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Comparative Study on Yield and Quality Adaptability of *Japonica* Rice Varieties under Various Transplanting Methods

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Abstract This study mainly discussed the yield and quality performance of *japonica* rice under different transplanting methods, compared several common cultivation methods, such as mechanical pot seedling transplanting, blanket seedling transplanting, mechanical direct seeding and manual transplanting, to see their effects on the growth, yield structure and quality of rice, analyzed which method is more stable, and also studied how *japonica* rice varieties respond under different planting conditions. Such as the changes in some agronomic traits and the patterns of quality formation, special attention was also paid to the interaction between varieties and the environment to see how much of a role this interaction plays when choosing transplanting methods. This study hopes to provide some ideas for the cultivation methods of high-yield and high-quality *japonica* rice in the future, and also offer references for promoting appropriate cultivation methods in different regions.
Keywords *Japonica* rice; Transplanting methods; Varietal adaptability; Yield and quality; Genotype × Environment interaction

1 Introduction

Japonica rice (*Oryza sativa* L. ssp. *japonica*) is a very important food crop in the world. It plays a particularly important role in ensuring that people have enough to eat. Because it has a good taste and is relatively disease-resistant and stress-resistant, in countries like China, Japan and South Korea, the most widely grown type is *japonica* rice. Nowadays, with the increasing population and unstable climate, people are paying more and more attention to how to increase the yield and quality of *japonica* rice and make it more adaptable to the environment (Chen et al., 2025a; Zhang et al., 2025).

There are many ways to grow rice, such as manual transplanting, mechanical transplanting, direct seeding, carpet seedling transplanting and pot seedling transplanting, etc. In recent years, mechanical transplanting and mixed sowing techniques have been increasingly used. They are more labor-saving and can also improve the quality of seedlings (Deng et al., 2023). Different planting methods have a significant impact on the growth, yield and quality of rice. Mechanical transplanting can shorten the growth period of rice and better utilize light and heat, while mixed sowing is conducive to stronger seedling growth and easier survival after planting (Gao et al., 2023; Zhang et al., 2025).

"Adaptability" refers to whether a type of rice can perform well in different environments, such as whether the yield is stable and the quality remains unchanged. If a variety can not only achieve high yield but also withstand cold, heat, pests and diseases, then its adaptability is very strong (Farooq et al., 2021; Chen et al., 2025a; Wang et al., 2025). The performance of a variety is not only influenced by its own genes, but also closely related to where and how it is grown. This interaction of "variety × environment × management", that is, G×E, is the key to determining adaptability. Understanding adaptability is helpful for breeding and selection of planting areas.

This study compared the yield and quality changes of *japonica* rice varieties under different transplanting methods and explored how varieties and planting methods influence each other. This study aims to provide a theoretical basis and practical reference for high-yield and high-quality planting plans and variety breeding of *japonica* rice.

2 Agronomic Traits of *Japonica* Rice Varieties

2.1 Morphological and physiological features relevant to transplanting

The agronomic traits of *japonica* rice, such as plant height, tiller number, effective panicles, panicle grains, leaf area size, and root development, will directly affect its adaptability to different transplanting methods. Studies have found that applying more nitrogen fertilizer appropriately and increasing planting density can boost the number of effective panicles and grains per panicle. However, if too much is used, it may instead affect the output (Ren et al., 2024). In addition, whether the root system grows well or not, such as the number of roots, how deep they grow, and how vigorous they are, will also affect the ability to absorb water and nutrients. These will in turn affect the growth and yield after transplanting (Chu et al., 2019; Zhu et al., 2020). In adverse environments such as saline-alkali land or drought, some *japonica* rice varieties show good resistance, such as delayed heading time, shorter plants, shorter panicles, and reduced effective panicles and seed setting rate (Ahmad et al., 2021).

2.2 Genetic diversity and responsiveness to cultivation environments

The varieties of *japonica* rice vary greatly in terms of genetics and responses to the environment. *Japonica* rice in the south generally has wider and thicker grains, while that in the north has longer grains and a higher seed setting rate (Yan et al., 2024). Genomic association studies have found that traits such as plant height, panicle length, and grain shape all have corresponding quantitative trait loci (QTLs), and this genetic information can help explain why different varieties behave differently in different environments (Hori et al., 2017; Wang et al., 2025). Some good alleles can also increase yield, quality or disease resistance, and their adaptability varies in different regions (Zhang et al., 2022; Jiang et al., 2023).

2.3 Yield potential versus quality stability

The yield of *japonica* rice is closely related to some of its key traits, such as the number of effective panicles, the number of grains per panicle, plant height, and growth period, etc. (Li et al., 2019; Zou et al., 2024). High-yield varieties often increase the total yield by increasing the number of grains per panicle and the capacity of the yield reservoir. However, if one blindly pursues yield, it may lead to a decline in quality or weakened disease resistance. Nowadays, genomic selection methods have begun to be used in breeding to balance the relationship between high yield, good taste and disease resistance. For example, new *japonica* rice varieties like XY99 and JXY1 not only have high yield, but also good quality and strong disease resistance (Figure 1) (Xiao et al., 2021; Jiang et al., 2023). There are also some varieties that perform stably under conditions such as saline-alkali, drought, and low nitrogen, with the yield not easily dropping and the quality maintained. They are suitable for promotion in different regions and under different planting methods (Ahmad et al., 2021; Ren et al., 2024).

3 Classification and Characteristics of Transplanting Methods

3.1 Manual transplanting

Manual transplanting is a traditional method, which requires people to plant the seedlings one by one into the field. It is flexible to operate and can adjust the row spacing and density according to the size and shape of the field. The seedlings are easy to survive and grow well in the early stage. However, this method is too laborious and inefficient, and is not suitable for large-scale rapid planting (Wu et al., 2022).

