Japan Bilingual Publishing Co.

**New Countryside**
https://ojs.bilpub.com/index.php/nc

**ARTICLE**

# Techno-Economic Assessment of Rice Seedling-Raising Trays in Northern Iran

***Alireza Allameh***

*Rice Research Institute of Iran (RRII), Agricultural Research, Education and Extension Organization (AREEO), Rasht 41996-13475, Iran*

## ABSTRACT

Mechanized rice transplanting has become an essential practice in modern rice cultivation due to its economic advantages, reduced labor requirements, and shorter operation time compared with manual transplanting. However, successful mechanized transplanting depends on the provision of high-quality mat-type seedlings, which are produced in specially designed plastic trays. These trays play a critical role in seedling establishment and ultimately influence crop performance. In this study, nine types of rice seedling-raising trays were evaluated—four made from high-quality virgin materials and five from recycled plastics—to assess their effects on seedling mat quality, transplanting efficiency, yield, and yield components. The experiment was conducted using a Randomized Complete Block Design (RCBD) with three replications. Results showed that seedling mats raised in high-quality trays (P10, PK, P50, and RF) exhibited significantly better performance ($p < 0.05$) compared to those raised in recycled trays. Seedlings grown in quality trays had greater shoot cross-sectional area and higher strength, resulting in improved mechanical transplanting efficiency. Key transplanting traits—including the number of hills per unit area, hill spacing uniformity, number of seedlings per hill, and rates of missing, buried, or damaged seedlings—were all significantly superior in the quality tray treatments. Similarly, grain yield and yield components were significantly higher for seedlings raised in quality trays,

*CORRESPONDING AUTHOR:
Alireza Allameh, Rice Research Institute of Iran (RRII), Agricultural Research, Education and Extension Organization (AREEO), Rasht 41996-13475, Iran; Email: a.allameh@areeo.ac.ir

ARTICLE INFO
Received: 15 May 2025 | Revised: 20 October 2025 | Accepted: 27 October 2025 | Published Online: 4 November 2025
DOI: https://doi.org/10.55121/nc.v5i1.440

CITATION
Allameh, A., 2026.Techno-Economic Assessment of Rice Seedling-Raising Trays in Northern Iran. New Countryside . 5(1): 42–52. DOI: https://doi.org/10.55121/nc.v5i1.440

which also demonstrated greater resistance to lodging. In contrast, recycled trays exhibited substantial deformation (bulging, twisting, and breakage) due to weak polymer bonding, leading to poor mat uniformity. The economic analysis confirmed that, despite their higher purchase price, using quality trays was economically justified, with a production cost of approximately 0.23 USD per kilogram of paddy, compared with 0.29 USD for recycled trays.

***Keywords:*** Rice; Mechanized Transplanting; Seedling Trays; Seedling Vigor; Crop Yield; Techno-Economic Assessment

# 1. Introduction

Rice (*Oryza sativa* L.) is one of the most important cereal crops worldwide, serving as a major source of calories and nutrients for more than half of the global population. It ranks second after wheat in total consumption and production. Rice is cultivated mainly through two methods: direct seeding and transplanting. Although direct seeding has gained popularity in some regions, most rice farmers continue to prefer transplanting due to its higher yield potential and more effective weed control. However, traditional manual transplanting is labor-intensive, time-consuming, and costly, often requiring significant manpower and prolonged working hours [1].

In recent decades, rice producers have increasingly adopted mechanized transplanting systems, which reduce labor requirements, shorten the operational period, and improve precision and management efficiency. This mechanization trend reflects a broader shift in the agricultural sector toward technologies that enhance productivity and sustainability. Recent economic studies across South Asia have reaffirmed the advantages of mechanized transplanting over traditional methods. For instance, researchers [2] reported that mechanical rice transplanting reduced total input costs by approximately 20% and increased the benefit–cost ratio from 2.42 to 3.44 in spring paddy production in Nepal, demonstrating substantial economic gains. In a similar context, it was found that mechanical transplanting improved productivity by 10–12% and enhanced the benefit–cost ratio from 1.28–1.33 to 1.40–1.44 for Basmati rice varieties in Pakistan, reaffirming its labor-saving and profitability advantages [3]. Furthermore, scientists showed that mechanized transplanting achieved an internal rate of return exceeding 45% and reduced the investment payback period to only two years in Bangladesh, highlighting its potential for agro-entrepreneurship and rural development [4]. Nonetheless, successful mechanized transplanting depends on the compatibility and performance of various components—including the seedling-raising trays that serve as the foundation for healthy seedling mats.

In Iran, rice seedlings are generally raised in plastic trays designed for mat-type seedlings. These trays support early growth and facilitate transplanting by machine once seedlings reach an appropriate stage. The performance of these trays affects seedling uniformity, mat strength, and ultimately, the efficiency of field establishment. Uniform and vigorous seedlings are crucial for achieving high grain yield and reducing transplanting losses.

A wide range of studies has explored both manual and mechanized transplanting methods, focusing on agronomic parameters, machinery performance, and economic feasibility [5–9]. Recent research has introduced improved nursery systems such as pot-type, bowl-type, and blanket-type trays, each exhibiting distinct effects on plant growth and field establishment [10,11]. Studies in Southeast Asia and Africa have also demonstrated that tray design, material composition, and seed density play key roles in seedling quality and transplanting success [12,13]. Moreover, according to the National Institute of Standards and Technology (NIST), recycling processes reduce polymer molecular integrity, causing recycled plastics to lose stiffness and structural stability when exposed to heat and moisture [14]. This degradation explains the frequent warping and cracking observed in recycled seedling trays used under nursery conditions.

