A Review of Iron-Coating Technology to Stabilize Rice Direct Seeding onto Puddled Soil

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ABSTRACT
Transplanting is a widely practiced traditional plant establishment method for rice (Oryza sativa L.) production in Asia. To reduce costs, there is a desire to change the method from transplanting to direct seeding. Problems associated with this management change include inconsistent seedling establishment and heavy weed infestation. Because puddling in flooded soil, which is a common land preparation in transplanting, destroys the soil structure and smooths the surface, directly seeded seeds float and fail to anchor. This paper analyzes the development of high-density Fe-coated seeds and the procedure of water seeding these seeds onto puddled soil. Pre-germinated seeds were granulated using a mixture of reduced Fe powder and calcined gypsum. The Fe powder on the seed surface was oxidized, producing rust, which serves as a binder for the formation of a hard coating layer. The dried Fe-coated seeds could be prepared manually or mechanically in large quantities and stored for more than 1 yr at room temperature. The seeds are characterized as resistant to sparrow attack and seed-borne diseases and are seeded onto the puddled soil surface by broadcasting, row seeding, or hill seeding. In addition, the coated seeds could be successfully seeded onto non-puddled soils using the water seeding or dry seeding methods. This technology could be applied to rice production worldwide following further study.

Core Ideas
- The innovation of rice direct seeding with Fe-coated seeds was analyzed.
- The Fe-coated seeds were prepared through the oxidation of reduced Fe on husks.
- The high-density Fe-coated seeds are resistant to birds and seed-borne diseases.
- Iron-coated seeds exhibit improved anchorage in water seeding in puddled fields.

RICE is a staple food in Asia and has been traditionally cultivated there intensively mainly by transplanting. Raising seedlings in nurseries, pulling and bundling, transporting to the field, and transplanting are laborious and time-consuming.

The monsoon weather that covers most Asian countries wets the soil before planting. Wet land tillage consists in plowing, soaking, and puddling, during which soil clods and aggregates are broken, dispersed, segregated, and then settled smoothly as sediment (De Datta, 1981; Adachi, 1992). Puddling reduces the percolation rate, which conserves water, and increases the efficiency in nutrient uptake and herbicide use. Rice grain yield has been maximized at a percolation rate between 5 and 15 mm d⁻¹ (Isozaki, 1961). Therefore, puddling is useful for rice production when the percolation rate of the field is greater than 15 mm d⁻¹.

Puddled soil is soft, which not only facilitates the transplanting work of farmers but also favors the growth of seedlings. Puddling controls weeds efficiently by killing them before planting and by suppressing the emergence of new weeds after planting.

Labor shortages brought about by high economic growth prompted farmers in the 1980s to shift from transplanting to direct seeding in Asia. The area that shifted to direct seeding reached as much as 14% of all irrigated rice fields, but further expansion has been limited by inconsistent plant stands and the infestation of weeds that are difficult to control (Pandey and Velasco, 2005).

The spread of direct seeding in Japan represents 1% of the rice area, making it much more limited than in other Asian countries (Ministry of Agriculture, Forestry, and Fisheries, Japan, 2008). Although farmers in Japan have been encouraged to adopt direct seeding for decades, they have been slow to adopt this technology.

A technology in which Fe-coated primed dry rice seeds (Fig. 1) are sown directly onto a flooded, puddled field was invented in 2004 (Yamauchi, 2004, 2010a). Agricultural machinery companies and the National Federation of Agricultural Cooperative Associations in Japan have been engaged in the extension of this technology nationwide. The Kubota Corporation machinery company reported that they handled 5500 ha in 2012 and that the area has doubled every year since 2008 (Miyakoshi, 2011). The National Federation of Agricultural Cooperative Associations (2016a) estimated the area to be 15,000 ha in 2015. The technology was successfully implemented in Korea (Park and Yamauchi, 2011; Park et al., 2016). The development of complementary management...
practices associated with soil fertility and weed control has apparently accelerated the spread of this technology.

This paper aims to analyze the innovation of direct seeding using Fe-coated seeds for rice scientists and growers so that they can examine and evaluate this technology internationally.

THE DEVELOPMENT OF IRON-COATED SEEDS

Constraints of Direct Seeding onto Puddled Soil

The direct seeding of rice is roughly classified into dry, water, and wet seeding methods (Kumar and Ladha, 2011). In dry seeding, intact seeds are sown at a 1- to 3-cm depth in dry soil after dry land preparation. The field is managed in the same way as dry land crops from land preparation and seeding to plant establishment, and then flooded thereafter. The use of dry seeding in lieu of transplanting is limited in Asia because the land is wet after the start of the monsoon season.

Water seeding in the United States, Australia, and Italy is conducted after dry land tillage (De Datta, 1981; Hill et al., 1991; Blanche et al., 2012). The most important soil characteristic for the water seeding rice production is the presence of an impervious subsoil layer that minimizes the percolation of irrigation water. The seedbed is fairly rough, with clods as large as 10 cm in diameter and corrugated or V-shaped surface grooves. The fields are flooded, and pre-germinated seeds are then sown. They float less, because they are trapped in the crevices between the clods or in the grooves.