3.2 Mechanical transplanting

There are two common types of mechanical rice transplanting: basket-shaped seedlings and pot-shaped seedlings. Mechanical transplanting of blanket seedlings (MC) is to lay the whole seedling in the field. It is fast and very suitable for large-scale planting, and also saves labor (Bian et al., 2018; Wu et al., 2022). Mechanical transplanting of pot seedlings (MT/PS) is to raise seedlings in small grids. Each seedling is relatively strong, grows fast after transplanting, turns green early, can distribute more nutrients to the spike and grain in the later stage, has a high yield, and has a stronger ability to absorb fertilizer (Hu et al., 2020; Fu et al., 2021). This type of transplanting method is particularly suitable for field cultivation where there are few people and high yield is desired (Hu et al., 2018; Wu et al., 2022).

3.3 Tray nursery and seedling throwing methods

The method of throwing seedlings involves first raising seedlings in seedling trays and then scattering them into the field either manually or by machine. This method is convenient and labor-saving, and is suitable for irregular fields or places where machines are not working well. It turns green quickly and the seedlings grow well in the early stage. However, due to uneven sprinkling, it may affect the field structure and yield in the later stage (Zhou et al., 2015).

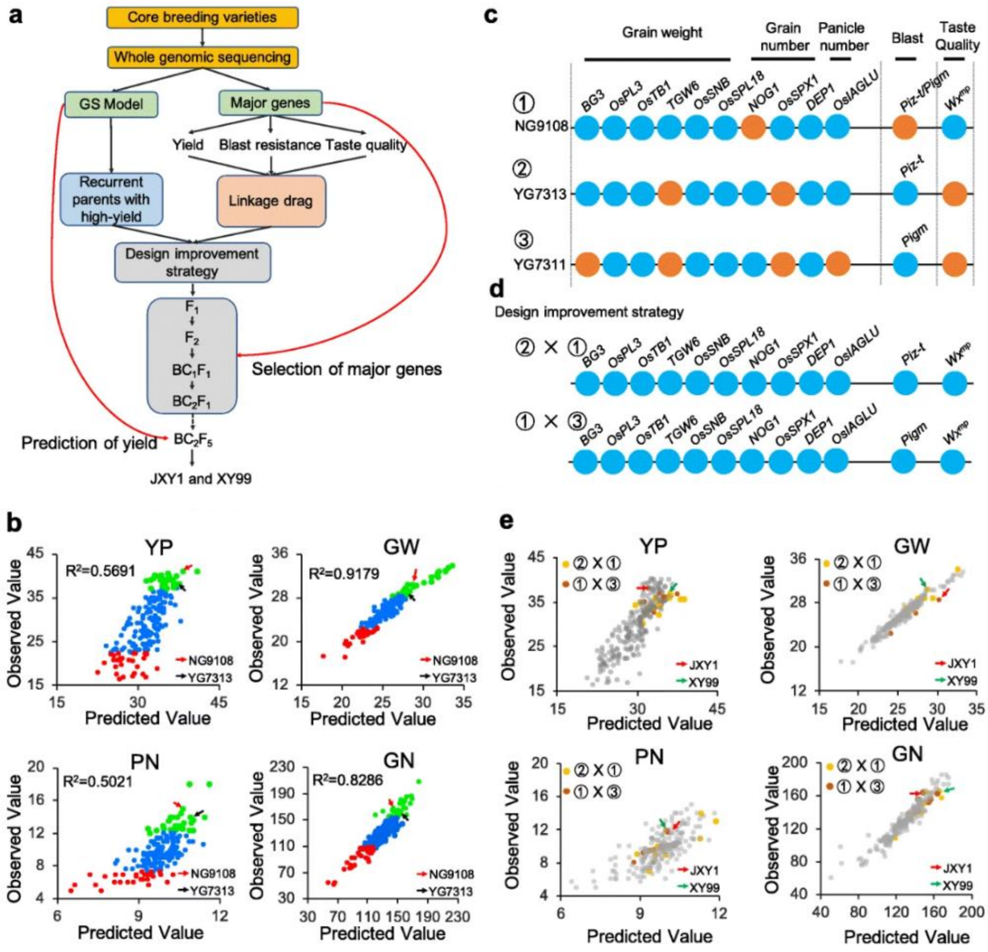

Figure 1 Molecular design strategy for pyramiding of superior genes related to yield, taste quality, and blast resistance (Adopted from Xiao et al., 2021)

Image caption: a Molecular design strategy for breeding novel *japonica* varieties with high yield, excellent taste quality, and blast resistance. b. The accuracy of observed and predicted yield traits by rrBLUP model of 200 *japonica* rice varieties. YP, yield per plant (g); GW, 1000-grain weight (g); PN, panicle number per plant; GN, grain number per panicle. Based on the genomic selection model, YG7313 and NG9108 were selected as high-yield core parents. The green dots, blue dots, and red dots indicate the top 40, bottom 40, and other random varieties for YP, GW, GN, and PN, respectively. c Superior genes for yield, blast resistance, and excellent taste quality distributed in NG9108, YG7311, and YG7313. d Two improved strategies, ② × ①, respect the strategy of precise design of novel lines with high yield and excellent taste on the background of blast resistance through YG7311 as a recurrent parent. ① × ③ respects the strategy of new blast-resistant lines' precise design on the background of high yield and excellent taste quality using NG9108 as a recurrent parent. e rrBLUP model was used to predict the yield, grain weight, grain number, and panicle number of recombination lines. Green arrows represent the elite line selected from the recombination lines with pyramiding of high yield, blast resistance, and excellent taste quality, named as "JXY1". Red arrows represent the elite line selected from recombination lines with high yield, blast resistance, and excellent taste quality, named "XY99". YP, yield per plant (g); GW, 1000-grain weight (g); PN, panicle number per plant; GN, grain number per panicle (Adopted from Xiao et al., 2021)