In Iran, farmers increasingly adopt mechanized transplanting due to its operational efficiency, but they face challenges related to the quality of seedling trays. High-quality trays, typically made of virgin polypropylene, are durable but more expensive, whereas low-cost recycled trays often deform or crack, compromising seedling uniformity. Since seedling mats are critical to successful mechanized transplanting, understanding the technical and economic implications of tray quality is essential.

Therefore, this study aimed to evaluate the **techno-economic performance of different rice seedling-raising trays**, comparing high-quality and recycled types in terms of seedling vigor, transplanting efficiency, yield components, and total operational cost. The results provide practical insights for improving rice production sustainability and guiding equipment selection for mechanized transplanting systems.

# 2. Materials and Methods

## 2.1. Study Site and Plant Material

This study was conducted during the 2021–2022 cropping season at the **Rice Research Institute of Iran (RRII)**, located in Rasht (37°12′N, 49°38′E). The experimental site represents a typical paddy field ecosystem in the northern rice-growing zone of Iran. The local rice cultivar *Hashemi*, which dominates the region due to its desirable grain quality and consumer preference, was selected as the test variety. Certified seeds with a germination rate of 98% were used for seedling raising.

## 2.2. Experimental Design and Tray Selection

Nine types of seedling trays were selected for evaluation. Four trays were made from high-quality virgin plastic materials, whereas the remaining trays were fabricated using recycled plastics of varying compositions. **Table 1** presents the technical specifications of each tray type. For each treatment, 15 trays were used to raise seedling mats. The physical condition and structural integrity of trays were recorded both before and after use to assess deformation, cracking, and durability.

**Table 1.** Seedling trays characteristics.

| Code | Ingredients | Company |
|---|---|---|
| P10 | PP 90% + Additives 10% | AS |
| PK | PP 80% + PC 20% | AS |
| P50 | PP 50% + Granules + Additives | AS |
| RF | Refined recycled granular | AS |
| A | Recycled plastics | BM |
| B | Recycled plastics | KL |
| C | Recycled plastics | TCR |
| D | Recycled plastics | ZM |
| E | Recycled plastics | PE |

## 2.3. Seedling Raising in the Nursery

Seedling raising followed the technical guidelines of the RRII [12]. Approximately 25 kg of intact seeds were soaked and pre-germinated before sowing. Then, 180 g of germinated seeds were evenly distributed on each tray using a mechanical seeder. The trays were pre-filled with a 2 cm layer of soft nursery soil, and seeds were covered with an additional 0.5 cm soil layer. Moisture was maintained through partial watering, and trays were incubated for two days before being transferred to the open nursery.

Throughout the 25-day nursery period, temperature and moisture were monitored, and pest and disease control measures were implemented. Seedlings reached the ideal transplanting stage (2–3 leaves, 15–20 cm height) under these conditions, ensuring uniform growth for machine transplanting.

## 2.4. Field Preparation and Transplanting Operations

The transplanting field (4000 m²; 100 m × 40 m) was prepared using a paddy tractor equipped with a moldboard plough to a depth of 15 cm, followed by double puddling and land leveling. The field was flooded to a water depth of 2–3 cm and left for one week before transplanting. A four-row walking-type transplanter (Daedong DP 480, Korea) was used. Machine settings were as follows: intra-row spacing of 15 cm, 2–3 seedlings per hill, planting depth of 5 cm, and a fixed inter-row spacing of 30 cm.

Nutrient management included nitrogen (urea, 90 kg ha$^{-1}$), phosphorus (TSP, 120 kg ha$^{-1}$), and potassium ($K_2SO_4$, 100 kg ha$^{-1}$). Weed control was achieved using the selective herbicide **Bispyribac-sodium (Clean Weed 40%)**, applied at a rate of 100 mL per acre at the 2–3 leaf stage.

### 2.5. Performance Evaluation and Data Collection

Experimental data were collected at three stages:

#### 2.5.1. Nursery Stage

For each treatment, 10 seedlings were randomly selected from each of the 15 trays (total n = 150 seedlings per treatment) to measure key morphological traits, including emergence rate, height, number of leaves, stem thickness, and seedling strength. Seedling strength was quantified as the shoot dry mass-to-length ratio (mg/mm), calculated after harvesting a subsample of 10 seedlings per tray. Shoot length was measured prior to drying, and samples were then oven-dried at 70°C for 48 hours to achieve a constant dry weight. The resulting ratio was used as an indicator of mechanical robustness, with higher values indicating greater seedling strength [11].

#### 2.5.2. Transplanting Stage

Field performance indices were evaluated according to **ANTAM (Asian and Pacific Network for Testing of Agricultural Machinery)** standards [13]. Parameters included hill density, hill spacing, number of seedlings per hill, planting depth, missing hills, consecutive missing hills, buried seedlings, floating seedlings, and damaged seedlings.

#### 2.5.3. Harvest Stage

Yield and yield components were measured from a 1 m × 1 m quadrat per plot. Data included grain yield (kg ha$^{-1}$), biological yield (kg ha$^{-1}$), harvest index (%), lodging index [15], number of tillers, panicles, kernels per panicle, 1000-grain weight, and plant height. The total planting cost was calculated as the sum of tray purchase cost, nursery operations, and transplanting labor.

