense competition between ineffective and effective tillers at the same time, which deteriorates panicle development and grain filling. Thus, it tends to cause a small-size panicle type and poor rice quality [13]. Furthermore, influenced by the rice–wheat rotation planting system, the late sowing time and short growth period are not conducive to the full utilization of temperature and light resources in the direct seeding of rice, so the yield potential is severely limited [14]. But the UAS method differs from the conventional wet direct seeding methods owing to its vastly improved seeding uniformity [15]. The high degree of uniformity guarantees space and a nutrient supply for the seedlings, avoiding a large amount of ineffective growth due to competition for growth space and weak physiological and biochemical activity of the seedlings caused by an insufficient nutrient supply [16,17]. Under the UAS method, the seedlings could produce more low-position tillers and make the canopy close faster. Hence, studies of traditional wet planting methods might not accurately describe the production characteristics of unmanned aerial seeding rice.

Setting optimum planting density is an important part of rice cultivation measures, since planting density has a huge impact on the population structure, yield formation, and rice quality. Low-density planting could maintain high photosynthesis and improve individual productivity by adjusting the leaf shape, such as lengthening the leaves and increasing the leaf angle [18]. The rice grown using this method tends to be of great quality. However, it is always limited by the size of the population, making it difficult to achieve high yields. On the contrary, too-intensive planting would exacerbate the growing contradiction between the individual and the population. On the one hand, it is not conducive to the establishment of an appropriate population canopy structure, and then grain yield declines instead [19]. On the other hand, the single stem becomes thin and weak, its physiological and biochemical activities are weak, and the production and transportation of photosynthetic products are unstable, leading to the deterioration of rice quality [20]. At the same time, the plant is more susceptible to infection by diseases, and insect pests and weeds are also more frequent [21]. Therefore, the appropriate number of basic seedlings is an extremely important cultivation indicator for high-yielding and high-quality rice production. A previous study has found that mechanized direct seeding with 100–200 basic seedlings/m^2 could achieve a higher yield [17]. Beyond this range, increasing the planting density does not have a good yield increase effect and might even contribute to a reduction in production. However, when tillage conditions are insufficient, up to 300 seedlings/m^2 can be required to achieve a high yield [22,23]. The existing research on suitable basic seedlings has mainly focused on dry direct seeding with ground machinery covering the soil, while few studies concentrating on UAS have been reported. Seedlings planted using the UAS method have a higher quality as they benefit from adequate soil moisture content and the near absence of sowing depth [24,25]. Such seedlings require only a low planting density for a high yield. As a result, current research results on the number

of basic seedlings struggle to meet the cultivation requirements for coordinating the yield and quality of unmanned aerial seeding rice.

Hence, three unmanned planting methods were designed in this study, namely unmanned aerial seeding (UAS), unmanned dry direct seeding (UDDS), and unmanned carpet transplanting (UCT). In addition, various basic seedling density treatments were set up under the UAS method, with the other methods applied as the control. This research investigated the effects of different basic seedling densities on rice yield and quality using the UAS method and compared the differences in yield and quality among the unmanned methods. The aims were to: (1) find out the optimum basic seedling density for the UAS method and (2) determine the yield and quality characteristics of the UAS rice.

2. Materials and Methods

2.1. Experimental Site and Weather Conditions

The field experiment was performed in Sihong County, Suqian City, Jiangsu Province, China (33.48° N, 118.22° E), during the rice growing season (from May to November). The cropping system in this region is a rice–wheat rotation system. The field soil was a clay loam with 27.31 g kg^{-1} organic matter, 1.89 g kg^{-1} total N, 32.34 mg kg^{-1} available P, and 85.64 mg kg^{-1} available K.

Meteorological data were collected and provided at a weather station near the experimental site. The daily mean temperature, sunshine hours, and precipitation during the rice growing season were 24.51 and 24.68 °C, 723.6 and 910.5 h, and 968.6 and 619.1 mm, respectively (Figure 1).

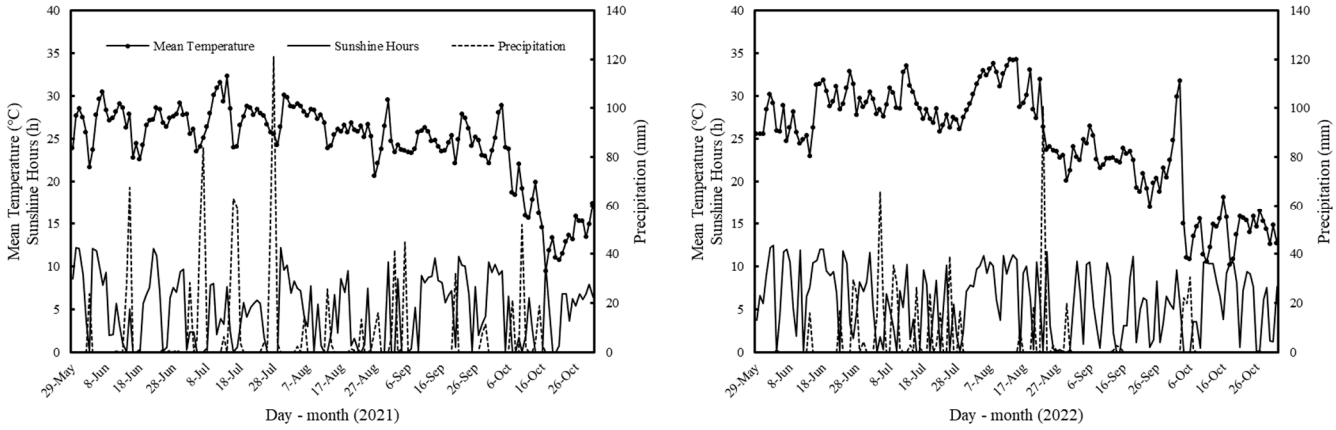

Figure 1. Daily mean temperature, sunshine hours, and precipitation during the rice growing season in 2021 and 2022.

2.2. Plant Materials and Experimental Design

The high-quality *japonica* rice variety Nanjing 5718 (NJ5718) was selected for this experiment. NJ5718 is an inbred *japonica* rice variety released in 2019 with Ning 7022 as the female parent and Yanjing 608 as the male parent. It is suitable for cultivation in the central and Huaibei regions of Jiangsu Province.

The sowing and transplanting dates were designed for the three unmanned planting methods: unmanned aerial seeding (UAS), unmanned dry direct seeding (UDDS), and unmanned carpet transplanting (UCT). For UDDS and UCT, appropriate cultivation practices were used based on the results of previous studies to attain the maximum achievable yield [22,26].

UAS soil was subjected to water rotary tilling after the wheat harvest. When the soil moisture content of paddy was kept saturated but no water layer was accumulated, dry seeds were sown by an agricultural drone (T30, DJI Corporation, Shenzhen, China) on 18 June 2021 and 2022. A seeding operation with 4.5 m line spacing, 3 m height, 5 m/s flight speed, and 800 r/min seeding apparatus speed was performed.