In water seeding, water control is classified into three methods, according to the period of drainage during plant establishment: continuous, pinpoint, and delayed flooding (Blanche et al., 2012). In continuous flooding, the field is not drained, and the seedlings are assumed to be firmly anchored to the soil. In pinpoint flooding, the field is drained at the time of coleoptile emergence for several days which aims to ascertain the penetration of roots into the ground. Then, the field is re-flooded controlling the water level precisely at the depth of seedling height. In delayed flooding, drainage period after the coleoptile emergence is prolonged for several weeks. Although the establishment of plants is most common in delayed flooding and least common in continuous flooding, weeds are least suppressed in delayed flooding and most suppressed in continuous flooding among the three water control methods.

In contrast, water seeding is uncommon in Asia (Balasubramanian and Hill, 2002; Chauhan, 2013). When farmers change the planting method from transplanting to direct seeding, they generally practice puddling. Floating is a major cause of poor plant stands when using water seeding in puddled soil (Tuong et al., 2000). Because the surface of the puddled soil is smooth and because the density of the sown seeds is not large enough to prevent floating, plants fail to root and anchor. Seeds do not float in wet seeding. Although the field is puddled, it is drained before the seeding and thereafter until the completion of plant stand establishment. Farmers break the levee and dig shallow ditches across the field after puddling to ensure the drainage of the entire fields (Pathinayake et al., 1991). The differences in practices of successful farmers between wet seeding and water seeding are as follows: the former is puddled, whereas the latter is not, and sowing is conducted after drainage in the former and during flooded conditions in the latter.

Weed infestation is heavier in wet seeding than in transplanting. Although fields are flooded most of the time in transplanting, they are drained for prolonged periods in wet seeding. Weeds and weedy rice become problems when farmers switch from transplanting to wet seeding (Chauhan, 2013), which is the main reason why adoption of wet seeding has been slow.

Sowing seeds in the subsurface layer of flooded soil prevents the seedlings from floating (Mitsushi, 1975, 1982). However, this can result in oxygen deficiency (Jones, 1933), soil reduction (Aomine and Narita, 1943), and sulfide (Kawaguchi, 1944; Akamatsu, 1969) and ferrous Fe (Hagiwara and Imura, 1993; Yamauchi, 2000) toxicity. The use of Ca peroxide (Yamada, 1952; Ota and Nakayama, 1970) or anoxia-tolerant cultivars (Yamauchi et al., 2000) makes subsurface seeding feasible.

The adoption of subsurface seeding in farmers’ fields has been limited because of the cumbersome practice of seed
coating in the middle of the busy farming season and because of the requirement of precise seeding depth. Controlling seeding depth is difficult in puddled soil because the soil surface condition changes from fluid and soft to sticky and hard over time after puddling.

Pre-germinated seeds are used in water seeding and wet seeding because they germinate faster than dry seeds. In addition, they are superior in landing and settling on the surface of flooded soil relative to dry seeds because the density of pre-germinated seeds (1.3 Mg m\(^{-3}\)) is greater than that of dry seeds (1.0–1.1) due to the soaked water (Mitsuishi, 1975). However, pre-germinated seeds have a disadvantage: they have to be prepared just before seeding; when seeding is delayed, their germination progresses too far, and their handling becomes difficult.

**Seed Priming**

Seed priming is a technique that improves seed vigor by exposing seeds to wetting and drying, low temperatures, salt solution, or osmoticum (Heydecker, 1974). High-vigor seeds germinate and establish faster than low-vigor seeds (Association of Official Seed Analysts, 1983).

Seed germination is subdivided into the imbibition, activation of metabolic processes, and post-germination growth stages (Takahashi, 1960; Yoshida, 1981). Imbibition is a physical process that takes 18 to 24 h. Activation is a chemical process and is affected by temperature. It is known that treatments in which seeds are soaked in water, incubated, dried, and then stored increase the germination rate (speed) of various plants (Hanson, 1973; Lush and Groves, 1981; Pill, 1994; Turner, 2008).

We confirmed that the seed treatment of soaking, incubation, and drying increases the germination rate of rice even at low temperatures or under anoxia and that the treatment is effective not only in Japonica but also in Indica cultivars (Yamauchi, 2002b; Mori et al., 2012). Andoh and Kobata (2002) reported that seeds that had been soaked and then dried have increased α-amylase activity and a high germination rate. Thus, the treatment of soaking, incubation, and drying is a useful priming method. Primed rice seeds could be utilized in direct seeding in lieu of pre-germinated seeds.

**Improvement of Anchorage**

Seedlings should be anchored firmly to the soil in the successful plant stand establishment in water-seeded puddled fields. Mitsuishi (1975) increased the seed density, by placing different lead weights on individual seeds. The seeds were floated less and rooted and anchored better as the increase in the density. It was determined that rice seeds with a density greater than 2.11 Mg m\(^{-3}\) allowed the seminal roots to penetrate into the puddled soil at a water depth of 10 cm.

The reported genetic variation in seed density is between 1.08 and 1.14 Mg m\(^{-3}\) in southern U.S. long grain rice (Gravois, 1992). Seeds of a single cultivar have a wide range of densities. Selecting high-density (1.20 Mg m\(^{-3}\)) seeds using salt water is feasible. However, the densities of these seeds are not sufficiently high for proper anchoring.

