

Raising of Rice Seedling and Mechanical Transplanting: A Review and Perspectives

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Abstract: The mechanical rice transplanter offers effective solutions for timely seedling transplanting, mitigating labor shortages, and enhancing cropping intensity in rice farming. A key factor for successful mechanized transplanting is mat-type seedlings, which are essential for seamless operation. Mechanized seeding offers an efficient alternative for large-scale rice farms, significantly reducing labor requirements while enhancing uniformity. This paper explores crucial aspects of seedling raising, including seedling density, plant height, age, stem thickness, and growth base material. It also provides a comparative analysis of traditional methods for cultivating and transplanting rice seedlings, outlining their respective advantages and limitations. The review highlights current practices and challenges in adopting mat-type seedling techniques. Utilizing a mechanical rice transplanter with mat-type seedlings presents unique opportunities to mechanize rice production. Key benefits include timely planting, lower planting costs, increased crop yields, and reduced labor demands. The study proposes strategies to make mat-type seedling techniques more accessible and cost-effective for rice farmers, ultimately positioning mechanical transplanting as a viable pathway to sustainable rice production in Bangladesh.

Keywords: mat-type seedling, seedling raising, growing media of seedling, seedling parameter, mechanical transplanting

Citation: Paul, H., B. C. Nath, M. A. Hossen, S. Paul, S. Islam, M. G. K. Bhuiyan, M. K. Pinto, and M. M. Ahmmed. 2026. Raising of rice seedling and mechanical transplanting: A review and perspectives. *Agricultural Engineering International: CIGR Journal*, 28(1):44-71.

1 Introduction

Bangladesh is the fourth-largest rice-producing country and has achieved self-sufficiency in rice production, like many other nations (Gurung et al., 2017; Nath et al., 2024). Rice security is essential in ensuring food security in Bangladesh (Brolley, 2015; Nath et al., 2021), which currently has a production surplus, feeding approximately 174 million people

(Jalilov et al., 2022). Rice contributes around 4.5 percent to the national gross domestic product (GDP) of Bangladesh (Khushi et al., 2020). As Bangladesh's most economically and politically significant crop, rough rice is produced in 38.70 million tons across the Aus, Aman, and Boro seasons, covering an area of 11.77 million hectares with an average yield of 3.18 tons per hectare (Hossain, 2020).

Labor scarcity and high labor costs are significant

Received date: 2025-02-15 **Accepted date:** 2025-07-15

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challenges during rice cultivation, particularly during transplanting and harvesting (Nath et al., 2021). The total labor requirement for rice cultivation is between 642 and 708 man-hr per ha, with seedling raising and transplanting accounting for 19%-22% of this demand (Islam et al., 2016). Delayed planting results in a productivity loss of approximately 4.75% (Kabir et al., 2020). The share of hired labor in agriculture declined from 19.4% to 15.5% between 2000 and 2010 due to increased urban migration (Emran and Shilpi, 2018). Additionally, rice yield is heavily influenced by the timing of transplantation. Given these conditions, mechanical rice transplantation is essential to address labor shortages during transplanting seasons, reduce overall cultivation costs, ensure timely operations, and boost production output per hectare (Ashik-E-Rabbani et al., 2018).

Bangladesh's agriculture-driven economy is steadily shifting from traditional practices to modern agricultural systems (Mujeri and Mujeri, 2021). At the heart of this transformation is farm mechanization, which is progressively expanding. Mechanization helps ease the drudgery of manual labor, tackles labor shortages during critical periods, lowers production expenses, and supports the conservation of vital resources (Biggs and Justice, 2015). The innovation and advancements in mechanized transplanting technology are significant milestones for rice-producing countries. Japan invented the first rice transplanters in the 1960s, with widespread adoption and improvements seen throughout the 1970s and 1980s (Haytham et al., 2010). A two-row Japanese rice transplanter (AP200) can transplant rice seedlings approximately 20 times faster than manual methods, achieving nearly 100% accuracy with minimal missing hills (Hossen et al., 2022a). Since the 1980s, Bangladesh has seen an increase in the use of mechanical involvement in agricultural activities, with several processes, such as tillage, irrigation, and threshing, already mechanized. However, certain operations, such as transplanting and harvesting, remain largely untouched by mechanization (Islam and Shirazul, 2009; Nath et al., 2021). Recently,

mechanical transplanting has become popular in various regions of Bangladesh, where farmers have responded positively to its benefits (Paul et al., 2016). However, seedling preparation remains challenging due to the lack of available technology, hands-on agronomic practices, and adoption initiatives.

The mechanized transplanting system represents a modern approach that combines agricultural machinery with agronomic techniques (Syed et al., 2019). To ensure effective coordination, seedling production and transplanting services should be integrated. Achieving uniform seedling density is essential for the success of mechanical transplanting. Seedlings intended for this method must fulfill three main criteria: (1) a compact seedling mat with a density of 2–3 seedlings per cm² at the 3-leaf stage; (2) well-bound roots with a soil layer of 2.0–2.5 cm; and (3) healthy seedlings with a height of 12–15 cm, free from disease. These seedlings can be grown using different techniques, including dry or soft seedbeds placed on polythene sheets, or in flexible and rigid trays (Sarolia et al., 2018).

Using a rice transplanter is fundamental for mechanized rice transplanting, with mat-type seedling raising being both mandatory and advantageous due to its compatibility with transplanters and superior seedling performance (Hossen et al., 2022a). Although mat-type seedling raising has attracted global interest, limited research remains on its application in Bangladesh, especially across different farm sizes. Due to technical limitations and social acceptance challenges, the potential of this seedling method may not be fully realized in the country. A thorough evaluation of seedling-raising methods, coverage rates, agronomic practices, and seedling characteristics is essential to close this research gap. While prior studies have examined aspects like seedling preparation (Sarkar et al., 2019), the timing of transplanting (Sarker et al., 2013), soil setting periods (Paul et al., 2016), seedling placement accuracy (Basir et al., 2021; Rahman et al., 2023), and transplanter efficiency (Huda et al., 2024), a comprehensive review of mat-type seedling raising remains absent. This study

responds to the need by undertaking a comprehensive review of existing literature on rice seedling practices, identifying the most suitable technologies for Bangladesh, assessing their social implications, and comparing the advantages and limitations of various methods. The review aims to support sustainable seedling management and promote the transition to mechanized and environmentally friendly rice cultivation. It reveals existing knowledge gaps, identifies challenges farmers encounter with mat-type systems, and proposes areas for future research to enhance the adoption of these techniques among growers.

2 Geographic and climatic perspective of Bangladesh and importance of seedling raising

Bangladesh lies between 20°34' and 26°38' north latitude and 88°01' and 92°41' east longitude, within the fertile delta formed by the Ganges, Brahmaputra, and Meghna rivers. This geographical setting offers plentiful water resources, nutrient-rich alluvial soils, and a subtropical monsoon climate that is highly favourable for rice cultivation (Rahman, 2021). The country supports three primary rice-growing seasons—Aus (pre-monsoon), Aman (monsoon), and Boro (dry winter)—each corresponding to specific rainfall and temperature patterns (Al Mamun et al., 2025). Annual precipitation ranges from about 1,200 mm in the northwest to over 5,000 mm in the northeast and southeast, with average temperatures generally between 20°C and 30°C. These environmental factors, along with the extensive river systems and floodplains, provide ideal conditions for rice farming. Nonetheless, production is also affected by climatic challenges such as floods, droughts, soil salinity, and cold stress during the Boro season, highlighting the need for adaptive strategies and resilient rice varieties.

Seedling raising is a crucial component of rice transplanting in Bangladesh's agricultural system, primarily due to the country's reliance on rice as a staple food and economic driver. With rice cultivated

across over 11.55 million ha, the quality of seedlings directly influences crop establishment and yield, underscoring the importance of proper seedling-raising practices (Al Mamun et al., 2021). Farmers can protect seedlings from diseases and environmental stressors by providing optimal growing conditions in nurseries, resulting in more vigorous plants that thrive post-transplantation (Gallegos-Cedillo et al., 2024). The significance of seedling raising is amplified by Bangladesh's distinct rice-growing seasons—Aman, Boro, and each—which present unique climatic challenges. Controlled environments for seedling raising help mitigate the adverse impacts of weather, such as cold spells and heavy rains, particularly during the Boro season (Tamanna et al., 2021). This strategy ensures a consistent supply of healthy seedlings, facilitating continuous crop production despite fluctuating climatic conditions. Additionally, effective seedling raising supports the increasing adoption of mechanized rice transplanting, which is vital in addressing labor shortages. Mechanized systems require uniform, healthy seedlings grown in mat-type nurseries to withstand mechanical transplanting (Choudhary and Machavaram, 2023). Furthermore, managing diseases like seedling blight—common in traditional nurseries due to high humidity—is crucial for maintaining seedling health (Singh et al., 2019). Techniques such as applying iron compounds and fungicides can effectively control this disease, leading to higher survival rates and improved growth after transplantation. Ultimately, robust seedlings enhance the cost-efficiency of rice production by ensuring better crop stands, reducing gaps in the field, and increasing overall yields. This efficiency enables farmers to shorten the time required for crop establishment, optimize land use, and support more crop cycles each year. Given rice's central role in ensuring food security and supporting the economy, seedling raising is essential for maintaining the productivity and sustainability of Bangladesh's agricultural sector.