### 2.6. Statistical Analysis

The effect of tray type on seedling quality, transplanting performance, and yield components was analyzed using a **Randomized Complete Block Design (RCBD)** with three replications. Tray type served as the independent factor (nine levels), while dependent variables included seedling vigor, mechanized transplanting indices, and yield traits. Data were processed in **Microsoft Excel (2013)** and analyzed using **Minitab 20.3 (Minitab LLC, 2021)**. Statistical significance was determined at $p < 0.05$.

## 3. Results and Discussion

### 3.1. Nursery-Stage Seedling Characteristics

Statistical analysis revealed that the type of seedling-raising tray had no significant effect on seedling emergence per area or number of leaves, whereas other morphological traits were significantly affected (**Table 2**). Since an identical seeding rate and distribution were used across all trays, this result indicates that uniform seed dispersal minimized variation in emergence. Similar observations were reported by Yao et al. and Islam [16,17].

**Table 2.** Measured traits at the nursery stage.

| Tray | Test Traits | | | | |
|---|---|---|---|---|---|
| | Seedling Emergence Per Area | Plant Height (cm) | No. of Leaves | Shoot Cross- Sectional Area (mm$^2$) | Seedling Strength (mg mm$^{-1}$) |
| P10 | 5.5$^a$ | 18.16$^a$ | 2.9$^a$ | 1.28$^{ab}$ | 0.17$^a$ |
| PK | 5.3$^a$ | 18.47$^a$ | 2.8$^a$ | 1.37$^{ab}$ | 0.17$^a$ |
| P50 | 5.3$^a$ | 19.08$^a$ | 2.7$^a$ | 1.44$^a$ | 0.18$^a$ |
| RF | 5.4$^a$ | 19.18$^a$ | 2.9$^a$ | 1.31$^{ab}$ | 0.17$^a$ |
| A | 4.8$^a$ | 16.19$^b$ | 2.5$^a$ | 0.93$^c$ | 0.13$^b$ |
| B | 4.4$^a$ | 15.87$^b$ | 2.4$^a$ | 0.96$^c$ | 0.13$^b$ |
| C | 4.6$^a$ | 14.86$^{bc}$ | 2.6$^a$ | 0.94$^c$ | 0.11$^b$ |
| D | 4.6$^a$ | 15.31$^b$ | 2.3$^a$ | 0.89$^c$ | 0.09$^b$ |
| E | 4.9$^a$ | 16.13$^b$ | 2.4$^a$ | 0.84$^c$ | 0.09$^b$ |

In each column, a common letter means no significant difference at the 5% level.

Seedling height differed significantly among tray types, particularly for trays **P50, PK, P10, and RF**, which produced taller seedlings than those grown in other trays. This indicates variability in microenvironmental conditions within trays. Uneven seedling growth directly affects the efficiency of mechanized transplanting, as non-uniform seedlings tend to cause uneven mat thickness and picking errors during transplanting [17,18].

Although tray type did not influence the number of leaves significantly, stem thickness and seedling strength were both higher in trays P50, PK, P10, and RF. These parameters are strong indicators of seedling vigor and mechanical resilience during transplanting. Factors such as soil texture, seedling mat thickness, and temperature regime are known to affect these attributes [19,20]. Because the variety, soil, and environmental conditions were identical across treatments, it can be inferred that **tray design and material quality** influenced mat uniformity and shoot development.

Post-nursery examination of trays (**Table 3**) showed that floor bulging, twisting, and warping were common in trays made from recycled materials. These structural deformations caused uneven soil layers and variable mat thickness, resulting in heterogeneous seedling growth and weaker mats. Trays fabricated from virgin polypropylene exhibited minimal deformation. The degradation of polymer chains during recycling reduces molecular bonding strength, making recycled trays more prone to deformation when exposed to water, heat, and pressure [14,21,22]. Consequently, **tray material quality** proved critical for ensuring uniform and robust seedling mats suitable for mechanized transplanting.

**Table 3.** Structural changes of trays after the nursery.

| Tray | Structural Features | | | | |
|---|---|---|---|---|---|
| | **Floor Bulging (%)** | **Latitudinal Twist (%)** | **Floor Crack (%)** | **Breakage (%)** | **Longitudinal Twist (%)** |
| P10 | 0 | 33.3 | 0 | 0 | 0 |
| PK | 0 | 26.6 | 6.6 | 6.6 | 0 |
| P50 | 0 | 6.6 | 0 | 0 | 0 |
| RF | 0 | 20 | 0 | 0 | 0 |
| A | 66.6 | 26.6 | 0 | 0 | 0 |
| B | 13.3 | 20 | 13.3 | 0 | 0 |
| C | 13.3 | 73.3 | 13.3 | 13.3 | 0 |
| D | 10.0 | 100 | 20 | 0 | 86.6 |
| E | 6.6 | 86.6 | 33.3 | 6.6 | 0 |

## 3.2. Field-Stage Transplanting Performance

As shown in **Table 4**, tray type significantly affected most transplanting indices except planting depth. Given that all treatments were raised under identical nursery conditions, the differences observed at transplanting can be attributed to tray-induced variations in seedling mat characteristics. Previous studies have confirmed that mat uniformity, thickness, and seedling density directly influence transplanting accuracy and field establishment [11].