Morohashi et al. (1988) found that adding clay to rice seeds is effective for preventing seedlings from floating. These authors used polyvinyl acetate resin adhesive to prevent the dispersion of clay in water. The seed density required for direct seeding should be determined not only by field conditions but also by cultural practice. Field conditions may include water movement as affected by wind speed and soil physical surface conditions. The density required in the continuous flooding of water seeding might be greater than that required in pinpoint or delayed flooding.

**Producing High-Density Seeds with Reduced Iron Powder**

Reduced Fe powder was found to be promising as a coating material for increasing seed density (Yamauchi, 2002a). The density of reduced Fe is 7.9 Mg m\(^{-3}\), which is greater than that of Fe oxides (5.1–5.7), Ca peroxide (1.7), Ca sulfate (2.3), the primary material of soil (i.e., crystal, orthoclase, and muscovite) (2.5–3.1), and organic matter (1.2–1.7). Although the densities of Cu, Ag, Pb, Au, and Pt are between 8.9 and 21.4 Mg m\(^{-3}\), their use as seed-coating materials is not cost effective.

The coating layer should have both mechanical and underwater strength. The mechanical strength is required to prevent the smashing of the coating layer during seeding. Because the seeds are sown and germinate in water, the coating layer should not collapse or separate from the seeds in water. Because rice is produced in large areas annually, the amount of material used for the coating would be substantial. Therefore, the coating materials should preferably be natural, exerting a minimal effect on the environment.

We found that rust (Fe oxide), the oxidation product of reduced Fe, serves as a binder which helps form a coating layer (Yamauchi, 2004, 2010a). Water and oxygen are required for the oxidation of Fe, which is accelerated in the presence of sulfate or chloride salts. Calcined gypsum is convenient among the tested salts because of its low solubility (and therefore does not cause salt injury to seeds) and because of its ability to coagulate when it contacts water (which helps in the process of seed granulation with Fe powder).

We analyzed the composition of Fe in the coating layer (Yamauchi, 2010a). The oxidized Fe in the coating layer was composed of 0.97 to 0.99 kg kg\(^{-1}\) amorphous Fe oxides and 0.01 to 0.03 kg kg\(^{-1}\) α, β, γ-Fe oxyhydroxide and magnetite. We may assume that amorphous Fe oxides operate as a binder that does not dissolve in water, preventing the collapse of the coating in water.

The weight ratio of oxidized Fe to total Fe in the coating layer ranged from 0.23 to 0.34, suggesting that reduced Fe was partially oxidized (Yamauchi, 2010a). We believe that the surface of Fe particles is oxidized such that it can bind to the other Fe particles or to seed husks and that the inner part of the particle is not oxidized.

Reduced Fe is easily oxidized, producing heat in the presence of salts and water. The heat increases the seed temperature if it is not discharged, and ultimately, the seeds lose their viability. One prerequisite is to discharge the heat by spreading the granulated seeds as a thin layer under the atmosphere or by ventilating them with air. The former can be done without mechanization, but the latter requires special devices.

**Integration of Seed Priming and Iron Coating**

When farmers use primed seeds, they do not need to pre-germinate the seeds before planting. The use of Fe-coated seeds prevents the occurrence of floating seedling in the water.
seeding of puddled soil. Integrating the preparation of primed and Fe-coated seeds makes water seeding in puddled soil without soaking and incubation during the busy farm season feasible. Because dry seeds are storable, Fe-coated seeds could be prepared during the off-season.

**PROCEDURE FOR DIRECT SEEDING WITH IRON-COATED SEEDS**

The direct seeding technology with Fe-coated, primed dry seeds was first proposed in 2004 (Yamauchi, 2004, 2010a). Then, the Kubota Corporation and the National Federation of Agricultural Cooperative Associations, in cooperation with the steel, machinery, fertilizer, pesticide, and herbicide industries, evaluated the technology in farmers’ fields nationwide and began disseminating it. The technology has been improved iteratively through the modification of the procedure according to its performance in the farmers’ fields. Iron-coated seeds were prepared by farmers or supplied from agricultural cooperatives or private companies. The procedure described below is currently recommended for use by farmers in the latest manuals (Yamauchi, 2010b; Yamauchi et al., 2016a; Kubota Corporation, 2014).

**Preparation of Iron-Coated Seeds**

Iron-coated seeds are prepared in three steps: the granulation of pre-germinated seeds with a mixture of reduced Fe powder and calcined gypsum, followed by surface coverage with calcined gypsum or silica gel; the oxidation of Fe on the husk with the simultaneous discharge of heat; and drying (Fig. 2).

**Seeds**

The optimum temperature and time of soaking and incubation vary between cultivars and/or seed sources. For most of the cultivars used in Japan, suitable temperatures and times range between 13 and 20°C and between 3 and 6 d, respectively. The percentage and rate of germination are reduced by Fe coating, presumably due to the requirement of increased penetration power for coleoptiles through the coating layer and due to the deterioration of seed physiology associated with drying after pre-germination. When seeds have a germination percentage of >95%, the Fe-coated seeds have a germination percentage of >90% (Yamauchi, 2004). The decrease in germination percentage by the coating treatment increases when we use seeds with a low germination percentage.