3 Seedling raising method

Rice cultivation begins with nurturing high-quality seedlings, which significantly influence yield, accounting for around 50% of the total harvest (Haider et al., 2022). Rice is commonly grown using two main methods: direct seeding and transplanting. In direct seeding, seeds are sown directly into the field, whereas transplanting involves first raising seedlings in a

nursery and then moving them to the main field for cultivation. Seedlings can be raised using various methods, such as wet bed, dry bed, dapog, mat, or modified mat techniques, depending on local conditions, soil type, ecosystem, and resource availability (Figure 1).

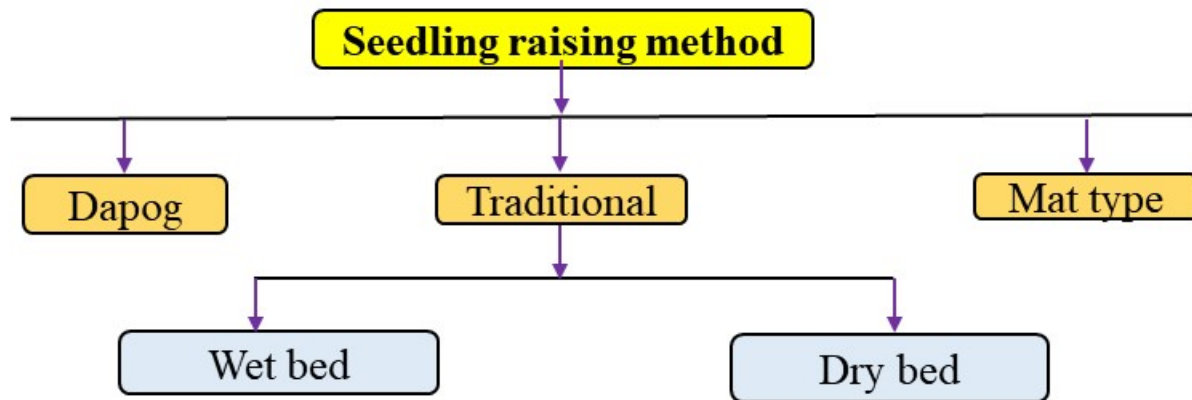


Figure 1 Seedling raising method

3.1 Traditional seedling raising

In the traditional method of raising rice seedlings, the seedbed is prepared by puddling the soil and leveling the surface. Seeds are pre-soaked in water and kept in a warm environment to encourage sprouting. Once sprouted, the seeds are evenly distributed over the seedbed. Depending on the rice variety, seedlings are typically transplanted into wet fields at 20 to 30

days of age (Rao et al., 2017). This process involves uprooting the seedlings, washing them, bundling them, and transporting them to the main field for transplanting. It is highly labor-intensive, requiring over 300 labor-hours per hectare for seedling production, uprooting, and transplanting (Table 1) (Hossen et al., 2020b).

Table 1 Facts of the traditional seedling raising method

	Particulars	References
	Simple and popular method	
Advantages	Suitable in local conditions and resource availability Effective for small to medium-scale operations	(Rao et al., 2017;
Disadvantages	High labor requirement Time-consuming process Risk of seedling damage during uprooting and washing Requires a large land area for seed beds	Hossen et al., 2020b)
Labor Requirement	Requires more than 300 workers/ha for seedling raising, uprooting, and transplanting Intensive labor input for the entire process	(Hossen et al., 2020b)
Cost	Generally lower initial cost compared to mechanized methods Costs associated with manual labor and land preparation	

3.1.1 Wet bed seedling raising method

The wet bed technique is commonly used in areas with dependable water supplies (Figure 2). In this method, the soil is puddled and leveled before seeds are broadcast, with drainage channels added to manage excess water. A small amount of inorganic fertilizer supports vigorous seedling growth. Typically, seedbeds are prepared two weeks before planting, with

a width of 1-1.5 m and a height of 4-5 cm, which is suitable for the field area (Table 2). Seeds are soaked for 24 hours, then incubated for another 24 hours, and finally spread evenly across the seedbed. Around 50 kg of seed is needed for 500 m², which supplies one ha of transplanted field (Kega et al., 2015). Other studies echo these practices; Gautam et al. (2013) recommend preparing beds 25-30 days in advance, using 1-1.5 m

wide raised beds with 15 cm high and 30 cm wide channels between them. This approach uses roughly 800 m² of seedbed area ha⁻¹, with sprouted seeds sown in moist beds for 4-5 days, ready for transplanting within 25-30 days. Cheng et al. (2018) suggest that

after two days of puddling, a narrower bed of 1.25 m with 30 cm wide channels suits sloped fields. For even distribution, two to three fistfuls of seed m⁻² are required, and seedlings are ready for transplanting at 20-25 days of age



Wet-bed method

Dry-bed method

Dapog method

Figure 2 Different types of seedling beds

The International Rice Research Institute (IRRI) recommends using a seedbed area of approximately 10% of the intended transplant area, which requires 40-50 kg of seed ha⁻¹. Improved varieties are best transplanted 15-21 days post-germination. Similarly, the Rice Research and Development Institute (RRDI)

prescribes 50 kg of sprouted seeds ha⁻¹, soaked for 24 h, incubated for 48 h, and spread evenly over the moist seedbed, with seedlings ready for transplanting in 12-21 days, depending on the variety (Shweta and Malik, 2016).

Table 2 Facts of the wet-bed seedling raising method

Advantages	Disadvantages	Remarks	References
Efficient use of water where supply is available. Produces vigorous seedlings. Suitable for areas with drainage facilities. Reduces weed infestation.	Requires significant labor for puddling and drainage canal construction. Needs a constant water supply. Potential soil erosion if drainage is improper.	Requires proper preparation and seed soaking timing to ensure the best seedling quality for transplanting. Ensuring proper moisture and drainage is essential for developing vigorous seedlings; excessive water can lead to poor seedling health, and water stress can inhibit growth.	(Sahu and Kumar, 2020; Bouman et al., 2007)

3.1.2 Dry bed seedling raising method

The dry bed seedling raising technique is commonly utilized in regions with limited water availability (Table 3). Seedbeds are typically 50-100 cm wide and 5-10 cm high, accounting for approximately 10% of the transplantable area (Saha et al., 2015). This method requires a higher seed input, typically 80-100 kg, due to lower seed establishment rates than the wet bed method. Seedlings are pulled 15-21 days after establishment and transplanted immediately. Maintaining the seedbeds in a moist state for optimal growth (Mondal et al., 2021). A significant advantage of the dry bed technique is its resilience to heavy rains, which can hinder the wet bed method. Although the dry bed method is not widely popular,

light soils are considered ideal for this practice (Shahid et al., 2021). The soil is prepared by pulverizing it without the use of water. Raised beds, 8-10 cm in height, 1-1.5 m in width, and 8-10 m in length, are formed, with 30 cm-wide drainage channels between them. To support one hectare of land, 50-60 seedbeds are required (Vries and Meertens, 2014). Seedbeds should be 1.25 meters wide with a height of 15 centimeters, separated by 30-centimeter-wide drainage channels to ensure adequate water drainage. Seeds should be sown in rows 10 cm apart in dry or moist soil, ensuring the seedbeds remain consistently moist. A thin layer should be applied five days after sowing. Dehghan et al. (2016) also suggests that 50 kg of seed and 500 m² of seedbed area are sufficient for planting

one hectare. Water applications can be regulated to control seedling growth, and the seedlings are usually ready for transplanting 25-30 days after sowing. The RRDI supports the use of raised seedbeds and planting approximately 150 kg of seed ha⁻¹, recommending a

layer of half-burnt paddy husk or sawdust for easier uprooting (Salman et al., 2023). The dry bed technique remains a practical and efficient approach, especially in water-scarce regions, promoting healthy seedling growth with minimal irrigation requirements.

Table 3 Features of the dry bed seedling method

	Particulars	Remarks	References
Advantages	Suitable for areas with limited water. Allows seedlings to grow even during heavy rain. Requires less water for bed preparation.	Highly effective for regions where irrigation is difficult or limited during seedling preparation.	(Wang et al., 2017)
Disadvantages	Higher seed rate (80-150 kg ha ⁻¹) due to lower establishment rates. Requires constant moisture control.	More seeds are required, and controlling moisture without excess water can be challenging.	(Mahapatra et al., 2012)
Optimal Bed Dimensions	Width: 50-100 cm. Height: 5-10 cm. Length: Variable.	Proper bed height and drainage ensure healthy seedling growth, preventing waterlogging and moisture stress.	(Gautam et al., 2013)
Seed Requirements	Drainage channels: 15-30 cm wide between beds. 80-150 kg of seed ha ⁻¹ , depending on region and variety. Seed beds cover approximately 10% of the transplantable area.	Seed quantity is higher due to a reduced seedling establishment rate, so this should be considered during planning.	(Soriano et al., 2018)
Water Management	Beds kept moist but not waterlogged. A thin layer of water may be used after 5 days of sowing. No moisture stress allowed.	Maintaining a delicate balance of moisture is critical for seedling health without causing excessive water consumption.	(Nagargade et al., 2018)

Table 4 Comparison of dapog method

Advantages	Disadvantages
Requires less land and water, making it suitable for areas with limited resources.	Higher initial costs due to materials like plastic sheets and rice straws.
Seedlings grow faster and more uniformly, allowing for earlier transplanting and potentially higher yields.	Shallower root systems and slower establishment in the field.
It is easier to manage, with less labor for weeding and irrigation.	Waterlogging is a potential risk, requiring careful management.
The risk of soil erosion is minimized due to the hard surface of the nursery bed.	Environmental conditions, such as temperature and moisture, must be controlled for optimal results.
Seedlings can be easily transported, providing convenience for fields far from the nursery.	The risk of disease is higher, necessitating regular monitoring and possible treatments.
	Fertilizers and chemicals may be required, which can increase both costs and environmental impacts.