3.4 Comparative technical advantages and field application scenarios

Each transplanting method has its own advantages and limitations. Manual transplanting is suitable for complex areas such as small plots or mountains, and for places with a large number of workers. However, it is relatively slow and tiring to plant (Wu et al., 2022). Mechanical transplanting of carpet seedlings has high efficiency and is suitable for large-scale planting and when there is insufficient manpower. However, the seedlings are relatively weak and turn green slowly, which somewhat affects the yield (Bian et al., 2018; Wu et al., 2022). The seedlings of mechanical transplanting of pot-shaped seedlings are vigorous, have a fast greenness recovery, high yield and good nutrient absorption. They are suitable for farms that pursue high yield and have mechanical equipment. However, the requirements for seedling management are high and the technical threshold is also high (Hu et al., 2018; Hu et al., 2020; Fu et al., 2021). The method of throwing seedlings is simple and convenient, and is very suitable for fields where machinery cannot enter. However, the seedlings do not grow very evenly and the yield is unstable (Zhou et al., 2015).

4 Influence of Transplanting Methods on Yield Components

4.1 Tiller number, panicle density, and grain filling

Under the appropriate planting density (e.g. 26.88×10^4 holes/hectare), transplanting with mechanical pot seedlings in wide and narrow rows can significantly increase the number of effective panicles and the total number of flowers per mu, thereby enhancing the yield. Compared with equal-row spacing or carpet seedling transplanting, this transplanting method has more tillers and panicles, and higher seed setting rate and grain weight (Hu et al., 2020). Mechanical transplanting, such as pot seedling transplanting and blanket seedling transplanting, can generally bring more panicles and grains. Among them, the pot seedling method shows the most outstanding performance in terms of seed setting rate and 1000-grain weight (Hu et al., 2018; Fu et al., 2021). In addition, under these transplanting methods, more photosynthetic products accumulate in the later stage of rice, which is conducive to grain filling and plumpness.

4.2 Yield variation across methods and planting densities

Different transplanting methods and densities have a significant impact on the yield. Under the mechanical pot seedling wide and narrow row transplanting, the yield was the highest when the density was 26.88×10^4 holes per hectare. If the density is too high or too low, the output will decrease instead, showing a trend of “high in the middle and low on both sides” (Hu et al., 2020). Overall, the yield of mechanized transplanting (pot seedlings or blanket seedlings) is generally higher than that of manual transplanting and direct seeding. This is mainly because there are more panicles and more biomass accumulation (Wu et al., 2022). At an appropriate density (195 plants per square meter), the yield of direct seeding by unmanned aerial vehicle (UAV) was slightly higher than that of dry seeding by UAV. Although it was still slightly lower than mechanical transplanting, the number of panicles and grains per panicle were also considerable (Zhu et al., 2023).

4.3 Harvest index and biomass accumulation

Transplanting seedlings in mechanical POTS can also increase the total dry matter mass, especially during the period from heading to maturity when more is accumulated. The harvest index of this approach is also higher (Fu et al., 2021). Under high-yield conditions, both the biomass and harvest index of this method are higher than those of carpet seedlings or equal row spacing transplanting, indicating that photosynthetic products can be transported to the grains more effectively (Hu et al., 2020). In addition, mechanical transplanting enables the plants to absorb more nitrogen in the later stage and increases the biomass, which is an important reason for the increase in yield (Hu et al., 2024).

5 Impact on Grain Quality

5.1 Milling quality: brown rice rate, head rice rate

Different transplanting methods can have a significant impact on the milling quality of *japonica* rice. Mechanical blanket transplanting (MC) can usually increase brown rice rate and whole polished rice rate, and is more suitable for improving processing quality than mechanical direct seeding (MD) (Bian et al., 2018; Bassuony and Zsembeli, 2019; Abou-Khalifa et al., 2021). If mechanical pot transplanting (MT) is adopted, the rates of brown rice and whole polished rice can be further increased (Fu et al., 2021). Under appropriate densities, such as wide and narrow row transplanting, it is also possible to improve processing quality while ensuring yield (Hu et al., 2020). Overall, the transplanting method performs better than the direct seeding method in processing.

5.2 Appearance and eating quality: grain shape, chalkiness, taste

In terms of appearance, the rice under mechanical direct seeding (MD) has a higher aspect ratio, lower chalky grain rate, chalky rate and chalky degree, and looks better (Bian et al., 2018; Yun et al., 2023). However, the appearance of the MC mode is relatively ordinary. In terms of taste, mixed sowing and transplanting can reduce chalkiness, amylose and protein content, and also improve gum consistency and overall taste score (Gao et al., 2023). However, the influence of different transplanting methods on the taste value is not particularly significant. Soft rice varieties have the best taste, followed by common *japonica* rice, and hybrid *japonica* rice has the worst (Bian et al., 2018). When encountering high-temperature weather, the transplanting method has more advantages in maintaining the whole polished rice rate, gum consistency and amylose content, indicating that it is more resistant to adverse conditions (Zang et al., 2022).

5.3 Nutritional traits and market acceptance

The transplanting method can also affect the nutritional components of rice. Under mechanical carpet seedling transplanting (MC), the protein content is higher than that by direct seeding. Under the MD method, the protein content is relatively low and the nutritional quality will be poorer (Bian et al., 2018). Mixed seeding and transplanting can further reduce the content of protein and amylose, thereby making the rice softer and more fragrant (Gao et al., 2023). From a market perspective, the MC method has good processing quality and nutritional level, so consumers are more willing to buy this kind of rice (Abou-Khalifa et al., 2021). In addition, different transplanting methods have little effect on the amino acid composition, and the biological nutritional value of rice remains basically unchanged.