Four seedling densities (UAS105, UAS150, UAS195, and UAS240 = 105, 150, 195, and 240 seedlings/m^2, respectively) were used in 2021 and 2022. The seedling densities were achieved by adjusting the seeding rate according to the germination rate and seedling emergence rates measured in a preliminary experiment, and the actual seeding density for each treatment was investigated during the three-leaf stage.

UDDS seedling were sown directly and automatically after the wheat harvest, on 18 June 2021 and 2022, by a multifunctional seeder with 25 cm row spacing and 2–3 cm sowing depth. The seeder was developed by Yangzhou University and equipped with an unmanned driving system and the Beidou Navigation System. It integrated fertilization, straw returning to the field, primary compaction, seed row digging, seeding, soil covering, secondary compaction, and drainage ditch digging. The seedling density was designed to be 255 seedlings/m^2, and the seeding rate and the actual seedling density were determined by adopting the same method as the treatments for UAS.

UCT seedlings were sown automatically on plastic carpet seedling trays (58 cm length × 28 cm width × 2.8 cm height) with 120 g seeds per tray by a seedling tray seeder (SR-K800CN Kubotian Corporation, Osaka, Japan) on 29 May 2021 and 2022. The seedlings with a 20-day seedling age were transplanted with a density of 30 cm × 11 cm and 4 seedlings per hill by the unmanned carpet-seedling transplanter (2ZG–6D (G61), Jofae Corporation, Suzhou, China) equipped with the Beidou Navigation System on 18 June 2021 and 2022.

Six independent fields (60 m × 100 m) were used in the experiment, of which four were subjected to unmanned aerial seeding treatments with different basic seedling numbers and the other two were used for the unmanned dry direct seeding treatment and the unmanned carpet transplanting treatment, respectively. These fields had consistent conditions, such as topographic location, soil type, and initial conditions. In every treatment, the field was divided equally into three plots by bunds covered with plastic film, and an experimental area (5 m × 5 m) was set up in each plot for plant sampling and grain harvest. Therefore, there were six treatments in this experiment and each treatment had three replications, resulting in a total of eighteen experimental areas (Figure 2). The total application of pure nitrogen was 270 kg ha^{-1}, which was applied to the fields in the form of controlled-release mixed fertilizer (Zhidaodi, Moith Corporation, Dezhou, China) one day before seed sowing or seedling transplanting. The element formula of the fertilizer was N:P_2O_5:K_2O = 30:7:13. In the early and middle tillering stages, wet irrigation was mainly adopted to promote seedling growth and tiller occurrence in the fields. When the tiller number reached 80% of the expected panicle number, drainage began. After jointing, alternate wetting and moderate soil drying irrigation management measures were applied until 5–7 days before harvest. Weed, insect, and disease control followed local recommendations throughout the growing season to minimize loss of yield over the years.

2.3. Plant Sampling and Measurements

The dates of the sowing (SO), transplanting, jointing (JI), heading (HD), and maturity (MA) stages were recorded with the targets of accurate sampling and understanding of the rice growth process.

After the three-leaf stage in the UAS and UDDS treatments and the transplanting stage in the UCT treatment, the tiller number of a series of rice plants in each plot was marked at seven-day intervals until the heading stage. In the UAS treatment, all plants in a 1 m × 1 m square area were measured in each plot; in the UDDS treatment, one in two adjacent and consecutive rows (3 m) were measured correspondingly; and in the UCT treatment, 10 adjacent and consecutive hills were measured accordingly.

Percentage of the productive tiller (%) = panicle number at MA/the maximum tiller number during the whole growth period × 100

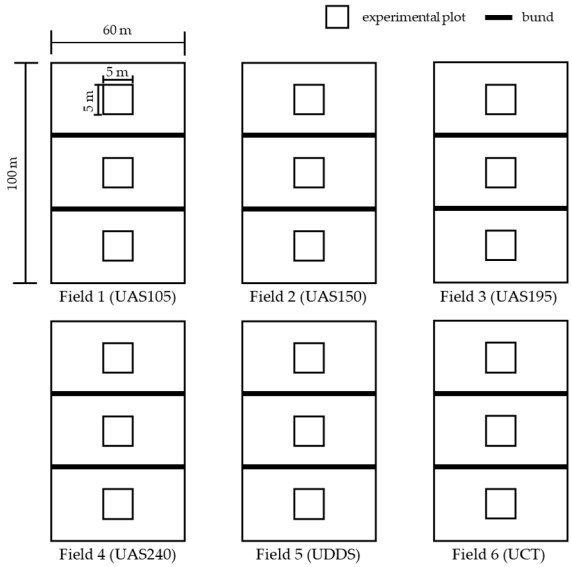

Figure 2. Field distribution and experimental plot design schematic map.

Leaf area and biomass accumulation were determined at the jointing, heading, and maturity stages. Samples were calculated and collected according to the mean tiller number (panicle number at MA) at the corresponding stage. In detail, samples in each UAS plot area were collected, respectively, by a 0.3 m × 0.3 m square area, ones for UDDS were collected correspondingly by consecutive 0.5 m areas in a row, and ones for UCT were collected correspondingly in the form of 3 hill plants. All samples were separated into leaves, stem-sheaths, and panicles (heading stage and maturity stage). Green leaf areas were measured with a leaf area meter (LI-3100, LI-COR, Lincoln, NE, USA). The leaf area index was expressed as the leaf area of effective tillers per unit area, and the highly effective leaf area was defined as the leaf area of the top three leaves. Samples of each plant part were dried and weighed separately to determine the aboveground biomass accumulation per unit area per plot. Each component of these was oven-dried separately at 105 °C for 30 min and then at 80 °C to a constant weight [27].

$$\text{Decreasing rate of leaf area (LAI d}^{-1}\text{)} = \text{(LAI at HD} - \text{LAI at MA)/Days from HD to MA}$$

$$\text{Crop growth rate (g m}^{-2}\text{ d}^{-1}\text{)} = \text{(Biomass accumulation at MA} - \text{Biomass accumulation at HD)/Days from HD to MA}$$

$$\text{Net assimilation rate (g m}^{-2}\text{ d}^{-1}\text{)} = [\ln\text{ (LAI at HD)} - \ln\text{ (LAI at MA)/(LAI at HD} - \text{LAI at MA)}] \times \text{Crop growth rate}$$

At MA, the panicle number (PN) was marked by using the same method used in the tiller number before harvest. Then, all plants in a 2 m × 2 m area in the middle of each plot were hand harvested, and the grain yield was weighed. The final grain yield was adapted to a moisture content of 14.5%. The spikelet number per panicle (SP), the filled-grain percentage, and the 1000-grain weight were determined from samples at MA and by the measurement procedures described by Yoshida et al. [27].

