Effects of different machine transplanting methods on the physiological and yield characteristics of late rice in China

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Abstract: To address problems caused by rice machine transplanting such as injury to the seedlings and recovery period that extend growth period, this study explored the effects of different machine transplanting methods on the physiological and yield characteristics of late rice in China, and determine the appropriate machine transplanting method for late rice, which was expected to provide a basis for high-yield and high-efficient cultivation of machine-transplanted late rice. Hybrid indica rice Taiyou 398 and conventional indica rice Jing Gangruanzhan were selected as the research objects, and large-pot carpet seedling machine transplanting (M1), conventional pot carpet seedling machine transplanting (M2) and ordinary carpet seedling machine transplanting (M3) were adopted respectively to analyze their effects on seedling quality, population physiological characteristics, yield and its components and economic benefits of late rice. The results showed that compared with M2 and M3, M1 achieved higher seedling quality, showing significant advantages in the early stage despite average root entwining force that met the requirement of machine transplanting. The seedlings transplanted using M1 had shorter recovery period after mechanical transplanting, with earlier tillering, earlier peak seedling, and slower declining of stems and tillers in the late stage; the peak seedling number was not high, but the effective tiller number and earbearing tiller percentage were significantly higher than those achieved by the other two machine transplanting methods. Also, M1 achieved stronger photosynthetic capacity of flag leaves before HS, with more photosynthetic products in stems and leaves transported to panicles and more efficiently after HS. Compared with seedlings transplanted using M2 and M3, the recovery period of those transplanted using M1 was shortened by 3 and 5 d, the heading stage (HS), and maturity stage (MS) were advanced, which effectively reduced the risk and impact of “cold dew wind” on machine-transplanted late rice. M1 had significant yield increase advantage and economic benefit, with better grain maturity, and “larger panicles, more panicles, more and fuller grains”. M1 achieved an average yield increase of 10.31%-11.10%, 20.67%-25.10% in 2 years, and an average income increase of 18.65%-131.06% and 62.85%-323.78%, respectively. Therefore, vigorously developing M1 is the key to the high-yield and high-efficient cultivation of machine-transplanted late rice in China.

Keywords: large-pot carpet seedling, machine transplanting, late rice, physiological characteristics, seedling quality, yield
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1 Introduction

Rice (*Oryza sativa* L.) is the second largest grain crop in the world, accounting for 40% of China’s total grain yield; more than 60% of China’s population live on rice, and rice production is of great significance to ensure China’s food security[1]. Mechanized planting is an important opportunity for the large-scale, simplified, commercialized and modern development of rice[2], which has the advantages of high yield, stable yield and high efficiency[3]. Double cropping rice can improve the multiple cropping index, which is an important way to increase grain production. However, in recent years, the planting area of late rice has shown a decreasing trend year by year[4], mainly due to the rush of early rice harvest and late rice planting, strong seasonality, large amount of labor, high work intensity and low mechanization level which has become the bottleneck restricting the large-scale planting of late rice[5-7].

At present, rice mechanized planting mainly includes machine direct seeding, machine transplanting and throw transplanting[8]. As a mature technology, machine transplanting can better address the needs of rice production season and cultivar growth period, with good lodging resistance and strong adaptability. It is an inevitable choice for the transformation and upgrading of rice production technology[9,10]. Cultivating strong seedlings suitable for machine transplanting is the key to the development of machine transplanting technology[11]. The traditional machine transplanting is the ordinary carpet seedling machine transplanting, with ordinary flat tray used to raise seedlings, which requires less land for seedling raising, has

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higher mechanical efficiency and is more conducive to large-scale rice production and management[12]. However, this machine transplanting method leads to high seeding density, small seedling growth space, poor quality of seedlings, large planting depth, great injury to the seedlings, and long recovery period after transplanting that prolongs the growth period of rice and increases the risk of late rice encountering "cold dew wind", and limits the full development of rice yield potential[3,13,14].

In recent years, as a new high-yield and high-efficient planting method, pot carpet seedling transplanting combines the advantages of ordinary carpet seedling transplanting and pot seedling transplanting. It has the advantages of high seedling quality, small injury to the seedlings, short recovery period and high yield. It is one of the main development directions of rice mechanized planting in China in the 21st century[15,16]. In 2009, China Rice Institute developed the rice pot carpet seedling machine transplanting technology. The seedling raising tray is conventional pot carpet seedling raising tray, raising carpet seedlings with pots below. The pot volume is small, which reduces the injury caused by machine transplanting and shortens the recovery period to a certain extent, increasing the yield by 6.2% compared with ordinary carpet seedling machine transplanting. It is popularized due to its low cost[17,18]. In 2015, China Agricultural University developed the mechanized large-pot carpet seedling raising and transplanting technology, with new type of raising tray-large-pot carpet seedling raising tray adopted, with smaller sowing density and larger pot volume, which could cultivate larger and stronger carpet seedlings with pots below[19]. This technology gives full play to the advantages of high yield and high quality of rice pot seedling cultivation and the operation efficiency and accuracy of machine transplanting. The injury caused during transplanting is smaller, which can greatly shorten the recovery period, prolong the suitable machine transplanting seedling age, and solve the problem of insufficient rice growth period in double cropping rice area[20]. This technology brings a new technical model for rice mechanized planting and is listed as one of the top ten major leading technologies of Ministry of Agriculture and Rural Affairs of China in 2021[21].

As a new mechanized seedling raising and transplanting technology, the large-pot carpet seedling of rice was rarely reported in researches. Based on the long-term practice and exploration of our team, different late rice cultivars were selected in this study to compare and study the effects of three machine transplanting methods (large-pot carpet seedling machine transplanting, conventional pot carpet seedling machine transplanting and ordinary carpet seedling machine transplanting) on the seedlings quality, population characteristics, yield and its components and economic benefits of late rice in China. The results are used to determine the appropriate machine transplanting method for late rice, which is expected to provide basis for high-yield and high-efficient cultivation of machine-transplanted late rice in China.

2 Materials and methods

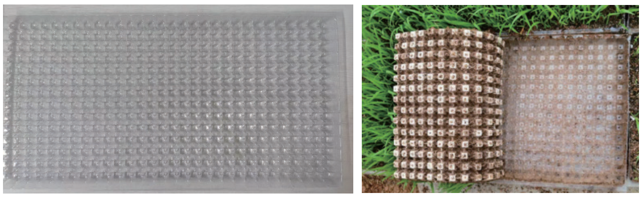
2.1 Experimental site and cultivars

The experiment was carried out from June to November 2019 and 2020 in Gao'an Base of Jiangxi Academy of Agricultural Sciences (115°7'5'E, 28°15'43'N), during which, field trials of late rice with different machine transplanting methods were conducted. The base is located in Gao'an City, Yichun City, Jiangxi Province, has an altitude of 40 m, belonging to double cropping rice planting area; it has a subtropical monsoon climate, with sufficient rainfall, annual average temperature of 17.7ºC, annual precipitation of 1560 mm, annual sunshine hours of 1667.2 h and frost free period of 276 d throughout the year. The shape of the experimental field was regular. The first crop was machine-transplanted early rice (yield 7520.25 kg/hm^2). The organic matter content of 0-20 cm soil tillage layer was 35.63 g/kg, nitrate nitrogen was 1.23 mg/kg, available phosphorus was 15.84 mg/kg, available potassium was 120.22 mg/kg, and pH value was 5.8.

The highly representative late rice cultivars with wide local application, age suitable for machine transplanting, stable yield and high quality, and close growth periods were selected, i.e. Taiyou 398 (A1), a hybrid indica rice, with a whole growth period of 111.2 d and Jing Gangruanzhan (A2), a conventional indica rice, with a whole growth period of 111 d.

2.2 Experimental design

Large-pot carpet seedling machine transplanting (M1) adopted the 9-inch large-pot carpet seedling raising soft tray with 420 pots (14×30, Figure 1). The transplanter took seedlings according to the pot, taking them 14 times horizontally, and the depth of taking them longitudinally was 19 mm. Considering the germination rate, five A1 seeds were sowed per pot, about 50 g dry seeds per tray, six A2 seeds were sowed per pot, and about 45 g dry seeds per tray, to ensure that A1 had 4-5 seedlings per cluster and A2 had 5-6 seedlings per cluster when transplanting.