**Materials for Coating**

The mean particle size of reduced Fe powder suitable for rice seed granulation should be <100 μm. The atomized Fe powder adheres less to the husk. The following materials have been commercialized for the preparation of Fe-coated seeds: reduced Fe powder F55 (JFE Steel Corporation, Tokyo, Japan), DAE1K (Dowa IP Creation Corporation, Okayama, Japan), and Fe powder for agricultural use (Tetsugen Corporation, Tokyo, Japan).

We use calcined gypsum suitable for ceramic molding with a high water carrying capacity, such as plaster of Paris for Class A pottery materials with a water carrying capacity of 73% (Mutsumi Chemical Industries, Mie, Japan). The calcined gypsum is mixed with Fe powder at 0.1 kg kg⁻¹.

Seeds covered with a mixture of reduced Fe powder and calcined gypsum tend to stick together, forming hard blocks during Fe oxidation. To prevent this effect, the surfaces of seeds granulated with the mixture of reduced Fe powder and calcined gypsum are covered with calcined gypsum at a rate of 0.05 of the Fe powder weight.

Silica gel is more effective for preventing the formation of blocks than calcined gypsum (Yamauchi, 2015). The silica gel suitable for this has a mean particle size of between 4 and 113 μm and a pore size between 7 and 21 nm. The silica gel suitable for preparing Fe-coated seeds is commercialized (Fuji Silysia Chemical Ltd., Aichi, Japan). The amount of silica gel needed is 0.015 kg kg⁻¹ of the seed dry weight.

**Iron-Coating Ratio**

The amount of Fe used to coat a seed is expressed as the Fe-coating ratio, that is, the weight of the reduced Fe powder to the weight of the seeds. The ratio can be varied from near 0 to 4.0. The optimum Fe-coating ratio varies with the seeding conditions. A ratio of 0.5 is commonly used in water seeding with pinpoint or delayed flooding water control. When we perform water seeding with continuous flooding in a puddled field, a ratio as high as 2 was preferable. Our preliminary study indicated that the Fe-coating ratio could be reduced to as low as 0.05 without sacrificing grain yield (Yamauchi, 2006).

**Granulation**

The seeds were covered with a mixture of Fe powder and calcined gypsum as an inner layer and with calcined gypsum or silica gel as an outer layer (Fig. 2 and 3) by using tumbling granulation. The seeds were rolled in a pan granulator or in a concrete mixer whose mixing blades were removed from the drum. We used a seed-coating machine (KC-151, Keibunsha Seisakusho, Fig. 2. Process of Fe coating rice seeds.)
Hiroshima, Japan) when coating <10 kg of seeds and a concrete mixer with a drum capacity of 110 L (NGM-4, Tombo Industry Corporation, Hyogo, Japan) when coating 40 to 80 kg of seeds.

Water was sprayed onto the rolling seeds in the granulator to allow the powdery mixture of Fe powder and calcined gypsum to adhere to the seed surface. The amount of water sprayed ranged from 0.27 to 0.12 kg kg⁻¹ of Fe powder and was influenced by the properties of the Fe powder and the amount of water contained in the seeds. Because the water in the granulated seeds is lost to evaporation over time, excess water application is preferable to limiting water application.

After covering the seeds with the mixture of Fe powder and calcined gypsum, calcined gypsum or silica gel was poured into the granulator so that the seed surface was wrapped.

**Iron Oxidation, Heat Discharge, and Drying**

The reduced Fe powder adhered to the surface of seeds must be oxidized, during which heat is generated. The heat must be discharged so that the seed temperature is below 40°C to maintain seed viability (Yamauchi et al., 2016a).

The seed temperature is determined by the balance between the generation and discharge of heat, which depends on the shape of the seed container, the properties of the reduced Fe powder, the amount of water contained in the granulated seeds, and the temperature, humidity, and wind speed of the work place.

The generation of heat is low when the Fe-coating ratio is low. When the coated seeds are left in bulk in a container, the seed temperature gradually increases, peaking as high as 60 to 80°C within a few hours, and then slowly decreasing to ambient levels.

The heat can be discharged by spreading the granulated seeds on a platform that exposes them to air (Fig. 3). We recommend using a nursery box (inner size of 580 mm length by 280 mm width by 28 mm height with drainage holes) to spread the granulated seeds at 1 kg per box. Because this box is standardized and commonly used in Japan for raising seedlings in machine transplanting by rice farmers, the condition of spreading the granulated seeds can be standardized among farmers. Although it is feasible to discharge the heat by spreading the granulated seeds onto the sheeted floor, we do not recommend doing so because the conditions could vary between farm yards, increasing the risk of heat injury.

The oxidation reaction ceases as the granulated seeds lose water due to evaporation. We spray water on the granulated seeds contained in the box to restart oxidation after one or more days (Fig. 3).

The seeds are air-dried thereafter for at least 1 wk. Although the surfaces of the granulated seeds become brown and dried, the seeds under the coating layer contain various amounts of water. Therefore, the seeds are stored in the box until seeding (Fig. 3). When we store the Fe-coated seeds in plastic bags, the water content of the seeds must be below 130 g kg⁻¹ to avoid the temperature increase over 40°C (Shiratsuchi et al., 2012). It is important to note that the processes of oxidation, heat discharge, and drying are not controlled and are variable, as determined by workplace and climate conditions.

