DEVELOPMENT OF BACK PACK BATTERY OPERATED MANUAL FERTILIZER SPOT APPLICATOR CALIBRATION OF DIRECT 8- ROW PADDY DRUM SEEDER

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Abstract:

This paper presents the development, calibration, and performance evaluation of two agricultural implements: a battery-operated backpack manual fertilizer spot applicator and an 8-row paddy drum seeder. The fertilizer applicator was designed for the precise, localized placement of granular fertilizers in the root zone of crops like cotton, aiming to reduce wastage and environmental loss. It features a cell-feed metering mechanism powered by a 12V DC system, allowing for adjustable application rates (16-44 g) based on motor speed (25-75 rpm). Field evaluation showed an effective field capacity of 0.03 ha/hr and 70% field efficiency. Concurrently, the direct paddy drum seeder was calibrated for both dry and pre-germinated seeds. The average seed rates were determined to be 28.21 kg/ha for dry seeds and 33.06 kg/ha for pre-germinated seeds, promoting a viable alternative to labor-intensive transplanting. This work demonstrates the potential of low-cost, precision mechanization to enhance input use efficiency for smallholder farmers.

Keywords: Precision Agriculture, Fertilizer Applicator, Drum Seeder, Calibration, Spot Application, SolidWorks Design.

I. Introduction

In the 21st century, the global agricultural sector is navigating an unprecedented convergence of challenges. Modern agriculture faces a combination of interlinked pressures. Global population growth—expected to approach 9.7 billion by 2050—will raise food demand by roughly half compared to 2013 estimates (FAO, 2017). This surge must be met against a backdrop of finite natural resources, climate change-induced volatility, and growing environmental concerns. Meeting these demands requires a shift away from conventional, input-intensive approaches toward precision-based, resource-efficient, and sustainable farming systems. The core of this transformation lies in "producing more with less"—optimizing the use of every unit of land, water, fertilizer, and labor.

Nowhere is this challenge more acute than in the context of smallholder farming, which dominates the agricultural landscape in many parts of the developing world, including India. Smallholder farmers play a vital role in ensuring regional food security, yet they face numerous constraints such as fragmented land, high input costs, limited financial access, and persistent labor shortages. The exodus of rural youth to urban areas has exacerbated the labor shortage, particularly for arduous tasks like manual fertilizer application and rice transplanting. Therefore, the development and dissemination of **appropriate-scale, affordable, and efficient mechanization** is not merely an option but an urgent imperative for enhancing smallholder productivity, profitability, and resilience.

A The Critical Challenge of Nutrient Management

Fertilizers have contributed substantially to yield improvements—estimated to account for roughly half of the total productivity gains during the 20th century (FAI, 2020). However, their misuse and inefficient application have created a double-edged sword. Conventional methods, primarily **broadcasting**, lead to rampant nutrient losses. Research indicates that crops absorb merely 30–50% of applied nitrogen fertilizers, while the remainder is lost through processes such as volatilization, leaching, and surface runoff. The remainder is lost to the environment through:

- **Volatilization:** Gaseous loss of ammonia to the atmosphere.
- **Leaching:** Nitrates moving down through the soil profile, contaminating groundwater.

- **Runoff:** Phosphorus and other nutrients being washed away into surface waters, causing eutrophication.

These losses represent a direct economic loss to the farmer and a significant environmental cost to society. Furthermore, the blanket application of fertilizers fails to address the specific, localized needs of individual plants, leading to uneven crop growth and yield variation. The solution lies in **localized placement** or **spot application**, where a measured quantity of fertilizer is placed directly in the root zone at the required depth. This method minimizes contact with the soil surface and atmosphere, drastically reducing losses and making nutrients immediately available to the plant. Despite its proven benefits, the mechanization of spot application has remained out of reach for most smallholders due to the high cost and complexity of existing machinery, creating a critical technological gap.

B The Laborious Burden of Crop Establishment: The Case of Rice

Rice is the staple food for more than half the world's population and in India, it occupies nearly 23.3% of the gross cropped area. For generations, its cultivation has been synonymous with the **manual transplanting** of seedlings from a nursery into a puddled field. While this method ensures a good plant stand, it is exceptionally demanding:

- **Labor-Intensive:** Requires 25-40 person-days per hectare.
- **Time-Critical:** Yield losses may increase by approximately one-quarter for every week of transplanting delay beyond the ideal schedule (Khan & Majid, 1989).
- **Water-Intensive:** Continuous flooding for puddling and maintenance consumes vast quantities of water.