3.1.3 Dapog method

The Dapog rice growing method, originating in the Philippines, is designed for efficiency in regions with limited space and resources by raising seedlings on flat surfaces without direct soil contact (Table 4). Seedbeds can be placed on platforms such as elevated surfaces, banana stalk rafts, or concrete floors, typically requiring only 100 m² ha⁻¹. Seeds are sown at a rate of 25-30 kg ha⁻¹, and seedlings are ready for transplanting within 12-15 days. Consistent irrigation is essential for preventing water stress. Kega et al. (2015) found that 25 kg of seed, spread over 60-75 m², can be sufficient for one ha in the dapog method. Biswas et al. (2009) supports the notion that 25-30 m² of space is adequate for seedling preparation. Singh et

al. (2020) confirmed the use of raised seedbeds, suggesting 1 kg of seed m⁻² with a 10% urea solution applied to 15-day-old seedlings for better establishment. According to the IRRI (http://www.knowledgebank.irri.org/ericeproduction/II.5_Nursery_systems.htm), sprouted seeds at a density of 1.5-3 kg m⁻² can provide sufficient seedlings for a 200 m² field. The RRDI (https://doa.gov.lk/rrdi_cropeestablishment_landpreparation_on_dapog/) indicates that the seedling area typically constitutes approximately 1/20th of the land used for transplantation. Seedlings are transplanted 12-14 days after germination, following a 48-hour soaking and 24-hour incubation process.

3.2 Mat type seedling

Mechanized transplantation involves more notable seedling development than conventional transplanting. Mat-type seedlings are produced using a casing or frame in a plastic tray or polythene sheet (Table 5). However, tray preparation includes the use of dry or clay soil. Seedling production is the most crucial stage for mechanical transplanting. The preparation of mat or tray-type rice seedlings may start 15-20 days before the expected transplanting time (Joseph et al., 2015). The mat-type seedling preparation requires considerable effort to fill the soil and distribute the germinated seeds on the tray (Ashik-E-Rabbani et al., 2017). The optimal mat thickness for seedling raising is around 20-25 mm, regardless of the time, diversity, and growth phase (Dixit et al., 2007). The seed rate is significant in maintaining the proper growth of seedlings. 130 g for bold grain, 140 g for medium and slender grain, and 120 g for extra-long and slender variety are recommended to avoid missing hills during the operation of a mechanical transplanter (Hossen et al., 2018a). The germination rate of paddy seeds used for making seedlings should be 90% or higher. If the seed germination rate is low, then the seed rate should be increased proportionally. The loose soil should be lightly covered after spreading the seeds on the tray. Then, light

irrigation should be given through jharna. Mechanical transplanting is typically best performed on seedlings that are 15 to 20 days old in Aman (non-irrigated and hot season) and 25 to 30 days old in Boro (irrigated and cold season) (Malik et al., 2019). It was also mentioned that this process takes 14-18 days to produce healthy seedlings, measuring 18-20 cm in height with 2-3 leaves, and reduces labor requirements for seedling raising. Mat-type rice seedling raising requires around 40% of the total energy in mechanical transplanting, while traditional seedling raising in manual transplanting requires only 11% of the total energy (Baruah et al., 2001). The technique of raising mat-type rice seedlings is somewhat complicated, and farmers are not familiar with executing proper seedling management, which substantially impacts machine efficiency. The Ministry of Agriculture in Bangladesh developed the notion of synchronized rice seedling transplanting to get around the obstacles with rural roads and smallholding constraints (Islam et al., 2021). It is still in the research stage. This type of seedling, grown in a thin layer of soil and organic compost mixture placed on a polythene sheet or a plastic tray, is indispensable for mechanical rice transplantation.

Table 5 Summarizing mat type seedling method

Mat-type seedling methods	Advantages	Comments	References
Plastic tray	Plastic trays are durable and can be reused multiple times, reducing the need for repeated purchases. Seedlings grow uniformly in trays, making transplanting easier and more consistent.	While plastic trays are reusable, their production and disposal can have significant environmental impacts if not managed properly.	(Haytham et al., 2010); Mamun et al., 2013; Hossen et al., 2018a)
Polythene sheet	Polythene sheets are relatively inexpensive and widely available. They allow for easy lifting of the entire mat, reducing root disturbance during transplanting. The sheet also helps retain moisture in the soil, promoting better seedling growth.	Polythene is not biodegradable, leading to waste management challenges if not disposed of properly.	(Joseph et al., 2015; Ashik-E-Rabbani et al., 2017; Malik et al., 2019)
Pot seedling	Each seedling can be individually monitored and cared for, enabling more effective management of rice seedlings. Seedlings experience minimal root disturbance during transplanting, which reduces transplant shock and promotes faster establishment of the plant.	The cost of pots and the time required for individual handling may be higher, making this method more suitable for smaller-scale, high-value cultivation rather than large-scale operations.	(Hu et al., 2014; Pitoyo and Idkham, 2021)

3.2.1 Mat-type seedling raising on a plastic tray

The seedlings are grown in plastic trays, commonly referred to as seedling trays, in a mat-type seedling raising system. Different-sized trays are used

based on the line-to-line spacing and the farmer's demand. One is a plastic tray with dimensions of 580 mm × 280 mm × 25 mm (Figure 3a). This tray size is suitable for a 30 cm line-to-line spacing in

transplanting. Two types of plastic trays, rigid and flexible, are used for raising seedlings. Rigid trays are expensive but reusable for many years. Flexible trays are economical but are only used once. The crushed and sieved soil is filled into the tray, and sprouted seeds are sown over it. Then, flat land is used to set up seedling trays, and the seedlings are raised. The seedling tray is placed on a van and carried to the rice fields after the seedlings are mature enough to be transplanted. A transplanter is then utilized to transplant the seedlings (Haytham et al., 2010).

Mamun et al. (2013) mention that the soil mixture (soil with cow dung, ash, sawdust, poultry manure, etc.) is placed into seedling trays arranged on a plain field with a height of 20 mm. The germinated seeds are spread uniformly over the tray. Then, the seeds are covered with the soil mixture prepared before and irrigated by sprinkling water to keep them moistened. Different amounts of seed are determined in each tray depending on the grain size. The seed is required to be 120-150 g tray⁻¹ according to grain size (Hossen et al., 2018c).

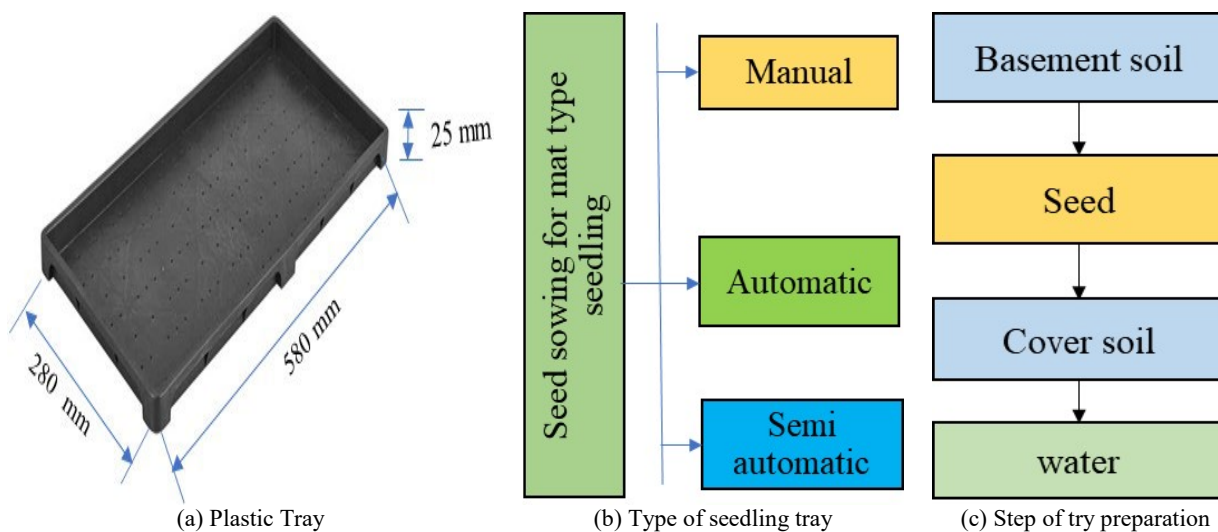


Figure 3 Mat-type seedling particulars

3.2.2. Mat-type seedling raising on polythene sheet

An alternative to seedling trays is typically polythene sheets. The polythene sheets are made with 0.2-0.3 cm diameter perforations spaced 2 cm apart (Figure 4). The perforated sheet assists in forming a dense mat, enhances drainage and aeration, and prevents the seedling roots from penetrating the surrounding soil. The field is well-plowed and leveled to prepare a wet bed for mat-type seedlings. A raised bed is ready, measuring 20 m in length, 1.5 m in width, and 10-15 cm in height. The bed settles for 36-48 h, and a perforated polythene sheet is placed over the bed. Then, the soil is set over the polythene sheet in a 1.27 cm thick layer (Jini and Joseph, 2019). Ashik-E-Rabbani et al. (2017) reported that a seedling bed dimension of 1.5 m wide, 2000 cm long, and 15 cm thick must be prepared on a leveled field for

mechanical transplanting of a 0.40 ha main field. The dry sieved soil, with a farm yard manure ratio of 4:1, is placed and leveled on a perforated polythene sheet with a thickness of 1.5-2.0 cm (Sudhir et al., 2017). Additionally, seedlings are raised on a thin layer of soil, ranging from 1.27 cm to 1.90 cm, placed on a perforated polythene sheet. However, a germination rate of above 80% at 10-15 kg of inbred or 8-10 kg of hybrid seed is required for one acre of mechanical transplanting with 26-28 hills m⁻¹ and 2-3 seedlings/hill, respectively (Jini and Joseph, 2019). After sowing the seeds, the seeding bed is enclosed with a 0.5 cm layer of the prepared soil mixture. Seedlings 18–20 cm in height, with 2 to 3 leaves, are the most suitable for mechanical transplantation (Sudhir, 2017).