**Mass Production**

An apparatus in which Fe oxidation, heat discharge, and drying are performed was developed through the alteration of a flat-type through-circulation dryer (Model HED330, Kaneko Co. Ltd., Saitama, Japan) (Fig. 4, Yamauchi et al., 2008). The granulated seeds were placed in net bags (10 or 20 kg in each). The maximum loading capacity of the drying box was 500 kg in terms of dry seed weight. The flow rate of the discharged air was 90 m³ min⁻¹.

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**Fig. 3. Procedure for producing Fe-coated seeds at the small scale. This diagram illustrates the procedure of using nursery boxes, which are commonly used in the machine transplanting culture of rice. For granulation using the seed-coating machine, pre-germinated seeds are wrapped with a mixture of reduced Fe powder and calcined gypsum with water spray. Then, the surfaces of the granulated seeds are covered with a thin layer of calcined gypsum or silica gel.**

For Fe oxidation, heat discharge, and drying, the granulated seeds are treated in nursery boxes. Wood blocks are placed between the nursery boxes to facilitate heat discharge. Because granulated seeds lose water to evaporation after one or more days, water is sprayed to restart oxidation. Next, the oxidation heat is discharged again, and the Fe-coated seeds are partially air-dried within a week.

The Fe-coated seeds are stored, simultaneously air-dried in nursery boxes. The nursery boxes are piled up to save space until they are used for seeding.
The processes of Fe oxidation, heat discharge, and drying could be completed in the apparatus within 2 d. Water was sprayed on the Fe-granulated seeds in the drying box at 10.6 L h⁻¹ for 6 to 12 h with simultaneous air circulation during Fe oxidation and heat discharge. Continuous air circulation is essential for the discharge of oxidation heat. After the water spray, the seeds were dried by circulating the air for 6 to 12 h at room temperature (10–30°C). Then, the temperature of the circulating air was set to 35°C for the next 24 h. The water content of the Fe-coated seeds prepared in this way was 0.1 kg kg⁻¹. The mass production of Fe-coated seeds has been conducted successfully by agricultural cooperatives (Muraoka et al., 2011) and private companies.

**Appearance, Germination, and Storage of Iron-Coated Seeds**

The prepared Fe-coated seeds varied in appearance, particularly in color (Fig. 1). When the Fe-coating ratio was low, we observed the surface roughness of the husk through the coating layer. The seeds whose Fe in the coating layer was well oxidized with plenty of water spray were completely brown, whereas those that underwent limited oxidation and less water

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**Fig. 4.** A conceptual diagram of an apparatus for the mass production of Fe-coated seeds. The Fe-coated seeds are placed in the drying box (size: 1800 by 1800 by 425 mm in length by width by height) with up to 500 kg in dry seed weight. Thick arrows indicate the air flow required to discharge the oxidation heat and dry the seeds. The water is sprayed from three nozzles placed above the drying box for 6 to 12 h, as indicated by dotted lines. Then, the seeds are air-dried for 12 h. Finally, the air temperature is increased by the burner to 35°C to dry the Fe-coated seeds for 24 h. The seeds are stored at room temperature and used for seeding.

**Fig. 5.** Types of water management in the direct seeding of Fe-coated rice seeds. The shaded area indicates flooding or irrigation.
Japan is reported to be 100 plants m–2 (Mitsuishi et al., 1990; plant density for high grain yield in broadcast direct seeding in percentage of established plants vs. sown seeds). The optimum density for achieving maximum grain yield and plant stand (the rate could be reduce to as low as 25 kg ha–1 for the hill seeding) are consistent even when the plant stand is varied. The seeding rate, conducting mechanical weeding, and reducing lodging.

The plant distribution is controlled precisely in hill or row seeding. Although hill or row seeding requires a seeding machine and is more time-consuming than broadcast seeding, the former might be advantageous over the latter for reducing the seeding rate, conducting mechanical weeding, and reducing lodging. The plant distribution is controlled precisely in hill or row seeding because the distances between hills or between rows are consistent even when the plant stand is varied. The seeding rate could be reduce to as low as 25 kg ha–1 for the hill seeding (Kubota Corporation, 2014). Currently, farmers in Japan prefer hill seeding over broadcast seeding because of the similarity in appearance to transplanting. Because the cultivars currently used by farmers were designed for transplanting, they might perform better using hill seeding than broadcast seeding.

**Cultivation with Iron-Coated Seeds**

**Seeding**

Iron-coated seeds can be directly seeded onto water-covered soil using broadcast, row, and hill seeding techniques (Fig. 5). No soaking or incubation is required before seeding. No furrow opening or covering is needed because of surface seeding. The seed is conducted after the settlement of soil particles in puddled field so that the seeds are positioned on the soil surface.

Broadcast seeding of Fe-coated seeds is conducted using a knapsack power applicator or radio-controlled helicopter in flooded fields. Broadcast seeding with a manned air flight is not practical because paddy fields in Japan are small.