The **Direct Seeding of Rice (DSR)** has emerged as a revolutionary alternative, circumventing the need for a nursery, puddling, and the back-breaking work of transplanting. It offers substantial benefits, including water savings of up to 30%, a shorter crop duration (7-10 days earlier maturity), and lower labor requirements. The **drum seeder** is a particularly effective technology for wet DSR, as it sows pre-germinated seeds in rows at uniform spacing in a single pass. However, the performance of this implement is highly dependent on its **calibration**—the process of setting it to deliver the correct seed rate. An incorrect seed rate can lead to sub-optimal plant populations, either through overcrowding (increased seed rate) or gapping (decreased seed rate), ultimately compromising yield potential. Therefore, precise calibration is a prerequisite for the successful adoption of this technology.

C The Present Study: Bridging the Mechanization Gap

This research is positioned at the intersection of these two critical challenges: inefficient fertilizer use and labor-intensive crop establishment. It responds directly to the need for context-specific, precision agricultural tools for smallholder systems. The work is presented in two complementary activities, each designed to develop, refine, and validate a practical mechanization solution.

Activity 1 is dedicated to the **design, fabrication, and evaluation of a novel Backpack Battery-Operated Manual Fertilizer Spot Applicator.** This initiative aims to democratize precision fertilizer placement by creating a device that is:

- **Low-Cost and Accessible:** Fabricated using readily available materials.
- **Ergonomic:** Designed as a backpack to reduce operator fatigue.
- **Precision-Based:** Incorporating a cell-feed metering mechanism and a DC motor-controlled system to allow for adjustable application rates.
- **Targeted:** Employing a dibbler to place fertilizer granules directly into the root zone, minimizing losses.

Activity 2 focuses on the **rigorous calibration of a commonly used Direct 8-Row Paddy Drum Seeder.** This activity moves beyond mere demonstration to provide farmers and extension agents with reliable, empirically-derived data on seed rates for both dry and pre-germinated paddy seeds. This ensures that the seeder can be used to its full potential, achieving the correct plant population for maximizing yield.

By integrating the development of a new precision application tool with the performance optimization of an existing establishment technology, this study offers a holistic contribution to sustainable intensification. It provides actionable engineering solutions that can empower smallholder farmers to enhance their productivity, reduce their environmental footprint, and improve their economic resilience in the face of mounting global challenges.

II. Materials and Methods

This study was conducted as two distinct but parallel activities. The experimental work for both activities was carried out at the Farm Machinery and Testing Centre of the ICAR-Central Institute of Agricultural Engineering, Regional Centre, Coimbatore, Tamil Nadu, India, between September and December 2022.

A. Development and Evaluation of a Backpack Battery-Operated Manual Fertilizer Spot Applicator

Design Philosophy and Conceptualization

The main design goal was to develop an affordable, farmer-friendly applicator capable of delivering fertilizer accurately at specific crop sites. Conceptually, the device consisted of a backpack structure operated by a DC motor that powered a volumetric metering unit, enabling stable and adjustable fertilizer output. The design prioritized farmer comfort, operational simplicity, and the accurate placement of fertilizer in the root zone (3-5 cm depth) to maximize nutrient use efficiency.

TABLE I MATERIALS AND SPECIFICATIONS FOR THE FERTILIZER SPOT APPLICATOR.

Component	Material/Specification	Key Dimensions/Properties	Function
Fertilizer Hopper	Medium-Density Polyethylene	300×200×110 mm; 4 kg capacity	Stores and gravity-feeds fertilizer to the metering mechanism.

Component	Material/Specification	Key Dimensions/Properties	Function
Metering Mechanism	Nylon Rotor & Scraper	10-cell feed rotor	Volumetrically measures a consistent quantity of fertilizer per revolution.
DC Geared Motor	12V DC	75 RPM maximum	Provides controlled rotational power to the metering rotor.
Battery	Sealed Lead-Acid (SLA)	12V, 7Ah	Powers the motor and control system for extended field operation.
Electronic Control Unit	Potentiometer, Switch, Wiring	N/A	Allows the operator to turn the system on/off and adjust motor speed (RPM).
Delivery Tube	Flexible PVC	35 mm diameter, 98 cm length	Channels the metered fertilizer from the hopper to the dibbler.
Dibbler	Stainless Steel Pipe	40×40 mm, 900 mm length	Penetrates soil to create a hole; a lever-operated flap releases fertilizer into it.