Trays exhibiting structural instability—such as bulging or twisting—resulted in uneven seedling density and poor mat integrity. Consequently, these treatments showed greater variation in hill spacing, higher numbers of missing and damaged hills, and reduced transplanting efficiency. In contrast, trays P50, PK, P10, and RF, which maintained uniform mat thickness, produced seedlings that were easily picked by the transplanter and properly established in the soil.

Traits such as seedling height, stem thickness, and leaf number play key roles in successful mechanical transplanting. Excessively tall or weak seedlings are more susceptible to burial or damage by transplanter fingers, whereas robust seedlings with moderate height and stem strength exhibit greater survival and establishment rates [11,17]. The findings of this study corroborate those of previous researchers who highlighted the significance of seedling vigor in minimizing missing hills and improving field uniformity.

**Table 4.** Traits tested at the machine transplanting stage.

| Tray | Traits | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **The No. of Hills Per Area** | **Hills Spacing (cm)** | **The No. of Plants Per Hill** | **Planting Depth (cm)** | **Missing Hills** | **Continuous Missing Hills** | **Buried Seedling** | **Floating Seedling** | **Damaged Seedling** |
| P10 | 18.0[c] | 16.94[d] | 3.2[a] | 5.18[a] | 1.2[c] | 0.0[c] | 0.0[d] | 0.3[c] | 0.4[c] |
| Pk | 18.2[c] | 16.91[d] | 3.16[a] | 5.08[a] | 0.4[d] | 0.0[c] | 0.0[d] | 0.3[c] | 0.2[c] |
| P50 | 21.2[a] | 16.12[d] | 3.24[a] | 5.08[a] | 0.2[d] | 0.0[c] | 0.2[c] | 0.2[c] | 0.0[c] |
| RF | 20.2[ab] | 17.98[d] | 3.22[a] | 5.03[a] | 0.2[d] | 0.0[c] | 0.2[c] | 0.2[c] | 0.0[c] |
| A | 15.4[d] | 20.58[bc] | 2.52[b] | 4.95[a] | 2.2[b] | 1.2[ab] | 1.6[b] | 1.0[b] | 1.4[b] |
| B | 15.0[d] | 24.5[a] | 2.76[b] | 5.04[a] | 3.4[a] | 1.4[ab] | 1.6[b] | 2.0[a] | 1.6[b] |
| C | 15.8[d] | 21.7[b] | 2.24[b] | 5.00[a] | 3.4[a] | 2.2[a] | 2.2[a] | 1.8[a] | 1.8[b] |
| D | 14.6[d] | 21.54[b] | 2.02[b] | 5.05[a] | 4.0[a] | 2.8[a] | 2.6[a] | 2.6[a] | 3.0[a] |
| E | 15.4[d] | 20.16[bc] | 2.14[b] | 4.96[a] | 2.8[b] | 1.6[ab] | 1.8[b] | 2.0[a] | 1.6[b] |

In each column, a common letter means no significant difference at the 5% level.

## 3.3. Yield and Yield Component Responses

At maturity, all yield components except **1000-grain weight** differed significantly among treatments (**Table 5**). Seedlings raised in quality trays (P50, PK, P10, RF) exhibited superior performance in plant height, number of tillers, panicles, and kernels per panicle compared with recycled trays. This suggests that high-quality trays provided better root aeration and physical support during the nursery stage, leading to improved growth and resource use efficiency after transplanting.

The **1000-grain weight** remained statistically unchanged, confirming that it is primarily a varietal trait with limited environmental dependence [23,24]. However, the number of filled grains per panicle increased significantly for seedlings raised in quality trays, consistent with earlier studies linking seedling vigor to reproductive success [25]. Stronger seedlings produce more effective tillers and panicles, ultimately leading to higher grain yield [26–29].

Trays with poor structural quality produced weak seedlings that struggled during the transition from nursery to field, resulting in fewer tillers and panicles per unit area. In contrast, trays P50, PK, P10, and RF facilitated the development of vigorous seedlings capable of rapid adaptation to field conditions, thereby improving biological yield and harvest index.

**Table 5.** Traits assessed at the harvest stage.

| Tray | Test Traits | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Grain Yield ($kg\ ha^{-1}$)** | **Biologic Yield ($kg\ ha^{-1}$)** | **Harvest Index** | **Lodging Index** | **Tillers Per Area** | **Panicles Per Area** | **Kernel Per Panicle** | **1000-Grain Weight (g)** | **Plant Height (cm)** |
| P10 | 3948[a] | 9148[a] | 43.15[a] | 141[b] | 322[a] | 311[a] | 77[b] | 24.4[a] | 134[a] |
| PK | 4011[a] | 9036[a] | 44.46[a] | 139[b] | 318[a] | 314[a] | 88[a] | 24.4[a] | 131[a] |
| P50 | 4133[a] | 9226[a] | 44.78[a] | 147[a] | 326[a] | 323[a] | 92[a] | 24.4[a] | 133[a] |
| RF | 4184[a] | 9036[a] | 46.31[a] | 139[b] | 325[a] | 319[a] | 82[a] | 24.3[a] | 129[a] |
| A | 3137[b] | 8261[b] | 37.96[b] | 130[c] | 241[b] | 258[b] | 54[b] | 24.2[a] | 113[b] |
| B | 3190[b] | 8284[b] | 38.5[b] | 130[c] | 230[b] | 229[b] | 62[b] | 24.3[a] | 123[b] |
| C | 3245[b] | 8208[b] | 39.52[b] | 134[c] | 241[b] | 234[b] | 50[b] | 24.4[a] | 115[b] |
| D | 3109[b] | 8260[b] | 37.62[b] | 128[d] | 230[b] | 224[b] | 53[b] | 24.2[a] | 117[b] |
| E | 3235[b] | 8350[b] | 38.7[b] | 129[d] | 236[b] | 234[b] | 51[b] | 24.3[a] | 120[b] |

In each column, a common letter means no significant difference at the 5% level.