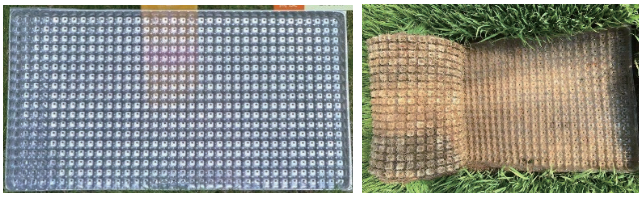


a. Large-pot carpet seedling raising tray b. Large-pot carpet seedlings

Note: M1: Large-pot carpet seedling machine transplanting

Figure 1 Seedling trays and seedlings used for M1

Conventional pot carpet seedling machine transplanting (M2) adopted the conventional 9-inch pot carpet seedling raising soft tray with 648 pots (18×36, Figure 2). The transplanter took seedlings according to the pot, taking them 18 times horizontally, and the depth of taking them longitudinally was 19 mm. Considering the germination rate, five A1 seeds were sowed per, about 75 g dry seeds per tray, and six A2 seeds were sowed per pot, about 68 g dry seeds per tray, to ensure that A1 had 4-5 seedlings per cluster and A2 had 5-6 seedlings per cluster when transplanting.



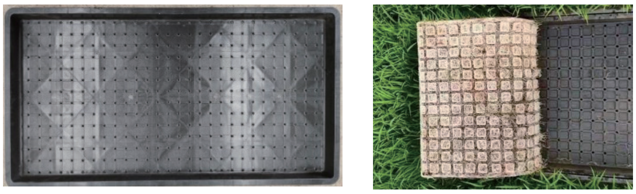
a. Conventional pot carpet seedling raising tray b. Conventional pot carpet seedlings

Note: M2: Conventional pot carpet seedling machine transplanting

Figure 2 Seedling trays and seedlings used for M2

Ordinary carpet seedling machine transplanting (M3) adopted the ordinary 9-inch hard flat seedling raising tray (Figure 3). The horizontal times and longitudinal depth of seedling taking by the transplanter were consistent with those of M2. The sowing amount was the same as that of M2 to ensure that A1 had 4-5 seedlings per cluster and A2 had 5-6 seedlings per cluster when transplanting.

In the experiment, composite substrate and natural soil which were proportioned according to volume were used as seedling raising substrate. The basal soil ratio was 2:1 and water content was 34.3%. In 2019, the seeds were sown on July 1, and seedlings were transplanted on July 26; In 2020, the seeds were sown on July 4, and the seedlings were transplanted on July 29. The seedling age was 25 d, and the method of wet-bed nursery was adopted. The three kinds of seedlings were transplanted by a machine transplanter (SPV-S6CMD, Kubota Corporation, Japan), as shown in Figure 4, with the same density of 238 100 cluster/hm^2, row spacing of 30 cm and plant spacing of 14 cm.



a. Ordinary flat tray b. Ordinary carpet seedlings

Note: M3: Ordinary carpet seedling machine transplanting

Figure 3 Seedling trays and seedlings used for M3

Figure 4 SPV-S6CMD Kubota seated high-speed transplanter

Split-plot design was adopted, with two rice cultivars arranged in main plots and three machine transplanting methods in sub-plots (6 treatments in total); each treatment was replicated 3 times, totaling 18 randomly arranged plots. The same field contrast experiment was adopted, with each treatment no less than 30 m^2; each plot was divided into sampling area and measuring area, each accounting for half of the plot. During the whole growth period, the experiment field was treated with management measures the same with other fields.

2.3 Plant sampling and measurements

Ten representative plants from each treatment were selected one day before transplanting to measure seedling height, leaf age, root number, root length, stem base width, SPAD value and tiller number and the selection was repeated three times. For each treatment, 300 representative plants were taken and divided into 3 parts. The plants were cut into aboveground and underground sections, de-enzymed at 105°C for 30 min, and dried to constant weight at 80°C. The dry matter weight was measured and the root shoot ratio was calculated.

Root Shoot Ratio=Dry matter weight of roots/Dry matter weight of aboveground organs

Three trays of seedlings were selected randomly for each treatment, the whole carpet of seedlings were taken out from the seedling tray on the day before transplanting. Then, one end was fixed with a wooden board, and the other end was clamped with a large clamping plate. The large clamping plate was pulled horizontally with SH200 electronic dynamometer until the whole seedling carpet was broken apart, and the maximum pulling force required to break the whole carpet was recorded as the root entwining force of the seedlings (unit: N).

One day after machine transplanting, 3 rows were randomly selected in each plot with 30 seedlings in each row to investigate the number of machine-transplanted seedlings per cluster, injured seedlings, overturned seedlings, floating seedlings, missing seedling clusters and planting depth in each plot. According to the Rice Transplanter Test Method[22], the seedling missing rate, seedling floating rate, seedling injury rate, seedling overturning rate, uniformity pass rate after transplanting and pass rate of relative uniformity were calculated.

The accurate times of the main growth stages of rice in each plot, such as sowing date (SD), transplanting stage (TS), initial tillering stage (ITS), middle tillering stage (MTS), jointing stage (JS), booting stage (BS), heading stage (HS), full heading stage (FHS), filling stage (FS), milk ripe stage (MRS), and maturity stage (MS) were observed and recorded.

In each plot, 30 consecutive clusters with relatively consistent growth trend were selected once every 7 to 10 d to investigate the dynamics of tiller growth and decline at fixed time and location, until the tiller number was stabilized; and then the earbearing tiller percentage was calculated.

Earbearing tiller percentage = (Effective tiller number/Peak seedling number) ×100%

In each plot, 10 consecutive clusters with relatively consistent growth trend were selected, and the chlorophyll content of the top fully expanded leaf of the plant was measured by the SPAD-502 chlorophyll meter at fixed time and location at different growth stages. The chlorophyll content of the flag leaf was measured after it was expanded.

Diagonal sampling method was used to take 5 rice plants from each plot for seed test, and the panicle length, grain number per panicle, seed-setting rate and 1000-grain weight were measured. About 3 m^2 plants of each plot were cut, and the PM-8188-A grain moisture meter was used to measure the moisture content of wet grain on the spot. The actual yield was calculated after converting the moisture content into the standard moisture content (13.5%), and the impurity content was 2.0%.

The cost of different treatments such as seedling tray cost, substrate cost, seed cost, labor cost of seedling raising, transplanting operation cost, herbicide cost, etc., as well as the rice income were calculated to compare and analyze the economic benefits of the three machine transplanting methods.

2.4 Data calculation and statistical analysis

The experimental data was input into Microsoft Excel 2016 and processed and charted; the DPS data processing system V18.10 advanced version was used for statistical analysis. The results of the 2 years were basically the same. This study took the data of 2019 as an example for analysis. The “cold dew wind” often occurs in Jiangxi Province, mainly in the middle and late September. It is easy to cause low temperature damage to late rice in heading, flowering and filling stages, resulting in failure of heading and flowering or seed-setting, thus causing yield loss or no yield[23,24]. From September 17 to October 19, 2020, the experimental base experienced multiple rounds of moderate to severe “cold dew wind”, with a daily average minimum temperature of 17.64°C and a daily average maximum temperature of 23.18°C. The “cold dew wind” had a great impact on the growth period, yield and its components and economic benefits of rice. In order to analyze the impact of “cold dew wind” on these indicators under different machine transplanting methods, two years of data were used.

3 Results

3.1 Seedling quality analysis

Seedling quality plays an important role in the adaptability of the seedling to machine transplanting and the recovery period after machine transplanting, which is the basis of ensuring high yield of rice. Different machine transplanting methods had a significant impact on various morphological indexes of seedlings (Table 1). In terms of leaf age, stem base width, aboveground dry matter weight, underground dry matter weight, root shoot ratio, SPAD value and tiller number, the three methods ranked as follows on the whole: M1>M1>M3; in terms of plant height, root length and root number, the three methods ranked as follows on the whole: M1<M2<M3.