Grains harvested from each plot were dried at 35 °C until the grain moisture was 14.5% and then stored at 4 °C for 3 months. Rice quality analysis was performed according to the national standard of the People's Republic of China (GB/T17891–2017). Brown rice rate, milled rice rate, and head-milled rice rate were expressed as percentages of the total grain weights. Chalkiness rate was defined as the number of grains containing over 20% white belly, white center, or white back. Chalkiness size was expressed as a percentage of the total area of the kernel. Chalkiness rate, chalkiness size, and chalkiness degree were all measured with a rice appearance scanner (SC-E, Wseen Corporation, Hangzhou, China). Amylose content was measured according to the Rice Quality Mea-

surement Standards (NY/T83–2017). Protein content was measured with a grain analyzer (Infratec TM 1241, FOSS, HillerØd, Denmark). Cooking and eating quality were measured by a taste analyzer (STA1A, Satake Corporation, Hiroshima, Japan) which converts various physicochemical parameters of rice into taste values.

2.4. Statistical Analysis

The data were analyzed and processed by the SPSS 20.0 Statistical Software Program. All data were analyzed using a two-way ANOVA including year and treatment. Means were tested by the least significant difference at $p = 0.05$ (LSD0.05). Graphs and tables were prepared by MS Excel 2021 for Windows, and all error bars indicate the standard error of the means. The correlation analyses were handled and produced by OriginPro 2022.

3. Results

3.1. Growth Stage and Period

Different basic seedling treatments in UAS had no difference in their growth stages (Table 1). The UAS treatment had the shortest whole growth period, which was 1–2 days shorter than UDDS and 12–22 days shorter than UCT. In detail, the period during SO-JI was shorter in UAS than in UDDS, resulting in the growth stages happening earlier. On the other hand, UCT had a longer time in each period, especially the one before jointing. But due to the advanced seeding date, the JI and HD in UCT were the earliest.

Table 1. Growth stages of the rice cultivar with different unmanned planting methods.

Year	Treatment [1)]	Sowing	Trans-Planting	Jointing	Heading	Maturity	Total Growth Period (d)
2021	UAS105	18 Jun.	--	13 Aug.	7 Sem.	29 Oct.	132
	UAS150	18 Jun.	--	13 Aug.	7 Sem.	29 Oct.	132
	UAS195	18 Jun.	--	13 Aug.	7 Sem.	29 Oct.	132
	UAS240	18 Jun.	--	13 Aug.	7 Sem.	29 Oct.	132
	UDDS	18 Jun.	--	15 Aug.	9 Sem.	31 Oct.	135
	UCT	29 May	18 Jun.	7 Aug.	6 Sem.	30 Oct.	154
2022	UAS105	18 Jun.	--	14 Aug.	9 Sem.	31 Oct.	135
	UAS150	18 Jun.	--	14 Aug.	9 Sem.	31 Oct.	135
	UAS195	18 Jun.	--	14 Aug.	9 Sem.	31 Oct.	135
	UAS240	18 Jun.	--	14 Aug.	9 Sem.	31 Oct.	135
	UDDS	18 Jun.	--	15 Aug.	10 Sem.	1 Nov.	136
	UCT	29 May	18 Jun.	1 Aug.	30 Aug.	23 Oct.	147

[1)] UAS105, UAS150, UAS195, and UAS240 represent unmanned aerial seeding with 105, 150, 195, and 240 basic seedlings/m^2, respectively; UDDS, unmanned dry direct seeding; UCT, unmanned carpet-seedling transplanting.

3.2. Grain Yield and Yield Components

Increasing basic seedlings in UAS resulted in a parabolic trend in grain yield, where UAS195 was the peak and UAS105 was the bottom (Figure 3). Specifically, UAS195 reached 10.27 t ha^{-1} in 2021 and 9.81 t ha^{-1} in 2022, remarkably higher than the other UAS treatments. In terms of planting methods, UAS195 had a significant reduction compared to UCT, but it was still much higher than UDDS with an increase of 3.79–6.18%.

The trend in the total spikelet number (TSP) was consistent with the trend in the yield (Table 2). In the process of basic seedling increase, PN increased significantly, but SP decreased obviously on the whole at the same time. Compared with UCT, the TSP was smaller in UAS195 and UDDS, especially in the latter where it reached a significant level. Although their PN was noticeably more than that of UCT, their SP decreased sharply. In terms of the grain-filling rate, there was a certain gap between UAS195 and UCT, while UDDS had the highest due to its low total spikelet number.

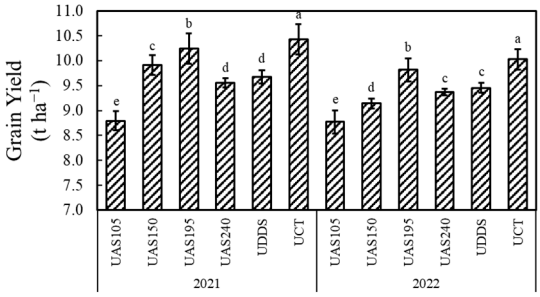

Figure 3. Grain yield of NJ5718 with different UAS basic seedlings and unmanned planting methods in 2021 and 2022. UAS105, UAS150, UAS195, and UAS240 represent unmanned aerial seeding with 105, 150, 195, and 240 basic seedlings/m^2, respectively; UDDS, unmanned dry direct seeding; UCT, unmanned carpet-seedling transplanting. Different letters indicate statistical significance at the 0.05 probability level. Bars mean standard error (n = 3).

Table 2. Yield components of NJ5718 with different UAS basic seedlings and different unmanned mechanical planting methods.

Year	Treatment [1)]	Panicle Number ($\times 10^4$ ha^{-1})	Spikelets per Panicle (No. per Panicle)	Total Spikelet Number ($\times 10^6$ ha^{-1})	Filled-Grain Percentage (%)	1000-Grain Weight (g)
2021	UAS105	294.01e	103.18b	303.34e	95.09a	30.69a
	UAS150	379.08c	94.99c	360.10bc	94.13b	30.03bc
	UAS195	407.86b	91.73c	374.12ab	93.84bc	29.99bc
	UAS240	452.86a	78.60e	355.92cd	93.22c	29.83c
	UDDS	390.96c	87.55d	342.30d	95.02a	30.25b
	UCT	353.46d	108.96a	385.11a	94.31ab	29.78c
2022	UAS105	266.50d	126.16a	336.13d	92.13c	29.65a
	UAS150	306.80c	112.81b	346.09cd	92.09c	29.57ab
	UAS195	335.70b	109.73b	367.97ab	91.91c	29.57ab
	UAS240	358.19a	99.19d	355.11bc	91.53c	29.37bc
	UDDS	331.48b	103.93c	344.41cd	95.34a	29.73a
	UCT	295.90c	127.71a	377.47a	93.96b	29.18c
Analysis of variance						
Year		**	**	NS	**	**
Treatment		**	**	**	**	**
Year × Treatment		**	NS	**	**	*

[1)] UAS105, UAS150, UAS195, and UAS240 represent unmanned aerial seeding with 105, 150, 195, and 240 basic seedlings/m^2, respectively; UDDS, unmanned dry direct seeding; UCT, unmanned carpet-seedling transplanting. Different lowercase letters within the same column indicate significant differences at $p \leq 0.05$. NS, not significant at the $p = 0.05$ level. * and ** mean significant correlation at the 0.05 and 0.01 levels, respectively.