### 3.4. Lodging Resistance and Economic Performance

Tray type also significantly influenced the **lodging index**, which reflects the plant's mechanical resistance to bending or breaking. Lodging is affected by multiple factors such as nutrient status, stem thickness, and root anchorage. In this study, since all agronomic conditions were uniform, the observed differences were attributed to the quality of seedlings originating from different trays. Seedlings grown in quality trays developed thicker, stronger stems and deeper root systems, reducing lodging occurrence. Similar results were reported by Aslam et al. and Awan et al. [30,31].

The economic evaluation (**Table 6**) revealed that while high-quality trays had greater initial purchase costs, they produced significantly higher grain yields, resulting in a more favorable **cost–benefit ratio** (**Figure 1**). Recycled trays, though cheaper, led to reduced yield due to weaker mats and greater replanting labor requirements caused by missing hills. Therefore, from both a technical and economic standpoint, the use of durable, high-quality trays is justified.

**Table 6.** List of operations and their corresponding costs.

| Item | Type of Tray | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | P10 | PK | P50 | RF | A | B | C | D | E |
| Initial cost (US$) | 7.5 | 8.4 | 6.9 | 5.4 | 6.3 | 5.22 | 6.0 | 5.76 | 6.18 |
| Seed (US$) | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Nursery (US$) | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 | 18 |
| Transplanting (US$) | 11.2 | 11.2 | 11.2 | 11.2 | 11.2 | 11.2 | 11.2 | 11.2 | 11.2 |
| Labor (US$) | 3.12 | 3.12 | 3.12 | 3.12 | 3.12 | 3.12 | 3.12 | 3.12 | 3.12 |
| Transfer (US$) | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 | 1.12 |
| Fertilizer (US$) | 4.75 | 4.75 | 4.75 | 4.75 | 4.75 | 4.75 | 4.75 | 4.75 | 4.75 |
| Herbicide (US$) | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| Total (US$ plot$^{-1}$) | 48.14 | 49.04 | 47.54 | 46.04 | 46.94 | 45.86 | 46.64 | 46.40 | 46.82 |
| Total (US$ ha$^{-1}$) | 962.8 | 980.8 | 950.8 | 920.8 | 938.8 | 917.2 | 932.8 | 928 | 936.4 |

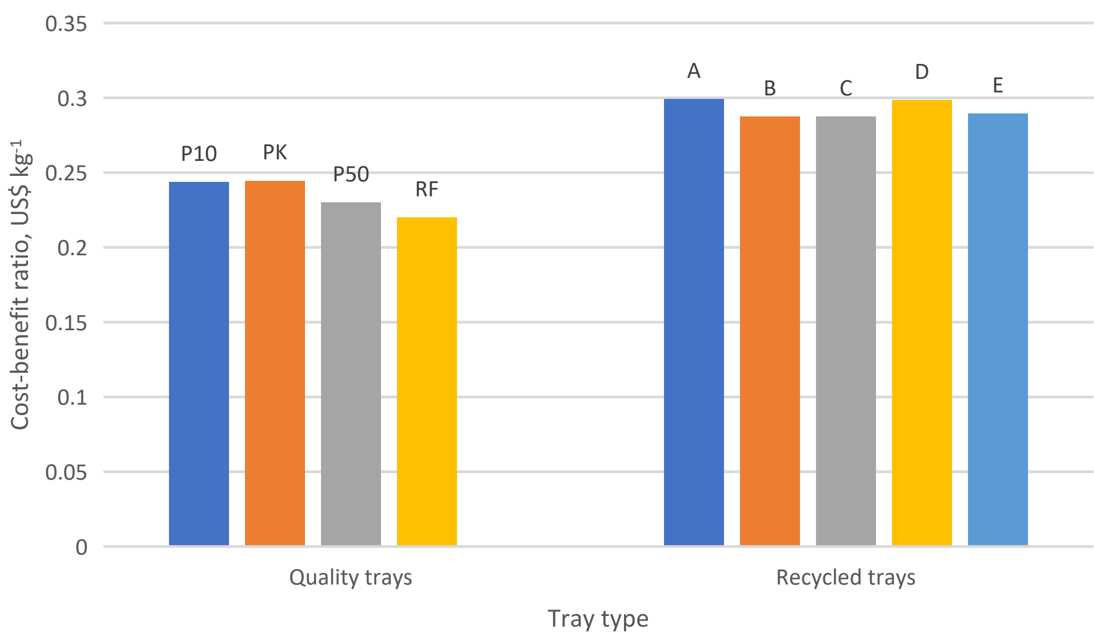


**Figure 1.** Cost-benefit ratio of different seedling-raising trays.

(CBR values represent system-level economic outcomes derived from plot-scale total inputs and outputs, and are therefore reported as point estimates without error bars.)