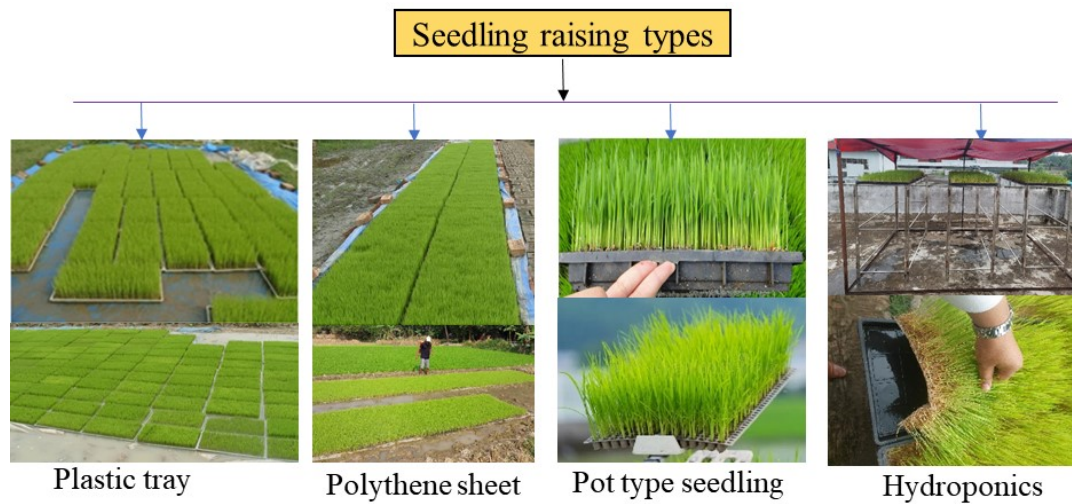


Figure 4 Seedlings raised on various materials

3.2.3. Pot-type seedling

Mechanical pot seedling transplantation for rice is an innovative method that can replace mechanical mat-type seedling transplanting (Figure 5). This method utilizes advanced technology for transplanting rice seedlings in fields according to specific row and hill spacing, thereby minimizing plant injury. Hu Qun et al. (2017) reported that rice transplanted with mechanical pot seedlings had a shorter seedling growth period, rapid initial growth, an appropriate peak population quantity, greater yield, and better quality. For hybrid rice, mechanical pot seedling transplantation resulted in a proper panicle number, a high-quality starting population, and more substantial photosynthetic matter production, leading to an increase in the number of spikelets/panicle (Table 6). However, the enormous row spacing of the transplanting machine, even with the minimal plant spacing of 12 cm, leads to low-density planting for typical standard japonica rice varieties, which reduces crop yield. The rice seeds are sown in specific amounts of 2- 4 into every hole using a plastic pot for seedlings. The quantity of sowing

seeds will be much more efficient in fewer numbers (Pitoyo and Idkham, 2021). Kega et al. (2015) stated that the plastic tray with dimensions of 59 cm x 34 cm and 434 embedded holes is used to raise pot-type seedlings. Approximately 750 trays and 250 m² of seedbed area are required for planting on one hectare. The seed rate is 15–20 kg to plant one ha. The effects of plant spacing on plant shape and micrometeorology influence the transplanting of pot seedlings (Guo et al., 2015). A planting density of 26.88×10⁴ hills ha⁻¹ in mechanical pot seedling transplanting using wide-narrow row generated considerably more panicles/area and somewhat more grain number/panicle, resulting in the maximum yield (Hu et al., 2020). Mechanical pot-type seedling transplanting is sown rice seeds earlier, while early sowing advances rice heading and increased average daily temperatures of the filling stage accelerate the grain filling method (Xing et al., 2017; Yao et al., 2011). Yield is increased using pot seedling transplanting technology and maximum efficiency (Zhu et al., 2014).

Table 6 Summarizing the features of a tray for pot-type seedling transplantation

Substances	Description	References
Soil	- Typically includes a growing medium suitable for seedling development - Often a mixture of soil and organic substances	(Hu et al., 2014; Pitoyo and Idkham, 2021)
Water	-Required to maintain moisture for seedling growth - Regular irrigation is needed to keep the soil in the tray moist	(GUO et al., 2015; Kega et al., 2015)
Seed	- Rice seeds are sown in specific amounts, usually 2-4 seeds/hole - Efficient seeding in a minimal number of holes	(Pitoyo and Idkham, 2021)
Area Cover	-Plastic trays are covered to maintain humidity and prevent drying - Tray dimensions are specified (e.g., 59 cm x 34 cm)	(Kega et al., 2015)



Figure 5 Pot-type seedling for rice transplanter

4 Growing media preparation for mat-type seedling

A special seedbed is needed for mat-type seedling raising (Dixit et al., 2007). The soil is the main hindrance to the development of mat-type seedlings due to the use of topsoil on agricultural land. Therefore, the regular height of agrarian land will gradually be reduced to an average level. Different growing media can also be used to avoid utilizing topsoil in mat-type seedling preparation. Research has utilized various media for mat-type seedling growth (Hossen et al., 2022a). Raising the seedling involves physical labor, including soil preparation and placement. Different types of soil media can be used to raise seedlings. The pulverized soil is filtered to prepare a seedling bed and fill the trays. The tray is made by pouring the mud from a low area. The polyethylene sheet is set up on the soil bed, and any accessible mud from the lowland is placed on it. The mud soil developed better roots (Ashik-E-Rabbani et al., 2017).

4.1 Soil with organic substances as growing media

The use of raised mat-type seedlings has a significant influence on the composition of the growing media. Seedlings are produced on plastic trays using two different types of soil: sandy clay loam and sandy clay, both of which are mixed with organic elements derived from decomposed cow dung, rice bran, rice husk, and tea waste to achieve optimal combinations (Table 7). Sandy clay loam performed superior in seedling mat rolling quality over sandy clay soil. The growing media, which consisted of 10% to 15% cow dung or rice bran mixed with both types of

soils, was suitable for producing good-quality mat-type seedlings for mechanical transplanting (Hossen et al., 2020a). Further research showed that both soil types were ideal for mat-type seedlings and seedling height, when supplemented with 10% to 30% cow dung, organic rice straw fertilizer, vermicompost, 10% poultry litter, and 20% to 30% rice bran. However, the quality of the seedlings differed among the organic fertilizers in the following order: cow dung, rice bran, vermicompost, poultry litter, rice straw organic fertilizer, and mustard cake. Clay loam soil performed higher on rolling quality than sandy loam soil (Hossen et al., 2018b). Additionally, high-quality mat-type seedlings are produced by mixing 5% to 15% cow dung and rice bran with sandy clay loam and sandy loam soil, respectively. On the contrary, applying 15% to 20% rice husk and tea waste to sandy clay loam soil, and 10% to 15% to sandy loam soil, produced good outcomes (Shahed et al., 2020). Mamun et al. (2013) also found that a medium containing 25% cow dung, rice husk, or poultry manure mixed with 75% soil grows good-quality seedlings and improves field performance.

Using rice straw as a seedbed is another medium that has improved the characteristics of seedlings, including shoot length, root weight, shoot dry weight-to-shoot length ratio (DW/L), nutritional content, biomass, and seedling vigor. Mat-type seedlings were more easily obtained. The seedling mat could be planted using a rice transplanter without remodeling (Haytham et al., 2010). Different proportions of media are used to raise stable and strong rice seedlings. Purwantoro (2016) reported that the mixed growing

media (domestic peat: sand = 2:1 and wormcast: domestic peat: sand =2:1:1) were suitable for the growth of rice seedlings. Pratiwi et al. (2020) stated that a water recirculation system is used with an appropriate combination of soil, compost, and biochar (soil: compost: biochar = 2:2:1) as a growing medium

for rice cultivation. Furthermore, as noted by Win et al. (2015), a 9:1 ratio of soil and rice hull ash as a media produced healthy seedlings with better seedling height and a higher seedling vigor index for mat-type seedlings during the dry season.

