Review

The development status of rice iron-coated wet direct seeding technology in Japan

El estado de desarrollo de la tecnología de siembra directa en agua con semillas de arroz recubiertas de hierro en Japón

O status de desenvolvimento da tecnologia de semeadura direta em água com sementes de arroz revestidas com ferro no Japão

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Abstract

This review examines the development and potential of iron-coated wet direct seeding technology in Japanese rice cultivation, emphasizing its role in mitigating labor shortages and enhancing the sector's competitiveness. The technology, which has been rapidly adopted, improves seedling emergence, reduces seed drifting, and minimizes damage from birds and rodents by increasing seed weight and hardness. Comprising cost-effective materials such as iron powder and calcium sulfate, the coating process is both straightforward and economical. While some studies report a modest 5 % reduction in yield relative to transplanting, others suggest comparable or even improved yields. The technology offers significant advantages in reducing labor input, lowering production costs, and improving seedling establishment, positioning it as a promising solution not only for Japan but also for other rice-producing regions facing similar challenges.

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Resumen

Esta revisión examina de manera crítica el desarrollo y el potencial de la tecnología de siembra directa húmeda con recubrimiento de hierro en el cultivo de arroz en Japón, destacando su papel en la mitigación de la escasez de mano de obra y en el fortalecimiento de la competitividad del sector. La tecnología, que ha sido adoptada rápidamente, mejora la emergencia de las plántulas, reduce el desplazamiento de las semillas y minimiza los daños causados por aves y roedores al aumentar el peso y la dureza de las semillas. Compuesta por materiales rentables como polvo de hierro y sulfato de calcio, el proceso de recubrimiento es sencillo y económico. Aunque algunos estudios reportan una reducción modesta del 5 % en el rendimiento en comparación con el trasplante, otros sugieren rendimientos similares o incluso superiores. La tecnología ofrece ventajas significativas en la reducción del trabajo manual, la disminución de los costos de producción y la mejora del establecimiento de las plántulas, posicionándose como una solución prometedora no solo para Japón, sino también para otras regiones productoras de arroz que enfrentan desafíos similares.

Palabras clave: escasez de mano de obra, eficiencia de producción, características agronómicas, cultivo de siembra directa, innovación agrícola.

Resumo

Esta revisão examina criticamente o desenvolvimento e o potencial da tecnologia de semeadura direta molhada com revestimento de ferro na cultura de arroz no Japão, enfatizando seu papel na mitigação da escassez de mão de obra e no aumento da competitividade do setor. A tecnologia, que foi rapidamente adotada, melhora a emergência das plântulas, reduz o desvio das sementes e minimiza os danos causados por aves e roedores, ao aumentar o peso e a dureza das sementes. Composta por materiais econômicos como pó de ferro e sulfato de cálcio, o processo de revestimento é simples e acessível. Embora alguns estudos relatem uma redução modesta de 5 % no rendimento em comparação com o transplante, outros sugerem rendimentos semelhantes ou até superiores. A tecnologia oferece vantagens significativas na redução do esforço laboral, diminuição dos custos de produção e melhoria no estabelecimento das plântulas, posicionando-se como uma solução promissora não apenas para o Japão, mas também para outras regiões produtoras de arroz que enfrentam desafios semelhantes.

Palavras-chave: escassez de mão de obra, eficiência de produção, características agronômicas, cultivo de semeadura direta, inovação agrícola.

Introduction

In recent years, Japan's agricultural population has been rapidly declining at an annual rate of 5 %. As of 2015, the proportion of agricultural workers aged 65 and over had reached a staggering 63 %. The lack of successors are driving many elderly small-scale farmers in Japan to abandon rice production, worsening the aging crisis in agriculture (Kim *et al*., 2023). Conversely, the number of individuals under 49 engaged in large-scale agricultural production is on the rise. Similar to the situation in China, land consolidation and large-scale farming are gradually becoming the mainstream trend in Japanese agricultural development. Consequently, many farmlands abandoned by aging small-scale farmers are being taken over by relatively younger large-scale farm operators. From 2005 to 2010, this polarization of farm sizes accelerated significantly, with the number of farms under 5 ha decreasing sharply while the number of farms over 10 ha continued to rise (Fukumoto *et al*., 2019). However, the issue of labor shortage remains unresolved, and labor input per unit area is still insufficient. Additionally, with an influx of Southeast Asian rice into the Japanese market, domestically produced rice faces cost disadvantages and declining market competitiveness (He *et al.,* 2018). Reducing labor input in rice production on a larger scale, while lowering production costs to enhance the competitiveness of rice products, has become an urgent task for Japan's rice industry.