The cost–benefit ratio (CBR) was calculated as the total production cost per hectare (US$ $ha^{-1}$) divided by grain yield per hectare (kg $ha^{-1}$), yielding a unit of US$ per kilogram of paddy. Total production cost included all expenses related to seedling raising and transplanting, such as tray purchase, seed, nursery operations, transplanting labor, fertilizer, and herbicide (**Table 6**). A lower CBR indicates higher economic efficiency, as it reflects a lower cost incurred to produce each kilogram of grain.

### 3.5. Sensitivity Analysis of Economic Performance

To evaluate the robustness of the economic results, a sensitivity analysis was performed by varying the major cost parameters—**labor cost** and **tray purchase price**—by ±20% relative to their baseline values (**Table 6**). The analysis revealed that the cost–benefit ratio (CBR) was more sensitive to fluctuations in **tray purchase cost** than to labor cost.

When labor cost increased by 20%, the CBR of quality trays rose slightly from 0.23 to 0.25 USD per kilogram of paddy, whereas that of recycled trays increased from 0.29 to 0.32 USD $kg^{-1}$. Conversely, when the cost of trays increased by 20%, the CBR for quality trays rose to 0.27 USD $kg^{-1}$, while a 20% reduction lowered it to 0.20 USD $kg^{-1}$. This pattern demonstrates that even under cost escalation scenarios, high-quality trays maintain a superior profitability margin compared with recycled trays.

### 3.6. Comparison with Manual Transplanting

Several field studies indicate that mechanized transplanting substantially reduces labor requirements and can lower per-hectare transplanting costs by approximately 25–50% compared with traditional manual transplanting, depending on local wage rates, machine ownership/hire costs and scale of operation [5,32,33]. Applying these ranges to the cost-per-kg estimates obtained in the present study (0.23 USD $kg^{-1}$ for quality trays and 0.29 USD $kg^{-1}$ for recycled trays) yields an estimated cost of production under manual transplanting in the order of ~0.31–0.46 USD $kg^{-1}$ (against quality-tray mechanization) and ~0.39–0.58 USD $kg^{-1}$ (against recycled-tray mechanization). These back-of-envelope calculations suggest that mechanized transplanting — particularly when coupled with high-quality, durable trays — remains economically advantageous under a wide range of realistic scenarios, especially where labor costs are high or labor availability is limited.

## 4. Conclusions

The present study demonstrated that the quality and structural characteristics of rice seedling-raising trays exert significant effects on seedling vigor, transplanting performance, and crop yield. Trays fabricated from recycled plastics exhibited the highest degree of deformation, bulging, and structural failure during the nursery period, resulting in non-uniform seedling mats and lower transplanting efficiency. Conversely, trays made from high-quality virgin polypropylene (P50, PK, P10, RF) maintained their shape integrity, produced vigorous seedlings, and ensured smooth transplanting operations.

Seedlings raised in these high-quality trays developed thicker stems and greater mechanical strength, enabling better establishment and lodging resistance under field conditions. Consequently, they achieved higher biological and grain yields as well as a superior harvest index. Although the purchase price of these trays was higher, their long-term durability and performance advantages justify the additional cost. Using inferior or unstable trays not only reduces field uniformity and grain yield but also increases production costs due to additional replanting labor and transplanting inefficiencies.

### 4.1. Environmental Considerations

The long-term sustainability of rice mechanization depends not only on economic efficiency but also on material durability and environmental responsibility. As emphasized in the NIST life-cycle review [14], plastic components used in agricultural systems should be designed for multiple reuse cycles to minimize the cumulative carbon and waste footprint. Promoting the use of high-quality, recyclable materials for seedling trays can substantially reduce resource consumption over time. Since recycled trays in this study showed significant deformation and were typically discarded after a single use, their lower upfront cost may be offset by higher long-term material consumption and waste generation compared to durable, multi-season virgin trays. This highlights a critical trade-off often overlooked in agricultural input selection: while recycled trays offer lower initial purchase costs, their short functional life leads to higher cumulative expenses and environmental burdens over time. In contrast, high-quality trays—though more expensive upfront—deliver superior economic returns and reduce waste through multi-season reuse. Thus, the apparent conflict between economic gain and environmental stewardship is reconciled when durability and lifecycle performance are prioritized.

### 4.2. Practical Implications

For rice farmers, particularly those adopting mechanized transplanting, the use of durable, high-quality trays provides measurable long-term benefits. Despite higher initial investment, these trays reduce operational disruptions, enhance machine efficiency, and increase yield stability. Extension services and policymakers could consider offering **subsidies or credit support** for smallholders to adopt quality trays. For small-scale rice farmers with limited capital, the higher upfront cost of quality trays may pose a barrier. However, several practical strategies can improve accessibility:

- Cooperative purchasing: Neighboring farmers can pool resources to buy high-quality trays in bulk, reducing individual costs.
- Shared tray pools: Communities or agricultural cooperatives can establish collective tray inventories that are rented out per season.
- Prioritize semi-durable options: Among the tested trays, RF (refined recycled granular) offers a favorable balance between cost and performance—making it a suitable entry point for budget-constrained farmers.
- Tray maintenance: Even recycled trays can be used more effectively if inspected before each use and retired once deformation exceeds 10–15% (as observed in **Tables 3** and **4**, severe deformation directly increases missing hills and replanting labor).
- In light of the demonstrated economic and technical superiority of high-quality trays, the following concrete policy interventions are recommended:
- Input subsidies: Provide targeted financial support (e.g., 30–50% cost coverage) for the first-time purchase of durable trays by smallholders.
- Tray recycling programs: Establish local collection and recycling centers for end-of-life trays to promote circular economy practices and reduce plastic waste.
- Quality certification: Introduce a national standard for seedling trays (e.g., minimum reusability of 5 seasons, max. deformation <10%) and label compliant products.
- Integration into extension packages: Include tray quality as a mandatory component of government-led mechanization programs and farmer training courses.