Table 1 Effects of different machine transplanting methods on seedling quality

Treatment		Leaf age	Plant height/cm	Root length/cm	Root number	Stem base Width/cm	100 plants dry matter weight/g		Root shoot ratio	SPAD value	Tiller number
Cultivar	Method						Aboveground	Underground			
A1	M1	5.33^{a}	18.83^{c}	6.79^{b}	13.37^{b}	5.03^{a}	6.90^{a}	3.48^{a}	0.50^{a}	36.77^{a}	2.42^{a}
	M2	4.58^{b}	21.71^{b}	7.60^{a}	15.30^{a}	4.20^{b}	6.18^{a}	2.66^{b}	0.43^{b}	36.05^{b}	1.74^{b}
	M3	4.05^{b}	22.49^{a}	7.96^{a}	15.96^{a}	3.27^{c}	5.10^{b}	1.65^{c}	0.32^{c}	35.87^{b}	1.08^{c}
A2	M1	4.96^{a}	17.17^{c}	5.62^{c}	11.47^{b}	4.50^{a}	4.65^{a}	2.33^{a}	0.50^{a}	36.60^{a}	2.39^{a}
	M2	4.29^{b}	18.95^{b}	6.31^{b}	13.47^{a}	3.73^{b}	4.27^{a}	1.68^{b}	0.39^{b}	35.77^{ab}	1.52^{b}
	M3	4.03^{b}	20.07^{a}	6.96^{a}	14.34^{a}	3.43^{c}	3.07^{b}	1.14^{c}	0.37^{b}	35.33^{b}	1.03^{c}

Note: Values are means of 3 replications. Different lowercase letters in the same column indicate significant differences between different treatments (p<0.05). 10 plants are included in a group to test the stem base width.

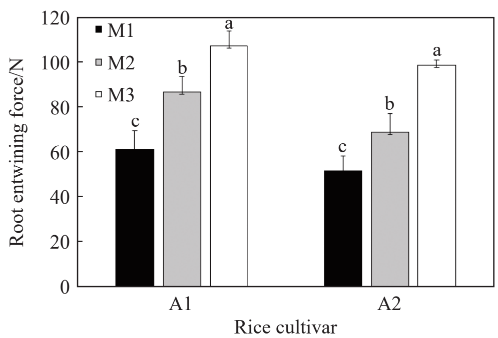
The plant height suitable for machine transplanting of late rice is 12-20 cm[25]. The height of seedlings transplanted with M1 was suitable for machine transplanting, which was significantly lower than those planted with M2 and M3; the plant heights of A1 planted with M2 and M3 were 21.71 cm and 22.49 cm respectively, and the plant height of A2 planted with M3 was 20.07 cm, which were not suitable for machine transplanting. Root length and root number mainly affect the carpet forming of seedlings, and underground dry matter weight and root shoot ratio affect root robustness. M1 had no advantage in root length and root number. The root number was 15.94% and 22.20% lower than those of M2 and M3 respectively, and the root length was 12.18% and 20.54% lower than those of M2 and M3 respectively. The differences were all significant, indicating that M2 and M3 achieved better carpet forming. The underground dry matter weight of seedlings transplanted with M1 was 34.76% and 107.65% higher than those of seedlings planted with M2 and M3 respectively, and the root shoot ratio was 22.27% and 45.41% higher than those of M2 and M3 respectively; the difference were significant, indicating that M1 achieved more robust root system. Stem base width and aboveground dry matter weight reflect the strength of seedlings. M1 achieved stem base width 20.20% and 42.57% more than those of M2 and M3 respectively, and aboveground dry matter weight 10.27% and 43.38% higher than those of M2 and M3 respectively, which showed that seedlings transplanted using M1 were stronger. M1 achieved SPAD value 5.35% and 7.60% higher than those achieved using M2 and M3, respectively, and this significant difference indicated that the photosynthetic capacity of seedlings transplanted with M1 was stronger. The tillers at seedling stage (SS) are generally low position tillers formed by the first leaf and the second leaf, with higher earbearing tiller percentage, which can lay a foundation for the formation of high-yield population. M1 achieved tiller number 48.73% and 128.06% higher than those of M2 and M3, respectively.

In general, M1 achieved significantly better seedling quality than those achieved using M2 and M3, showing significant advantage in the early stage.

3.2 Root entwining force analysis

Root entwining force is an important index to evaluate the carpet forming of seedlings. It shall be strong enough to meet the requirement of machine transplanting, that is, the whole carpet seedlings shall not be scattered or broken during seedling lifting, seedling transportation, seedling removing from tray and seedling loading; otherwise it will affect the quality and efficiency of machine transplanting.

The root entwining force increased significantly in the order of M1, M2 and M3 (Figure 5), that was, in terms of carpet forming of seedlings achieved, the three methods could be ranked as follows: M1<M2<M3, which was consistent with the results of root number and root length of seedlings in Table 1. As for cultivar A1, M1 achieved a root entwining force of 61.24 N, which was 29.42% and 42.95% lower than that achieved using M2 and M3 respectively; as for A2, M1 achieved a root entwining force of 50.82 N, which was 24.69% and 47.58% lower than those achieved using M2 and M3 respectively. During the experiment, it was found that when the root entwining force of seedlings was higher than 40 N, the whole carpet seedlings would not broke during the operation. Although M1 had no advantage in root entwining force, it could still achieve a carpet forming meeting the requirement of machine transplanting. The greater the root entwining force of the seedlings, the more the roots entwined together. During machine transplanting, the seedling claws would divide the seedlings by blocks, which would cause serious mechanical injury to the roots. There was a recovery period after transplanting, which prolonged the growth period of rice.



Note: Different lowercase letters in the same column indicate significant differences between different treatments (p<0.05).

Figure 5 Effects of different machine transplanting methods on the root entwining force

3.3 Machine-transplanting quality analysis

Different machine transplanting methods had a significant effect on machine-transplanting quality (Table 2). In terms of planting depth, seedling missing rate, seedling floating rate, seedling injury rate, and seedling overturning rate, the three methods could be ranked as follows: M1<M2<M3. In terms of uniformity pass rate after transplanting and relative uniformity pass rate, the three methods could be ranked as follows: M1>M2>M3. According to the agronomic requirements of rice, shallow planting of rice is beneficial to early tillering. The planting depth using M2 and M3 were 15.52% and 22.78% deeper than that using M1. M1 achieved a seedling missing rate 2.22% and 4.45%, seedling floating rate 0.54% and 1.54%, and seedling injury rate 1.06% and 1.34%, and an average seedling overturning rate 2.78% and 5.56% lower than those of M2 and M3 respectively. The uniformity pass rate after transplanting and relative uniformity pass rate are important indicators to evaluate machine-transplanting quality. M1 achieved uniformity pass rate significantly higher than those of M2 and M3 by 6.32% and 12.53% on average, and a relative uniformity pass rate significantly higher than those of M2 and M3 by 1.69% and 3.33% on average.

Table 2 Effects of different machine transplanting methods on machine-transplanting quality

Treatment		Planting Depth /cm	Seedling missing Rate/%	Seedling floating Rate/%	Seedling injury Rate/%	Seedling overturning Rate/%	Uniformity pass rate after transplanting/%	Pass rate of relative uniformity/%
Cultivar	Method							
A1	M1	1.90^{c}	0^{b}	0.99^{b}	1.46^{b}	0^{b}	95.85^{a}	95.40^{a}
	M2	2.21^{b}	2.22^{ab}	1.52^{b}	2.53^{a}	3.33^{ab}	89.21^{b}	93.79^{b}
	M3	2.38^{a}	4.44^{a}	2.34^{a}	2.82^{a}	6.67^{a}	84.33^{c}	91.90^{c}
A2	M1	1.97^{b}	1.11^{b}	0.97^{c}	1.39^{b}	0^{b}	96.11^{a}	96.04^{a}
	M2	2.26^{a}	3.33^{ab}	1.51^{b}	2.43^{a}	2.22^{ab}	90.11^{b}	94.28^{b}
	M3	2.37^{a}	5.56^{a}	2.69^{a}	2.70^{a}	4.44^{a}	82.57^{c}	91.12^{c}

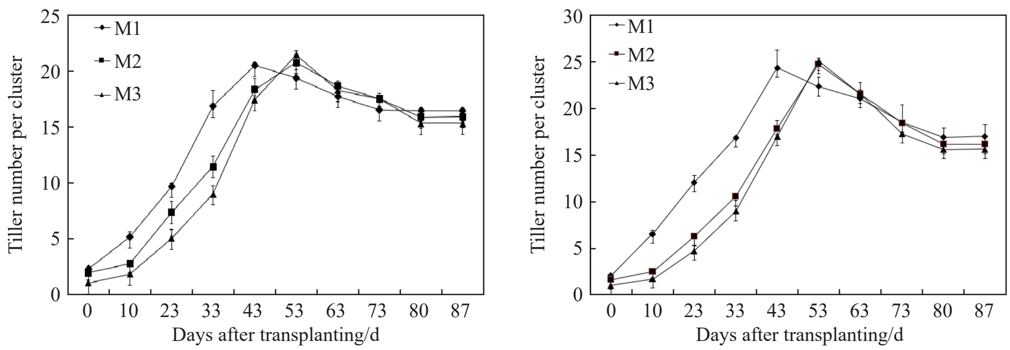
Note: Values are means of 3 replications. Different lowercase letters in the same column indicate significant differences between different treatments (p<0.05).