3.3. Number of Stems and Tillers and Percentage of Productive Tillers

When the number of basic seedlings rose, the tiller number at the peak stage (PK) and critical growth stages all increased (Table 3). Most of these increases were significant. However, the number of ineffective tillers that vanished during JI-HD increased overall at the same time. By analyzing the planting methods, the number of tillers at all stages was generally similar between UAS195 and UDDS, and significantly higher for those in UCT. From the growth stage, the JI/MA ratio was much larger in UAS195 and UDDS than in UCT. This meant that the number of ineffective tillers in UAS195 and UDDS reduced rapidly, while the number in UCT gradually decreased.

The percentage of productive tillers in the adjacent UAS treatments decreased slightly with the addition of basic seedlings in both years. Among the methods, UCT achieved the highest percentage, significantly higher than the others, followed by UDDS, and UCT with the lowest.

Table 3. Number of tillers and percentage of productive tillers of NJ5718 with different UAS basic seedlings and different unmanned planting methods.

Year	Treatment [1)]	Number of Tillers				Percentage of Productive Tillers (%)
		Peak Stage ($\times 10^4$ ha^{-1})	Jointing Stage ($\times 10^4$ ha^{-1})	Heading Stage ($\times 10^4$ ha^{-1})	Maturity Stage ($\times 10^4$ ha^{-1})	
2021	UAS105	424.37e	367.11e	301.30d	294.01e	69.29b
	UAS150	554.30c	473.32c	390.56bc	379.08c	68.38b
	UAS195	602.81b	508.60b	421.82b	407.86b	67.66b
	UAS240	684.65a	570.84a	475.94a	452.86a	66.14bc
	UDDS	608.82b	531.87b	416.47b	390.96c	64.22c
	UCT	476.98d	436.17d	381.21c	353.46d	74.09a
2022	UAS105	414.40d	384.25d	291.35d	266.50d	64.31b
	UAS150	482.30c	444.00c	336.15bc	306.80c	63.61b
	UAS195	536.40b	492.50b	368.30ab	335.70b	62.58b
	UAS240	583.55a	523.20a	399.35a	358.19a	61.37b
	UDDS	537.90b	502.60ab	356.85b	331.48b	61.62b
	UCT	400.90d	386.80d	311.15cd	295.90c	73.85a
Analysis of variance						
Year		**	**	**	**	**
Treatment		**	**	**	**	**
Year × Treatment		**	**	NS	**	NS

[1)] UAS105, UAS150, UAS195, and UAS240 represent unmanned aerial seeding with 105, 150, 195, and 240 basic seedlings/m^2, respectively; UDDS, unmanned dry direct seeding; UCT, unmanned carpet-seedling transplanting. Different lowercase letters within the same column indicate significant differences at $p \leq 0.05$. NS, not significant at the $p = 0.05$ level. ** means significant correlation at the 0.01 levels.

3.4. Leaf Area Index

There were differences in LAI indicators among the UAS treatments at the growth stages, but the trends were not completely consistent across stages (Table 4). When basic seedlings increased, the LAI at JI rose, but the LAI at HD and MA attained a parabolic trend. The highest values were observed in UAS195. In addition, the highly effective LAI showed a similar trend, but with a reduced percentage. In terms of the decreasing rate of the leaf area, it rose slightly in most of the adjacent treatments.

Among these methods, the LAI trends at all stages showed that UAS195 > UDDS > UCT, and the differences tended to be significant, but UAS195 and UCT differed slightly at MA. In terms of highly effective leaves, the LAI trend was similar to the effective LAI, but the percentage trend showed that UCT > UDDS > UAS195. For the decreasing rate, both UAS195 and UDDS were much higher than UCT.

3.5. Biomass Accumulation and Harvest Index

As the seedling density increased in UAS, the biomass accumulation rose during SO-JI, but it increased first and then decreased during JI-HD and HD-MA (Figure 4), and it resulted in the highest biomass accumulation in UAS195 at HD and MA. In the different methods, the accumulation in UAS195 was concentrated before heading, and the amount tended to be remarkably higher than in the other methods. UCT accumulated much more biomass than UAS and UDDS after heading. Combined with the accumulation during JI-HD, UCT obtained the highest accumulation over the entire growth period.

In terms of harvest index, the UAS treatments decreased slightly with the increase in basic seedlings (Figure 5). UAS195 and UDDS were at the same level and both were lower than UCT. The gap reached a significant level in 2022.

Table 4. Leaf area index (LAI) of NJ5718 with different UAS basic seedlings and different unmanned planting methods.

Year	Treatment [1)]	Jointing Stage	Heading Stage			Maturity Stage	Decreasing Rate of Leaf Area (LAI d^{-1})
			Effective LAI	Highly Effective Leaf Area			
				LAI	Percentage (%)		
2021	UAS105	3.81e	6.60d	3.32d	50.33a	3.19d	0.0655d
	UAS150	4.44b	6.90b	3.45ab	50.08ab	3.32b	0.0688bc
	UAS195	4.59a	6.99a	3.47a	49.64cd	3.36a	0.0697ab
	UAS240	4.60a	6.90b	3.42b	49.59d	3.25c	0.0702a
	UDDS	4.32c	6.88b	3.40b	49.91bc	3.34ab	0.0681c
	UCT	4.15d	6.70c	3.37c	50.23ab	3.27c	0.0634e
2022	UAS105	3.82e	7.07d	3.50c	49.58a	3.28c	0.0729b
	UAS150	4.16c	7.17bc	3.54ab	49.44ab	3.34b	0.0735ab
	UAS195	4.33a	7.25a	3.57a	49.16cd	3.40a	0.0742a
	UAS240	4.34a	7.19b	3.52bc	49.00d	3.32b	0.0745a
	UDDS	4.26b	7.18b	3.54ab	49.28bc	3.37a	0.0732ab
	UCT	3.95d	7.12c	3.52bc	49.41ab	3.29c	0.0710c
Analysis of variance							
Year		**	**	**	**	**	**
Treatment		**	**	**	**	**	**
Year × Treatment		**	**	**	*	**	**

[1)] UAS105, UAS150, UAS195, and UAS240 represent unmanned aerial seeding with 105, 150, 195, and 240 basic seedlings/m^2, respectively; UDDS, unmanned dry direct seeding; UCT, unmanned carpet-seedling transplanting. Different lowercase letters within the same column indicate significant differences at $p \leq 0.05$. NS, not significant at the $p = 0.05$ level. * and ** mean significant correlation at the 0.05 and 0.01 levels, respectively.