6 Evaluating Yield and Quality Adaptability across Methods

6.1 Definition and indicators of adaptability

Adaptability generally refers to whether a variety can maintain high yield and good quality under different cultivation methods or transplanting approaches. When evaluating adaptability, several aspects are usually considered: such as yield per unit area, number of effective panicles, number of grains per panicle, seed setting rate and other yield indicators; Quality indicators such as processing quality, appearance, nutritional components, palatability value, amylose and protein content are also considered. Growth conditions such as leaf area index, dry matter accumulation and nitrogen absorption are also taken into account (Wu et al., 2022; Ren et al., 2024). In addition, it is also crucial whether the yield of a variety can be stable and whether the quality will change little (Chen et al., 2025a).

6.2 Multi-location and seasonal performance variability

After conducting experiments at multiple sites and in various seasons, it was found that *japonica* rice varieties respond very differently to the environment under different transplanting methods. Some studies have pointed out that mechanical transplanting methods (such as pot seedlings, blanket seedlings, direct seeding) perform better in terms of yield and some qualities compared with manual transplanting, but there will also be an interactive effect of “genotype × environment” depending on the variety (Hu et al., 2018; Wu et al., 2022). For instance, under the condition of appropriate density, mechanical pot seedling wide and narrow row transplanting can achieve the maximum yield and also improve processing and nutritional quality (Hu et al., 2020); while mechanical live streaming has a better appearance, its processing and nutritional quality are slightly inferior (Bian et al., 2018). Regional trials also showed that some hybrid *japonica* rice varieties (such as Zhegengyou2035 and Changyou20-2) performed well in different regions and had stable yields (Chen et al., 2025a).

6.3 Varietal stability under transplanting stress or environmental fluctuations

When a variety is confronted with transplanting pressure (such as mechanical operation, density changes) or environmental changes like climate and soil, its stable performance is also an important manifestation of adaptability. Studies have found that the yield and nitrogen absorption capacity of hybrid *japonica* rice are generally stronger, especially under new technologies such as mechanical pot seedling transplanting, the advantages can be better exerted (Chen et al., 2025a; Chen et al., 2025b). Some conventional *japonica* rice varieties have relatively stable processing quality, while soft rice varieties are less affected in terms of nutrition and taste (Bian et al., 2018). In addition, reasonable density and nitrogen application strategies can further enhance the yield and quality performance of varieties under different transplanting methods (Hu et al., 2020; Ren et al., 2024).

7 Physiological and Environmental Factors Affecting Adaptability

7.1 Root development, nutrient uptake, and photosynthetic efficiency

The root structure and function of *japonica* rice directly affect its ability to absorb water and nutrients, and it is the basis for whether it can adapt to different planting methods and environments (Zhu and Shen, 2024). The development of roots is controlled by many hormones, such as auxin, cytokinin and jasmonic acid. If there are many lateral roots, long roots and large root surface area, it will be more conducive to absorption, which can help rice be more drought-resistant and cold-resistant, and the yield will also be higher (Meng et al., 2019; Panda et al., 2021; Muzaffar et al., 2024). Some varieties have strong root activity and high antioxidant capacity. Under low temperature or drought weather, they can still maintain the accumulation and transportation of photosynthetic products, which is very helpful for the later panicle differentiation and grain formation (Jia et al., 2022; Miyoshi et al., 2023). Roots can also absorb amino acids and mineral elements, such as amino acids through proteins like OsLHT1, which will affect the growth and yield of the aboveground parts (Guo et al., 2020; Wang et al., 2022; Manna et al., 2024). If the roots can coexist with beneficial bacteria, such as *Piriformospora indica*, not only can the roots grow better, but also the efficiency of water and nutrient absorption can be improved, and the resistance to external stress can be enhanced (Figure 2) (Bandyopadhyay et al., 2022; Mani et al., 2023).

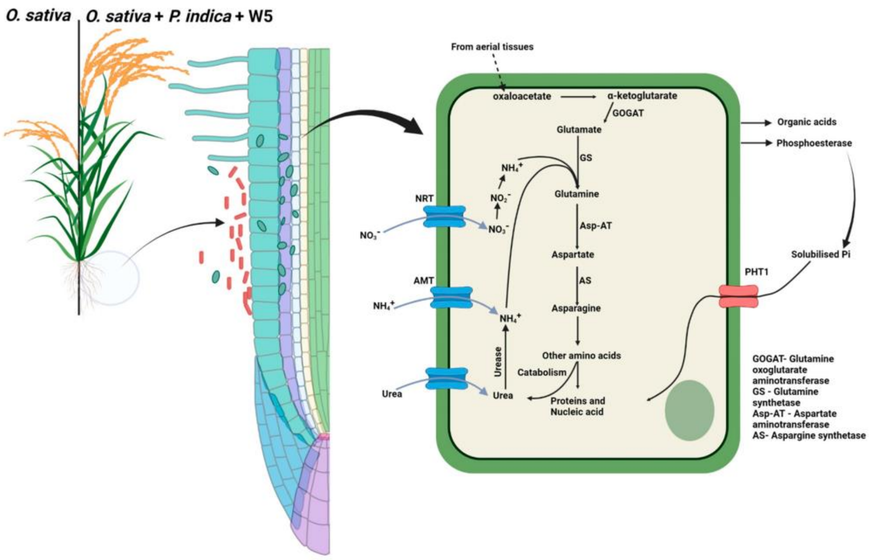

Figure 2 Hypothetical model for explaining the mechanism of nutrient uptake that promotes higher plant growth and biomass in the presence of endophytic fungus *P. indica* and plant growth-promoting rhizobacterium *A. chroococcum* strain W5 (Adopted from Bandyopadhyay et al., 2022)