Table 7 Summarizing the organic substances used in growing media and their effects

Organic Substance	Remarks	References
Cow dung	Improved seedling quality and mat rolling Superior to other organic fertilizers in quality	(Hossen et al., 2020a); (Mamun et al., 2013)
Rice bran	Effective for good quality mat-type seedlings Better than some other organic fertilizers	(Hossen et al., 2020a); (Mamun et al., 2013)
Vermicompost	Suitable for seedling growth Lower quality compared to cow dung and rice bran	(Hossen et al., 2020a)
Rice husk	Effective when mixed at 15-20% with sandy clay loam Good outcomes for seedling production	(Shahed et al., 2020)
Rice straw	Lesser quality compared to cow dung, rice bran, and vermicompost	(Hossen et al., 2020a)
Domestic peat	Mixed with sand and worm cast, suitable for rice seedling growth	(Purwanto, 2016)
Worm cast	Mixed with domestic peat and sand, effective for rice seedling growth	(Purwanto, 2016)
Compost	Combined with soil and biochar (2:2:1 ratio), suitable for rice cultivation	(Pratiwi et al., 2020)
Biochar	Combined with soil and compost (2:2:1 ratio), it improves rice seedling growth	(Pratiwi et al., 2020)

4.2 Soilless substrates as growing media

The soilless substrate, hydroponically grown long-mat seedlings, is a novel growing medium for raising mat-type seedlings. The long-mat seedlings were compared to seedlings produced in organic substrates and traditional nutritive soil in terms of seedling quality, mechanical transplanting quality, field growth features, yield, and benefit-cost ratio. However, the tiller dynamics and crop cultivation of the long-mat seedlings, organic substrates, and control seedlings were not considerably different. Long-mat seedlings can replace conventional nutritive soil in growing seedlings without reducing crop yield (Lei et al., 2017). The hydroponically grown long-mat seedlings exhibited a more robust root system, a considerably lower leaf area index, and a prolonged transplantation period. The long-mat seedlings achieved high yield and efficiency of rice production because their mechanical transplantation quality was equivalent to that of the traditional soil method, and their seedling quality was superior to that of the control (Li et al., 2016). The 6 m-long and 28 cm-wide seedling mat was made of nonwoven fabric and entangled with plant roots. It was robust and adequate to handle a nonwoven cloth. Mat-type seedlings were obtained by rolling the long mat with hydroponically grown rice seedlings

(long-mat seedlings). The weight of mat-type seedlings was approximately 12 kg m⁻² and around one-fifth that of a traditional mat with seedlings produced in a soil bed. Coconut coir has been used as a medium for cultivating plants in hydroponic systems. (Urayama and Maruyama, 2009) state that the raising seedlings were hydroponically grown on coconut coir media, but their features are comparably inferior to those of the seedlings grown in soil media. Investigating the popularization and implementation of long-mat seedlings on a large scale is desirable to reduce the reliance on organic substrates and topsoil during mat-type seedling production.

5 Seed sowing techniques for mat-type seedlings

Sowing seeds at the right time is crucial for producing strong, vigorous seedlings, which contribute to healthy plant growth and a successful yield. Based on the rice variety and growing season, seeds should be sown approximately 15–20 days before transplanting (Joseph et al., 2015). When the main field area is too extensive to be transplanted all at once, staggered sowing in multiple phases is recommended to ensure each section receives seedlings of the appropriate age.

5.1 Manual seed sowing for mat-type seedling

Rice seeds are generally sown by hand on a tray or polythene sheet for mat-type seedling-raising activities. Seeds are spread out in a uniform density for the mat-type seedling; however, maintaining uniformity in hand broadcasting is challenging due to its laborious and time-consuming nature. The mat-type seedling raising required 71-77 man-hr ha⁻¹ (Islam et al., 2016). Seeds with a germination rate above 90% require growing seedlings. The effect of high-quality seeds is a lower seed rate, more uniform germination, vigorous seedlings, reduced replanting, fewer weeds, and a 5–20% increase in yields. After a 24-hour soaking and 24-hour incubation period, the seeds sprout (bud), and the first seed root grows 2–3 mm long. The pre-germinated seeds are approximately one seed cm⁻², evenly distributed and covered with a thin layer of dry soil (Killenga et al., 2020). Hossen et al. (2018b) confirmed that the germinated seeds/area depended on the paddy's seed rate and germination percentage. Sprouted seeds are suitable for spreading when the radicals and coleoptiles have lengthened to one-third of the seed length. After sowing, fine and loose soil was spread over the seeds to a depth of 3-5 mm, and the trays were kept in the shade (Dixit et al., 2007). It was also evaluated that at least 2-3 seeds cm⁻² are suitable for sowing to raise mat-type seedlings.

5.2 Mechanical seed sowing for mat-type seedling

Seedling uniformity is essential before transplanting rice with a mechanical rice transplanter. The spreading of seeds makes it difficult to achieve uniformity in manual seeding. The manual method of seeding is being gradually replaced by the more efficient mechanical method. The seeding machine reduces the seeding time and makes the seedling-raising process easier, requiring less effort and labor. Seeding machines are essential for facilitating sowing practices. Seedling transplanting with a mechanical device requires substantially less effort and time (1-2 ha person⁻¹ day⁻¹) than conventional transplanting (0.07 ha person⁻¹ day⁻¹) (Choudhary and Machavaram, 2022).

5.2.1 Mechanical seed sowing using a manually

operated seeding machine

A low-cost, manually operated seeding machine was developed to enhance efficiency and reduce labor in sowing operations, with ongoing research across organizations continually improving its design (Table 8). Comparative tests revealed a significant efficiency ratio of 51:1 between machine seeding and manual methods, showing improved seed distribution uniformity (Hossen et al., 2020b). Researchers have also developed Internet Things-enabled seed-sowing machines suitable for large-scale farms, allowing remote control and precise seed placement. For mat-type seedling raising, a seeding machine minimizes manual effort by sowing seeds uniformly (Senthilnathan et al., 2018). Baladarshini et al. (2017) introduced a universal automated seeder capable of planting various seeds with adjustable rates, enhancing versatility for different crops. Sharma and Singh (2008) devised a nursery raising device achieving a desirable density of 80-100 g mat⁻¹ at 1.03 mm sprout length with soil depth precision, reducing the time by 72.07%, labor by 33.33%, and costs by Tk. 1009 ha⁻¹. Garg and Dixit (2003) refined mat-type seeding by calibrating a seeder to accommodate different sprout lengths, saving 70%-80% of the time typically required for manual seed dropping. Adalinge et al. (2017) developed a single-operator machine that strategically places seeds and fertilizer in rows, ensuring optimal depth and spacing while compacting soil over the seed, thereby boosting yield potential. Kathiravan and Balashanmugam (2019) created an efficient, manually operated seed with a direct drive shaft for seed metering, eliminating pulleys and belts to reduce costs. This machine simplifies seed placement at optimal depth and spacing, reducing labor and energy requirements and enhancing productivity by effectively compacting soil over seeds to promote maximum germination and yield.

5.2.2 Mechanical seed sowing using a power-operated seeding machine

A power-operated automatic seed-sowing machine for large-scale mat-type seedling production can efficiently handle all essential tasks, including soil

spreading, seed sowing, covering, and controlled watering for germination (Table 9). This machine is designed to sow seeds uniformly at an optimal density, which is crucial for high rice yield. Research across institutions has supported its economic viability, encouraging new entrepreneurs to produce mature-type seedlings, as seen in developed countries, where this is commercially available. The effective use of such machines could also enhance the adoption of rice transplanters, benefiting commercial rice-sowing operations. The performance of the power-operated seed-sowing machine (Model: JK 3000, South Korea) was evaluated with various rice varieties under different conditions, demonstrating its efficiency (Figure 6). Capable of preparing approximately 440 trays h^{-1} with only 2-3 laborers, it is a time-saving technology that reduces manual labor (Paul et al., 2019). Rizaldi (2017) designed a mechanical seedling

machine that achieved accuracy rates of 94.4% for soil thickness, 83.4% for seed distribution, and 55.5% for fertilizer application. Each tray was prepared in approximately 10 seconds, consuming an average of 247.5 watts of power. Further developed an automated tray-laying system featuring a gantry truss and sensor controls, achieving up to 380 trays hr^{-1} with a horizontal tray spacing accuracy of 25 ± 5 mm, improving efficiency by 35.7% (Zhou et al. (2021). Deshmukh and Verma (2018) developed an automatic seed-sowing machine equipped with a DC motor and chain drive, capable of sowing 12 kg hr^{-1} , thereby reducing labor and costs. Shinde and Awati (2017) developed a machine with battery-powered wheels and a seed drum mechanism, integrating an ultrasonic sensor to prevent obstructions, ensuring smooth and waste-free operation.