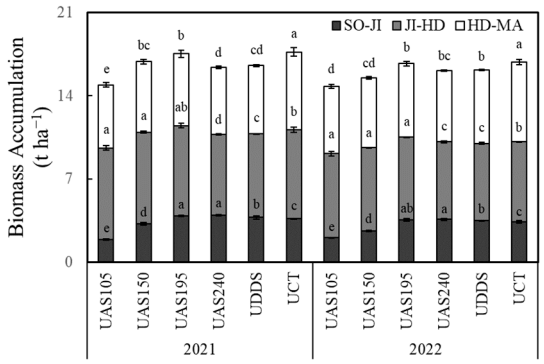

Figure 4. Biomass accumulation of NJ5718 with different UAS basic seedlings and different unmanned planting methods in 2021 and 2022. UAS105, UAS150, UAS195, and UAS240 represent unmanned aerial seeding with 105, 150, 195, and 240 basic seedlings/m^2, respectively; UDDS, unmanned dry direct seeding; UCT, unmanned carpet-seedling transplanting. Different letters indicate statistical significance at the 0.05 probability level. Bars mean standard error (n = 3).

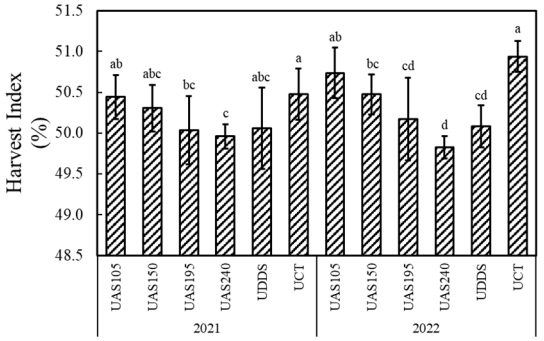

Figure 5. Harvest index of NJ5718 with different UAS basic seedlings and different unmanned planting methods in 2021 and 2022. UAS105, UAS150, UAS195, and UAS240 represent unmanned aerial seeding with 105, 150, 195, and 240 basic seedlings/m^2, respectively; UDDS, unmanned dry direct seeding; UCT, unmanned carpet-seedling transplanting. Different letters indicate statistical significance at the 0.05 probability level. Bars mean standard error (n = 3).

3.6. Crop Growth Rate and Net Assimilation Rate

When the UAS seeding density rose, the crop growth rate (CGR) and net assimilation rate (NAR) during HD-MA increased initially but decreased later (Figure 6). UAS195 achieved the highest crop growth rate and net assimilation rate in both years, increasing by 2.02–13.72% and 0.86–7.34%, respectively, over other UAS treatments. Among the methods, it was found that UAS195 was better than UDDS in the two indicators, but both were significantly smaller than UCT.

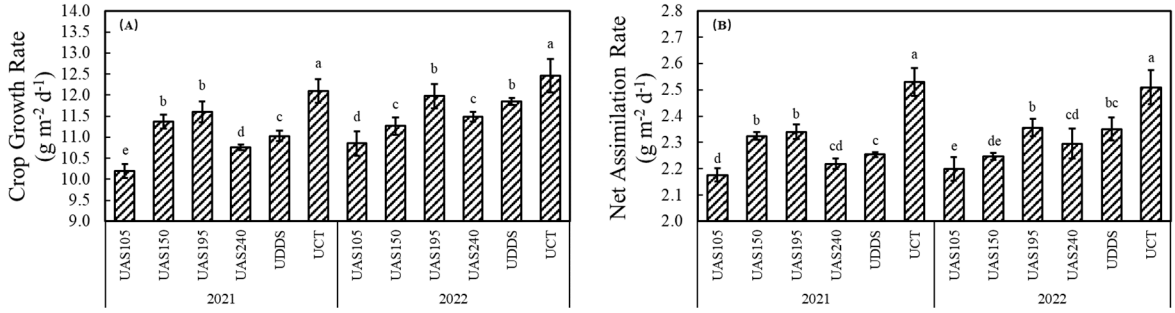

Figure 6. Crop growth rate (**A**) and net assimilation rate (**B**) of NJ5718 with different UAS basic seedlings and different unmanned planting methods during HD–MA in 2021 and 2022. UAS105, UAS150, UAS195, and UAS240 represent unmanned aerial seeding with 105, 150, 195, and 240 basic seedlings/m^2, respectively; UDDS, unmanned dry direct seeding; UCT, unmanned carpet-seedling transplanting. Different letters indicate statistical significance at the 0.05 probability level. Bars mean standard error (n = 3).

3.7. Processing and Appearance Quality

As shown in Table 5, increasing basic seedlings in UAS had certain negative effects on the rice processing and appearance quality, but the effects were not at the same level. The processing quality among the adjacent treatments generally showed a slight decrease, but the appearance quality mainly showed a significant one.

Table 5. Processing and appearance quality of NJ5718 with different UAS basic seedlings and different unmanned planting methods.

Year	Treatment [1)]	Brown Rice Rate (%)	Milled Rice Rate (%)	Head Milled Rice Rate (%)	Chalkiness Rate (%)	Chalkiness Size (%)	Chalkiness Degree (%)
2021	UAS105	82.11b	69.66bc	65.37c	14.19d	14.28d	3.84c
	UAS150	81.84bc	69.28bcd	64.96cd	20.82c	21.17c	6.93b
	UAS195	81.46cd	68.54cd	64.17d	27.07a	27.24a	8.85a
	UAS240	81.02d	68.25d	64.01d	27.47a	27.97a	9.37a
	UDDS	82.41ab	70.15b	66.88b	24.77b	24.97b	7.57b
	UCT	82.85a	71.32a	68.32a	15.16d	15.24d	4.45c
2022	UAS105	81.93bc	69.03b	61.53bc	19.83d	16.81d	4.46e
	UAS150	81.77c	68.82b	61.04bc	21.45c	21.25c	6.85cd
	UAS195	81.68c	68.69b	60.48c	24.29b	24.18b	8.08b
	UAS240	81.65c	68.54b	59.22d	29.24a	29.00a	9.89a
	UDDS	82.41ab	69.61b	62.02b	23.91b	23.57b	7.36bc
	UCT	82.86a	70.79a	65.80a	17.76d	17.18d	6.10d
Analysis of variance							
Year		NS	NS	**	NS	NS	NS
Treatment		**	**	**	**	**	**
Year × Treatment		NS	NS	NS	**	**	*

[1)] UAS105, UAS150, UAS195, and UAS240 represent unmanned aerial seeding with 105, 150, 195, and 240 basic seedlings/m^2, respectively; UDDS, unmanned dry direct seeding; UCT, unmanned carpet-seedling transplanting. Different lowercase letters within the same column indicate significant differences at $p \leq 0.05$. NS, not significant at the $p = 0.05$ level. * and ** mean significant correlation at the 0.05 and 0.01 levels, respectively.