Rice direct seeding technology, which can streamline production processes, save time and effort, reduce costs, and facilitate large-scale mechanized operations, has gradually been accepted by rice farmers and chosen by Japan's Ministry of Agriculture, Forestry and Fisheries as a significant technology for nationwide promotion. Particularly, wet direct seeding technology, due to its advantages over dry direct seeding such as stable seedling establishment and easier weed control has seen the most extensive application. However, it still faces issues like seed drifting and yield reduction caused by bird and rodent damage. Therefore, there is an urgent need for a new direct seeding technology that can ensure stable germination rates while addressing issues caused by birds and rodents.

To address the challenges of direct rice seeding, Japan has developed and promoted iron-coated wet direct seeding technology. This method involves coating rice seeds with a mixture of iron powder and calcium sulfate, which increases seed weight and hardness, thereby reducing seed drifting and animal predation. It also facilitates surface seeding, which enhances germination rates by minimizing damage associated with soil seeding. The objective of this review is to provide a comprehensive analysis of iron-coated wet direct seeding technology, examining its development, operational process, and advantages.

Methods

This review was conducted through a comprehensive literature search and analysis of published research on iron-coated wet direct seeding technology in rice cultivation. The primary sources of information included peer-reviewed journal articles sourced from academic databases such as Web of Science, Scopus, and Google Scholar. Additionally, government reports and statistical data on adoption rates and application areas were gathered from documents published by Japan's Ministry of Agriculture, Forestry, and Fisheries, as well as agricultural departments in other countries. Patent documents, including the original patent for the iron-coating method filed by Yamauchi (2010), provided detailed technical insights into the process. Furthermore, personal communications with agricultural scientists and extension specialists who have direct experience with iron-coated seeding technology were conducted to supplement the published literature.

Discussion

Promotion and Popularization of Iron-coated Wet Direct Seeding Technology

The Japan's Ministry of Agriculture, Forestry, and Fisheries introduce and promote iron-coated wet direct seeding technology in the early 21st century. The earliest paper on this technology in Japan dates back to 2001, when Kitano *et al*., investigate the effects of iron oxide coating on seed germination and seedling establishment (Kitano *et al*., 2001). More comprehensive discussions on iron-coated wet direct seeding technology are later presented in papers by Yamauchi (2012).

Beginning in 2004, promotional activities for iron-coated direct seeding technology are launched nationwide, with technical manuals on the subject being printed and disseminated (Yamauchi, 2017). From 2008 onwards, empirical trials of the technology are conducted across Japan (Muraoka *et al*., 2011). Figure 1 illustrates the adoption and promotion of iron-coated wet direct seeding technology in Japan. Starting in 2008, the application area of this technology has shown a steady increase. Over the course of just eight years, the area expand significantly—from 272.4 ha in 2008 to 15,166.5 ha in 2015—representing approximately 33.6 % of the total direct seeding area. This rapid growth reflects the widespread recognition and acceptance of the technology among rice farmers engaged in direct seeding cultivation.

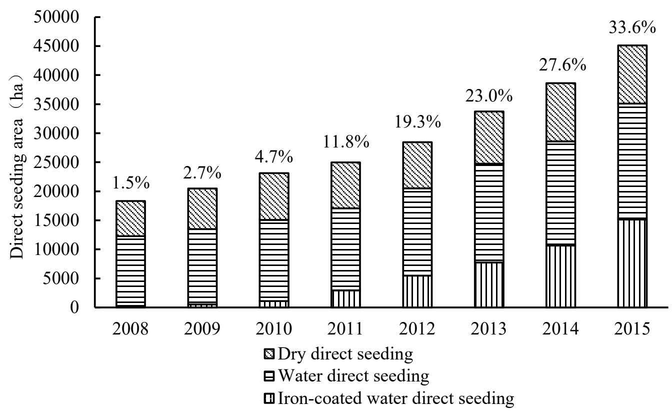

Figure 1. Promotion and Application of Iron-Coated Technology in Japan

Definition of Iron-Coated Wet Direct Seeding Technology

Iron-coated wet direct seeding technology involves coating rice seeds with a mixture of iron powder and dihydrate calcium sulfate, which serves as both an oxidation accelerator and an adhesive (Yamauchi, 2012). These coated seeds are then directly sown on the soil surface in water. The patent for this technology, titled “Method for Manufacturing Iron-Coated Rice Seeds,” is filed by Yamauchi in 2004. It is published in July 2005 and approved by the Japan Patent Office in 2010 (Yamauchi, 2010).