Table 8 Overview of advanced seeding technologies for efficient and sustainable rice cultivation

Researcher(s)	Technology Developed	Key Features	Impact/Outcome
Hossen et al. (2020b)	Low-cost, manually operated seeding machine	Improved efficiency, reduced labor, improved seed distribution	Efficiency ratio 51:1 vs manual sowing
Senthilnathan et al. (2018)	Seeding machine for mat-type seedling raising	Uniform seed sowing, reduced manual effort	Efficient for raising mat-type seedlings
Baladarshini et al. (2017)	Universal automated seeder	Adjustable seed rates, suitable for multiple crops	Enhanced versatility across crop types
Sharma and Singh (2008)	Nursery raising device	Achieved 80–100 g/mat seed density, 1.03 mm sprout length, precise soil depth	Reduced time by 72.07%, labor by 33.33%, and cost by Tk. 1009 ha^{-1}
Garg and Dixit (2003)	Calibrated mat-type seeder	Accommodates different sprout lengths	Saved 70%–80% of the time needed for manual seed dropping
Adalinge et al. (2017)	Single-operator machine for seed and fertilizer placement	Ensures proper spacing, depth, and soil compaction	Improved yield potential
Kathiravan and Balashanmugam (2019)	Manually operated seed drill with direct drive shaft	Eliminates pulleys/belts, reduces cost, simplifies seed metering	Reduced labor and energy use, improved germination and yield
	IoT-enabled seed-sowing machines	Remote-controlled, precise seed placement	Suitable for large-scale farming

Table 9 Different types of seed-sowing machines and their features

Type	Features	References
Manual	<ul style="list-style-type: none"> - Low cost - Ratio of machine seeding to manual seeding is 51:1 - Uniform seed distribution - Suitable for small-scale use - Can be operated by a single operator 	(Senthilnathan et al., 2018; Sharma and Singh, 2008; Garg and Dixit, 2003; Adalinge et al., 2017; Kathiravan and Balashanmugam, 2019)
Semi-automatic	<ul style="list-style-type: none"> - Place seed and fertilizer in rows - Minimizes effort and cost 	(Kathiravan and Balashanmugam, 2019)
Automatic	<ul style="list-style-type: none"> - Reduces seeding and fertilizer placement time compared to conventional methods - Performs soil spreading, seed sowing, covering, and watering - Can prepare up to 440 trays hr^{-1} - Reduces labor requirements and drudgery - Accurate soil, seed, and fertilizer application - High efficiency with tray laying 	(Rizaldi, 2017; Zhou et al., 2021; Deshmukh and Verma, 2018; Shinde and Awati, 2017)



(a) Manually-operated seed sowing machine

(b) Power-operated seed sowing machine

Figure 6 Rice seed sowing machine for mat-type seedling

6 Strategies to mitigate cold stress in rice seedling establishment in cold weather (Boro season)

Cold stress significantly limits rice growth and production at the seedling stage, affecting its geographic spread and yield, particularly during the Boro season when winter planting often delays transplanting (Figure 7). Studies show that delaying rice transplanting from the usual sowing date reduces yield by approximately 9% (Islam et al., 2008). Polythene sheds are commonly used to shield seedlings from cold weather, mitigating cold stress by effectively retaining solar radiation and increasing air temperature. For instance, seedling trays covered with a 0.04 mm thick white polyethylene shed daily and at night, experience less cold injury, enhancing seedling

growth (Kamruzzaman et al., 2014). Research by Tamanna et al. (2021) suggests that using 0.08 mm thick white polythene and a potassium-based treatment (MoP) further boosts seedling growth. Pre-treating seeds with fungicides like Atavo and Autostin under polythene covers also helps prevent fungal infections (Hossen et al., 2022b). Shahed et al. (2020) observed that mixing organic components with the base soil improves seedling quality, though it may increase fungal susceptibility. Polyhouse nurseries have shown potential for maintaining favorable conditions in cold weather, allowing earlier transplanting by a month (Parajuli et al., 2022). Meanwhile, rice breeders are actively working to develop cold-tolerant rice varieties at the seedling stage to address this persistent issue (Ratre et al., 2014).



Figure 7 Cold tolerance during the seedling period during cold weather (Boro season)

Low temperatures influence various physiological processes in rice, impacting its growth from germination to crop establishment. For rice seeds, 30°C is the optimal temperature for germination; however, they can still germinate satisfactorily at 20°C, though the rate steadily decreases below this threshold. Germination ceases altogether below 10°C, considered the critical minimum temperature. Similarly, root development is most favorable between 12°C–16°C, while shoot development can occur as low as 7°C–16°C, with 10°C being critical for both root and shoot growth (Basuchaudhuri, 2014). Cold tolerance at the seedling stage is particularly crucial for rice grown in direct seeding systems, as low temperatures can severely hinder seedling height, root formation, and overall survival (Priyanka and Jaiswal, 2017, Lone et al., 2018). This constraint is notable in Boro season rice production, where cold stress can directly impact the plant during germination, seedling, and reproductive stages. Shaikh et al. (2022) observed that during the Boro season, temperature fluctuations led to

variances in seedling emergence, mortality, and growth, underscoring the importance of timing and environmental control to mitigate the effects of cold stress.

7 Seedling parameter

The attributes of mat-type seedlings (mat thickness, seeding density, seedlings m², seedling age, and base material) must be adapted following the soil type to enhance the effectiveness of the transplanter (Hu et al., 2018). High seeding density, high rate of seedling mortality, poor seedling quality, and numerous seedlings/hills can all work against a high-yielding variety (Wang et al., 2014).

7.1 Seedling density

Seedling density in trays significantly influences seedling quality, making it essential to optimize the seeding rate for a uniform stand with an ideal plant population (Hamid et al., 2015). The density of seedlings/tray is affected by seed rate, germination rate, and seedling survival rate, which ensure optimal plant

establishment (Hossen et al., 2019). For indica rice, achieving a density of 1.5–3 seedlings/100 mm² is ideal for reducing missing hills and ensuring sufficient seedlings/hill (Choudhary and Machavaram, 2022). Seed requirements also vary by grain type, with 140 g tray⁻¹ for short, bold grains, 130 g for medium, slender grains, and 120 g for extra-long, slender grains to achieve the desired seedling quality and density for efficient transplanting (Hossen et al., 2018b). For rice varieties such as BRRRI dhan86, BRRRI dhan89, and BRRRI dhan92, 150–160 gm of seeds/tray yielded vigorous, mat-type seedlings suitable for mechanical transplanting (Shaikh et al., 2021). Studies by Kitagawa et al. (2004) recommend a seed density of 130–150 g tray⁻¹ to produce 3–5 seedlings hill⁻¹, though higher densities (over 160 g) can reduce emergence rates (Hossen et al., 2018b). Further research indicates that 120 g tray⁻¹ produces optimal results for hybrid paddy transplants (Basir et al., 2020). The success of mechanical transplanting is closely tied to seeding density and quality, underscoring the importance of precise seed rate adjustments to support high-quality rice seedling production (Liu et al., 2017).

7.2 Seedling height

Seedling height is a critical factor in mechanical transplanting, as lower seedling heights can lead to extended buried hills during transplantation (Rahaman et al., 2022). For optimal results, seedling heights should range from 100 to 120 mm during the Aman season, while shorter seedlings, around 80 mm or less, are preferable for the Boro season. A 120 to 150 mm seedling height with three leaves is typically considered ideal for mechanical transplantation (Manjunatha et al., 2010). Seed rates also significantly impact seedling height; for instance, BRRRI dhan92 consistently meets mechanical transplanting height criteria across different regions (Shaikh et al., 2021). Hossen et al. (2018a) found that a 130-g seed rate yielded a maximum seedling height of 112 mm, although variations in height may depend on the specific rice variety and regional factors. Additionally, Dhananchezhiyan et al. (2013) reported that while

maximum heights of 170.6 mm were achieved in organic soil media, a desirable height of 120 mm is most suitable for efficient transplantation.

7.3 Stem thickness

Stem thickness in rice seedlings is influenced by seeding time, with earlier seeding generally resulting in thicker stems. This characteristic is vital for mechanical transplantation, as stem thickness determines the number of seedlings delivered per stroke; a thicker stem limits the quantity of seedlings that can be offered. However, slender stems are more susceptible to shredding by the picker during transplantation. In a study by Shaikh et al. (2021), BRRRI dhan89 exhibited a maximum stem thickness of 1.72 mm across various locations, while BRRRI dhan86, BRRRI dhan89, and BRRRI dhan92 displayed stem thicknesses between 1.60 and 1.70 mm in the Rangpur region. Further research by Shaikh et al. (2022) reported that BRRRI dhan92 achieved the thickest stem at 2.21 mm. Factors such as soil fertility, environmental temperature, and the seedling medium also influence stem thickness and strength (Shahed et al., 2020). Notably, Hossen et al. (2018a) mentioned that a 100 to 120 g seed density/ray for BRRRI dhan28 resulted in significantly thicker stems than other densities and varieties. However, stem thickness generally decreases as the seed rate increases.

7.4 Seedling age

Seedling age is a crucial factor in rice cultivation, particularly for mechanical transplantation, as it significantly impacts plant establishment and yield. For optimal results, seedlings aged 15–20 days in the Aman season and 25–30 days in the Boro season are recommended for mechanical transplanting (Hossen et al., 2020b). Islam et al. (2016) corroborated this, suggesting that 12- to 15-day-old seedlings in the Aman and Aus seasons and 25- to 30-day-old seedlings in the Boro season are ideal for maximum yield. Similarly, Dixit et al. (2007) found that seedlings aged 15–25 days were well-suited for mechanical transplanting. Shaikh et al. (2021) observed that using 25- to 30-day-old seedlings minimized mortality in

tray-grown seedlings. Islam et al. (2015) highlighted that seedling age should range between 12 and 25 days, depending on the variety and season. Furthermore, Kumar and Kumar (2017) identified a positive correlation between seedling age and productivity, with 26-day-old seedlings transplanted using an 8-row self-propelled transplanter achieving high production efficiency. Li et al. (2020) noted that grain yield declined with seedling age, although no substantial yield difference was observed between 13- and 20-day-old seedlings. Vasudevan et al. (2014) also recommended treating 15-day-old seedlings with GA3 at 50 ppm and 20-day-old seedlings with an improved establishment with a walk-behind mechanical transplanter.