7.2 Soil temperature, moisture, and transplanting shock

Soil temperature and humidity also affect the activity of roots. If the temperature in the root zone is above 29°C, it will be more conducive to the absorption of nutrients by the roots, especially the metabolism of nitrogen, and also beneficial to the growth of the entire rice plant (Vu et al., 2020; Farooq et al., 2021). Conversely, when encountering low temperatures or drought, root activity will decline, pollen vitality will deteriorate, and panicle development will also be affected, ultimately affecting yield (Jia et al., 2022; Miyoshi et al., 2023). When transplanting rice seedlings, root injuries combined with sudden environmental changes can easily lead to "transplanting shock", which results in a short-term decrease in root absorption capacity and photosynthetic efficiency, affecting the process of rejuvenation. At this time, reasonable arrangement of water and fertilizer, such as intermittent irrigation and reasonable nitrogen application, can slow down the aging of roots, help leaves maintain photosynthesis, and increase rice yield and fertilizer and water utilization rate (Wang et al., 2022; Manna et al., 2024).

7.3 Interaction with diseases, pests, and abiotic stress

In addition to absorbing water and nutrients, roots also play a significant role in resisting various stresses. Whether it is high temperature, salt, heavy metals, or pests and diseases, roots will regulate their own structure and enhance their adaptability to stress through hormone signals, such as jasmonic acid, reactive oxygen species, calcium, etc. (Finatto et al., 2015; Wang et al., 2023; Biswash et al., 2024). High temperatures can affect photosynthesis, disrupt the transport of carbon and nitrogen, shorten the grain-filling period and deteriorate the quality. The heat tolerance of different *japonica* rice varieties also varies (Malini et al., 2023; Li et al., 2024). However, if the roots can collaborate with beneficial bacteria, it can not only enhance the ability to resist pests and diseases and stress, but also help to better distribute nutrients and improve the efficiency of carbon and nitrogen utilization (Bandyopadhyay et al., 2022; Mani et al., 2023).

8 Case Study: Adaptability Evaluation of Three *Japonica* Varieties under Different Transplanting Methods

8.1 Experimental design and transplanting scenarios

This case selected three typical *japonica* rice varieties, representing hybrid *japonica* rice, conventional *japonica* rice and soft *japonica* rice respectively. The experimental design includes several common transplanting methods: mechanical blanket seedling transplanting (MC), mechanical pot sports seedling wide and narrow row transplanting (K), equal row spacing mechanical transplanting (D), and mechanical direct seeding (MD). Field random block design was adopted for each variety, and indicators such as yield, quality and adaptability were recorded (Hu et al., 2020; Bian et al., 2021).

8.2 Comparative results in yield, quality, and adaptability indices

Under appropriate density conditions (26.88×10^4 holes/hectare), wide and narrow row transplanting of pot seedlings (K) significantly increased the number of panicles and yield per unit area, which was better than equal row spacing and carpet seedling transplanting (Hu et al., 2020). Overall, mechanical transplanting (MET) has high yield and biomass, and can yield 0.6 to 3.1 tons per hectare more than manual transplanting and direct seeding (Wu et al., 2022). After reducing the density, the K method can still improve the processing quality, appearance quality and nutritional quality, but the amylose content and palatability value will decrease (Hu et al., 2020). The milled rice rate and whole milled rice rate in the MC mode are both higher than those in the MD mode, while the MD mode has better appearance quality, for example, it can reduce the chalky grain rate. Different varieties also respond differently in terms of quality. The edible taste of soft *japonica* rice changes the least under various transplanting methods and shows stable performance. The processing quality of conventional *japonica* rice is the most stable (Bian et al., 2018; Bian et al., 2021). Hybrid *japonica* rice has a strong nitrogen absorption capacity, a large accumulation of biomass and the most obvious increase in yield under pot seedling transplantation (Hu et al., 2018). The responses of different varieties to transplanting methods vary significantly. Soft *japonica* rice is not sensitive to quality changes, while conventional *japonica* rice shows the most obvious response to appearance changes.

8.3 Implications for cultivar-specific transplanting recommendations

The results show that mechanical pot seedling wide and narrow row transplanting is particularly suitable for hybrid *japonica* rice and conventional *japonica* rice that aim for high yield and better quality. Especially after density optimization, it can take into account both output and some quality indicators (Hu et al., 2018; Hu et al., 2020). If the goal is processing quality, mechanical blanket transplanting is more suitable for conventional *japonica* rice. If appearance quality is emphasized, mechanical live streaming is more suitable. Soft *japonica* rice has strong adaptability and can adapt to various transplanting methods, and is suitable for flexible selection according to market demand (Bian et al., 2018; Bian et al., 2021).

9 Challenges and Future Perspectives

9.1 Current limitations in adaptability evaluation frameworks

At present, the commonly used methods for evaluating adaptability mainly involve conducting multi-point field trials to observe the performance of varieties. However, nowadays there are more and more transplanting methods and environmental differences are also increasing. This traditional approach is no longer sufficient to comprehensively assess the true adaptability of varieties. For instance, the interaction between genotype and environment (G×E) has a significant impact on yield and quality. However, traditional methods have difficulty accurately analyzing this issue, which makes it hard for some superior varieties to be accurately selected for promotion (Chen et al., 2025a). In addition, some evaluation systems only focus on output and do not give sufficient consideration to aspects such as quality and resistance (Bian et al., 2018).