Among the methods, the trends in the processing and appearance quality were consistent, and both showed that UAS < UDDS < UCT. The UAS195 treatment significantly differed from others in most of the processing quality indicators, and the differences expanded as the processing deepened. Moreover, this expansion also occurred between UDDS and UCT. In terms of appearance quality, UAS195 consistently had more chalkiness than the other treatment, and the differences tended to be significant, excepting UAS195 and UDDS in 2022.

3.8. Nutrition, Cooking and Eating Quality

As the basic seedlings increased, protein content showed an upward trend, but amylose content and taste value showed a downward one (Figure 7). The differences between most of the neighboring treatments were minor, but the amylose content in 2022 showed significant differences. Among the taste indicators, hardness showed a similar trend with protein content, but the appearance, viscosity, and balance degree remained consistent with the changes in taste value (Table 6).

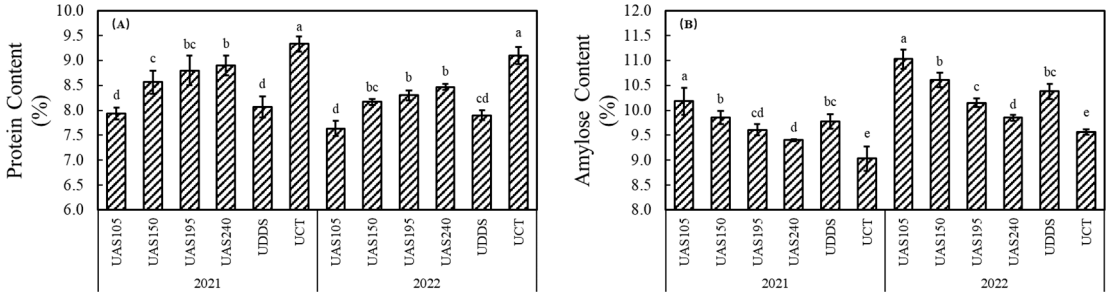

Figure 7. Protein content (**A**) and amylose content (**B**) of NJ5718 with different UAS basic seedlings and different unmanned planting methods in 2021 and 2022. UAS105, UAS150, UAS195, and UAS240 represent unmanned aerial seeding with 105, 150, 195, and 240 basic seedlings/m^2, respectively; UDDS, unmanned dry direct seeding; UCT, unmanned carpet-seedling transplanting. Different letters indicate statistical significance at the 0.05 probability level. Bars mean standard error (n = 3).

Table 6. Nutrition, cooking, and eating quality of NJ5718 with different UAS basic seedlings and different unmanned planting methods.

Year	Treatment [1)]	Taste Value	Appearance	Hardness	Viscosity	Degree of Balance
2021	UAS105	71.67a	6.73a	6.53c	7.27a	6.93a
	UAS150	69.33bc	6.40bc	6.67bc	6.83bc	6.50b
	UAS195	68.33cd	6.27cd	6.73abc	6.63c	6.30bc
	UAS240	67.33d	6.10d	6.80ab	6.60c	6.17c
	UDDS	70.67ab	6.63ab	6.53c	7.00b	6.73a
	UCT	65.33e	5.80e	6.93a	6.27d	5.93d
2022	UAS105	74.00a	7.20a	6.23d	7.43a	7.27a
	UAS150	71.67bc	6.73b	6.53bc	7.27ab	6.93b
	UAS195	70.33cd	6.53bc	6.63b	7.03bc	6.67c
	UAS240	69.33d	6.47c	6.67ab	6.90c	6.53c
	UDDS	73.00ab	7.00a	6.37cd	7.37a	7.13ab
	UCT	66.67e	6.03d	6.87a	6.40d	6.03d
			Analysis of variance			
Year		**	**	**	**	**
Treatment		**	**	**	**	**
Year × Treatment		NS	NS	NS	NS	NS

[1)] UAS105, UAS150, UAS195, and UAS240 represent unmanned aerial seeding with 105, 150, 195, and 240 basic seedlings/m^2, respectively; UDDS, unmanned dry direct seeding; UCT, unmanned carpet-seedling transplanting. Different lowercase letters within the same column indicate significant differences at $p \leq 0.05$. NS, not significant at the $p = 0.05$ level. ** means significant correlation at the 0.01 levels.

Among the methods, the trend of protein content was UCT > UAS195 > UDDS, while the trend of the amylose content was the opposite (Figure 7). UCT varied significantly from the other methods for both of the above indicators, but the difference between UAS195 and UDDS only reached a significant level for protein content rather than amylose content. The trend of taste value was similar to that of amylose content, and there were significant differences among the methods (Table 6).

3.9. Correlation of Yield Formation and Quality Characteristics

From Figure 8, it was found that grain yield was highly significantly and positively correlated with TSP, percentage of productive tillers, and biomass accumulation during –HD-MA. In addition, grain yield was extremely significantly positively correlated with PN, CGR, and NAR during this period. Meanwhile, these yield formation indicators, except for LAI, were significantly positively or highly significantly positively correlated with protein content, but significantly or highly significantly negatively correlated with amylose content and taste value. Regarding the processing and appearance quality, grain yield, PN, TSP, and biomass accumulation after heading were all positively correlated with head-milled rice rate and chalkiness to varying degrees. However, grain-filling rate, 1000-grain weight, and percentage of productive tillers were only positively correlated with head-milled rice rate and negatively correlated with chalkiness degree, which was the opposite of LAI after heading.