Detailed Component Specification and Fabrication

The fabricated prototype comprised several integrated subsystems. The specifications, materials, and functions of each component are detailed below:

1. **Fertilizer Hopper:**

- **Material:** Medium-Density Polyethylene (MDPE) plastic sheet.
- **Dimensions:** 300 mm (Length) × 200 mm (Width) × 110 mm (Height).
- **Wall Thickness:** 3 mm.
- **Capacity:** 4 kg of granular fertilizer (e.g., Urea, DAP).
- **Design Features:** The hopper was designed as an airtight container to prevent moisture ingress. Its geometry featured a tapered bottom with a small opening to facilitate gravity feed to the metering mechanism. It was integrated with the harness of a knapsack sprayer for comfortable carrying.

2. **Metering Mechanism:**

- **Type:** A cell-feed metering unit was employed, chosen for its capability to dispense a defined volume of fertilizer consistently over time.
- **Components:**

1. **Rotor:** A circular plate machined from Nylon, chosen for its low friction and resistance to corrosion by fertilizers.
2. **Cell Configuration:** 10 equally spaced cells (cavities) were engraved on the periphery of the rotor. The volume of each cell directly determined the base application rate.
3. **Nylon Rod:** To maintain dosing uniformity, a fixed nylon wiper removed surplus granules from each rotor cavity during rotation, allowing precise discharge per cycle.

- **Operation:** As the rotor turns, each cell fills with fertilizer from the hopper, transports it, and then releases it by gravity into the delivery tube.

3. **Power and Drive System:**

- **DC Geared Motor:** 12V, rated for a maximum of 75 RPM. The gear reduction provided high torque for reliable operation under load and allowed for precise speed control.
- **Battery:** Sealed Lead-Acid (SLA), 12V, 7Ah. This battery type was selected for its safety, low cost, and ability to provide stable power over the duration of a typical field operation.
- **Coupling:** A simple shaft coupling connected the motor output shaft directly to the metering rotor shaft.

4. **Electronic Control Unit (ECU):**

- **Function:** To regulate the speed of the DC motor and, consequently, the fertilizer discharge rate.
- **Components:**

1. **Potentiometer:** A variable resistor wired in series with the motor. By adjusting the resistance, the voltage supplied to the motor was varied, allowing for seamless RPM control from 0 to 75 RPM.
2. **Toggle Switch:** A simple ON/OFF switch for power control.
3. **Housing:** The ECU components were mounted in a small, rugged plastic box attached to the side of the hopper for easy access by the operator.

5. **Fertilizer Delivery System:**

- **Delivery Tube:** A flexible, transparent PVC hose (35 mm diameter, 98 cm length) connected the outlet of the metering mechanism to the dibbler. Its transparency allowed for visual confirmation of fertilizer flow.
- **Dibbler:**

- **Material:** Stainless steel square pipe (40mm x 40mm, 2mm thickness, 900mm length) to prevent rust.
- **Mechanism:** Featured a spring-loaded flap or "boot" at the bottom. The operator presses the dibbler into the soil, and a hand-operated lever (adapted from a bicycle brake lever and cable) opens the flap to release the fertilizer into the created hole. Releasing the lever closes the flap, preventing soil from entering the tube.

Calibration of the Fertilizer Applicator

Calibration experiments were performed to establish how variations in motor speed affected fertilizer output.

- **Procedure:** During calibration, the unit was held stationary, and urea fertilizer was metered under controlled motor speeds of 25, 50, and 75 RPM, each run lasting one minute. Rotor speed was verified using a digital tachometer. The fertilizer discharged during this period was collected and weighed using a precision electronic balance (accuracy ±0.1g).
- **Experimental Design:** This process was repeated for three different hopper fill levels (100%, 50%, and 25% of 4kg capacity) to account for the effect of head pressure on the metering mechanism. Each combination of speed and fill level was replicated three times.
- **Data Calculated:** The discharge rate was calculated in grams per minute (g/min). This data was later used to determine the application rate per plant based on walking speed and plant spacing.

TABLE II. EXPERIMENTAL DESIGN FOR FERTILIZER APPLICATOR CALIBRATION.

Independent Variable	Levels	Replications	Dependent Variable
Motor Speed (RPM)	25, 50, 75	3	Fertilizer Discharge Rate (g/min)
Hopper Fill Level (%)	100%, 50%, 25%	3	

Field Performance Evaluation

The performance of the prototype was evaluated under actual field conditions in an onion field at the research station.

- **Parameters Measured:**
  - **Operating Speed:** The average walking speed of the operator was measured over a 50-meter stretch (0.3 km/h).
  - **Depth of Placement:** The depth of the hole created by the dibbler was measured manually with a ruler at random locations (3-5 cm).
  - **Width of Operation:** Determined by the crop spacing (0.75 m).

- **Field Capacity and Efficiency:** The total area covered and the total time taken (including turning and stoppages) was recorded.

