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Design and development of a low-cost self-propelled mechanical rice transplanter

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Abstract

High cost of rice production has challenged the goal to reduce the price of rice because more than 40% of rice production cost is attributed to the labor requirement for manual transplanting which requires 306man-h. To help resolve this challenge, a low-cost mechanical transplanter made of locally available materials using local manufacturing technology was designed, fabricated and tested to evaluate its performance as prescribed by the Philippine National Standard (PNS) for mechanical rice transplanter, such as field capacity, planting efficiency and field efficiency, percent missing hill, percent damaged hill, number of seedlings per hill, depth and fuel consumption. The prototype was tested in a 1000 m^2 puddled and levelled field using a 19-day old rice seedlings at an average operating speed of 1.07 km/h. Results revealed that the machine has a field capacity of 0.11 ha h^{-1} with an average planting efficiency and average field efficiency of 97.4% and 93.98%, respectively, which are higher than the minimum 80% efficiencies required by the PNS. It was observed that average percent missing hills and percent damage hills of the machine is 2.7% and 1%, respectively, which is lower than the maximum 10% missing and damaged hills required by the PNS. The depth of transplanting was 8.5 mm with the average number of seedlings per hill of 5.77. The machine entailed an investment cost of Php 55,261.40; benefit-cost ratio of 1.01, break-even use of 42.02 ha/year, and an ROI of 101.53 %. Annual net generated income of Php 302,230.16. The projected time needed to recover the cost of the machine based from its field capacity is 0.83 years.

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Introduction

Rice, as a staple food, holds paramount importance in the agricultural landscape of the Philippines, serving as a cornerstone of the nation's food security and economic development. With its substantial land area dedicated to rice cultivation and the cultivation of various rice varieties, the country's agricultural sector plays a vital role in ensuring the sustainability and resilience of rice production because it is a key component of securing the future of humanity.

Moreover, in the intricate process of rice production, transplanting stands out as a labor-intensive yet vital step (Tado *et al.*, 2000), where young seedlings are carefully moved from nurseries to the main fields. Farmers manually transplant rice seedlings by hand, bending over for extended periods, and meticulously placing each seedling into the mud (Bekele *et al.*, 2020). While this agricultural practice has been the backbone of rice cultivation for centuries, it is time-consuming and demands substantial physical effort requiring 13 laborers at P400 each per day to transplant one hectare. On the other hand, if a mechanical rice transplanter is used, it typically requires a team of 2-3 laborers and enables farmers to plant one hectare per day. Significantly, the overall expenses are reduced from P25,000 per hectare to P6,000 (Pagaduan, 2023). In a techno demo facilitated by Rice Competitiveness Enhancement Fund (RCEF)-Seed Program, farmers who used the farm machine for one season said that it reduced transplanting cost by almost 50%. The cooperators reported that they used to spend P7,000 for manual transplanting, but with the mechanical transplanter, they only spent P3,000 for the rent including hauling (Jimenez, 2021). Thus, the mechanical transplanting of rice is considered the most promising option, as it saves labor, ensures timely transplanting and attains optimum plant density, which can contribute to high productivity (IRRI, n.d.; Juliano, 2005).

Furthermore, the transition from traditional to mechanical rice transplanting represents a significant shift in agricultural practices, aiming to improve productivity and address labor-related constraints. While there are indeed existing machines in the market known for their high efficiency in rice transplanting, it is still recognized the need for innovation to address specific challenges and requirements within the agricultural sector. A problem faced by farmers is their limited capacity to own and operate such specialized equipment (Elepaño, 2009). The initial cost of acquiring these transplanters is a barrier for small-scale or resource-limited farmers and its adaptability is limited in terrains with difficult access (Tababa, 2023). And also, a small size land restricts the operation of larger size farm machinery. Maintenance is another consideration, as regular upkeep is essential, and associated costs and downtime for repairs may arise.

In response to these challenges, the study focused on the design, fabrication, and performance evaluation of a self-propelled mechanical rice transplanter. The machine was locally manufactured, supporting local economies and providing faster access to parts and service for farmers in the region. In addition, since agricultural landscape in the Philippines is dominated by small-scale farmers (Go, 2021), there is a need to promote self-propelled walking type rice transplanters (Hossen, 2022). Thus, the researchers of this study created a compact design of the self-propelled mechanical rice transplanter while maintaining its functionality. The compact design would allow it to navigate through narrow pathways and tight spaces in rice paddies with ease. Whether it's navigating through muddy fields, traversing uneven terrain, the transplanter would demonstrate adaptability. This would also allow operators regardless of gender, to operate the equipment effectively.