9.2 Need for integrated phenotyping and modeling approaches

With the application of methods such as mechanical pot seedling transplanting, carpet seedling transplanting, and direct seeding, as well as the variation in planting density, there have been very complex changes in the yield and quality performance of varieties. These changes are often not linear, that is to say, it is not a simple relationship where the higher the density, the higher the output (Bian et al., 2018; Wu et al., 2022). At present, many studies still only look at individual traits or only rely on field performance, lacking methods that combine high-throughput phenotypic techniques with crop models. This also makes it difficult for us to accurately predict the adaptation of a certain variety under a certain transplanting method (Hu et al., 2020). In the future, phenotypic data, molecular markers and environmental information from different sources need to be integrated. With the help of big data and artificial intelligence, a more accurate adaptive evaluation model should be established to help select suitable varieties more quickly (Song et al., 2024; Chen et al., 2025a).

9.3 Future directions in breeding and cultivation matching strategies

In the future, *japonica* rice breeding should also pay more attention to the coordination and cooperation among varieties, transplanting methods and planting areas. On the one hand, molecular breeding or gene editing techniques (such as CRISPR-Cas9) can be utilized to rapidly cultivate new varieties that are both high-yielding and highly adaptable, and can better cope with conditions such as light, temperature and adverse conditions (Song et al., 2024; Wang et al., 2025). On the other hand, it is also necessary to strengthen the supporting research among “varieties - cultivation patterns - environment”, combine regional trials, phenomics and model analysis, and formulate more targeted management plans to achieve simultaneous improvement of yield and quality.

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Conflict of Interest Disclosure

The authors affirm that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

References

Abou-Khalifa A., Ziden A., Elshenawy M., and Hassan H., 2021, Effect of planting methods and cultivars on rice grain quality, Journal of Plant Production, 12(11): 1247-1254.
https://doi.org/10.21608/jpp.2021.209336

Ahmad M., Wu B., Wang H., and Kang D., 2021, Identification of drought tolerance on the main agronomic traits for rice (*Oryza sativa* L. ssp. *japonica*) germplasm in China, Agronomy, 11(9): 1740.
https://doi.org/10.3390/agronomy11091740

Bandyopadhyay P., Yadav B., Kumar S., Kumar R., Kogel K., and Kumar S., 2022, *Piriformospora indica* and *Azotobacter chroococcum* consortium facilitates higher acquisition of N, P with improved carbon allocation and enhanced plant growth in *Oryza sativa*, Journal of Fungi, 8(5): 453.
https://doi.org/10.3390/jof8050453

Bassuony N., and Zsembeli J., 2019, Effect of planting methods on the quality of three Egyptian rice varieties, Agriculture (Pol’nohospodárstvo), 65(3): 119-127.
https://doi.org/10.2478/agri-2019-0012

Bian J., Xu F., Han C., Qiu S., Ge J., Xu J., Zhang H., and Wei H., 2018, Effects of planting methods on yield and quality of different types of *japonica* rice in northern Jiangsu plain, China, Journal of Integrative Agriculture, 17(12): 2624-2635.
https://doi.org/10.1016/S2095-3119(18)62141-0

Bian J.L., Ren G.L., Xu F.F., Zhang H.C., and Wei H.Y., 2021, Comparison of grain yield and quality of different types of *japonica* rice cultivars in the northern Jiangsu plain, China, Journal of Integrative Agriculture, 20(8): 2065-2076.
https://doi.org/10.1016/s2095-3119(20)63348-2

Biswash M., Li K., Lu H., Shi Y., Uwiringiyimana E., Guo L., and Xu R., 2024, Effect of Cd(II) adsorption onto rice roots on its uptake by different indica and *japonica* rice varieties and toxicity effect of Cd(II) under acidic conditions, Environmental Science and Pollution Research International, 31: 30399-30414.
https://doi.org/10.1007/s11356-024-33228-7

Chen R., Wang G., Yu J., Lu Y., Tao T., Wang Z., Hua Y., Li N., Wang H., Gharib A., Zhou Y., Xu Y., Li P., Xu C., and Yang Z., 2025a, Yield, stability, and adaptability of hybrid *japonica* rice varieties in the east coast of China, Agronomy, 15(4): 901.
https://doi.org/10.3390/agronomy15040901

Chen Y., Song J., Hong X., Zhang H., Hu T., and Zhu G., 2025b, Growth traits and yield performance of *japonica* hybrid rice bred by the new strategy in the Yangtze River region of China, Agronomy, 15(1): 152.
https://doi.org/10.3390/agronomy15010152

Chu G., Chen S., Xu C., Wang D., and Zhang X., 2019, Agronomic and physiological performance of *indica*/*japonica* hybrid rice cultivar under low nitrogen conditions, Field Crops Research, 243: 107625.
https://doi.org/10.1016/j.fcr.2019.107625

Deng S., Gao P., Wang H., Chen Y., Wei H., and Dai Q., 2023, Effects of mixed planting on machine transplanting adaptability and grain yield of hybrid rice, Agriculture, 13(2): 384.
https://doi.org/10.3390/agriculture13020384

Farooq M., Gyilbag A., Virk A., and Xu Y., 2021, Adaptability mechanisms of *japonica* rice based on the comparative temperature conditions of Harbin and Qiqihar, Heilongjiang Province of northeast China, Agronomy, 11(11): 2367.
https://doi.org/10.3390/agronomy11112367

Finatto T., De Oliveira A., Chaparro C., Da Maia L., Farias D., Woyann L., Mistura C., Soares-Bresolin A., Llauro C., Panaud O., and Picault N., 2015, Abiotic stress and genome dynamics: specific genes and transposable elements response to iron excess in rice, Rice, 8: 13.
https://doi.org/10.1186/s12284-015-0045-6

Fu Z., Ma Z., Wei H., Xing Z., Liu G., Hu Q., and Zhang H., 2021, Effects of controlled release fertilizer ratio on yield formation and nitrogen absorption and utilization of late-maturing medium *japonica* rice under different mechanized cultivation methods, Acta Agronomica Sinica, 48(1): 165-179. https://doi.org/10.3724/sp.j.1006.2022.02087