- **Calculations:**
    - **Theoretical Field Capacity (TFC):** T.F.C (ha/hr) = (Speed (km/h) × Width (m)) / 10
    - **Effective Field Capacity (EFC):** E.F.C (ha/hr) = Area Covered (ha) / Total Time (hr)
    - **Field Efficiency (%):** (EFC / TFC) × 100

B. Calibration of a Direct 8-Row Paddy Drum Seeder

Equipment and Seed Preparation

- **Seeder:** A commercially available manually pulled, 8-row paddy drum seeder was used. The nominal width was 1.2 m (8 rows × 0.15 m spacing).
- **Seeds:** Two types of seeds were used for calibration:

TABLE III. EXPERIMENTAL DESIGN FOR DRUM SEEDER EVALUATION.

Factor	Levels	Replications	Response Variables
Seed Type	1. Dry Paddy Seed 2. Pre-germinated Paddy Seed	3	1. Seed Rate (kg/ha) 2. Hill Spacing (cm) 3. Number of Seeds per Hill

1. **Dry Paddy Seeds:** Untreated, with a moisture content of 12-14%.
2. **Pre-germinated Paddy Seeds:** Prepared using the standard method:

a. **Soaking:** Seeds were soaked in a saltwater solution (10% w/v) for 24 hours to remove light, non-viable seeds.

b. **Draining & Incubation:** After draining, the seeds were kept in gunny bags for a further 24 hours for incubation, surrounded by paddy straw to maintain warmth.

c. **Sprout Length:** The sprout length was carefully monitored and maintained at 1-2 mm. Longer sprouts can entangle and clog the seeder's holes.

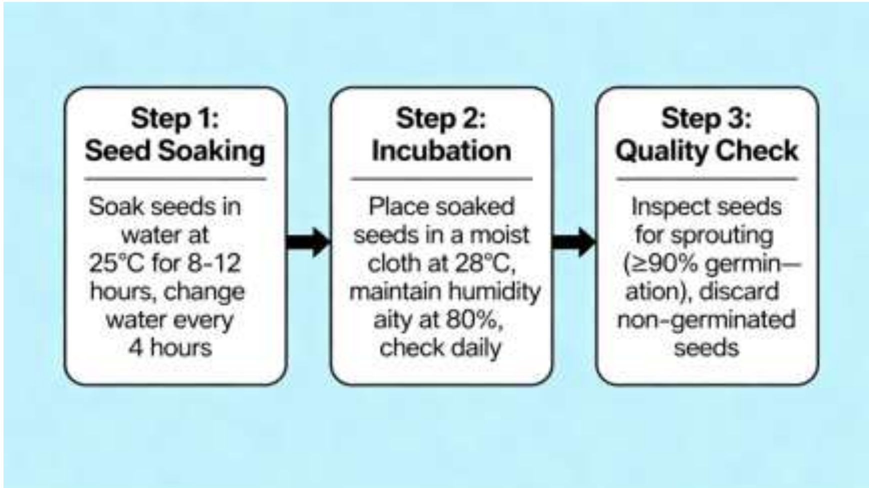

Fig 1. Flowchart for Preparation of Pre-Germinated Paddy Seeds.

Laboratory Calibration Procedure for Seed Rate

The calibration was performed in the laboratory as per the Indian Standard (IS 6316:1993) and RNAM guidelines. The goal was to determine the seed rate in kg/ha for a given seeder setting and operating speed (1 km/h).

1. **Determine Nominal Width (W):** W = Number of Rows × Row Spacing = 8 × 0.15 m = 1.2 m
2. **Calculate Area for Calibration:** A convenient fraction of a hectare (1/100th ha) was chosen.

- Area, A = 1/100 ha = 100 m^2
- Length of strip (L) to cover 100 m^2 = A / W = 100 m^2 / 1.2 m = 83.33 m

3. **Determine Ground Wheel Revolutions (N):**

- The diameter (D) of the ground wheel was 0.6 m.
- Circumference of wheel = π × D = 3.1416 × 0.6 m = 1.885 m
- Number of revolutions (N) to cover 83.33 m = L / Circumference = 83.33 / 1.885 ≈ 44.2 revolutions.
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4. **Seed Collection and Weighing:**

- The seeder's drums were filled with the test seeds (dry or pre-germinated).
- The drive wheel was jacked up and rotated manually for N = 44 revolutions, simulating the travel over 1/100th of a hectare.
- The seeds discharged from all eight outlets were collected and weighed accurately (w, in grams).