Hill or row seeding is conducted simply by dropping Fe-coated seeds from the hopper to the soil surface. Although the field is flooded after puddling, it must be temporarily drained so that the seeds settle onto the soil surface in the form of a hill or row, to avoid being affected by water movement.

Water is introduced soon after seeding.

We recommend a seeding rate of 50 kg intact seeds ha–1 for direct seeding of Fe-coated seeds. The seeding rate was determined by the relationship between the optimum plant density for achieving maximum grain yield and plant stand (the percentage of established plants vs. sown seeds). The optimum plant density for high grain yield in broadcast direct seeding in Japan is reported to be 100 plants m–2 (Mitsuishi et al., 1990; Nagashima et al., 1990; Kataoka et al., 2006). Moreover, the plant stand of Fe-coated seeds is mostly 50% of the sown seed number, varying from as low as 30% to as high as 70% across Japan. The seeding rate was calculated on the basis of the seed number, assuming that the weight of a single seed is 25 mg.

Although hill or row seeding requires a seeding machine and is more time-consuming than broadcast seeding, the former might be advantageous over the latter for reducing the seeding rate, conducting mechanical weeding, and reducing lodging. The plant distribution is controlled precisely in hill or row seeding because the distances between hills or between rows are consistent even when the plant stand is varied. The seeding rate could be reduce to as low as 25 kg ha–1 for the hill seeding (Kubota Corporation, 2014). Currently, farmers in Japan prefer hill seeding over broadcast seeding because of the similarity in appearance to transplanting. Because the cultivars currently used by farmers were designed for transplanting, they might perform better using hill seeding than broadcast seeding.

**Weed Control**

Weeds are effectively suppressed by puddling. The water control of continuous or pinpoint flooding is advantageous over delayed flooding in the suppression of weed emergence after seeding. To ensure weed suppression, pre- and early post-emergence herbicides, which are safe for germinating rice seeds, are applied at seeding. Long or intensive drainage reduces the effectiveness of pre- and early post-emergence herbicides. When weeds emerge vigorously during the surface drainage period, we use post-emergence herbicides containing cyhalofop-buty1 and bentazone.

A post-emergence herbicide mixture, which is formulated by combining two to five active ingredients and which controls a wide variety of weed species with a single treatment, is applied to control weeds in fields. Herbicides containing cyhalofop-buty1, bentazone, and linuron are applied to yield improvement. Herbicides are applied at the appropriate growth stage of weeds to achieve maximum weed control effectiveness. Although herbicides are used to control weeds, they may affect the soil microorganisms and the growth of rice plants. The recommended herbicide rates are determined by field conditions and the growth stage of weeds.

**Water Control**

Water after seeding Fe-coated seeds is controlled in the same way as for pre-germinated seeds in water seeding after dry land tillage (Fig. 5). In pinpoint and delayed flooding, the field is surface drained at the emergence of coleoptile. It is re-flooded after rooting and first leaf emergence in pinpoint flooding and after the development of the second to fourth leaves in delayed flooding. Water is intermittently supplied during the drainage period when the Fe-coated seeds desiccate due to soil dryness (Sato et al., 2011).

The surface drainage at emergence protects the seeds from damage due to soil reduction, pests, aquatic living organisms, and water birds. Because the seeds are exposed directly to atmospheric oxygen, they may escape from the toxicity found in reduced soil (Yamauchi, 2000; Yamauchi et al., 2016a).

Rice water weevil (Lissorhoptrus oryzophilus), tadpole shrimp (Triops spp.), rice seed midges (Chironomus spp.), golden apple snail (Pomacea canaliculata), and pond snail (Lymnaeidae spp.) have been found to damage the seedlings of Fe-coated seeds in flooded soil (Kurihisa, 2009; Takimura and Hoshino, 2010). Infection with Pythium arrhenomanes, one of the causes of seedling rot, occurs in Fe-coated seeds in flooded soil at the stage between germination and first leaf development (Matsuura et al., 2012, 2013). These damages are similar to those reported in water seeding of pre-germinated seeds in non-puddled soil (Hill et al., 1998). No pests that are specifically associated with Fe-coating treatment have been detected. The insecticides and fungicides registered for these pests are effective in preventing damage.

Although complete drainage is a prerequisite for achieving stable plant stand establishment in pinpoint or delayed flooding water seeding, it is difficult to achieve this in puddled fields because puddling reduces the percolation rate. When we intend to drain the field after puddling, it is common for patches of shallow water pools to remain and not disappear in slick spots in slightly depressed portions of a field for a prolonged time. These patches occur even in the laser-leveled fields after puddling. Installing internal open-channel drains or digging shallow ditches across or around a field is effective in diminishing the appearance of water pools (Yamauchi et al., 2016a).

The required surface drainage period varies according to the conditions of fields, particularly the activity of pests and aquatic living organisms and the speed of seedling growth. This period must be as long as 3 wk with delayed flooding when the fields are infested with golden apple snails or harbored by water birds. In contrast, plant stands in continuous or pinpoint flooding systems are successful when the temperature is low because of the low activity of living aquatic organisms, because of the lower intensity of soil reduction, and because of the favorable conditions for seedling growth due to the heat-maintaining effect of water.
at the time of plant stand establishment (i.e., the first to fourth leaf stages, under flooded conditions). Fields sown with Fe-coated seeds are managed in the same way as fields used for transplanting cultures after the application of the herbicide mixture. A list of herbicides suitable for the direct seeding of Fe-coated seeds has been reported (Japan Association for Advancement of Phyto-Regulators, 2016).