7.5 Seedling leaf

Leaf number is an alternative feature representing the physiological stage of transplanting seedlings in the field. Utilizing a specific seeding density has not noticeably improved the number of leaves or tillers (Pathania et al., 2016). Shaikh et al. (2021) reported that the number of seedling leaves in BRR1 dhan86, BRR1 dhan89, and BRR1 dhan92 achieved three leaves at 20 days after seeding and 4 to 5 leaves at 25 to 30 days after planting, respectively. Feng et al. (2015) state that seedlings with 4 to 5 leaves are suitable for mechanical transplanting into the field. Furthermore, machine transplanting requires seedlings with three leaves and a height of 120 to 150 mm (Manjunatha et al., 2010; Kitagawa et al., 2004). Priyanka and Jaiswal (2017) also evaluated whether seedlings with 2 to 3 leaves and a height of 18-20 cm are optimal for transplanting in the field.

8 Tray requirement and distribution strategies for efficient mechanical rice transplanting

The number of trays required for transplanting operations is directly linked to the number of seedlings/hills, which varies based on seedling density on mats, preset seedling adjustment options of the rice transplanter, and factors such as rice ecosystem, planting technique, seed quality, and rice variety. Tray

requirements can be classified into mechanical transplanting, gap filling, and pocket area filling. According to Islam et al. (2015), the tray requirement ranged from 148 to 183 trays ha⁻¹, with an average daily need of 167. Trays are utilized for mechanical transplantation in approximately 92% of cases, with only about 2% of missing hills requiring manual transplanting and 6% filled manually in pocket areas due to irregular plot shapes, a challenge arising from land fragmentation. The combination of seedling density in trays and machine density settings leads to variability in tray requirements, from 153 to 222 trays ha⁻¹, with distribution found to be 90% for transplanting, 6% for gap filling, and 4% for pocket areas, necessitating 18–20 man-hr ha⁻¹ for manual gap filling (Islam et al., 2017).

In another research, Hossen et al. (2018b) demonstrated that the number of practical strokes tray⁻¹ and the desired number of trays ha⁻¹ are influenced by the rotary picker's stroke area and the pre-setting of nine seedling adjustment options in the rice transplanter, revealing that the number of strokes/tray decreased from 1200 to 656 as the number of trays ha⁻¹ increased from 185 to 339 with adjustment changes. Hossen et al. (2020b) further noted that approximately 0.85 to 1.0 tons of loose soil are needed to prepare 185 to 225 trays for one ha of land. The requirement for seedling trays in mechanical transplantation typically ranges from 215 to 230 trays ha⁻¹, emphasizing the importance of calibrating space and seedling density settings before operations to determine appropriate plant spacing and tray needs. Islam et al. (2015) also found that higher density settings led to more seedlings being dispensed/hill, increasing tray consumption. In addition, about 25–27 trays are needed for a 33-decimal area, while approximately 190–200 trays are necessary for a ha. Specifically, Tegra requires 214 trays ha⁻¹ with a field capacity of 0.17 ha hr⁻¹ in Bogra and Natore. In contrast, an optimal tray consumption rate of 170 trays ha⁻¹ is economical for commercial transplanting, achieving a field capacity of over 0.2 ha hr⁻¹ (Islam, 2018).

9 Importance of healthy seedlings and

disease management

Growing healthy seedlings is crucial for successful rice cultivation, mainly using mechanical transplanters. Disease-free, robust seedlings are the foundation for achieving higher rice yields and ensuring efficient transplanting. One of the primary challenges in raising healthy seedlings is managing diseases such as seedling blight, which thrives under the high humidity conditions typical of mat-type seedling-raising systems. Ensuring proper nutrient management, agronomic practices, and disease prevention techniques can significantly enhance seedling health, resulting in more vigorous plants that are better equipped to withstand transplantation and environmental stress.

9.1 Nutrient-enriched growing media

The choice of growing media plays a pivotal role in developing healthy rice seedlings. Nutrient-rich substrates contribute to the overall growth characteristics of the plants, including better root development, increased height, and higher dry weight. Organic-based substances, such as mixtures of cow dung, rice bran, and poultry manure, provide essential nutrients like nitrogen (N), phosphorus (P), and potassium (K), which enhance seedling growth. Studies have shown that seedlings raised on nutrient-enriched media, particularly those with added nitrogen and phosphorus, accumulate up to 100% more dry matter than those grown in conventional soils (Ros et al., 1997). The presence of amino acids and other vital nutrients in organic-based media encourages early radical growth, making the seedlings more robust and stress-tolerant (Taiz and Zeiger, 2003). In particular, the nitrogen content is higher in seedlings grown on poultry manure than in other organic mixtures, such as cow dung and rice husk (Mamun et al., 2013), which contributes to more vigorous seedling health and lower mortality rates.

9.2 Agronomic management

Effective agronomic management is vital to raising healthy seedlings. Proper nutrient management during the early stages of seedling growth ensures that the

plants develop strong root systems, which improves their ability to absorb water and nutrients. The use of organic fertilizers like vermicompost, rice straw, and mustard cake has been found to have varying effects on seedling quality, with some media offering better results in terms of dry weight, height, and root density (Hossen et al., 2018b). Additionally, applying nitrogen and phosphorus during the seedling-raising period improves the seedlings' robustness. It enhances their tolerance to environmental stresses such as drought and nutritional deficiencies, ultimately leading to higher yields after transplanting (Ros et al., 2015). Furthermore, using media with high organic content, such as cow dung or rice bran mixtures, can lead to higher nutrient availability. However, excessive mixing of organic substances with the base soil can reduce the rolling quality of the seedling mat and increase fungal infections (Shahed et al., 2020).

9.3 Disease management

Managing diseases such as seedling blight is crucial for producing healthy seedlings, particularly when using the mat-type raising method. Seedling blight affects young rice plants and is common in high-humidity environments, such as those created in mat-type seedling trays. Infected seedlings often turn reddish-brown and dry out, their root systems becoming underdeveloped and prone to lodging (Saha et al., 2015). One of the most effective ways to control seedling blight is by applying iron compounds, which suppress the formation of tropolone, a compound associated with the disease (Ando et al., 2014). Fungicides like Carbendazim (Atostin) and Emistertop have also been shown to protect seedlings from fungal infections, especially in the cool and humid conditions of the Boro season (Shaikh et al., 2021). Proper water management, such as draining the seedling trays before applying fungicides, is essential to preventing the spread of infections. In addition to chemical treatments, agronomic practices such as using MoP fertilizer during the seedling stage can reduce biotic stress caused by low temperatures and fungal diseases, thereby improving the seedlings' overall health and survival rate (Hossen et al., 2022b).

10 Research in Bangladesh on mat-type seedling raising

Mechanization in rice transplanting is progressively advancing in Bangladesh, facilitated by interventions from various government and private organizations. Mechanical transplanting is emerging as a valuable technology that saves time, ensures timely planting, and contributes to higher yields (Sreenivasulu and Reddy, 2014). Until recently, these activities were confined mainly to research institutes. The Bangladesh Rice Research Institute (BRRI) initiated work on walking and riding mechanical rice transplanters from 2011 to 2013, evaluating their acceptance at the farmer level under the NATP-1-funded project (Hossen et al., 2013; Hossen et al., 2018c). A significant barrier to the popularity of rice transplanters in Bangladesh has been the reliance on mat-type seedling raising. Various factors, including seasonal weather conditions, grain size, seed rate, root formation capacity of different varieties, and soil type, heavily influence mat formation, seedling quality, and machine performance (Chaudhary and Varshney, 2003).

Seedling height is generally unaffected by seed rate, although it varies among rice varieties, with BRRI dhan50 producing the longest seedlings. In contrast, increasing seed rates can lead to a reduction in leaf number, stem thickness, and shoot dry weight, while the root-to-shoot ratio increases significantly (Hossen et al., 2018b). Varieties such as BRRI Dhan 86, BRRI Dhan 89, and BRRI Dhan 92 can yield 150-160 grams of seeds/tray, supporting higher harvest indices and population development for increased crop yields (Shaikh et al., 2021). Seedling density directly affects seed rate, which in turn impacts seedling quality and the establishment of sufficient plant populations (Runsick and Wilson, 2009). The density in seedling trays is influenced by seed rate, germination percentage, and seedling survival rates after growth (Hamid et al., 2015).

In Bangladesh, sandy loam, clay loam, or loam topsoil is typically used for tray preparation (Hossen et

al., 2022b). Both dry and wet soil can be employed for mat-type seedling raising. Farmers are increasingly accepting plastic trays and polythene film for this purpose. Approximately 0.85 to 1.0 tons of loose soil are required to prepare 185 to 225 trays covering one hectare (Hossen et al., 2020b). Alternative growing media have been explored to mitigate the use of agricultural topsoil. For instance, Shahid et al. (2020) mixed 15%-20% rice husk and tea waste with sandy clay loam soil or 10%-15% with sandy loam soil, producing quality mat-type seedlings. Key factors for quality seedlings include acceptable seedling height, leaf number, and stem thickness, as well as minimizing issues such as soil inhibition, picker misses, floating hills, and mechanical damage. Islam (2018) noted that the minimum seedling height should exceed 80 mm during the cold season, while another study indicated that a height of 120 to 150 mm with three leaves is acceptable for mechanical transplantation (Manjunatha et al., 2010). The number of seedling leaves remains consistent across rice varieties and seed densities (Pathania et al., 2016), although Rickman et al. (2015) recommended 4 to 5 leaves for optimal mechanical transplanting. The number of seedlings/hill/stroke is influenced predominantly by stem thickness, which can vary with the growing medium, soil conditions, and environmental temperatures (Shahed et al., 2020). Stem thickness tends to decrease with higher seed rates/tray sizes, aligning with findings from Hossen et al. (2018b), which showed that a seed density of 100 to 120 g tray⁻¹ for BRRI dhan28 markedly improved stem thickness compared to other varieties. Seedlings with greater strength are less susceptible to damage during mechanical transplanting. Hossen et al. (2020a) suggested producing 15-16-day-old seedlings on trays or polythene for the Aman season and 25-30-day-old seedlings for the Boro season. This approach extends the lifespan of paddy in the field, facilitating increased tiller production.