5. **Seed Rate Calculation:**

- Seed Rate (kg/ha) = [Weight of seeds (g) × 100] / 1000
- This simplifies to: Seed Rate (kg/ha) = w / 10

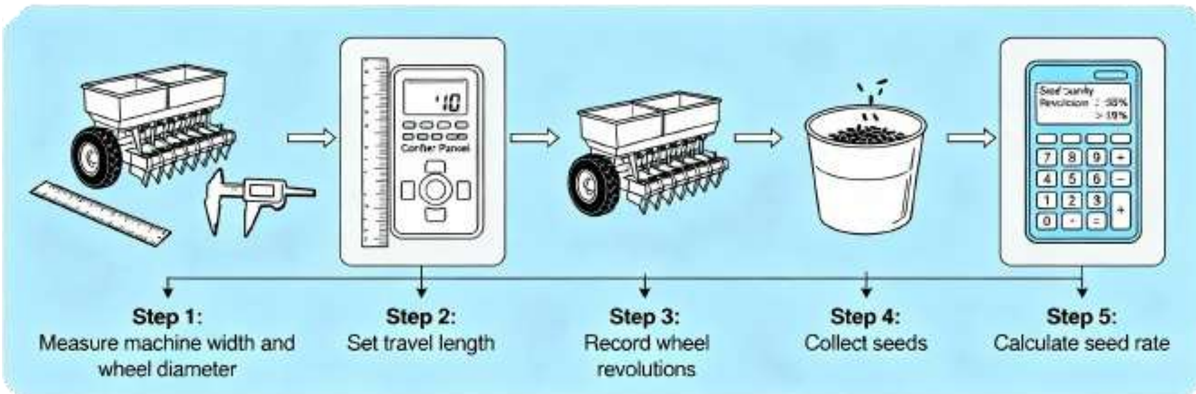

Fig 2. Methodology for Calibrating the Paddy Drum Seeder.

6. **Replication:** The entire process was repeated three times for each seed type to ensure statistical reliability.

Evaluation of Seeding Uniformity (Sand Bed Method)
To assess the performance of the metering device in terms of spacing and distribution, the sand bed method was employed.

- **Procedure:** A smooth sand surface, 25 cm deep and approximately 5 m long, was prepared matching the working width (1.2 m) of the seeder. The pre-germinated seed-filled unit was drawn across the bed to record seed impressions. The seeds dropped and created impressions on the sand surface.
- **Measurements:** For 100 consecutive seeds, the following were measured:
  - **Hill-to-Hill Spacing (cm):** The distance between the centers of two adjacent seed impressions.
  - **Number of Seeds per Hill:** The number of seeds found in a single "drop" or cluster.
- **Replication:** This test was also replicated three times. Statistical analysis of spacing data included computation of mean, standard deviation, and coefficient of variation to quantify uniformity in seed placement.

III. Results and Discussion

This section presents and discusses the data obtained from the calibration and field evaluation of both the fertilizer spot applicator and the paddy drum seeder. The results are analyzed in the context of the study's objectives and existing literature.

A. Performance of the Backpack Battery-Operated Fertilizer Spot Applicator

Calibration: Fertilizer Discharge Rate
Calibration data showed that fertilizer output increased notably with metering-rotor speed, providing the basis for defining recommended application rates.

TABLE IV. FERTILIZER DISCHARGE RATE (G/MIN) AT DIFFERENT MOTOR SPEEDS AND HOPPER FILL LEVELS.

Motor Speed (RPM)	Hopper Fill Level	Discharge Rate (g/min) [Mean ± SD]	Coefficient of Variation (%)
25 RPM	Full	16.6 ± 0.5	3.0
	Half	16.7 ± 0.6	3.6
	Quarter	17.1 ± 0.4	2.3
50 RPM	Full	25.3 ± 0.8	3.2
	Half	30.9 ± 1.1	3.6
	Quarter	31.6 ± 0.9	2.8
75 RPM	Full	39.6 ± 1.2	3.0
	Half	42.8 ± 1.4	3.3
	Quarter	43.6 ± 1.1	2.5

SD: Standard Deviation

Effect of Motor Speed: A clear proportional rise in discharge was observed as motor speed rose from 25 to 75 RPM, with output increasing by roughly 1.4–1.6 times. This is because a higher RPM means more cells on the rotor pass the discharge point per unit time. The device offered a flexible adjustment range of approximately 17 to 44 g of fertilizer per minute, depending on rotor speed.