Pesticide Usage

Pest control of direct seeding is more laborious and time consuming than that of transplanting. In transplanting culture, pests are controlled efficiently by the top dressing of a mixture of fungicides and insecticides to the seedlings before transplanting. In contrast, when using direct seeding of Fe-coated seeds, farmers must spray pesticides in the fields when they observe an outbreak of pest damage (Kubota Corporation, 2014).

A pest control method oriented for use in hill and row seeding Fe-coated seeds was developed and commercialized in 2015. The insecticide (a mixture of clothianidin and spinetoram) and fungicide (isotianil) are applied in the soil under hills or rows during seeding (Japan Agricultural Development and Extension Association and Kubota Corporation, 2015). This method is not applicable for broadcast seeding.

Grain Yields and Production Costs

There was no difference in grain yield between transplanting and water seeding of Fe-coated seeds in experimental fields (Yamauchi, 2006). When we increase grain yields, lodging should be reduced by the use of hill or row seeding or the introduction of suitable cultivars. The grain yields obtained by using Fe-coated seeds have been shown to increase when hill seeding is followed by drainage because lodging was reduced (Sato and Azuma, 2013). In another study, the use of a lodging-resistant cultivar produced as much grain as transplanting (Terata, 2016).

The use of fertilizers designed for direct seeding may increase grain yield (National Federation of Agricultural Cooperative Associations, 2015b). Currently, many farmers are using fertilizers designed for transplanting in direct-seeded fields.

The grain yield in direct seeding of Fe-coated seeds is approximately 90% of the yields obtained from transplanting in farmers’ fields (National Federation of Agricultural Cooperative Associations, 2015a, 2015b). However, labor cost is effectively reduced by the shift from transplanting to the water seeding of Fe-coated seeds. One study showed that the labor requirement for the water seeding of Fe-coated seeds was 70% of the transplanting (National Federation of Agricultural Cooperative Associations, 2015a, 2015b, 2016a, 2016b).

On the other hand, the cost of material inputs was not significantly reduced by the shift. The cause was increased herbicide use due to the failure of weed control by farmers inexperienced with direct seeding. We may expect the herbicide use could be reduced over time as farmers become familiar with direct seeding.

In addition, it was found that the current low grain yield in farmers’ fields originated from inadequate cultural practice. An analysis of data obtained in experimental and farmers’ fields from 2003 to 2015 demonstrated that the seeding rate in farmers’ fields ranged between 25 and 65 kg ha⁻¹ and that the grain yield decreased when the seeding rate was <40 kg ha⁻¹ (Yamauchi et al., 2016b). Optimizing the seeding rate may increase grain yields to the levels obtained from transplanted rice.

CHARACTERISTICS OF IRON-COATED SEEDS

Seed Density

Iron coating efficiently controlled seed density over the range of 1.1 and 3.1 Mg m⁻³ with a coating ratio between 0 (non-coating) and 4 (Fig. 6). A density of 1.2 Mg m⁻³, which could be obtained through genetic improvement or selection with salt water, could be attained by adding Fe at a coating ratio of 0.08. The seeds prepared using a standard Fe-coating ratio of 0.5 had a density of 1.6 Mg m⁻³, which is not attainable biologically. Therefore, Fe coating is an efficient method for increasing seed density.

Bird Control

Protecting sown seeds from bird attack is a prerequisite for establishing a successful plant stand. In Japan, direct seeding is commonly complicated by interference by the tree sparrow (Passer montanus) and spot-billed duck (Anas poecilorhyncha). When a field is drained, sparrows attack and destroy the seeds, and when a field is flooded, ducks eat the rice seeds. Therefore, it is difficult to protect direct-seeded rice from avian attacks.

In experimental fields, we observed that Fe-coated seeds are resistant to sparrow attack (Yamauchi, 2003). This observation was later confirmed in production fields (Mizusawa, 2009). Seed coating also provided protection against the Oriental greenfinch (Carduelis sinica) (Watanabe et al., 2006).

The damage of rice seeds by sparrows or greenfinches seems to be reduced by increasing the mechanical strength of the coating and does not originate from repellent action. Sparrows and greenfinches are observed in fields sown with Fe-coated seeds, and some of the seedlings are eaten or uprooted. When the Fe-coating ratio is increased, the damage is reduced (Yamauchi, 2006; Chikawa et al., 2014). The Fe-coating ratios required for preventing sparrow and greenfinch attack are 0.5 and 1.0, respectively.

Ducks fly in flooded fields and eat Fe-coated rice seeds. Because ducks do not visit drained fields and because sparrow attack is prevented by Fe coating, drainage is the best method for protecting fields from sparrows and ducks.

Control of Seed-Borne Diseases

It is well known that seed-borne diseases are serious in rice (Goto et al., 1988; Kato et al., 1988). In transplanting culture, seeds must be disinfected with chemicals or hot water (60°C for 10 min) before preparing seedlings.