Considering all indicators comprehensively, M1 could ensure higher machine-transplanting quality, with better quality of seedling blocks and a relative higher uniformity pass rate of 95%.

3.4 Tillering dynamics analysis

Tillering is one of the inherent characteristics of rice and an important factor affecting the yield of machine-transplanted rice. The tillering dynamics of all treatments were roughly the same, i.e., after transplanting, the tillering curve went upward over time, and then downward after reaching peak seedling, and finally tended to be flat (Figure 6). Because the tiller number of each treatment was different at the time of transplanting, there was a great difference at the starting point of tillering curve. Within 10 d after transplanting, the tillering rate of seedlings transplanted with M1 was significantly higher than that of those transplanted with M2 and M3, however, M2 and M3 achieved faster tillering 10 d after transplanting, and exceeded that of M1 in MTS. The reason was that M2 and M3 seedlings were seriously injured during machine transplanting, and there was a recovery period after transplanting. The seedlings transplanted with M2 and M3 had less tillers within 10 d after transplanting. On the contrary, the seedlings transplanted using M1 were slightly injured during transplanting, the recovery period was shorter, and the seedlings entered the growth period and started tillering immediately after transplanting. The tiller number of seedlings transplanted with M1 reached the peak seedling 43 d after transplanting, and the same of those transplanted with M2 and M3 reached the peak seedling 53 d after transplanting.

To sum up, transplanting with M1 could achieve slighter planting injury, shorter recovery period, earlier tillering, with earlier peak seedling, more tillers in the low position, slower tiller decline in late stage, and reasonable tiller dynamic development of population, which was more conducive to the formation of effective tiller.



a. Tillering dynamics of A1 b. Tillering dynamics of A2

Note: Error bars indicate SD (n=3).

Figure 6 Effects of different machine transplanting methods on tillering dynamics

3.5 Earbearing tiller percentage analysis

The number of tiller and earbearing tiller percentage directly affect the number of effective panicles per unit area, and then affect the yield of rice. It could be seen from Table 3 that when the cultivar was A1, there was no significant difference between peak seedling number of rice plants transplanted with M1 and M2, which were significantly lower than M3; when the cultivar was A2, there was no significant difference between peak seedling number of rice plants transplanted with M1 and M2, while those transplanted with M1 had significantly lower seedling number than those transplanted with M3. Different transplanting methods had significant effects on effective tiller number and earbearing tiller percentage, which showed M1>M2>M3. The effective tiller number of those transplanted with M1 was significantly higher than the same of those transplanted with M2 and M3 by 4.49% and 8.20%, respectively, and the earbearing tiller percentage achieved by M1 was significantly higher than those of M2 and M3 by 4.15% and 8.27%, respectively.

To sum up, M1 had lower peak seedlings number than M2 and M3, but higher effective tiller number and earbearing tiller percentage. The reason for the lower earbearing tiller percentage of M2 and M3 was that after recovery period, the number of tillers experienced explosive growth, and most of them were tillers in the (medium) high positions, with large number of weak and underdeveloped tillers. After the peak seedling, the ineffective tillers died quickly, resulting in the decrease of earbearing tiller percentage.

Table 3 Effects of different machine transplanting methods on earbearing tiller percentage

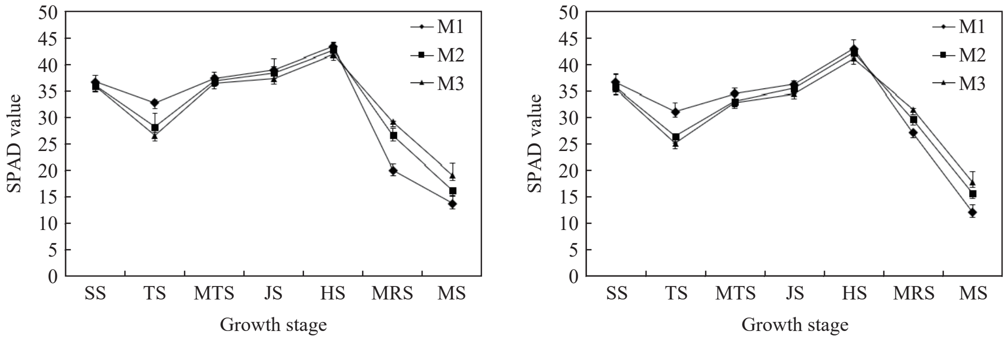
Treatment		Peak seedling number	Effective tiller number	Earbearing tiller percentage/%
Cultivar	Method			
A1	M1	20.53^b	16.50^a	80.36^a
	M2	20.80^b	15.93^b	76.60^b
	M3	21.50^a	15.33^c	71.32^c
A2	M1	24.33^b	17.00^a	69.87^a
	M2	24.69^{ab}	16.13^b	65.33^b
	M3	25.07^a	15.63^c	62.37^c

Note: Values are means of 3 replications. Different lowercase letters in the same column indicate significant differences between different treatments (p<0.05).

3.6 Chlorophyll content (SPAD Value) dynamics analysis

Leaf photosynthesis provides 90%-95% of the nutrients required for rice yield formation directly or indirectly[26]. Chlorophyll content (SPAD value) directly affects photosynthesis, thus affecting yield ultimately. The SPAD value of each treatment showed a consistent trend with the delay of growth period (Figure 7): it decreased from SS to TS, increased to the maximum value from TS to HS, then decreased rapidly, and reaches the minimum value at MS.

Before HS, the three methods could be ranked as M1>M2>M3 based on the SPAD value, and after HS, they were ranked as M1<M2<M3. The SPAD values of seedlings transplanted with M1, M2 and M3 decreased by 12.82%, 23.75%, and 27.43%, respectively from SS to TS. During this time, the SPAD value of seedlings transplanted with M1 were higher than those of M2 and M3, with smaller decrease, because M2 and M3 caused larger plant injury during transplanting, the recovery period was longer, making the stems and leaves turn yellow. A larger SPAD value at TS is conducive to recovery. Before HS, seedlings transplanted with M1 had higher SPAD value than those of M2 and M3, indicating that the photosynthetic capacity of flag leaf of seedlings transplanted with M1 was stronger, which provided sufficient material basis for grain filling at the later stage. After HS, lower SPAD value of seedlings transplanted with M1 than those transplanted with M2 and M3, with faster decline rate, indicated that more photosynthetic products in the stems and leaves of M1 were transported to the panicles and more efficiently; also, lower SPAD of seedlings transplanted with M1 at MS than that of those transplanted with M2 and M3, causing yellow stems and leaves indicated better grain maturity. Among them, the SPAD value of those transplanted with M1 at TS was 16.83% and 23.80% higher, the same value at HS was 1.69% and 4.08% higher, and that at MS was 23.69% and 42.69% lower than those of M2 and M3, respectively.



a. SPAD value dynamics of A1 b. SPAD value dynamics of A1

Note: SS, seedling stage; TS, transplanting stage; MTS, middle tillering stage; JS, jointing stage; HS, heading stage; MRS, milk ripe stage; MS, maturity stage. Error bars indicate SD (n=3).

Figure 7 Effects of different machine transplanting methods on SPAD value dynamics

3.7 Growth stage analysis

Different machine transplanting methods had a certain impact on the whole growth period of rice (Table 4). In 2019, the whole growth periods of A1 transplanted with M1, M2, and M3 were 112 d, 115 d, and 119 d respectively. The whole growth period of A2 was 1 d longer than that of A1. In general, when using M2 and M3, the two cultivars had whole growth period 3 d and 7 d respectively longer than that when M1 was adopted. Compared with M2 and M3, M1 achieved a shorter whole growth period because it ensured a shorter recovery period and earlier tillering after transplanting, resulting in the advance of HS and MS. Using M1, tillering began 2 d after transplanting, 3 d and 5 d earlier than that when using M2 and M3 respectively, that was, the recovery period of seedlings transplanted with M1, M2 and M3 were 2 d, 5 d and 7 d respectively. A1 experienced 44 d from TS to HS when M1 was used, 4 d and 7 d shorter than those when M2 and M3 were used respectively; A2 experienced 47 d from TS to HS when M1 was used, which was also 4 d and 7 d shorter than that when M2 and M3 were used. Different treatments had little effects on HS and subsequent growth stages: 11 d from HS to FHS and 10 d from FHS to FS; A1 experienced 22 d, 21 d and 22 d from FS to MS when M1, M2 and M3 were used respectively, and A2 experienced 20 d, 19 d and 20 d from FS to MS when M1, M2 and M3 were used respectively.