Operational Process of Iron-Coated Wet Direct Seeding Technology

Select high-germination-rate rice seeds that have been screened. Soak the seeds in water at a temperature of 15-20 °C for 3-4 days. The seeds should remain in a non-germinated state after soaking. Although dry seeds can also be used directly for coating, their germination will be significantly delayed compared to soaked seeds. During soaking, use a seed disinfectant that does not react with either iron powder or dihydrate calcium sulfate.

Thoroughly mix iron powder and dihydrate calcium sulfate (gypsum) in a 5:1 weight ratio to prepare the coating mixture. Mix the seeds and the coating mixture in a 10:3 weight ratio. Place the seeds in a mixer (if using dry seeds, pre-coat them with an agent that does not react with iron powder or dihydrate calcium sulfate). Gradually add the coating mixture to the seeds in small amounts while spraying water to facilitate adhesion. After all the coating mixture has been added, let the mixer rotate for an additional 2-3 minutes to ensure thorough mixing. If necessary, add more dihydrate calcium sulfate to achieve the desired thickness of the seed coat.

Since dihydrate calcium sulfate generates heat upon contact with water, immediately spread the coated seeds in a thin layer (not exceeding 2 cm in thickness, using existing seedling trays if available). Place the trays in a cool, shaded area to dry thoroughly, which usually takes 2-3 days. Check the seeds every 6-8 hours for color change and dryness. If the seeds become too dry, lightly mist them with water to promote oxidation. The seeds are ready for seeding when over 85 % have turned a noticeable rust color. For seeds not immediately sown, continue drying them for long-term storage, which should not exceed 3 months (Yamauchi, 2010; Yamauchi, 2012). Figure 2 shows the process described.

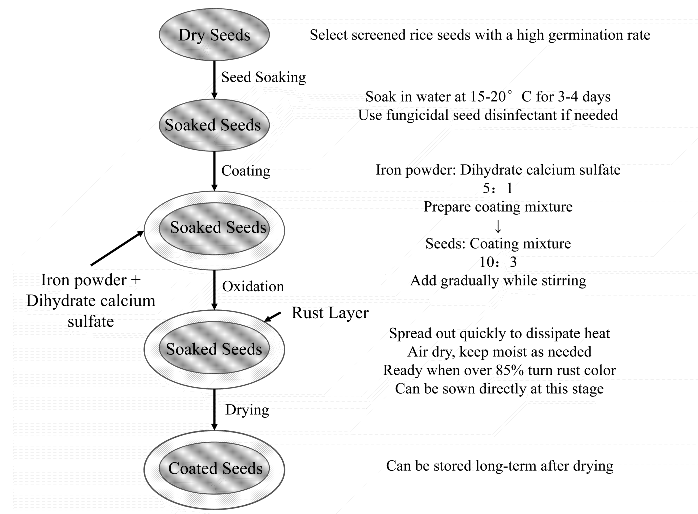

Figure 2. Operational Process of Iron-Coated Wet Direct Seeding Technology

Current Issues in Wet Direct Seeding Cultivation Technology

Surface seeding involves seeding directly on the field surface after plowing, either with or without a water layer, so that the seeds do not enter the soil. This method is widely used in rice production in countries such as the United States and Australia (Masarei *et al*., 2019; Frischie *et al*., 2020). The main issues encountered in production include: In some wet direct seeding fields, due to hard soil, uneven field surfaces, or coarse plowing resulting in large soil clods, the seeds cannot make contact with the soil (He *et al*., 2018). This leads to seed desiccation and death after drainage, or the seeds germinating but failing to absorb water in a timely manner, resulting in their death. Maintaining a water layer after wet direct seeding can cause insufficient oxygen for the seeds, leading to poor seedling emergence (Mei *et al*., 2017). Draining and then re-irrigating after wet direct seeding can cause the seeds to shift, leading to seedling gaps near the inlet and seedling clumping away from the inlet (Jikawa *et al*., 2013). Since direct seeding uses rice seeds directly, it is highly susceptible to bird damage (*e.g., sparrows*) and rodent damage, resulting in seedling gaps and reduced yield in the field (Fenangad & Orge 2015).