Generally, the study aimed to design, fabricate, and evaluate the performance of a self-propelled mechanical rice transplanter. Specifically, it aimed to:

1. evaluate the machine in terms of the following:
   - 1.1. Percent missing hill (%),
   - 1.2. Percent damaged hill (%),
   - 1.3. Planting efficiency (%),
   - 1.4. number of seedlings per hill,
   - 1.5. transplanting depth (mm),

1.6. fuel consumption (L/h),
1.7. actual field capacity (ha/h),
1.8. field efficiency (%); and
2. conduct an investment and economic analysis of the machine
2.1. model 1: selling of units
2.2. model 2: mechanical transplanter for rentals

Materials and methods

This study employed an engineering design through planning and comprehensive analysis to achieve the objectives of the study. Guided by the Philippine National Standard-Philippine Agricultural Engineering Standard (PNS-PAES) for mechanical rice transplanter, a series of testing trials were done in a 1000 m² area to determine the performance of the machine. This involved good analysis and evaluation of the different parameters to realize the expected outcome.

Design and construction of the self-propelled mechanical rice transplanter

The design of a self-propelled mechanical rice transplanter involved various factors to optimize its functionality and performance in the context of rice cultivation. Firstly, the ergonomics of the transplanter was designed to ensure ease of operation for local farmers. Also, the choice of locally available materials would ensure cost-effectiveness and ease of maintenance.

The self-propelled mechanical rice transplanter was designed to consist of the major components: (1) frame assembly, (2) seedling board, (3) picker assembly, (4) floater, (5) ground wheel, and (6) transmission system. The perspective view of the machine is shown in Fig. 1. The frame was constructed using a 20 mm × 20 mm G.I. tubular. The frame has an overall length of 1626.34 mm.

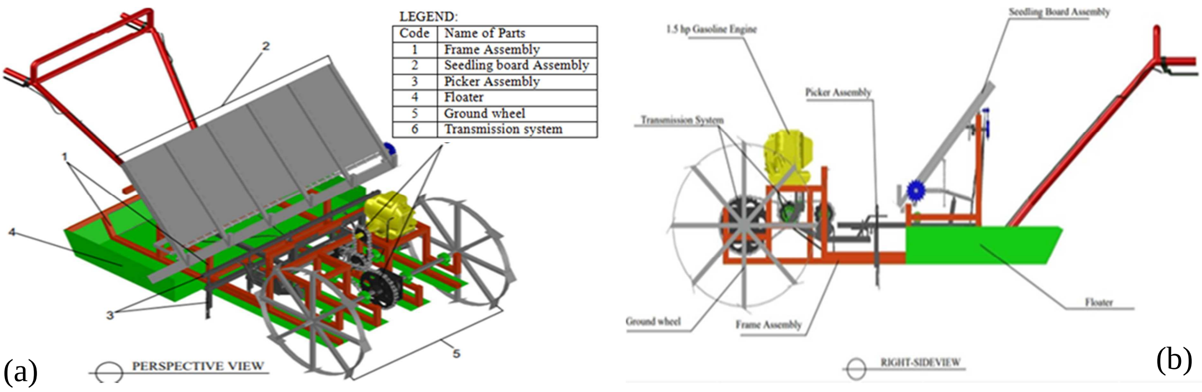

Fig. 1. Component parts of the self-propelled mechanical rice transplanter (a) perspective view and (b) right side view

The seedling board assembly is a platform designed to hold seedlings ready for transplanting. It features a guard rod that will serve as a protective barrier to prevent seedlings from falling off the seedling board during the transplanting process. The spiked-cylindrical roller, as shown in the given figure, will assist in conveying the seedlings. It typically helps move the seedlings from the tray to the planting location, ensuring a continuous and controlled flow during the transplanting process. Additionally, it has rollers on its bottom to facilitate movement, enabling the seedling board to glide smoothly from left to right in an interchangeable manner.

The assembly was made up of a 414.08 mm × 1046 mm G.I. sheet and six (6) 16 mm × 20 mm G.I. tubular components. The guard rod is 1046 mm in length and has a diameter of 2 mm. The spiked-cylindrical roller had a diameter of 15 mm and a length of 970 mm.

The picker assembly was designed to hold and plant seedlings. It is a pivotal part that facilitates the process of transplanting young plants into the soil efficiently. Additionally, it can be adjusted from 180 mm up to 200 mm. It was made up of G.I. tubular equipped with arm and fingers which has a total dimension of 890 mm × 16 mm × 16 mm (l×w×h). The arm of the transplanter had a total dimension of 20 mm × 20 mm steel. The fingers had a total dimension of 117 mm × 4 mm × 1.5 mm (l×w×h) stainless steel.