Coating rice seeds with Fe has been shown to suppress the occurrence of seed-borne diseases, including bacterial seedling blight (Burkholderia plantarii), bacterial grain rot (Burkholderia glumae), bacterial brown stripe (Acidovorax avenae subsp. avenae), “Bakanae” disease (Gibberella fujikuroi), brown spot (Cochliobolus miyabeanus), and rice blast (Pyricularia grisea) (Inoue et al., 2009, 2012; Miyagawa et al., 2013). Hoshino et al. (2008) found that Fe coating reduces the viability of white-tip nematode (Aphelenchoides besseyi) in seeds and the occurrence of disease symptoms. It has been suggested that the active oxygen that evolves from the Fe-coated layer is involved in disease suppression (Fujiwara et al., 2012).
The physiology of seed priming should be studied to improve Fe-coating technology and plant-stand establishment. It has been reported that the germination rate does not always increase following consecutive soaking, incubation, and drying treatments (Andoh and Kobata, 2000; Chikawa et al., 2014). Additionally, in some cases, we observed a decrease in the germination percentage (Andoh and Kobata, 2000; Chikawa et al., 2014). Moreover, field experiments in India showed that Fe coating was effective for promoting plant growth and grain yield in an area where it rains heavily at seeding (GuruPraka et al., 2014). It has been explained that the shift from transplanting to direct seeding in Asia is caused not only by labor shortages but also by water scarcity (Kumar and Ladha, 2011). Further study is required for the technology to be utilized widely in view of water conservation.

**Evaluating the Performance in Varying Soil and Water Conditions**

The performance of Fe-coated seeds should be evaluated in different soil and water conditions. Although Fe coating is practiced in water seeding puddled fields, Fe-coated seeds could be applied in wet seeding simply by both advancing and delaying the time of drainage (Fig. 5).

When the water holding of the field is high enough to produce a rice crop, puddling may be omitted. Because the rice grain yield is maximized at a percolation rate between 5 and 15 mm d$^{-1}$ (Isozaki, 1961), fields with a percolation rate <15 mm d$^{-1}$ would not require puddling. The feasibility of the direct seeding of Fe-coated seeds in non-puddled soils has been demonstrated in two ways with the same seeding depth and seeding rate used in water seeding.

The first method is water seeding in non-puddled soil with Fe-coated seeds (Fig. 5). Although water seeding in non-puddled soil is widely practiced in the United States with pre-germinated seeds, there is no need to prepare the grooves in seedbeds when Fe-coated seeds are employed due to the prevention of seedling float. This seeding method was demonstrated to be feasible in warm and cold regions in Japan (Yamauchi, 2010c, 2011; Sasaki and Kumagai, 2011).

The second method is the dry seeding of Fe-coated seeds (Fig. 5) in tilled and non-tilled dry soil. Sowing on ridge produces a better plant stand than on flat soil (Tanabe et al., 2013). Seeding depth and water management are different from the commonly practiced dry seeding with intact dry seeds: Fe-coated seeds are seeded on the soil surface, whereas intact dry seeds are in the subsurface layer; Water is introduced soon after seeding Fe-coated seeds, whereas after plant establishment, that is, 2 to 3 wk after seeding intact seeds. Flash irrigation or flooding should be performed shortly after dry seeding of Fe-coated seeds because the prolonged exposure of dry Fe-coated seeds to sunlight increases the temperature of the Fc (Yamauchi, 2011).

Reducing the Production Cost and Increasing Profits

Lowering the Fe-coating ratio may not only ease seed coating work but also reduce the cost of Fe. The improvement of cultivation technology may reduce the Fe-coating ratio.

The Fe-coating ratio could be further reduced if cultivars that float less are employed. A difference in anchorage among cultivars has been reported (Inoue et al., 1997; Uchimura et al., 2001). Although hybrid rice produces more grain than conventional cultivars, they have been produced by transplanting culture.
because of the high cost of seeds. A high seeding rate is generally considered one disadvantage of direct seeding compared with transplanting. Now that the seeding rate required for direct hill seeding of Fe-coated seeds is equivalent to that required for transplanting, hybrid rice could be produced by direct seeding (Wang et al., 2014). However, this possibility needs to be verified. The change in the socioeconomics of rice farming associated with the introduction of direct seeding with Fe-coated seeds should be clarified. Farmers who practice direct seeding wish to purchase Fe-coated seeds rather than prepare them by themselves so that they may have more time to spare and then intensify the production of crops more profitably than rice.

CONCLUSION

Iron-coated rice seeds exhibit high density, improved anchorage, and resistance to sparrow attack and seed-borne diseases. Iron-coated rice seeds are prepared by oxidizing reduced Fe powder on the husk of pre-germinated seeds manually or using mechanization for large amounts of seeds. These seeds can be stored at room temperature for more than 1 yr and can be sown without soaking or incubation. This technology has been successfully introduced in water seeding in puddled fields in an irrigated ecosystem by broadcast, row, and hill seeding. The technology is available internationally without restriction by patents and could be applicable to not only puddled but also non-puddled rice fields in water and dry seeding with further onsite studies.

REFERENCES


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