The "cold dew wind" in 2020 had a great impact on the whole growth period of each treatment. The whole growth periods of A1 were 114 d, 122 d and 126 d when M1, M2 and M3 were used respectively. The whole growth period of A2 was 2 d longer than that of A1. In general, the whole growth period of seedlings transplanted with M2 and M3 were 8 and 12 d longer than those transplanted with M1, respectively, and the two cultivars showed the same performance. There were two reasons: firstly, the recovery period of seedlings transplanted with M2 and M3 was longer after transplanting, and the tillering occurred later, thus prolonging the time from TS to HS; secondly, the HS were later when M2 and M3 were used, making the plants suffer the "cold dew wind" at the beginning of heading, thus prolonging the time from HS to FHS. The time from TS to ITS and TS to HS were consistent with those in 2019. When M1 was used, the period between HS and FHS of plants was 12 d, an increase of 1 day compared with 2019; when

M2 and M3 were used, the periods between HS and FHS of the plant were all 17 d, an increase of 6 d compared with 2019, and 5 d longer than that of plants transplanted with M1. Different treatments had little effect on FHS and subsequent growth stages: both A1 and A2 experienced 10 d from FHS to FS; A1 experienced 23 d, 22 d and 23 d respectively from FS to MS under the treatments of M1, M2 and M3, an increase of 1 d compared with 2019; A2 experienced 22 d, 21 d and 22 d respectively from FS to MS under the treatment of M1, M2 and M3, an increase of 2 d compared with 2019.

Table 4 Effects of different machine transplanting methods on the main growth stages of rice

Year	Treatment		Date of each growth stage							
	Cultivar	Method	SD	TS	ITS	BS	HS	FHS	FS	MS
2019	A1	M1	07-01	07-26	07-28	08-26	09-08	09-19	09-29	10-21
		M2	07-01	07-26	07-31	08-29	09-12	09-23	10-03	10-24
		M3	07-01	07-26	08-02	09-01	09-15	09-26	10-06	10-28
	A2	M1	07-01	07-26	07-28	08-28	09-11	09-22	10-02	10-22
		M2	07-01	07-26	07-31	09-01	09-15	09-26	10-06	10-25
		M3	07-01	07-26	08-02	09-04	09-18	09-29	10-09	10-29
2020	A1	M1	07-04	07-29	07-31	08-29	09-11	09-23	10-03	10-26
		M2	07-04	07-29	08-03	09-01	09-15	10-02	10-12	11-03
		M3	07-04	07-29	08-05	09-04	09-18	10-05	10-15	11-07
	A2	M1	07-04	07-29	07-31	08-31	09-14	09-26	10-06	10-28
		M2	07-04	07-29	08-03	09-03	09-18	10-05	10-15	11-05
		M3	07-04	07-29	08-05	09-07	09-21	10-08	10-18	11-09

Note: SD, sowing date; TS, transplanting stage; ITS, initial tillering stage; BS, booting stage; HS, heading stage; FHS, full heading stage; FS, filling stage; MS, maturity stage.

Due to the influence of "cold dew wind" in 2020, the whole growth period of each treatment was relatively long. Under the treatments of M1, M2 and M3, the whole growth periods of A1 were 2 d, 7 d, and 7 d longer than those in 2019 respectively, and those of A2 were 3 d, 8 d, and 8 d longer than those in 2019.

In conclusion, the shortening of the whole growth period under the treatment of M1 was due to the shortening of the recovery period by 3 d and 5 d after transplanting compared with M2 and M3, making earlier tillering, which in turn shortened the time from TS to HS, effectively reduced the risk and impact of "cold dew wind" on late rice, thus providing favorable conditions for safe full heading of late rice, and ensuring high and stable yield of rice.

3.8 Yield and its components analysis

The panicle length, effective panicle number, grain number per panicle, seed-setting rate and 1000-grain weight are the key components to ensure high yield of rice. As listed in Table 5, the effects of different machine transplanting methods on the yield and its components of late rice were significant. In terms of the yield and its components achieved in the use of M1, M2, and M3, the three methods could be ranked in the following sequence M1>M2>M3, and in terms of moisture content of wet grain, they could be ranked as follows M1<M2<M3.

Table 5 Effects of different machine transplanting methods on yield and its components of rice

Year	Treatment		Panicle length/cm	Effective panicle number/×10^{4}·hm^{-2}	Grain number per hpanicle	Seed-setting rate/%	1000-grain weight/g	Moisture content of wet valley/%	Yield/kg·hm^{-2}	
	Cultivar	Method							Theoretical	Actual
2019	A1	M1	21.92^{a}	396.83^{a}	113.65^{a}	81.36^{a}	23.13^{a}	22.10^{c}	8579.85^{a}	8331.40^{a}
		M2	20.78^{b}	368.26^{b}	112.85^{b}	80.28^{b}	22.78^{b}	24.50^{b}	7599.46^{b}	7684.20^{b}
		M3	20.65^{b}	357.15^{b}	112.02^{c}	78.83^{c}	22.12^{c}	25.70^{a}	6975.35^{c}	6685.00^{c}
	A2	M1	19.63^{a}	408.74^{a}	163.90^{a}	85.10^{a}	17.94^{a}	27.43^{c}	10229.38^{a}	10026.15^{a}
		M2	18.69^{b}	380.17^{b}	162.73^{b}	84.06^{b}	17.28^{b}	28.63^{b}	8983.89^{b}	8936.80^{b}
		M3	17.70^{c}	368.26^{b}	161.91^{c}	82.74^{c}	16.82^{c}	30.33^{a}	8297.55^{c}	7984.65^{c}
2020	A1	M1	21.57^{a}	392.87^{a}	107.12^{a}	65.12^{a}	22.52^{a}	28.67^{c}	6169.25^{a}	6184.10^{a}
		M2	20.38^{b}	379.37^{b}	105.52^{ab}	62.86^{b}	22.15^{b}	30.73^{b}	5573.60^{b}	5664.05^{b}
		M3	19.99^{b}	365.09^{c}	102.55^{b}	61.41^{b}	21.92^{b}	32.70^{a}	5040.58^{c}	5188.20^{c}
	A2	M1	17.76^{a}	404.77^{a}	143.43^{a}	54.71^{a}	17.80^{a}	32.07^{c}	5653.42^{a}	5329.77^{a}
		M2	17.02^{b}	384.13^{b}	141.39^{b}	52.18^{b}	17.19^{b}	33.60^{b}	4873.30^{b}	4715.60^{b}
		M3	16.70^{b}	372.23^{c}	140.84^{c}	50.86^{c}	16.71^{c}	34.33^{a}	4455.80^{c}	4363.40^{c}

Note: Values are means of 3 replications. Different lowercase letters in the same column indicate significant differences between different treatments ($p<0.05$).

In 2019, A1 had an actual yield of 8331.40 kg/hm^{2} when M1 was used, which was significantly higher than those achieved using M2 and M3, with an increase of 8.42% and 24.63% respectively; A2 had an actual yield of 10 026.15 kg/hm^{2} when M1 was used, which was significantly higher than those achieved using M2 and M3, with an increase of 12.19% and 25.57% respectively. The panicle length achieved using M1 was 5.24% and 8.50% longer than those achieved using M2 and M3, with effective panicle number 7.64% and 9.25%, grain number per panicle 0.71% and 13.40%, seed-setting rate 1.06% and 2.45%, and the 1000-grain weight 2.68% and 5.61% higher than those achieved using M2 and M3. The moisture content of wet grain indicated the maturity of rice grain, and that achieved using M1 was 1.80% and 3.25% lower than those achieved using M2 and M3, respectively. The difference was significant, indicating that M1 achieved a better maturity. It could be seen from the above data that M1 had significant yield increase advantages, achieving "larger panicles, more panicles, more and fuller grains".