The floater is a base at the bottom of the frame that allows the machine to float on the water and mud. It consisted of four (100×60mm) G.I. Sheets that can be attached to various parts of the frame and one 960× 550 × 117 mm (l×w×h) G.I. Sheet.

The ground wheel presented was designed to facilitate traction and stability. It was made up of mild steel flat bar. It is inside and outside diameters are 496 mm and 500 mm respectively.

The transmission system of the transplanter consisted of components like chain and sprocket that will transfer power from the engine to the wheels or other moving parts. It enabled the transplanter to move and allowing the operator to navigate through the field while transplanting seedlings.

Principles of operation

The operation starts through loading rice seedlings grown in the nursery onto the seedling board. Then, the engine will be started, and will transmit the power to the ground wheel and also to the transplanting assembly. Simultaneously, the picker picks the seedlings in the feeder and moves downward until it reaches the soil. After that, the pushing rod pushesq the seedling out of the picker and positions them at depths in the soil. The transplanter continues planting until the entire field is covered with rice seedlings. When the clutch is disengaged the planting assembly will stop without affecting the ground wheel's moving process.

Rice seedling preparation

Rice seedlings were grown in a mat-type nursery. The surface was covered with plastic film to prevent seedling roots from penetrating the soil.

Preparation of soil mixture: The soil mix needed for each 950 cm² rectangular tray was a mixture of 70% soil and 20% carbonized rice hull.

Pre-germinating seed: Seeds were soaked for 24 hours. The soaked seeds was drained and incubated for another 24 hours. At this time, the seeds sprouted (bud) and the first seed root grows to 2–3 mm long.

Laying the soil mixture: The customized 190 mm × 500 mm wooden frame was placed on top of the plastic sheet. The frame was filled almost to the top with the soil mixture.

Sowing: The pre-germinated seeds were sown uniformly and it was covered with a thin layer of dry soil approximately 1 seed/cm². The nursery was watered as needed to keep the soil moist. Water was drained two days before removing the seedling mats for transplanting.

Design calculations and performance evaluation

1. Planting efficiency (%): This is the ratio of the number of hills with seedlings to the total number of hill expressed in percentage. It was determined using eq. 1 (PAES 152:2010- Agricultural machinery – Mechanical Rice Transplanter – Methods of Test).

$$P_e = \left(1 - \frac{H_m}{H_t}\right) \times 100 \quad \text{Eq. 1}$$

Where:

P_e = planting efficiency of the transplanter, %

H_m = total number of missing hills

H_t = total number of hills in sampling area

2. Percent damaged hills (%): This is the ratio of the total number of hills with seedlings damaged by cutting, bending or crushing during transplanting to the total number of hills. It was determined using eq. 2 (PAES 152:2010- Agricultural machinery – Mechanical Rice Transplanter – Methods of Test).

$$H_{pd} = \left(\frac{H_d}{H_t}\right) \times 100 \quad \text{Eq. 2}$$

Where:

H_{pd} = percent damaged hills, %

H_d = number of damaged hills in the sampling area

H_t = total number of hills in sampling area

3. Percent missing hills (%): This is the ratio of the total number of hills without seedlings to the total number of hills. It was obtained using eq. 3 (PAES 152:2010- Agricultural machinery – Mechanical Rice Transplanter – Methods of Test).

$$H_{pm} = \left(\frac{H_m}{H_t}\right) \times 100 \quad \text{Eq. 3}$$

Where:

H_{pm} = percent missing hills, %

H_t = total number of hills in sampling area

4. Number of seedlings per hill: Number of seedlings per hill will be measured by directly counting the number of seedlings picked by the planting finger and transplanted in the field per hill after transplanting (Diwan *et al.*, 2019).

5. Transplanting depth: The depth of transplanting was determined by uprooting the seedlings immediately after transplanting. The distance from that point to the tip of the root was measured by scale to find the depth of transplanting. Ten randomly selected observations were taken for depth of transplanting (Diwan *et al.*, 2019).

6. Fuel consumption (L/h): It refers to the fuel consumed by an engine in delivering a given amount of energy (Belonio, 2022). It was done by measuring the volume of fuel refilled after the test. The tank was filled to full capacity before and after each trial.