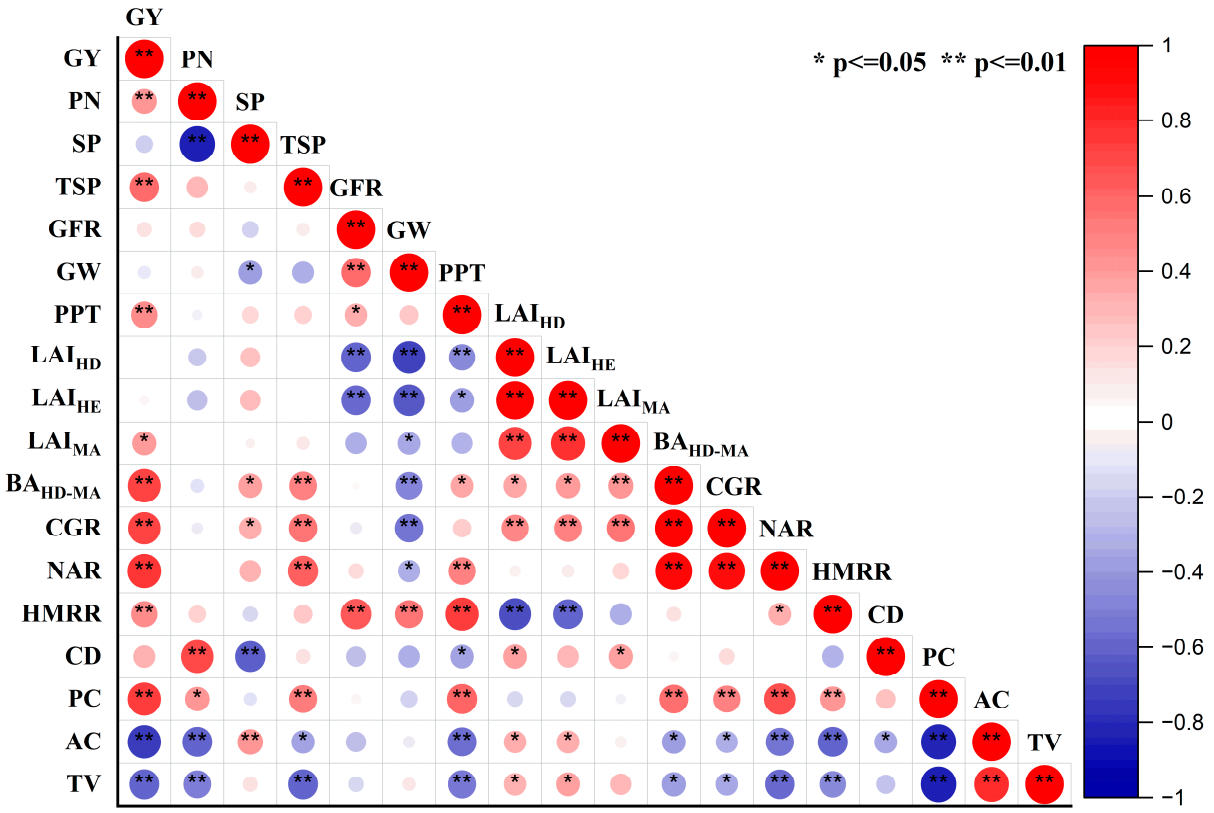

Figure 8. Correlation of yield formation and quality characteristics. GY, grain yield; PN, panicle number; SP, spikelet number per panicle; TSP, total spikelet number; GFR, grain-filling rate; GW, 1000-grain weight; PPT, percentage of productive tillers; LAI_{HD}, LAI at HD; LAI_{HE}, highly effective LAI; LAI_{MA}, LAI at MA; BA_{HDMA}, biomass accumulation during HD to MA; CGR, crop growth rate; NAR, net assimilation rate; HMRR, head-milled rice rate; CD, chalkiness degree; PC, protein content; AC, amylose content; TV, taste value. * and ** mean significant correlation at the 0.05 and 0.01 levels, respectively.

4. Discussion

4.1. Effects of Unmanned Aerial Seeding Density and Method on Yield Formation

Grain yield is highly significantly positively correlated with total spikelet number (TSP), so panicle number (PN) and spikelet number per panicle (SP) should be valued [28]. However, since the panicle type of high-quality inbred *japonica* rice is mainly small and medium, the potential for increasing SP is limited, and it might be more feasible to achieve a yield increase by increasing PN [29]. Increasing basic seedlings is an effective way to raise PN [22,30]. The present study showed that PN rose obviously when increasing basic seedlings, with a maximum increase of 44.70% on average over the past two years (Table 2). However, due to the compensatory relation between PN and SP [31,32], SP decreased simultaneously. As a result, UAS195 obtained the largest TSP among the treatments (Table 2). Meanwhile, grain yield is closely related to biomass and harvest index. In this study, it was found that increasing basic seedlings resulted in a slow descent in the harvest index and a huge ascent in biomass overall (Figures 4 and 5). Both UAS195 and UAS240 accumulated a large amount of biomass through high-density basic seedlings before jointing [12]. However, only UAS195 subsequently continued to maintain adequate photosynthetic production. Especially during the filling stage, it had high LAI and NAR, which provided sufficient sources for yield formation (Table 4 and Figure 6) [33]. In contrast, UAS240 had weak effective tiller physiological and biochemical activities due to the occurrence of many ineffective tillers, which intensified the competition inside the population [34,35]. Further, after the extinction of the ineffective tillers, the population lost an enormous amount of biomass and potential biomass sources. Therefore, it is appropriate to select 195 seedlings/m^2 as the basic seedling density in UAS. In addition, it has been reported that UAS could not only enhance seeding quality but also increase yields by about 6–10% over the conventional spreading method at the same planting density [15]. This is because the more vigorous seedlings could cause tiller occurrence and canopy closure earlier, which leads to faster and more photosynthetic accumulation [36]. Owing to the synergistic growth mechanism between the aboveground and underground parts, the growth and development of the lower root system are better, promoting tillering and panicle formation [37], while also delaying leaf aging and achieving a more substantial filling effect [38].

Different planting methods might have a significant impact on grain yields. This study showed that, although UAS195 reduced the yield much more than UCT, it still significantly increased the yield more than UDDS (Figure 3). Analysis of the TSP component showed that UCT was more dependent on SP, whereas UAS195 and UDDS were more concentrated in PN (Table 2). The longer vegetative growth period and panicle differentiation period in UCT were conducive to the formation of larger panicles by providing sufficient material and time (Table 1) [35], while UAS195 and UDDS achieved a much larger PN by having a higher number of basic seedlings. However, it is interesting to note that UAS195 had more PN even though it had fewer basic seedlings than UDDS. Previous studies suggest that, although high plant density is not conducive to tillering per plant, PN is still enlarged [22,23]. Hence, it might not be a consequence of the basic number of seedlings. On the one hand, the surface sowing characteristics and more uniform sowing effect of UAS promote tiller development and nutrient supply, increasing the percentage of productive tillers. On the other hand, the soil environment in UDDS could be another important cause. Oxygen-enriched conditions make straw in the soil more prone to decay, releasing more elements to promote the proliferation of soil microorganisms, and reducing the nutrients absorbed by rice in the early stage [39], leading tillering to be slow first and then rapid. Such tillering dynamics are not conducive to fully utilizing low-position tillers to form panicles and to develop large panicles, while high-position tillers tend to exhibit smaller panicle types or even could not form panicles [34,35]. As a result, UAS195 had fewer ineffective tillers and less wasted biomass than UDDS (Table 3), leading to obtaining more biomass accumulation before heading (Figure 4). For UCT, it did not have an advantage in accumulating biomass before heading, due to the fewer basic seedlings and severe mechanical damage, which resulted in tiller occurrence being delayed and less frequent. Photosynthetic production