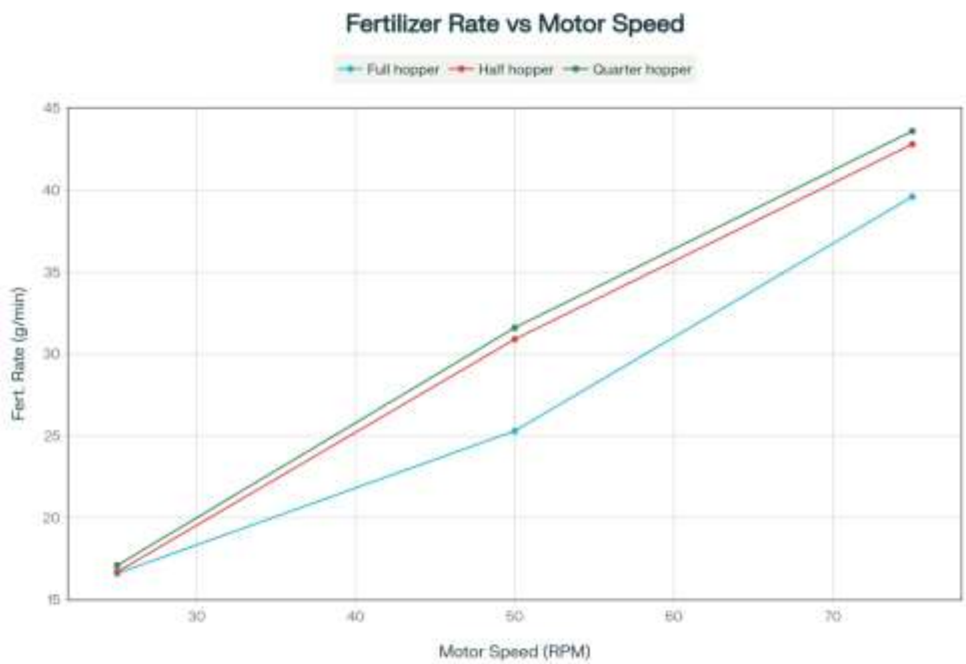

Fig 3. Effect of Motor Speed and Hopper Fill Level on Fertilizer Discharge Rate.

Effect of Hopper Fill Level: While discharge remained nearly constant at 25 RPM, reduced hopper fill levels produced a modest but measurable increase in output at higher motor speeds. This can be attributed to the reduced head pressure and the absence of compaction from the weight of the fertilizer above the rotor in a less-full hopper, allowing the cells to fill more completely and efficiently. A CV below 4% across tests confirmed the metering unit's stability and uniformity in fertilizer delivery.

TABLE V. FIELD PERFORMANCE PARAMETERS OF THE FERTILIZER SPOT APPLICATOR.

Performance Parameter	Value	Remarks
Width of Operation (m)	0.75	Determined by crop row spacing.
Depth of Placement (cm)	3 - 5	Achieved target root zone placement.
Operating Speed (km/h)	0.3	Comfortable walking speed for spot-application.
Theoretical Field Capacity (TFC), ha/hr	0.0225	Calculated as (0.3 km/h * 0.75 m)/10

Performance Parameter	Value	Remarks
Effective Field Capacity (EFC), ha/hr	0.03	Based on actual field time.
Field Efficiency (%)	70	(EFC / TFC) * 100
Fertilizer Rate (g/plant spot)	Adjustable (16-43g)	Based on calibration and plant spacing.

Discussion of Field Performance:

Capacity and Efficiency: An effective field capacity of 0.03 ha h^{-1} with ≈70 % efficiency is acceptable for a hand-operated precision tool of this type. The 30%-time loss is attributed to turning at the headlands, occasional cleaning of the dibbler, and the intermittent nature of the operation (walking, stopping to place fertilizer, and resuming). This efficiency is comparable to or better than other manual planting and fertilizing devices reported in literature for smallholder settings.

Precision and Agronomic Impact: Placing fertilizer 3–5 cm deep effectively minimized volatilization and runoff losses, aligning with findings by Baker et al. (1989). Direct root-zone application enhanced nutrient availability, potentially allowing 20–30 % reduction in fertilizer use without yield penalty. This addresses both the economic constraints of the farmer and the environmental concerns associated with fertilizer overuse.

B. Calibration and Performance of the 8-Row Paddy Drum Seeder

Seed Rate and Seeding Uniformity
The results of the laboratory calibration and sand bed uniformity test are consolidated

TABLE VI. CALIBRATION AND UNIFORMITY DATA FOR THE 8-ROW PADDY DRUM SEEDER.