These measures would not only enhance the adoption of quality inputs but also align rice mechanization with national goals for agricultural sustainability, productivity, and environmental stewardship.

These approaches enable smallholders to benefit from mechanization without compromising on seedling quality or incurring excessive long-term costs. This would enhance farm profitability and sustainability across rice-growing regions in Iran and other similar environments.

### 4.3. Limitations and Future Work

This study was conducted during a single cropping season (2021–2022) at one location—Rasht, northern Iran—using a single rice cultivar (Hashemi) under uniform agronomic management. While this controlled design enhanced internal validity and allowed precise comparison of tray performance, it inherently restricts the generalizability of the findings across diverse agro-ecological and socio-economic contexts. Regional variations in climate (e.g., temperature, rainfall patterns), soil characteristics (e.g., texture, organic matter content), availability and cost of labor, access to machinery, and prevailing rice varieties may all influence the technical suitability and economic viability of seedling trays. For instance, in regions with higher humidity or prolonged nursery periods, recycled trays may degrade even faster; conversely, in areas with very low labor costs, the economic advantage of durable trays might be less pronounced. Therefore, while the superiority of high-quality trays under the tested conditions is robust, these results should be validated through multi-year, multi-location trials encompassing a range of cultivars, soil types, and climatic zones before broad policy or extension recommendations are made.

## Funding

This research was supported by the **Rice Research Institute of Iran (RRII)** under project code **24-04-04-022-000592**.

## Institutional Review Board Statement

The study did not require ethical approval.

## Informed Consent Statement

The study did not involve humans.

## Data Availability Statement

The data used in this study are available from the corresponding author upon reasonable request.

## Acknowledgments

The author gratefully acknowledges the financial and administrative support from the **Rice Research Institute of Iran (RRII)**, as well as the technical assistance of the RRII mechanization research team.

## Conflicts of Interest

The author declares no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

## References

[1] Hossain, M.A., Becker, K., 2002. In vitro rumen degradability of crude protein in seeds from four Sesbania spp. and the effects of treatments designed to reduce the levels of antinutrients in the seeds. Animal Feed Science and Technology. 95(1–2), 49–62. DOI: https://doi.org/10.1016/S0377-8401(01)00310-8

[2] Chand, S.P., Gautam, S., Karki, R., et al., 2025. Productivity and basic economics in spring paddy production by mechanical rice transplanter versus traditional manual method. Discover Agriculture. 3, 209. DOI: https://doi.org/10.1007/s44279-025-00360-y

[3] Akmal, N., Hussain, A., Yousaf, M., et al., 2023. Exploring potential of mechanical transplanting of rice in Punjab, Pakistan. Pakistan Journal of Agricultural Research. 36(2), 169–182. DOI: https://doi.org/10.17582/journal.pjar/2023/36.2.169.182

[4] Sarkar, S., Saha, C.K., Ahamed, S., et al., 2024. Mechanical rice transplanting: A profitable business for Bangladeshi agropreneurs. Journal of Agricultural Machinery and Bioresources Engineering. 8(1), 202–225. DOI: https://doi.org/10.61361/jambe.v8i1.7

[5] Alizadeh, M.R., Yadollahinia, A.R., Rahimi-Ajdadi, F., 2011. Techno-economic performance of a self-propelled rice transplanter and comparison with hand transplanting for hybrid rice variety. International Journal of Natural and Engineering Sciences. 5(3), 27–30.

[6] Mamun, M.A.A., Rana, M.M., Miranda, A.J., 2013. Tray soil management in raising seedlings for rice transplanter. Canadian Journal of Pure and Applied Sciences. 7(3), 2481–2489.

[7] Niu, G., Wang, G., Li, B., et al., 2014. Design of rice factory three-dimensional carpet raising seedlings system engineering. IERI Procedia. 8, 93–100.

[8] He, H., You, C., Wu, H., et al., 2017. Effects of nursery tray and transplanting methods on rice yield. Agronomy Journal. 110(1), 104–114.

[9] Wayayok, A., Mohammad, U., Zubairu, U.B., et al., 2017. Comparative study on the performance of rice seedlings raised by single seedling nursery tray method and conventional system. American Journal of Plant Biology. 2(1), 1–4.

[10] Andoniaina, R.M., Yakiyama, H., Shoji, K., 2018. Thirty-row arrayed rice mat seedlings. Journal of JSAMFE. 80(5), 320–321.

[11] Shaikh, N.Y., Ashraful Alam, M., Kamruzzaman, M., et al., 2021. Effect of seedling density on mat type seedling quality for mechanical transplanting in dry season rice. Agricultural Sciences. 12, 1231–1243.