after heading is an important source of yield which is determined by both photosynthetic area and photosynthetic intensity. UAS195 and UDDS had higher LAI (Table 4), but lower CGR and NAR than UCT (Figure 6). This indicated that the photosynthetic intensity of UAS195 and UDDS lagged behind that of UCT. This could be related to the reduced root vigor after heading. Although the root system of direct-seeding rice is larger than that of transplanted rice [40], when root vigor declines, the large root system becomes a burden and increases competition for nutrients with the above-ground parts [10]. Therefore, the biomass accumulation and harvest index in UCT were higher than in other methods during HD-MA (Figures 4 and 5), and between the direct seeding methods, the photosynthetic production of UAS195 after heading was still better than that of UDDS, as wet direct seeding could be able to maintain a higher root vigor than dry seeding [10]. In summary, unlike the growth centers in UCT that focus on the booting and grain-filling phase, those in UAS195 and UDDS are more prone to pre-heading growth. Not only did UAS195 produce more low-position tillers than UDDS, it established large populations earlier after seeding for more biomass accumulation, and maintained a certain level of photosynthetic production even after heading.

4.2. Effects of Unmanned Aerial Seeding Density and Method on Rice Quality

Rice quality not only results from the genetic background of the variety, but is also influenced by various aspects such as climate, soil, and cultivation practices. Among them, planting density and planting methods have an important impact on rice quality. The processing and appearance qualities of rice are closely related to its commodity properties. The results of this study showed that the processing quality and appearance quality of rice decreased to varying degrees as the number of base seedlings increased (Table 5). High planting density causes severe canopy closure and poor lighting conditions, as well as causing the single-stem photosynthetic production to be relatively low and the materials for grain filling to be insufficient, deteriorating the above quality [20]. Moreover, canopy closure leads to an increase in temperature and humidity within the population, which is not beneficial to stable filling, and is prone to producing starch grain gaps, leading to loose and porous endosperm structures [41,42]. This structure promotes the refraction of light, resulting in an increase in chalkiness at the macro level [43]. Meanwhile, it also tends to make rice fragile, which is not conducive to the processing quality [44]. Among the studied methods, the current study showed that UCT was superior to UDDS, while UAS195 was the worst (Table 5). This is because UCT still had high photosynthetic capacity at the grain-filling stage, which provided a sufficient photosynthetic substrate for starch synthesis. But UAS195 and UDDS had inferior ones, causing lower filling rates and poorer filling results [20], especially so for UAS195, since the population distribution, aeration performance, and light conditions tended to be worse under the spreading method [42].

Edible rice requires a softer texture and greater palatability, which are mainly evaluated by the protein content, amylose content, and taste value of rice [45]. Protein is an important component of the composition and activity of life, and its content is a major indicator of the nutritional quality of rice. This study found that adding basic seedlings under the unmanned aerial seeding method would increase protein content and improve nutritional quality (Figure 7). This might be because GOGAT in grains is susceptible to high temperatures inside the population, which enhances its activity under high-density planting conditions, promoting protein synthesis [46,47]. Meanwhile, this experiment also observed a decreasing trend in amylose content with the increase in the number of basic seedlings (Figure 7). This is because high temperatures could also weaken the carbon metabolism in the grains, enhance the activity of α-amylase, and inhibit the synthesis of amylose [47,48]. The protein and amylose in rice can reduce the viscosity and increase the hardness of rice by limiting the water absorption, gelatinization, and expansion of starch grains, so rice with high-density planting had poor taste quality [49]. Among the studied methods, this study suggested that the protein content of UAS195 and UDDS treatment was significantly lower than UCT, while the amylose content was significantly

higher (Figure 7). The former might be due to more basic seedlings of direct-seeding rice and less nitrogen content that could be absorbed by a single plant [22]. The latter might absorb more nitrogen in single plants and have a more vigorous nitrogen metabolism, which inhibits carbon metabolism, leading to feeble amylose synthesis [50]. Between the unmanned direct seeding methods, the filling period of UAS195 was earlier than that of UDDS (Table 1), and the average temperature was higher (Figure 1), favoring protein synthesis over amylose synthesis. In addition, the trend was exacerbated by the population's worse canopy structure. Since the taste value was mainly influenced by the protein content [51], UDDS and UAS195, with the lower protein content, had greatly improved eating quality (Table 6). In summary, UCT not only produced a high yield but also had a high processing quality, appearance quality, nutritional quality, and certain taste quality, thus achieving the coordinated production of yield and quality. Although most of the rice quality in UAS195 and UDDS was not as good as that in UCT, the taste quality was improved and the yield level was in an acceptable range. Considering that unmanned aerial seeding technology has much higher operational efficiency than ground-based machinery, UAS195 could be an alternative unmanned planting method that could coordinate yield, quality, and efficiency.

4.3. Limitaions and Prospects

It should be noted that this experiment was conducted only in the middle and lower reaches of the Yangtze River, and that the findings obtained might apply only to the environment and cultivation conditions of that region. As China is a vast country with diverse topography and numerous rice distribution areas with different cropping systems, it is necessary to conduct experiments in several rice distribution areas to promote the UAS method. As well, only an inbred *japonica* variety with small and medium panicle types was used in this experiment. Previous studies have concluded that the best approach for achieving high yields varies for different panicle types: large-panicle varieties should moderately reduce planting density and increase PN; medium-panicle varieties should take into account both PN and SP to attain more TSP; and small-panicle varieties should rely mainly on the raising of PN [52]. Therefore, it is also urgent to conduct UAS experiments using rice varieties with multiple panicle types. In our future work, we would conduct further research to address the two major shortcomings mentioned above to refine and enrich the UAS rice cultivation system and contribute to the generalization of this method.

5. Conclusions

Increasing the basic seedlings in the UAS method led to a parabolic trend in grain yield, with UAS195 achieving a significantly higher yield. During the increase, the processing and appearance quality, amylose content, and taste value deteriorated, but the nutritional quality improved. UAS195 was less productive than UCT due to weaker photosynthetic production after heading and a lower grain-filling rate. But it still produced significantly more yield than UDDS owing to having more panicles, a higher spikelet number per panicle, fewer unproductive tillers, and more biomass accumulation. Compared to UCT, UAS195 and UDDS had poorer processing quality, appearance quality, and nutritional quality, as well as higher amylose content. However, they both showed a significant improvement over UCT in terms of taste quality. Hence, unmanned aerial seeding with high-quality *japonica* produced 195 basic seedlings/m^2. Given the efficiency of planting, this could be an alternative to unmanned planting methods that coordinate yield, quality, and efficiency.

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Conflicts of Interest: The authors declare no conflict of interest.

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