Gao P., Xiao J., Deng S., and Dai Q., 2023, Effects of two sowing methods on the growth, yield, and quality of hybrid rice under mechanical transplantation, Agronomy, 13(12): 2961.
https://doi.org/10.3390/agronomy13122961

Guo N., Hu J., Yan M., Qu H., Luo L., Tegeder M., and Xu G., 2020, *Oryza sativa* Lysine-Histidine-type Transporter 1 functions in root uptake and root-to-shoot allocation of amino acids in rice, The Plant Journal, 103(1): 395-411.
https://doi.org/10.1111/tpj.14742

Hori K., Yamamoto T., and Yano M., 2017, Genetic dissection of agronomically important traits in closely related temperate *japonica* rice cultivars, Breeding Science, 67: 427-434.
https://doi.org/10.1270/jsbbs.17053

Hu Q., Gu Y., Lu X., Jiang W., Zhang K., Zhu H., Li G., Xu F., Zhu Y., Liu G., Gao H., Zhang H., and Wei H., 2024, Effects of one-time reduced basal application of controlled-release nitrogen fertilizer with increased planting density on yield and nitrogen utilization of mechanically transplanted *japonica* rice, Agronomy, 14(12): 3072.
https://doi.org/10.3390/agronomy14123072

Hu Q., Jiang W., Qiu S., Xing Z., Hu Y., Guo B., Liu G., Gao H., Zhang H., and Wei H., 2020, Effect of wide-narrow row arrangement in mechanical pot-seedling transplanting and plant density on yield formation and grain quality of *japonica* rice, Journal of Integrative Agriculture, 19(5): 1197-1214.
https://doi.org/10.1016/s2095-3119(19)62800-5

Hu Y., Wu P., Zhang H., Dai Q., Huo Z., Xu K., Gao H., Wei H., Guo B., and Cui P., 2018, Comparison of agronomic performance between inter-sub-specific hybrid and inbred *japonica* rice under different mechanical transplanting methods, Journal of Integrative Agriculture, 17(4): 806-816.
https://doi.org/10.1016/S2095-3119(17)61819-7

Jia Y., Liu H., Wang H., Zou D., Qu Z., Wang J., Zheng H., Wang J., Yang L., Mei Y., and Zhao H., 2022, Effects of root characteristics on panicle formation in *japonica* rice under low temperature water stress at the reproductive stage, Field Crops Research, 277: 108395.
https://doi.org/10.1016/j.fcr.2021.108395

Jiang S., Zhang X., Yang X., Liu C., Wang L., Ma B., Miao Y., Hu J., Tan K., Wang Y., Jiang H., and Wang J., 2023, A chromosome-level genome assembly of an early matured aromatic *japonica* rice variety Qigeng10 to accelerate rice breeding for high grain quality in Northeast China, Frontiers in Plant Science, 14: 1134308.
https://doi.org/10.3389/fpls.2023.1134308

Li R., Li M., Ashraf U., Liu S., and Zhang J., 2019, Exploring the relationships between yield and yield-related traits for rice varieties released in China from 1978 to 2017, Frontiers in Plant Science, 10: 543.
https://doi.org/10.3389/fpls.2019.00543

Li Z., Wu H., Hassan M., Jiang Y., and Tu D., 2024, Exploring the effect of high-temperature on *japonica* rice yield by transcriptomics, Plant Growth Regulation, 104: 1033-1045.
https://doi.org/10.1007/s10725-024-01208-z

Malini M., Singla S., Priyadarsini P., Das A., Chinnusamy V., and Pal M., 2023, Photosynthesis and related gas exchange traits in rice subspecies under high temperature environment, Plant Physiology Reports, 28: 107-112.
https://doi.org/10.1007/s40502-023-00711-1

Mani K., Ameena M., Johnson J., Anith K., Pillai P., John J., and Beena R., 2023, Endophytic fungus *Piriformospora indica* mitigates moisture stress in rice by modifying root growth, Rhizosphere, 28: 100799.

Manna M., Rengasamy B., and Sinha A., 2024, Nutrient and water availability influence rice physiology, root architecture and ionomic balance via auxin signalling, Plant, Cell and Environment, 48(4): 2691-2705.
https://doi.org/10.1111/pce.15171

Meng F., Xiang D., Zhu J., Li Y., and Mao C., 2019, Molecular mechanisms of root development in rice, Rice, 12: 1.
https://doi.org/10.1186/s12284-018-0262-x

Miyoshi Y., Soma F., Yin Y., Suzui N., Noda Y., Enomoto K., Nagao Y., Yamaguchi M., Kawachi N., Yoshida E., Tashima H., Yamaya T., Kuya N., Teramoto S., and Uga Y., 2023, Rice immediately adapts the dynamics of photosynthates translocation to roots in response to changes in soil water environment, Frontiers in Plant Science, 13: 1024144.
https://doi.org/10.3389/fpls.2022.1024144

Muzaffar A., Chen Y., Lee H., Wu C., Le T., Liang J., Lu C., Balasubramaniam H., Lo S., Yu L., Chan C., Chen K., Lee M., Hsing Y., Ho T., and Yu S., 2024, A newly evolved rice- specific gene *JAUP1* regulates jasmonate biosynthesis and signalling to promote root development and multi-stress tolerance, Plant Biotechnology Journal, 22(5): 1417-1432.
https://doi.org/10.1111/pbi.14276

Panda S., Majhi P., Anandan A., Mahender A., Veludandi S., Bastia D., Guttala S., Singh S., Saha S., and Ali J., 2021, Proofing direct-seeded rice with better root plasticity and architecture, International Journal of Molecular Sciences, 22(11): 6058.
https://doi.org/10.3390/ijms22116058