[12] Padasht Dehkaee, F., Tajadodi Talab, K., Alizadeh, M., et al., 2016. Rice Instructions: Planting, Protecting, Harvesting, and Post-Harvest Operations. Agricultural Teaching Publication: Lexington, KY, USA.

[13] CSAM & UN ESCAP, 2017. ANTAM Standard Code for Testing of Paddy Transplanters. CSAM: Beijing,

China.
[14] Rikhter, P., Dinc, I., Zhang, Y., et al., 2022. Life cycle environmental impacts of plastics: A review (NIST GCR 22-032). National Institute of Standards and Technology: Gaithersburg, MD, USA.
[15] Zhang, J., Tong, T., Potcho, P.M., et al., 2020. Nitrogen effects on yield, quality and physiological characteristics of giant rice. Agronomy. 10(11), 1816. DOI: https://doi.org/10.3390/agronomy10111816
[16] Yao, X., Yang, W., Ren, W., 2009. Effects of seedling raising methods and sowing rates on machine-transplanted long-age rice seedling. Transactions of the Chinese Society of Agricultural Engineering. 25, 152–157.
[17] Islam, A.K.M.S., 2018. Rice Mechanization in Bangladesh: An Entrepreneurial Opportunity. SRL Printing Press: Dhaka, Bangladesh.
[18] Liu, Q., Zhou, X., Li, J., et al., 2017. Effects of seedling age and cultivation density on agronomic characteristics and grain yield of mechanically transplanted rice. Scientific Reports. 7, Article No. 14072. DOI: https://doi.org/10.1038/s41598-017-14672-7
[19] Pathania, R., Shekhar, J., Rana, S.S., et al., 2016. Evaluation of seeding rates of rice nursery on seedling vigour and its effect on crop productivity under system of rice intensification. Journal of Applied and Natural Science. 8(4), 2224–2230. Available from: https://pdfs.semanticscholar.org/574b/374605cec53dd7eaf2e77a2f59f4e745afeb.pdf
[20] Hossen, M.A., Hossain, M.M., Haque, M.E., et al., 2018. Effect of seed rate on seedling quality for mechanical rice transplanting. Bangladesh Rice Journal. 22, 9–23. DOI: https://doi.org/10.3329/brj.v22i1.41834
[21] Shahed, A.B.M., Hossen, M.A., Al Mamun, M.R., et al., 2020. Impact of organic substance on growth attributes of mat type rice seedlings in the trays for machine transplanting. Journal of Science, Technology and Environment Informatics. 10, 694–708. DOI: https://doi.org/10.18801/jstei.100120.70
[22] Crawford, R.J., 1981. Plastics Engineering. Pergamon Press Ltd.: Oxford, UK.
[23] Ali, M.S., Hasan, M.A., Sikder, S., et al., 2013. Effect of seedling age and water management on the performance of Boro rice (Oryza sativa L.) variety BRRI Dhan 28. The Agriculturists. 11(2), 28–37. DOI: http://dx.doi.org/10.3329/agric.v11i2.17484
[24] Ibrahimi, M., Majidian, M., Alizadeh, M., 2020. Effect of tillage and planting methods on soil physical characteristics, grain yield, and milling efficiency of rice (cv. Hashemi). Iranian Journal of Crop Sciences. 22(1), 66–80.
[25] Gholami Rezvani, N., Esfahani, M., Kabi Rahnama, S., et al., 2015. Effect of seed rate on grain yield and yield components of rice (cv. Hashemi) in direct seeding methods. Seed and Plant Production Journal. 31(2), 37–56.
[26] Singh, Y., 2013. Crop and water productivity as influenced by rice cultivation methods under organic and inorganic sources of nutrient supply. Paddy and Water Environment. 11(1–4), 531–542.
[27] Badshah, M., Naimei, T., Zou, Y., et al., 2014. Yield and tillering response of super hybrid rice Liangyoupeijiu to tillage and establishment methods. The Crop Journal. 2(1), 79–86.
[28] Huang, M., Zhou, X.F., Cao, F.B., et al., 2015. No-tillage effect on rice yield in China: a meta-analysis. Field Crops Research. 183, 126–137.
[29] Adhikari, B., Mehera, B., Haefele, S., 2013. Impact of rice nursery nutrient management, seeding density and seedling age on yield and yield attributes. American Journal of Plant Sciences. 4, 146–155.
[30] Aslam, M.M., Zeeshan, M., Irum, A., et al., 2015. Influence of seedling age and nitrogen rates on productivity of rice (Oryza sativa L.): A review. In: Chen, G.Q. (Ed.). Prime Archives in Plant Sciences. Vide Leaf: Hyderabad, India.
[31] Awan, T.H., Ali, R., Manzoor, Z., et al., 2011. Effect of different nitrogen levels and row spacing on the performance of newly evolved medium grain rice variety KSK-133. Journal of Animal and Plant Sciences. 21(2), 231–234.
[32] Vijay, J., Mahesh, L., Venkateshwar Rao, N., et al., 2024. Comparative study on cost analysis of mechanical and manual transplanting of rice. Journal of Scientific Research and Reports. 30(10), 39–43. DOI: https://doi.org/10.9734/jsrr/2024/v30i102428
[33] Rajendran, M., Ranganathan, T., 2025. Advancements in paddy transplanter mechanization implications for sustainable agriculture. Sustainable Futures. 10, 101235. DOI: https://doi.org/10.1016/j.sftr.2025.101235