Soil seeding involves embedding rice seeds into the soil during wet direct seeding cultivation. The main issues encountered in production include: After seeding, the seeds are in the anaerobic reducing layer of the soil, lacking direct contact with oxygen. As a result, the coleoptile and the first leaf of the seedlings are prone to reduction damage, leading to seedling death and decreased germination rates. In some fields where soil seeding is practiced, improper operations can lead to overly deep seeding, resulting in decreased germination rates or uneven germination (Yamauchi 2017).

Advantages of Iron-Coated Technology

The materials required for coating are inexpensive, consisting of iron powder and dihydrate calcium sulfate, with optional fungicidal seed treatment agents. Based on the prices of iron powder at 0.677 $USD.kg^{-1}$ and dihydrate calcium sulfate at 0.071 $USD.kg^{-1}$, the cost of iron coating is approximately 0.024 $USD.kg^{-1}$ of rice seed. With a seeding rate of 150 $kg.ha^{-1}$, the cost of iron coating is about 25.925 $USD.ha^{-1}$. The coating operation is straightforward and can be performed with just a mixer. The process is quick and easy to master. Since surface seeding is used, various seeding methods can be employed, including manual broadcasting, drone broadcasting, and mechanical seeding (Yamauchi, 2017).

Impact on Seedlings

Iron-coated seeds can be surface sown, which avoids the reduction damage associated with soil seeding and improves germination rates (Yamauchi 2017). Iron-coated direct-seeding technology recommends using soaked seeds for seeding, which significantly improves germination rates compared to using dry seeds (Jikawa *et al*., 2014). Moreover, soaked seeds show more pronounced advantages in low-temperature resistance, drought tolerance, and early growth traits compared to dry seeds (Avramova 2019; Nakao *et al*., 2020).

However, the seedling emergence rate using Iron-coated technology in direct-seeding fluctuates greatly. Previous studies have shown that using Japanese varieties as test varieties, the seedling emergence rate of Iron-coated direct-seeding technology ranges between 30 % and 89 % (Yamauchi *et al*., 2024). The reasons are low temperatures after seeding or deep seeding depth (Yang *et al*., 2022), as well as excessive coating amount causing delayed germination (Tanabe *et al*., 2013), leading to a decrease in the final seedling emergence rate. Additionally, during the coating process, the exothermic oxidation of the reducing iron powder can lead to a decrease in seed germination rate (Furuhata and Kurokawa 2022). However, under the same cultivation and external conditions, compared to using other coating materials or uncoated seeds, the final seedling emergence rate under Iron-coated direct-seeding conditions does not show a significant decline (Saito 2017), indicating that excluding environmental and human factors, Iron-coated direct-seeding technology has little impact on germination and seedling emergence.

The phenomenon of floating seeds and seedlings significantly affects seedling emergence in direct-seeding and also influences tillering and dry matter accumulation in the later growth stages, thus causing yield reduction (Van & Huynh, 2015). The main reason for floating seeds and seedlings is the low specific gravity of seeds. The iron coating increases the seed's thousand-grain weight, addressing the issue of seed displacement and clumping caused by water inflow in direct-seeded fields. According to the survey conducted by Jilin Agricultural Science and Technology College, the 1000-grain weight of iron-coated seeds increased by an average of 66.9 % compared to uncoated seeds. Iron-coated technology greatly increases the specific gravity of seeds, with the specific gravity of iron oxide-coated seed shells ranging between 3.8 and 5.2, fundamentally solving the problem of floating seeds and seedlings in direct-seeding (Yamauchi *et al*., 2023).

Impact on Yield and Quality

From 2008 to 2010, the Japan Agricultural Cooperative Association and the National Agriculture and Food Research Organization jointly conduct empirical tests of Iron-coated direct-seeding technology over three consecutive years. Results from 47 experimental plots across 18 prefectures in Japan show that the seedling count of Iron-coated direct-seeding technology is 80.3 $seedlings.m^{-2}$, with a yield approximately 5 % lower compared to conventional transplanting (Muraoka *et al*., 2011). In different experimental plots, the proportion of Iron-coated direct-seeding technology achieving yields of 100 % or more of transplanting yields is 58.3 % in 2008, 44.4 % in 2009, and 37.5 % in 2010. Some experimental plots that experienced yield reductions are speculated to be located in higher latitude cold regions, where low temperatures affected seedling emergence and caused yield losses. Additionally, the seeding rate for direct-seeding in Japan is about one-third of that in other country, which also affects the final seedling emergence rate and yield to some extent. Compared to yield, the quality of rice produced by Iron-coated direct-seeding show no significant difference compared to conventional transplanting.