7. Effective fuel consumption (L/ha): It refers to the amount of fuel consumed per unit of distance. It was determined using eq. 4 (PAES 152:2010- Agricultural machinery – Mechanical Rice Transplanter – Methods of Test).

$$F_e = \left(\frac{10000V}{A_e}\right) \quad \text{Eq. 4}$$

Where:

F_e = effective fuel consumption rate, L/ha

V = volume of fuel consumed, L

A_e = effective area covered, m2

8. Field efficiency (%): It is the ratio between the productivity of a machine under field conditions and the theoretical maximum productivity. It was determined using eq. 5 (PAES 152:2010- Agricultural machinery – Mechanical Rice Transplanter – Methods of Test).

$$Eff = \left(\frac{FC_A}{FC_T}\right) \times 100 \quad \text{Eq. 5}$$

Where:

E_{ff} = field efficiency of the transplanter, %

FC_A = actual field capacity

FC_T = theoretical field capacity

9. Actual field capacity (ha/h): It is the actual rate of transplanting in a given area per unit of time. It was determined using eq. 6 (PAES 152:2010- Agricultural machinery – Mechanical Rice Transplanter – Methods of Test).

$$FC_A = \left(\frac{A_T}{T_T}\right) \quad \text{Eq. 6}$$

Where:

FC_A = actual field capacity, ha/h

A_T = total area transplanted, ha

T_T = total operating time required for transplanting, h

Investment and economic analysis

An investment analysis was undertaken to evaluate the economic impact of the machine. In the conduct of the investment analysis, two models were considered. Investment Analysis Model 1 focused on the manufacturing and selling of a self-propelled mechanical rice transplanter, while Model 2 considered providing rental services using the same machine. Economic indicators such as break-even point, benefit-cost ratio, payback period, and return on investment were considered in both models. The economic evaluation framework Model 1 was adapted from the studies of Agcaoili *et al.* (2018), Ermitanio and Galvan (2023) and Galvan *et al.* (2018), which conducted cost-benefit and performance analyses of agricultural machinery, particularly motorized stripping, weeding and dehusking equipment while Model 2 was adapted from study of Ermitanio and Galvan (2023).

Results and discussion

Percent missing hills (%)

The percent missing hills across each trials was observed to have slight variation as illustrated on Table 1. During the first trial, 3.12 percent missing hills was recorded, while Trial 2 and Trial 3 are slightly lower at 2.4% and 2.64% respectively. The calculated mean, which was approximately 2.7%, provided a summarized trend across all trials. The presence of missing hills are due to soil clogs that impedes the movement of seedlings and some seedlings are not loaded correctly or are unevenly distributed in the seedling tray as an effect of uncontrolled vibration of the machine during operation which resulted the transplanter may fail to pick them up efficiently.

According to the Philippine National Standard-Philippine Agricultural Engineering Standards PAES 152:2010 on Mechanical Rice Transplanter, the acceptable percent missing hills shall not exceed 10%, this means that the missing hills of the designed rice transplanter is acceptable.

Percent damaged hill (%)

The percentage of damaged hills during the performance test reveals slight variability in the extent of hill damaged recorded. The highest percentage damaged hills of 1.4 percent was recorded and the lowest percentage damage hill is 0.24 percent. The average percent damage hill is 1 percent. It was observed that root damage of the seedlings was the cause of damage hills during operation.

According to PAES 151: 2010, it stated that percent damaged hills of a mechanical rice transplanter shall not exceed 10%, hence, the machine is acceptable.

Table 1. Summary table of the performance of the machine

Parameters	Trials			Grand mean	PNS-PAES	Remarks
	Trial 1	Trial 2	Trial 3			
Percent missing hills (%)	3.12	2.4	2.64	2.7	10%	Passed
Percent damaged hills (%)	1.2	1.44	0.24	1.0	10%	Passed
Planting efficiency (%)	97	97.7	97.4	97.4	80%	Passed
Number of seedlings per hill	5.9	5.9	5.5	5.77	n/a	n/a
Transplanting depth (mm)	87	81	86	84.7	n/a	n/a
Fuel consumption (L/h)	2.27	3.14	3.11	2.84	n/a	n/a
Actual field capacity (ha/h)	0.102	0.113	0.112	0.11	n/a	n/a
Field efficiency (%)	94.44	94.17	93.33	93.98	80%	Passed

Planting efficiency (%)

Planting efficiency across each three trials presents variability, with Trial 2 exhibiting the highest efficiency at 97.7%, followed closely by Trial 3 at 97.4%, and Trial 2 of 97%. The overall average efficiency, represented by the grand mean of 97%, indicates a relatively stable performance across the different planting trials.

According to the Philippine National Standard-Philippine Agricultural Engineering Standards PAES 152:2010, the acceptable planting efficiency of rice transplanter shall have a minimum of 80%, therefore, the designed rice transplanter is acceptable.