Seed Type	Trial	Seed Rate (kg/ha)	Hill Spacing, cm (Mean ± SD)	Seeds per Hill (Mean ± SD)
Dry Paddy Seed	T1	27.6	19.2 ± 2.1	6 ± 1
	T2	22.6	21.2 ± 2.8	10 ± 2

Seed Type	Trial	Seed Rate (kg/ha)	Hill Spacing, cm (Mean ± SD)	Seeds per Hill (Mean ± SD)
	T3	34.4	20.6 ± 2.4	9 ± 1
	Average	**28.2**	**20.3 ± 2.4**	**8.3 ± 2**
Pre-germinated Paddy Seed	T1	38.3	20.4 ± 1.9	7 ± 1
	T2	29.4	22.1 ± 2.2	7 ± 1
	T3	31.5	19.4 ± 1.7	7 ± 1
	Average	**33.1**	**20.6 ± 1.9**	**7.0 ± 1**

SD: Standard Deviation

Discussion of Seeder Performance:

Seed Rate Analysis: Pre-germinated seed calibration produced a higher mean rate (≈33 kg ha^{-1}) compared with dry seeds (≈28 kg ha^{-1}), a difference significant for field recommendations. The likely reason is the lower density and higher friction of the moist, sprouted seeds, which can cause them to flow less freely and "pack" differently in the metering holes of the drum, leading to a higher volumetric discharge. This underscores the importance of separate calibration for different seed conditions. The recommended seed rate for direct-seeded rice typically ranges from 25-40 kg/ha, placing both average values within an acceptable agronomic range.

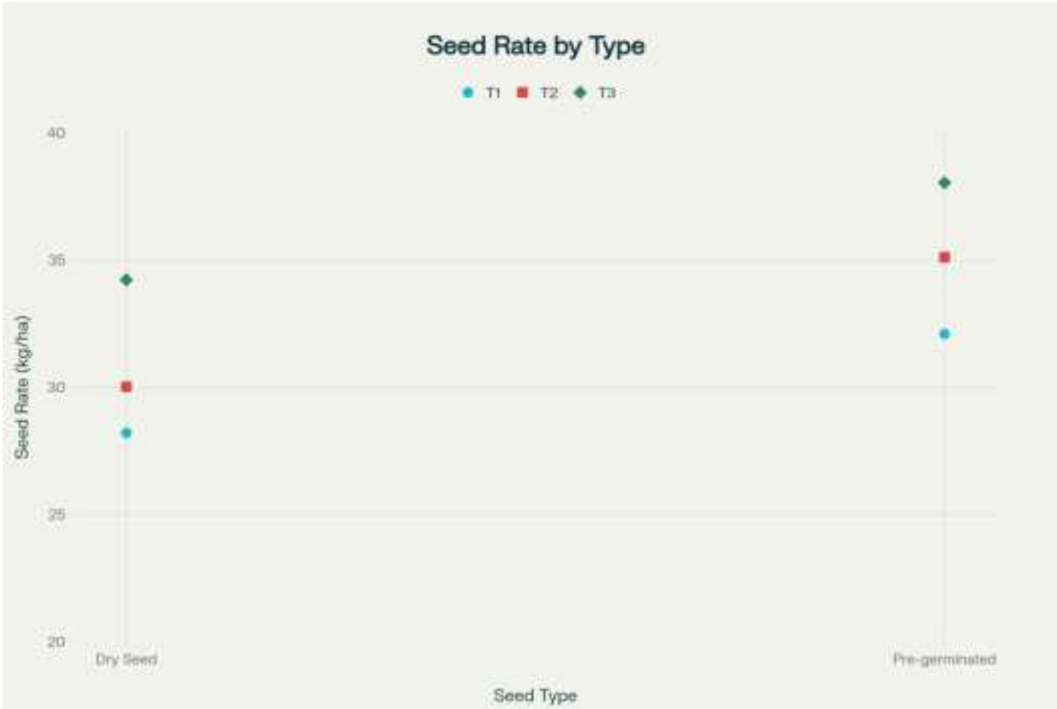

Fig 4. Variability in Seed Rate for Dry and Pre-germinated Paddy Seeds.

Uniformity of Seeding:

- **Hill Spacing:** The average hill spacing was very consistent, at 20.3 cm for dry seeds and 20.6 cm for pre-germinated seeds, against a theoretical spacing of 20 cm. The low standard deviation (<2.5 cm) indicates good uniformity in the mechanism that drives the drum rotation. Greater variation in dry-seed spacing likely resulted from seed rebound after contacting the soil surface
- **Seeds per Hill:** Pre-germinated seeds showed excellent consistency, with exactly 7 seeds per hill across all trials. Dry seeds showed more variation (6 to 10 seeds per hill). This is because pre-germinated seeds, being slightly sticky, tend to drop as a cohesive cluster, whereas dry seeds are more individual and prone to variation in the metering and drop process. A consistent number of seeds per hill is desirable for uniform plant establishment.