Impact on Bird and Pest Damage

Both wet direct-seeding and dry direct-seeding are significantly affected by bird damage, with sparrows, magpies, and ducks being the main pest birds. Studies by Yamauchi and Furuhata have shown that Iron-coated technology has a significant inhibitory effect on sparrows pecking at rice seeds (Yamauchi 2019; Furuhata *et al*., 2011), and this inhibitory effect becomes more pronounced with increased coating thickness (Tanabe *et al.,* 2013). It also has a certain deterrent effect on ducks pecking at rice seeds (Yamauchi, 2017). Since Iron-coated technology recommends using soaked seeds for coating, soaking agents can be added during soaking to prevent seed-borne diseases, offering better prevention compared to using dry seeds for seeding. Additionally, studies by Kumar and Reddy (2021) have shown that Iron-coated has good preventive effects against rice seedling blight, bakanae disease, bacterial streak, brown spot, and rice blast.

Application Prospects of Iron-coated Direct Seeding Rice Technology

In Europe, Australia, and the United States, direct seeding of rice is highly mechanized (Farooq *et al*., 2011). wet direct seeding is already extensively practiced in some Asian countries and is gradually being adopted in others (Kumar & Ladha, 2011). Similar to Japan, China also faces the ongoing reduction of rural labor population and the aging structure of agricultural labor (Du & Li 2023). Therefore, direct seeding technology for rice, which can reduce labor steps and lower manpower input, is gradually emerging (Feng *et al*., 2020). Large-scale direct seeding rice cultivation has begun in Heilongjiang, Ningxia, Jiangsu, and other regions (Jiang *et al*., 2023; Wang *et al*., 2024; Yin *et al*., 2023). In Heilongjiang Province, the direct seeding rice area in 2017 accounted for approximately 11.7 % of the total rice planting area, nearly 470,000 ha. In Ningxia, the dry direct seeding rice area in 2021 accounted for about 9.7 % of the rice planting area. In Jiangsu Province, the direct seeding rice area in 2022 accounted for more than one-quarter of the total rice planting area, reaching 567,000 ha (Zhang *et al*., 2024).

For wet direct seeding, the instability of seedling emergence caused by bird and rodent damage and floating seeds significantly affects rice yield formation, which is one of the main issues hindering the application and promotion of wet direct seeding technology. This is due to the staggered seeding period of wet direct seeding with other crops and inadequate field preparation. Iron-coated direct seeding technology can effectively solve these problems by increasing the specific gravity and hardness of seeds. Moreover, the coating materials used are inexpensive, the process is simple, and it has no adverse environmental impacts.

In 2015, Italy and Spain collectively accounted for approximately 75 % of the total rice-growing area, which was around half a million ha (Kraehmer & Vidotto 2017). The practice of direct seeding in saturated soil has become widely adopted in southern Brazil, Chile, Venezuela, Cuba, various Caribbean nations, and specific regions of Colombia (Muthuramu & Ragavan 2021). Particularly in Venezuela, the use of pre-germinated systems for wet direct seeding dominates rice cultivation (Singh *et al*., 2017). This provides a strong foundation for promoting the application of iron-coated seeding technology in wet direct seeding. With the continuous advancement in breeding varieties suitable for direct seeding cultivation in different rice production areas, Iron-coated direct seeding technology, as a technique that can significantly improve seedling emergence rates and ensure yield, shows broad application prospects. The popularization of this technology will undoubtedly bring new breakthroughs and opportunities to the rice planting industry.

Conclusions

Iron-coated wet direct seeding technology provides several advantages over traditional wet direct seeding methods, including increased seed weight and hardness, which help mitigate issues like seed drifting and damage from birds and rodents. These benefits contribute to more stable seedling establishment and potentially higher yields. While some studies have reported yield reductions of around 5% compared to conventional transplanting, the technology holds the potential for yield parity or even improvement with further refinement and adaptation to local conditions. The cost-effectiveness and simplicity of the coating process make this technology accessible to a wide range of farmers, facilitating its broader adoption. Beyond Japan, the technology shows great promise for other rice-producing regions, particularly in Asia, Europe, and South America, where similar challenges exist. With continued development, it could play a pivotal role in modernizing rice cultivation while reducing environmental footprints.

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