Number of seedlings per hill

Table 1 presents the data on the number of seedlings per hill across three trials. In Trial 1 and Trial 2, the number of seedlings remained consistent at 5.9 per hill. However, in Trial 3, there was a slight decrease to 5.5 seedlings per hill. Calculating the grand mean, this represents the average number of seedlings per hill across all trials, yielded 5.77

Transplanting depth (mm)

Table 1 presents the data on the planting depth across three trials. In Trial 1 and Trial 3, the planting depths have nearly identical depth with 87 and 86 mm. In Trial 2, shows a shallower depth of 81 mm seedlings per hill. However, the three trials show a small variation in transplanting depth with a grand mean of 84.7 mm.

Fuel consumption (L/h)

Table 1 displays the data regarding fuel consumption measured in liters per hour across three trials. In Trial 1, the fuel consumption rate was recorded at 2.27 liters per hour, whereas both Trial 2 and Trial 3 exhibited a slightly higher consumption rate of 3.14 and 3.11 liters per hour respectively. Upon calculating the grand mean, which represents the average fuel consumption rate across all trials, it was found to be 2.84 liters per hour.

Actual field capacity (ha/h)

The actual field capacity measured in hectares per hour (ha/h) presented in Table 1 reveals that there is variability across three different trials. While Trial 1 showed the highest field capacity, Trial 2 and Trial 3 had slightly lower values of 0.102, 0.113 and 0.112, respectively. The grand mean gives an overall average of 0.11 ha/h. This means that the prototype machine could finish transplanting a hectare rice field for at least 9 hours.

Field efficiency (%)

The field efficiency of the self-propelled mechanical transplanter is presented on Table 1. The highest field efficiency recorded was 94.44 percent and the lowest was 93.33 percent. The average field efficiency was calculated as 93.98 percent which represents the average efficiency across all trials.

Table 2. Comparison of results

Methods of operation	Actual field capacity, ha/h	Laborer	Cost of transplanting
Designed mechanical rice transplanting	0.11 ha/h	2	Php5,500/ha
Traditional rice transplanting	-	-	Php.15,000/ha*

*prevailing contract transplanting cost of rice per hectare in the study area.

This field efficiency of the designed machine is far greater than the minimum field efficiency criteria set by the Philippine National Standard-Philippine Agricultural Engineering Standard (PNS-PAES), for mechanical rice transplanter of at least 80 percent. This means that the designed rice transplanter is acceptable.

Economic analysis

Investment analysis was made to guide potential users of possible benefit projections in using the self-propelled mechanical rice transplanter machine. The standard costing of the machine was based on the direct cost of the materials, process operation, labor and overhead. The cost of the materials was ascertained on their latest market price.

Investment Model 1, which focuses on manufacturing, assembling, and selling machines, has an annual net income of ₱46,510.80, break-even sales of ₱309,350.14, a requirement to sell 6 units to cover the costs associated with producing three units, a payback period of 2.6 years, and a return on investment (ROI) of 28%.

In contrast, Investment Model 2, centered on rental services, incurs total operating costs of ₱252,169.84 and generates an annual gross income of ₱508,200, resulting in a significantly higher annual net income of ₱256,030.16. The payback period for Model 2 is notably shorter at 0.83 years, with a benefit-cost ratio of 1.01, a break-even use rate of 42.02, and a return on investment of 101.53%.

Comparative performance evaluation of manual transplanting between designed self-propelled mechanical rice transplanter

To comprehend the study, the traditional practice of transplanting based on the actual practice of farmers and the performance of the designed transplanter was compared. The designed mechanical rice transplanting method offers significant advantages over the traditional method, including reduced labor requirements, and lower costs as shown in Table 2. This makes the mechanical method more suitable for farming operations, optimize productivity and reduce expenses.

Conclusion

Based on the results of the study, the following conclusions were made:

1. The mean percent missing hill (%), mean percent damaged hill (%), mean planting efficiency (%), the mean field efficiency (%), the mean number of seedlings per hill, the mean transplanting depth (mm), the mean fuel consumption and the mean effective fuel consumption were 2.7, 1.0, 97.4, 91.39, 6, 84.7, 2.84, and 25.93, respectively.
2. The investment and economic analysis showed that a self-propelled mechanical rice transplanter machine has a satisfactory performance and was deemed economically viable with a total cost of ₱33,954.75.
3. Investment Model 2 (rental service) appears to be a more lucrative and quicker-return investment compared to Investment Model 1 (manufacturing and selling the machine).

Recommendations

1. Consider a higher hp rating (5 hp or higher) to increase workload while maintaining optimal performance.
2. For more competitive results, compare the performance of the designed machine with the existing commercially available transplanters.

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