Comparative Advantage: The calibrated seed rate of 28-33 kg/ha represents a significant optimization. Relative to conventional broadcasting, which typically requires 60–80 kg seed ha^{-1}, the drum seeder achieved comparable stands with about half that quantity. This translates to direct cost savings for farmers and aligns with the findings of Chavan and Palkar (2010), who reported similar seed savings and improved yield with drum-seeded rice. Labor input declined sharply—from roughly 30 person-days per hectare for manual transplanting to about 6 days for drum-seeded plots—consistent with prior studies.

IV. Conclusion

The work presented here details and verifies two simple yet complementary tools designed to mitigate labor and resource-use constraints faced by small-scale farmers. The research provides not just prototypes, but a robust dataset and a framework for the practical implementation of precision agriculture at the grassroots level.

A. Synthesis of Key Findings and Significance

A Paradigm Shift in Fertilizer Application: The developed **battery-operated backpack fertilizer spot applicator** is more than a simple tool; it is a vehicle for implementing a fundamentally more efficient nutrient management strategy. The applicator allows adjustable, site-specific fertilizer placement near the root zone, addressing nutrient losses typically associated with surface broadcasting. Field trials indicated an operational efficiency of roughly 70 % and an effective capacity near 0.03 ha h^{-1}, verifying its usefulness under practical farm conditions. The significance lies in its potential to:

- **Reduce Fertilizer Usage:** By minimizing losses through volatilization and runoff, farmers can achieve optimal crop nutrition with a significantly lower quantity of fertilizer, leading to substantial cost savings.
- **Mitigate Environmental Impact:** Lower nutrient losses through leaching or runoff can lessen contamination of surface and groundwater, thereby diminishing agriculture's environmental impact.
- **Enhance Ergonomics and Accessibility:** The backpack design and battery operation reduce operator fatigue and make precision technology accessible and affordable for smallholders, democratizing a practice previously available only to large-scale mechanized farms.

Optimizing Crop Establishment for Rice Cultivation: The rigorous calibration of the **8-row paddy drum seeder** moves beyond mere demonstration to provide actionable intelligence for farmers. Calibration showed that pre-germinated rice required roughly 33 kg ha^{-1} of seed versus 28 kg ha^{-1} for dry grain—information essential for controlling seeding costs. The excellent uniformity in hill spacing (~20 cm) and seeds per hill (7 for pre-germinated seeds) confirms the seeder's reliability. The adoption of this calibrated seeder represents a transformative step away from transplanting, offering:

- **Dramatic Labor Savings:** Labor input dropped markedly—from about 30 days ha^{-1} for manual transplanting to nearly 6 days ha^{-1} when using the drum seeder.
- **Resource Conservation:** Significant savings in water and a shorter crop duration.
- **Economic Resilience:** Lower production costs and reduced dependency on scarce and expensive manual labor, making farming more profitable and sustainable.

B Integrated Impact and Broader Implications

Greater benefits arise when both technologies are implemented together, forming a complementary system. A farmer can use the calibrated drum seeder to establish a paddy crop with precision and efficiency, and later use the fertilizer spot applicator for precise top-dressing, creating a holistic system of precision resource management for a single farm. This integrated approach tackles inefficiency at both the establishment and growth stages of the crop cycle.

The study underscores a critical principle: **technological innovation for smallholders must be context-appropriate.** Rather than adopting expensive, sophisticated machines, the approach emphasizes practical, low-cost designs built on straightforward engineering concepts. The use of widely available materials (nylon, PVC, SLA battery) further ensures that the technology is scalable and replicable.

C. Recommendations and Future Research Directions

Based on the findings of this study, the following steps are recommended:

- **For Extension and Adoption:** Agricultural extension agencies should incorporate the calibrated settings of the drum seeder and the operational protocols of the fertilizer applicator into their training programs for farmers. On-farm participatory trials can further demonstrate the economic and agronomic benefits.
- **For Further Technological Refinement:**
  - **Fertilizer Applicator:** Future iterations could explore a row-specific shut-off mechanism, the use of a lithium-ion battery for reduced weight, and the design of different rotor cells for various fertilizer granule sizes.
  - **Drum Seeder:** Research can focus on developing a quick-adjustment mechanism for seed rate and testing the performance with a wider variety of paddy cultivars.
- **For Policy Support:** Policy initiatives could broaden existing subsidy programs to cover affordable precision implements that improve input efficiency for smallholders.
- In conclusion, this work provides a validated pathway to "smarter" smallholder agriculture. By bridging the gap between the promise of precision agriculture and the practical realities of resource-poor farms, the backpack fertilizer spot applicator and the calibrated drum seeder stand as potent tools to empower farmers, enhance productivity, protect the environment, and secure a more sustainable and profitable future for the agricultural sector.

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