Affected by the "cold dew wind" in 2020, compared with 2019, the average yield of A1 decreased by 24.82%, and the average yield of A2 decreased by 46.48%. Heading and flowering of rice generally take place simultaneously, and the "cold dew wind" encountered at HS will affect the flowering and pollination of rice, which in turn affects grain filling. The seed-setting rate and grain number per panicle of each treatment in 2020 were significantly lower than those in 2019, which was the main reason for the yield reduction. Compared with 2019, the panicle length and 1000-grain weight decreased slightly, the moisture content of wet grain was significantly higher than that of 2019, and grain was less mature. Despite the "cold dew wind" in 2020, the yield, panicle length, effective panicle number, grain number per panicle, seed-setting rate and 1000-grain weight of rice plants transplanted with M1 were significantly higher than those when M2 and M3 were used. Using M1, the actual yield of A1 was significantly higher than those achieved using M2 and M3 by 9.18% and 19.20%, and the same of A2 was significantly higher than those achieved using M2 and M3 by 13.02% and 22.15%, respectively. M1 achieved significant yield increase thanks to higher effective panicle number, which increased the sink capacity of rice grains, and could make up for the reduction in yield caused by the sharp decline in the grains number per panicle and seed- setting rate caused by the "cold dew wind" to a certain extent.

3.9 Economic benefits analysis

The transplanting operation costs of all treatments in two years were the same, as were the other costs (Table 6). The costs of each treatment in 2019 were the same as those in 2020. According to their seedling raising costs mainly composed of seedling tray cost, substrate cost, seed cost and seedling raising labor cost, the three methods could be ranked in the following sequence: M1> M3>M2. Each seedling tray of M1, M2 and M3 could accommodate 420, 648 and 648 cluster, respectively. Therefore, higher number of trays per unit area were required in M1 than those in M2 and M3 and this was the main reason for the higher seedling raising cost of M1. The cost of seedling tray was affected by the price of seedling tray and the number of trays used per unit area, and in terms of the seedling tray cost, the three methods could be ranked as follows: M1>M3>M2. The substrate cost, seed cost and seedling labor cost trends were consistent with the number of trays used per unit area, thus, the three methods could be ranked as follows: M1>M2=M3. The herbicide costs of M2 and M3 were the same, which were twice that of M1. After transplanting, M1 achieved a shorter recovery period and faster growth rate of the plants, which could effectively inhibit the growth of weeds. Compared with M2 and M3, M1 could save herbicide spraying once during the whole growth period, reducing the pollution of pesticide to the rice field, was and thus ensuring sustainability.

Table 6 Effects of different machine transplanting methods on the economic benefits

Year	Treatment		Seedling tray cost	Substrate cost	Seed cost	Seedling raising labor cost	Transplanting operation cost	Herbicide cost	Other costs	Rice income	Economic benefit
	Cultivar	method									
2019	A1	M1	215.4	1576.0	1700.7	181.4	1500	300	9000	25 910.7	11 437.5
		M2	139.6	1021.5	1653.5	117.6	1500	600	9000	23 897.9	9866.2
		M3	183.7	1021.5	1653.5	117.6	1500	600	9000	20 790.4	6714.1
	A2	M1	215.4	1576.0	255.1	181.4	1500	300	9000	28 073.2	15 045.3
		M2	139.6	1021.5	249.9	117.6	1500	600	9000	25 023.0	12 394.9
		M3	183.7	102 1.5	249.9	117.6	1500	600	9000	22 357.0	9684.3
2020	A1	M1	215.4	1576.0	1700.7	181.4	1500	300	9000	19 232.6	4759.1
		M2	139.6	1021.5	1653.5	117.6	1500	600	9000	17 615.2	3583.5
		M3	183.7	1021.5	1653.5	117.6	1500	600	9000	16 135.3	2059.0
	A2	M1	215.4	1576.0	255.1	181.4	1500	300	9000	14 923.4	1895.5
		M2	139.6	1021.5	249.9	117.6	1500	600	9000	13 203.7	575.6
		M3	183.7	1021.5	249.9	117.6	1500	600	9000	12 217.5	−455.2

Note: Other costs include fertilizer, leasing, irrigation, management, etc., excluding equipment cost. The above parameters are calculated with reference to the current market price in the production quarter. Unit is CNY/hm^2.

The economic benefit was the result of subtracting total cost expenditure from rice income. The performance of rice income was consistent with the trend of yield. The three methods could be ranked as follows regarding total cost expenditure: M1>M3>M2, with small difference between M2 and M3. The higher total cost expenditure of M1 was mainly caused by the higher seedling raising cost. M1 had the highest economic benefits in both 2019 and 2020, followed by M2 and M3. In 2019, A1 using M1 achieved income increase by 15.92% and 70.35% compared with those achieved using M2 and M3 respectively, and A2 using A1 achieved income increase by 21.38% and 55.36% compared with those achieved using M2 and M3 respectively. In 2020, A1 using M1 achieved an income increase by 32.80% and 132.12% compared with M2 and M3 respectively, and A2 using M1 achieved an income increase by 229.31% and 516.42% compared with M2 and M3 respectively. Due to the "cold dew wind" in 2020, the yield had been reduced to varying degrees, and the income using M3 rice was the least, or even negative. The above results showed that M1 had better economic benefits and broader popularization prospects

4 Discussion

4.1 Effects of different machine transplanting methods on seedling quality of late rice

Seedling quality has a very important influence on the growth period and yield of rice in the field, and improving seedling quality can ensure high yield of rice[5,25]. Previous studies on different machine transplanting methods mainly focused on the effects of conventional pot carpet seedling machine transplanting and ordinary carpet seedling machine transplanting. Compared with ordinary carpet seedlings, pot carpet seedlings had a smaller planting density and relatively uniform and larger growth space, which was conducive to the cultivation of high-quality seedlings[27,28]. For the seedling carpets with pots below grown in pot carpet seedling raising tray, the machine transplanter could precisely transplant the seedlings by pot, ensuring lower seedling injury rate and seedling missing rate compared with ordinary carpet seedlings, thereby improving the machine-transplanting quality[6]. Due to the large amount of sowing, tillers of ordinary carpet seedlings generally did not occur at SS, and pot carpet seedlings had tillers at SS, mostly in the low positions[29].

The conclusion of this study was consistent with previous studies. Compared with M2, M3, M1 could achieve a plant height suitable for machine transplanting, with seedling quality indexes significantly better than M2 and M3. M1 could also achieve stronger stems and more robust root systems, making seedlings more adaptable for machine transplanting. Moreover, using M1, there were more tillers at SS, easily giving play to significant advantages in the early stage. The large-pot carpet seedling raising tray had significant advantages in the pot volume, which was 3.18, 3.59, 4.05, and 5.29 times that of the conventional pot carpet seedling raising tray with 14, 16, 18, and 20 horizontal pots[30]. Therefore, it could be concluded that M1 achieved higher seedling quality due to the lower sowing amount, smaller seedling density, growth in separate pot (reducing inter-seedling competition), larger soil pot and more sufficient nutrition, which laid a foundation for cultivating strong seedlings for machine transplantation. The pot volume of M1 was larger than that of M2, while M3 did not have a pot, so the seedlings of M1 would have more roots growing in the pots. Moreover, the seedling claws of the rice transplanter could accurately take and transplant seedlings by pot, only tearing a small amount of roots in the upper carpet, thereby reducing the injury to the seedlings. M1 had root length and root number significantly lower than those in M2 and M3, so the root entwining force was significantly lower than those of plants transplanted with M2 and M3, yet the carpet forming meet the requirement of machine transplanting. The whole seedling carpet was not broken, and without seedling scattered during seedling lifting, seedling transportation, removal from tray and seedling loading, thus ensuring the quality and efficiency of machine transplanting. During transplanting, M1 could effectively reduce the seedling missing rate, seedling floating rate, seedling injury rate and seedling overturning rate, realize shallow planting, with relative uniformity pass rate of more than 95%, thus achieving better machine-transplanting quality.