The height, density, and soil thickness in trays or polythene are critical for a successful mechanical transplant. Hossen et al. (2020a) also recommended is

a seedling height of 120-150 mm with 2-3 leaves, 3-4 seedlings/cm², and a soil thickness of 2.0-2.5 cm for optimal transplanter performance. An additional requirement during the Boro season is a cold abatement system at the seedling stage, as seedlings are developed in November and December. To minimize biotic and abiotic stress, including fungal infections, cover seedbeds with 0.08-0.06 mm thick white polythene and treat seeds and seedlings with Carbendazim fungicide 10-12 h before germination, or apply Muriate of Potash (MoP) (8-10 g tray⁻¹) immediately after seedling emergence has proven effective (Tamanna et al., 2021).

11 Challenges and opportunities of mat-type seedling raising

Mat-type seedling raising, a crucial component of mechanized rice transplantation in Bangladesh, presents several challenges and offers significant opportunities for advancement in the agricultural sector. One of the primary challenges in mat-type seedling raising is achieving proper land leveling and soil preparation, which requires consistent irrigation to maintain optimal moisture for healthy seedling growth. For small-scale farmers, the initial cost of establishing a mat-type nursery can be a significant financial burden. Moreover, this method demands specific technical knowledge and skills that many farmers may not possess. Infrastructure limitations—such as inadequate irrigation systems, lack of storage facilities, and poor transportation—further hinder effective implementation.

Weather variability, particularly during the monsoon (Aman and Aus) and winter (Boro) seasons, poses additional risks by affecting seedling quality and survival. This often leads to increased mortality rates. The presence of hard particles such as stones or gravel in the soil used for trays can damage delicate seedling roots and even break the pegging needles of rice transplanters (Islam et al., 2008). Collecting and transporting large volumes of topsoil (about 5–6 kg tray⁻¹) is also labor-intensive and costly, especially for large-scale operations. For instance, raising seedlings

for one hectare typically requires approximately one metric ton of surface soil (Tamanna et al., 2021). Additionally, manually placing seeds in trays is both time-consuming and physically demanding. This method can result in uneven seed distribution, which affects seedling uniformity (Choudhary and Machavaram, 2022)). The weight of each seedling tray (approximately 6 kg) adds logistical challenges, since trays must be repeatedly moved from nurseries to greenhouses or fields, then to transport vehicles, and finally to transplanting sites (Tasaka, 1999). During peak planting seasons, shortages of seedling trays are common, resulting in additional delays. Seedlings are also vulnerable to environmental stress: heavy rainfall during the Aman and Aus seasons can submerge young plants, while cold stress during the Boro season severely threatens seedling survival (Islam et al., 2016). These climatic extremes contribute to high mortality rates, especially in poorly managed nurseries. Perhaps the most critical barrier remains the limited adoption of mechanical transplanting technology (Hossen et al., 2022b). Nevertheless, despite these considerable challenges, there are numerous opportunities to improve and optimize mat-type seedling raising practices.

The potential for advancing mat-type seedling systems in Bangladesh is significant. This method offers a strategic pathway to promote mechanized rice transplanting, reduce labor requirements, and increase productivity (Rahaman et al., 2022). Designed specifically for use with mechanical transplanters, mat-type seedlings enhance operational efficiency and planting precision. Greater stakeholder engagement and widespread promotion could accelerate adoption. Technological advancements, such as automated seeding machines, address issues like non-uniform seed placement, making the process more efficient and less labour-intensive (Bazargani and Deemyad, 2024). Further research into climate-resilient nursery practices can help mitigate environmental risks associated with extreme weather events (Hoque et al., 2022). Mechanized transplanting using mat-type seedlings ensures uniform spacing, reduces

transplanting shock, and ultimately improves yield. Additionally, the production of robust, healthy seedlings opens new economic opportunities for both farmers and agri-entrepreneurs, contributing to a more sustainable and resilient rice production system in Bangladesh.

12 Smart seedling raising through vertical farming

Vertical farming represents a cutting-edge solution for smart seedling raising, particularly in densely populated nations like Bangladesh, where arable land is scarce. Vertical space allows cultivating seedlings in stacked layers within controlled environments, such as greenhouses or indoor farms. This method significantly enhances seedling production efficiency in smaller areas compared to traditional practices, making it particularly suitable for urban and peri-urban regions with limited land and water resources. Vertical farming often employs advanced methods like hydroponics and aeroponics, which eliminate the need for soil and reduce water consumption while minimizing the risk of soil-borne diseases (Saraswat and Jain, 2021). One of the core benefits of this approach is the precise control it offers over critical environmental factors like light, temperature, and humidity (Mir et al., 2022). LED grow lights, for instance, deliver optimal light wavelengths for seedling development, enabling healthy growth even in regions with erratic weather patterns, such as Bangladesh. The controlled environment also limits the use of pesticides and herbicides, reducing exposure to pests and weeds (Naresh et al., 2024). Innovative technologies, including automated nutrient systems, further enhance the efficiency of seedling raising by optimizing water and fertilizer use. Sustainability is another key feature of vertical farming, as it can integrate renewable energy sources, such as solar power. Vertical farming offers a resilient year-round seedling production system in a country vulnerable to climate change and frequent flooding, thereby contributing to food security during periods of climatic stress. This aligns with Bangladesh's focus on

modernizing agriculture through innovative technologies and mechanization, thereby creating opportunities for youth engagement and entrepreneurship. Although the initial investment and technical expertise required are significant, government support, private sector involvement, and research collaborations can facilitate the adoption of vertical farming. Integrating Information and Communication Technology (ICT), such as mobile apps for monitoring seedling growth, enhances scalability and allows farmers to manage their operations remotely (Mapiye et al., 2023). Vertical farming offers a sustainable, efficient, and innovative approach to seedling raising. It addresses the challenges of traditional methods while supporting the modernization of Bangladesh's agricultural sector.

13 Way forward

Mat-type rice seedling raising is fundamental for the successful mechanization of rice transplantation in Bangladesh, offering substantial improvements in both efficiency and crop productivity. The widespread adoption of this method is crucial for the long-term sustainability of mechanized farming, ensuring that it is both easy to produce and cost-effective, and beneficial for farmers. Despite the research on seedling-raising systems, further efforts are needed to address key areas for sustainable growth. Priority should be given to improving seedling quality and uniformity, particularly under challenging conditions like the Boro season. Additionally, farmers need reliable access to high-quality seeds, fertilizers, and other inputs tailored to mat-type seedling production. Government support will be pivotal in encouraging adoption through subsidies, training programs, and extension services. Furthermore, infrastructure development, such as enhanced irrigation and storage facilities, is essential to ensure a smooth and timely supply of seedlings to farmers. Effective communication of research findings to the farming community is also necessary for successful implementation. To secure the future of mechanized transplantation, it is vital to involve female workers

and engage youth as entrepreneurs in the seedling production process. Bangladesh can further modernize its agricultural sector and enhance food security by overcoming these challenges and capitalizing on the advantages of mat-type seedling raising.

14 Conclusion

The mat-type rice seedling-raising process is complex and labor-intensive, posing a challenge for Bangladeshi farmers who are often untrained in the specific management required for effective mechanical transplanting. The low adoption of mechanical rice transplanters is mainly due to the difficulty in raising mat-type seedlings, which demands skills and precision that many farmers have yet to acquire. Furthermore, the time-consuming nature of seedling preparation on trays has hindered its acceptance, highlighting a gap in proper stakeholder education on its benefits. To increase adoption, it is essential to provide hands-on training in mat-type seedling raising, requiring coordinated efforts from both the public and private sectors. Addressing the dependency on topsoil by exploring alternative growth media could also alleviate some practical barriers. Optimizing key factors, such as seedling density, plant height, age, stem thickness, and base material, based on local soil conditions, is crucial for efficient transplanting and minimizing gaps. Effective seed density management promotes seedling quality and reduces missing hills during transplanting, a challenge that manual sowing struggles to overcome due to its labor-intensive nature. Tackling challenges such as cold stress during the Boro season, which impedes seedling germination and survival, along with ensuring disease-free seedlings and proper fertilization, is critical to improving seedling quality and, consequently, the success of mechanized transplanting. Bangladesh's government strongly emphasizes the urgency of crop mechanization, promoting synchronized rice cultivation to facilitate the widespread use of machines nationwide. With ongoing efforts from government and private research organizations, robust mat-type seedling technology can be extended to farmers,

significantly enhancing the efficacy of mechanical transplanters and contributing to increased rice production.

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