Ren Y., Xu E., Zhang P., Zhan X., He Q., and Zou Y., 2024, Impact of key agronomic traits on economic yield traits in Anhui rice (*Oryza sativa* L. spp. *japonica*), Agronomy, 14(6): 1101.
https://doi.org/10.3390/agronomy14061101

Song J., Tang L., Fan H., Xu X., Peng X., Cui Y., and Wang J., 2024, Enhancing yield and improving grain quality in *japonica* rice: targeted EHD1 editing via CRISPR-Cas9 in low-latitude adaptation, Current Issues in Molecular Biology, 46(4): 3741-3751.
https://doi.org/10.3390/cimb46040233

Vu D., Stuerz S., and Asch F., 2020, Nutrient uptake and assimilation under varying day and night root zone temperatures in lowland rice, Journal of Plant Nutrition and Soil Science, 183(5): 602-614.
https://doi.org/10.1002/jpln.201900522

Wang C., Li J., Zhu Q., Li J., Zhang C., Hong R., Huang D., Zhang Z., Xu J., Li D., Wen J., Li C., Zhu Y., Lee D., and Chen L., 2025, Breeding D1-type hybrid *japonica* rice in diverse upland rainfed environments, International Journal of Molecular Sciences, 26(7): 3246.
https://doi.org/10.3390/ijms26073246

Wang H., Zhao X., Xuan W., Wang P., and Zhao F., 2023, Rice roots avoid asymmetric heavy metal and salinity stress via a RBOH-ROS-auxin signaling cascade, Molecular Plant, 16(10): 1678-1694.
https://doi.org/10.1016/j.molp.2023.09.007

Wang Z., Jia Y., Fu J., Qu Z., Wang X., Zou D., Wang J., Liu H., Zheng H., Wang J., Yang L., Xu H., and Zhao H., 2022, An analysis based on *japonica* rice root characteristics and crop growth under the interaction of irrigation and nitrogen methods, Frontiers in Plant Science, 13: 890983.
https://doi.org/10.3389/fpls.2022.890983

Wu W., Tu D., Xi M., Xu Y., Zhou Y., Li Z., Ji Y., Sun X., Yang Y., and Li F., 2022, Variations of rice yield and quality in response to different establishment methods at farmers' field, Agronomy, 12(12): 3174.
https://doi.org/10.3390/agronomy12123174

Xiao N., Pan C., Li Y., Wu Y., Cai Y., Lu Y., Wang R., Yu L., Shi W., Kang H., Zhu Z., Huang N., Zhang X., Chen Z., Liu J., Yang Z., Ning Y., and Li A., 2021, Genomic insight into balancing high yield, good quality, and blast resistance of *japonica* rice, Genome Biology, 22: 283.
https://doi.org/10.1186/s13059-021-02488-8

Yan Z., Deng R., Tang H., and Zhu S., 2024, Genetic diversity and divergence between southern *japonica* and northern *japonica* rice varieties in China, Genes, 15(9): 1182.
https://doi.org/10.3390/genes15091182

Yun Y., Kim G., Cho G., and Yun T., 2023, Effect of transplanting date on agronomic and grain quality traits using early-maturing rice varieties, Agronomy, 13(5): 1195.
https://doi.org/10.3390/agronomy13051195

Zang Q., Han X., Zhang M., Huang X., Jiang M., and Huang L., 2022, Effects of high temperature on quality of *japonica* rice at early and middle heading stage under different planting modes, Agronomy, 12(8): 1833.
https://doi.org/10.3390/agronomy12081833

Zhang H., Zhou G., and He Q., 2025, Effective combination of advancing transplantation date with high-yielding cultivars for paddy rice could increase the yield potential under climate warming in China, Agronomy, 15(1): 119.
https://doi.org/10.3390/agronomy15010119

Zhang Y., Zhou J., Xu P., Li J., Deng X., Deng W., Yang Y., Yu Y., Pu Q., and Tao D., 2022, A genetic resource for rice improvement: introgression library of agronomic traits for all AA genome *Oryza* species, Frontiers in Plant Science, 13: 856514.
https://doi.org/10.3389/fpls.2022.856514

Zhou Y.J., Wu W.G., Yan W.X., Wang S.Y., Zhou T.Z., Wang B., Xu Y.Z., and Chen G., 2015, Preliminary study on high yield cultivation techniques of "indica rice to *japonica* rice" under machincal transplanted condition along Yangtze River of Anhui Province, China Rice, 21(1): 48-51.

Zhu H., Lu X., Zhang K., Xing Z., Wei H., Hu Q., and Zhang H., 2023, Optimum basic seedling density and yield and quality characteristics of unmanned aerial seeding rice, Agronomy, 13(8): 1980.
https://doi.org/10.3390/agronomy13081980

Zhu K., Zhou Q., Shen Y., Yan J., Xu Y., Wang Z., and Yang J., 2020, Agronomic and physiological performance of an *indica* - *japonica* rice variety with a high yield and high nitrogen use efficiency, Crop Science, 60(3): 1556-1568.
https://doi.org/10.1002/csc2.20150

Zhu Y.L., and Shen Z.C., 2024, Response analysis of root and leaf physiology and metabolism under drought stress in rice, Rice Genomics and Genetics, 15(3): 19-27.
https://doi.org/10.5376/rgg.2024.15.0003

Zou Y., Hassan M., Xu E., Ren Y., Wang J., Zhan X., Ni D., and Zhang P., 2024, Evaluation of breeding progress and agronomic traits for *japonica* rice in Anhui Province, China (2005-2024), Agronomy, 14(12): 2957.
https://doi.org/10.3390/agronomy14122957