4.2 Effects of different machine transplanting methods on physiological characteristics, yield and its components of late rice population

When ordinary carpet seedlings was machine transplanted, the claws of machine transplanter would injure the seedlings root system, resulting in stagnation of the growth of the seedlings for 5-7 d after machine transplanting[14]. The low quality of rice seedlings slowed down seedling revival after machine transplanting, thus causing late tillering, low effective panicle number, delayed FHS, prolonged growth stage, and lower yield[16,31,32].The results of this study showed that M1 achieved higher seedlings quality, and during machine transplanting, the claws of machine transplanter could accurately pick the seedlings by pot, causing less injury to the root system, thus ensuring earlier growth and faster development after machine transplanting. Therefore, the ITS was 3 d and 5 d earlier than those when M2 and M3 were used respectively. To ensure high yield or super-high yield of rice and high number of panicles, reasonable tillering dynamics are required to address the contradiction between large panicle and high panicle, increase grain number per panicle, and ensure normal seed-setting rate and 1000-grain weight[33,34]. Compared with ordinary carpet seedling machine transplanting, pot seedling machine transplanting achieved a shorter period of seedling recovery, earlier growth and faster development, relatively low peak seedling number, but higher earbearing tiller percentage, which was more conducive to achieving better coordination between full panicles and large panicles with lower population starting point[14,27]. In this study, the seedlings transplanted with M1 had less planting injury, shorter recovery period and earlier and quicker tillering in the early stage, with earlier peak seedling, more tillers in the low positions, and slower tiller decline in later stage, presenting the law that the peak seedling number was not high but the effective tiller number and earbearing tiller percentage were significantly higher than those achieved using M2 and M3. The upper leaves with more chlorophyll content (SPAD value) had stronger photosynthesis ability[35], thereby increasing the photosynthesis rate, promoting the production and accumulation of dry matter, thus facilitating the transfer of nutrients from stems and leaves to grains[36]. The results of this study showed that before HS, the three methods could be ranked as follows according to SPAD value: M1>M2>M3, indicating that the M1 achieved stronger photosynthetic ability of flag leaves, thus providing sufficient material basis for grain filling in the late stage.

Compared with ordinary carpet seedling machine transplanting, pot seedling machine transplanting showed obvious advantages in yield increasing, with higher 1000-grain weight, fuller grains; the yield forming advantages were mainly " sufficient panicle number, large panicles and more grains" [14,37,38]. This study found that M1 achieved panicle length, effective panicle number, grain number per panicle, seed-setting rate, 1000-grain weight and yield significantly higher than those achieved using M2 and M3, with obvious yield increase advantages and better maturity. In 2019, M1 achieved actual yield increase by 10.31% and 25.10% respectively compared with M2 and M3, and in 2020, it achieved increase by 11.10% and 20.67% respectively. Effective panicle number contributed the most to the yield. To increase the yield of double cropping rice, attention should be paid to the effective panicle number, and a certain seed-setting rate and 1000-grain weight should be guaranteed, and the requirement on grain number per panicle could be appropriately relaxed[5]. The results of this study showed that in 2020, the grain number per panicle and seed-setting rate of late rice decreased significantly due to the "cold dew wind", but M1 achieved a higher effective panicle number compared with M2 and M3, which increased the sink capacity of rice grains, and could make up for the yield reduction caused by the significant decline of the grain number per panicle and seed-setting rate to a certain extent.

The pot seedling machine transplanting made the whole growth period 4-6 d earlier than that of seedlings using ordinary carpet seedling machine transplanting, because the HS and MS were advanced, which provided conditions for the safe full heading of rice[37,39]. The "cold dew wind" in Jiangxi Province mainly occurs in the middle and late September. The extension of the growth period of late rice can increase the probability of suffering from the "cold dew wind"[23,24]. This experiment showed that using M1, the whole growth period of the rice plant was 3 d and 7 d earlier than those transplanted with M2 and M3 respectively in 2019. In 2020, affected by the "cold dew wind", the whole growth period of each treatment was prolonged, but M1 still achieved whole growth period of 8 d and 12 d earlier than those of M2 and M3, and the reason lied in that the recovery period was shortened by 3 and 5 d, leading to earlier tillering, thus shortening the time from TS to HS, and this effectively reduced the risk and impact of "cold dew wind" on late rice, provided favorable conditions for full heading of late rice, and ensured high and stable yield of rice.

4.3 Effects of different machine transplanting methods on economic benefits of late rice

Compared with ordinary carpet seedling transplanting, pot seedling machine transplanting had higher seedling raising cost, but higher rice income and economic benefit[40,41]. This was consistent with the conclusion of this study. M1 achieved higher rice income, but with higher seedling raising cost compared with M2 and M3. The seedling raising cost included seedling tray cost, substrate cost, seed cost and seedling raising labor cost. The increase in the seedling raising cost of M1 was caused by the higher pot volume of large-pot carpet seedling raising tray, smaller number of pots per tray, which in turn increased the number of trays used for transplanting per unit area, thus increasing seedling tray cost, substrate cost, and seedling raising labor cost; although M1 had a lower sowing amount per tray, it used more trays per unit area for transplanting, which offset the advantage of lower seed cost per tray and increased the seed cost. After the seedlings were transplanted using M1, the recovery period was shorter and the growth rate was faster, which could effectively inhibit the growth of weeds. The herbicide spraying was reduced once in the whole growth period, and the cost of pesticides was reduced. The performance of rice income was consistent with the trend of yield. After subtracting the total cost, the economic benefit of M1 was significantly higher than those of M2 and M3. M1 achieved average income increase 18.65% and 62.85% higher than those of M2 and M3 in 2019, and 131.06%, 323.78% in 2020 respectively.

5 Conclusions

Based on the above analysis and discussion, the preliminary conclusions could be drawn as follows:

1) Compared with M2 and M3, M1 achieved higher seedling quality, with root entwining force met the requirement of machine transplanting; M1 achieved higher machine-transplanting quality, shorter recovery period, with earlier seedling growing and faster development; the peak seedling number was not high, but the effective tiller number and earbearing tiller percentage were higher, and the SPAD value was reasonably distributed in each growth stage.

2) Compared with M2 and M3, M1 shortened the recovery period by 3 d and 5 d, advanced the HS and MS, which effectively reduced the risk and impact of “cold dew wind” on late rice.

3) M1 had obvious yield increasing advantages and better maturity. In 2019 and 2020, the average yield achieved by M1 was 10.31%-11.10% and 20.67%-25.10% higher than those of M2 and M3 respectively. It achieved “larger panicles, more panicles, more and fuller grains”.

4) The economic benefit of M1 was significant. In both 2019 and 2020, M2 achieved average income increase 18.65%131.06% and 62.85%-323.78% higher than those of M2 and M3 respectively.

Therefore, vigorously developing large-pot carpet seedling transplanting is the key to high-yield and high-efficiency cultivation of late rice. The conclusions of this study are applicable to machine-transplanted large-pot carpet seedling of late rice. There are differences between late rice and early rice. The next step is to conduct a study on the applicability of large-bowl carpet seedling to machine-transplanted early rice.

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[References]

[1] Hu Q, Jiang W Q, Qiu S, Xing Z P, Hu Y J, Guo B W, et al. Effect of wide-narrow row arrangement in mechanical pot-seedling transplanting and plant density on yield formation and grain quality of japonica rice. Journal of Integrative Agriculture, 2020; 19(5): 1197–1214.

[2] Rashid M H, Goswami P C, Md Hossain F, Mahalder D, Rony M K I, Shirazy B J, et al. Mechanised non-puddled transplanting of boro rice following mustard conserves resources and enhances productivity. Field Crops Research, 2018; 225: 83–91.

[3] Li Y X, Liu Y, Wang Y H, Ding Y F, Wang S H, Liu Z H, et al. Effects of seedling age on the growth stage and yield formation of hydroponically grown long-mat rice seedlings. Journal of Integrative Agriculture, 2020; 19(7): 1755–1767.

[4] Zhong G H, Yao J H. Analysis of the response of farmers’ double cropping late rice planting area to the change of rice price-based on the nerlove model of the provincial panel. Prices Monthly, 2021; 7: 61–66. (in Chinese)

[5] Ye C, Li Y D, Cao Z S, Huang J B, Sun B F, Shu S F, et al. Effects of different seedling raising trays on plant type and grain yield of machine-transplanted double cropping rice. Chinese Journal of Rice Science, 2020; 34(5): 435–442. (in Chinese)

[6] Shi H Z, Zhu D F, Zhang Y P, Xiang J, Zhang Y K, Zhu C H, et al. Effects of biodegradable seedling tray and sowing rate on seedling quality and yield of mechanical transplanting rice. Transactions of the CSAE, 2017; 33(24): 27–34. (in Chinese)

[7] Zhang H, Yu C, Chen K W, Kong X S, Liu H L, Chen J Y, et al. Effect of direct-seeding methods on physiological characteristics and grain yield of rice and its cost analysis. Transactions of the CSAE, 2017; 33(13): 58–64. (in Chinese)

[8] Yu G H, Wang L, Sun L, Zhao X, Ye B L. Advancement of mechanized transplanting technology and equipment for field crops. Transactions of the CSAM, 2022; 53(9): 1–20. (in Chinese)

[9] Li Z H, Ma X, Li X H, Chen L T, Li H W, Yuan Z C. Research progress of rice transplanting mechanization. Transactions of the CSAM, 2018; 49(5): 1–20. (in Chinese)

[10] Zhang J H, Lin Y J, Huang J, Bai Z G, Sajid H, Zhu L F, et al. Effects of substrate types and uniconazole on mechanized transplanting qualities and grain yield for late rice with different seedling ages. Transactions of the CSAE, 2018; 34(1): 44–52. (in Chinese)

[11] Xing Z P, Wu P, Zhu M, Qian H J, Cao W W, Hu Y J, et al. Effect of mechanized planting methods on plant type and lodging resistance of different rice varieties. Transactions of the CSAE, 2017; 33(1): 52–62. (in Chinese)

[12] Hu Q, Jing W Q, Qiu S, Xing Z P, Hu Y J, Guo B W, et al. Effect of wide-narrow row arrangement in mechanical pot-seedling transplanting and plant density on yield formation and grain quality of japonica rice. Journal of Integrative Agriculture, 2020; 19(5): 1197–1214.

[13] Jia X, Song J N, Wang J C, Cao X L, Liu C L, Wan L P C, et al. Effects of seedling age and substrate soil ratio on the population quality and yield of late rice of machine-transplanted large-pot carpet seedlings. Transactions of the CSAE, 2022; 38(12): 1–11. (in Chinese)

[14] Lv T F, Shen J, Ma P, Dai Z, Yang Z Y, Xu H, et al. Effects of combined application of slow release nitrogen fertilizer and urea on the nitrogen utilization characteristics in machine-transplanted hybrid rice. Scientia Agricultura Sinica, 2021; 54(7): 1410–1423. (in Chinese)

[15] Song J N. Popularizing the technology of transplanting rice by machine suitable for China. Contemporary Farm Machinery, 2018; 5: 24–25. (in Chinese)

[16] Guan Z C. Effects of different density and nitrogen application rate on nitrogen utilization efficiency and yield formation of bowl mechanical-transplanting rice. Master dissertation. Guiyang: Guizhou University, 2020; 101p. (in Chinese)

[17] Cai J P, Xiao L P, Liu M H, Ye Y Y, Li T B, Chen X F. Development status and prospect of rice mechanization transplanting technology. Journal of Agricultural Mechanization Research, 2018; 40(10): 6–10. (in Chinese).

[18] Chen H Z, Zhu D F, Xu Y C. Mechanized planting technology of rice bowl-shaped blanket seedling and application effect. China Rice, 2009; 3: 5–7. (in Chinese)

[19] Jia X, Yang Q R, Wen X X, Wang J C, Chen Y, Wu A W, Song J N.

Research and application of mechanized seedling raising and transplanting technology of large-bowl blanket seeding of rice. China Rice, 2022; 28(1): 18–22. (in Chinese)

[20] Song J N. China Agricultural University has successfully developed a new technology of rice seedling raising and transplanting. China Agricultural Mechanization Herald, 2020; [2020-04-06]. (in Chinese)

[21] Department of Science, Technology and Education, Ministry of Agriculture and Rural Affairs. Notice on carrying out the major leading technologies integration demonstration work of the Ministry of Agriculture and Rural Affairs in 2021. http://www.moa.gov.cn/govpublic/KJJYS/202108/t20210826_6374933.htm. Accessed on [2021-12-15]. (in Chinese)

[22] GB/T6243-2017. Rice transplanter test method. Beijing: China Standards Press, 2017. (in Chinese)

[23] Liu D, Guo R G, Yang J, Cai Z. Spatial-temporal variation characteristics of antumn low temperature and its response to climate change in Jiangxi province. Acta Agriculturae Jiangxi, 2019; 31(10): 102–108. (in Chinese)

[24] Zhao S S. Cause analysis and countermeasures of “cold dew wind” harm to late rice production. Anhui Agricultural Science Bulletin, 2021; 27(17): 52–53. (in Chinese)

[25] Lin Y J, Zhang J H, Hu J J, Zhu L F, Cao X C, Yu S M, Jin Q Y. Effects of different seedling substrates on physiological characters and grain yield of mechanized-transplanted rice. Transactions of the CSAE, 2016; 32(8): 18–26. (in Chinese)

[26] Zhao Li M, Li M, Zheng D F, Gu C M, Na Y G, Xie B S. Analysis of the factors and their effect on the photosynthesis of rice. Northern Rice, 2014; 44(5): 66–71. (in Chinese)

[27] Hu Y J, Xing Z P, Gong J L, Liu G T, Zhang H C, Huo Z Y, et al. Study on population characteristics and formation mechanisms for high yield of pot-seedling mechanical transplanting rice. Scientia Agricultura Sinica, 2014; 47(5): 865–879. (in Chinese)

[28] Zhang H C, Gong J L. Research status and development discussion on high-yielding agronomy of mechanized planting rice in China. Scientia Agricultura Sinica, 2014; 47(7): 1273–1289. (in Chinese)

[29] Song Y S, Zhang H C, Dai Q G, Yang D L, Guo B W, Zhu C C, et al. Effect of rice potted-seedlings per hole by mechanical transplanting on tillers emergence, panicles formation and yield. Transactions of the CSAE, 2014; 30(10): 37–47. (in Chinese)

[30] Jia X. Experiment on mechanized cultivation and transplanting technology of large-pot carpet seedling of rice and improved design of machine tools. Beijing: China Agricultural University, 2021. (in Chinese)

[31] Yu L H, Ding Y F, Xue Y F, Ling Q H, Yuan Z H. Factors affecting rice seedling quality of mechanical transplanting rice. Transactions of the CSAE, 2006; 22(3): 73–78. (in Chinese)

[32] Zhang Z J, Wang J, Lang Y Z, Yu L H, Xue Y F, Zhu Q S. Growing characteristics of rice seedlings of over-optimum age for mechanical transplanting. Acta Agronomica Sinica, 2008; 24(2): 297–304. (in Chinese)

[33] Ling Q H, Zhang H C, Cai J Z, Cu Z F, Ling L. Investigation on the population quality high yield and its optimizing control programme in rice. Scientia Agricultura Sinica, 1993; 6: 1–11. (in Chinese)

[34] Li J, Zhang H C, Qian Y F, Guo Z H, Chen Y, Dai Q G, et al. Growth characteristics of two super-high-yielding japonica hybrid rice combinations. Chinese Journal of Rice Science, 2009; 23(2): 179–185. (in Chinese)

[35] Zhang D L. Study on association maooing of grain number and 1000-kernals weights and affection of canopy temperature/chlorophyll content on yield of wheat. Beijing: Chinese Academy of Agricultural Sciences, 2014. (in Chinese)

[36] Li J P, Liu H J, Huang Z W, Liu X Y, You J, Xu Z G. Effects of spectral distribution on photosynthetic and chlorophyll fluorescence characteristics of flag leaves at grain filling stage in rice. Scientia Agricultura Sinica, 2019; 52(16): 2768–2775. (in Chinese)

[37] Mi C S, Lu H K, Hong G B, Mao X Q, Huang B G, Liu W D. Difference of yield formation and growth trait between mechanized transplanting by rice pot-mat seedling and rice carpet seedling. Northern Rice, 2014; 44(4): 44–47. (in Chinese)

[38] Zhou Y, Ren H J, Che Y B. Population dynamics and yield components of pot-seedling mechanical transplanting rice. China Rice, 2018; 24(4): 81–83. (in Chinese)

[39] Wang J H. Effects of Different Cultivation Methods on Growth Period and Yield of Rice. Modern Agricultural Science and Technology, 2020; 5: 1–2. (in Chinese)

[40] Zhou B. Effects of different cultivation modes on yield and economic benefits of double cropping late rice. Modern Agricultural Science and Technology, 2020; 9: 12–14. (in Chinese)

[41] Chen X F, Peng W Q, Li S. Economic benefit analysis of large-pot carpet seedling transplanting with single season machine. Agricultural Machinery Science and Technology Promotion, 2020; 5: 52–54. (in Chinese)