



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; SP-9(1): 205-218
Received: 19-11-2025
Accepted: 25-12-2025

Gurav DM

Ph.D., Scholar, Department of Farm Machinery and Power Engineering, Dr. Annasaheb Shinde College of Agricultural Engineering and Technology, Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri, Ahmednagar, Maharashtra, India

Dr. SM Nalawade

Professor and Head, Department of Farm Machinery and Power Engineering, Dr. Annasaheb Shinde College of Agricultural Engineering and Technology, Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri, Maharashtra, India

Corresponding Author:

Gurav DM

Ph.D., Scholar, Department of Farm Machinery and Power Engineering, Dr. Annasaheb Shinde College of Agricultural Engineering and Technology, Mahatma Phule Krishi Vidyapeeth (MPKV), Rahuri, Ahmednagar, Maharashtra, India

Battery-powered belt-type vegetable seed planter

Gurav DM and SM Nalawade

DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i1Sc.4692>

Abstract

Agricultural mechanization is crucial for improving productivity and reducing reliance on manual labour. However, smallholder farmers often struggle to adopt advanced planting technologies due to their high costs and complicated operation. This study aims to bridge that gap by designing and assessing a battery-powered, single-row, belt-type vegetable seed planter tailored for small-scale vegetable farming. The goal was to develop an affordable, energy-efficient, and accurate planting tool capable of handling various seed types. The planter features a 24V DC motor-powered belt metering system driven by lead-acid batteries, enabling precise seed placement and spacing for vegetables like okra, onion, and cabbage. Laboratory tests were conducted to analyze seed physical properties, informing the design of the belt pockets. Factorial experiments were carried out to study the effects of three forward speeds (0.8, 1.2, and 1.5 km/h) and three sowing depths (10, 20, and 30 mm). Results showed that a speed of 1.2 km/h combined with a sowing depth of 20 mm achieved the best precision with minimal seed misses and overlaps. Field tests supported these findings, revealing consistent seed placement, high germination rates above 85%, and operational efficiency ranging from 81% to 85%, all while maintaining low power consumption. This planter offers a sustainable, budget-friendly, and user-oriented solution that helps smallholder farmer's transition from manual to mechanized planting, advancing precision agriculture in the vegetable sector.

Keywords: Agricultural mechanization, battery-operated planter, belt-type metering mechanism, precision sowing, smallholder farming, sustainable agriculture

Introduction

Background and Importance of Agriculture Mechanization

Agricultural mechanization stands as a fundamental element in today's farming practices, providing opportunities to boost efficiency, reduce manual labor, and increase overall farm productivity. In countries like India, where agriculture remains a primary means of livelihood, mechanization is especially important in tackling challenges such as labor shortages and increasing labor costs. Research shows that implementing mechanized solutions can improve productivity by 30-40%, while also ensuring that essential farming operations are completed on time an important factor for successful crop establishment ^[1]. Among the various farming operations, seed sowing is especially labor-intensive and time-sensitive. Even small delays or mistakes during this stage can lead to significant yield losses. Studies have shown that timely and uniform planting can boost crop yields by nearly 25% ^[2].

India ranks as the world's second-largest producer of vegetables, contributing approximately 212.55 million tonnes in 2023-24. This accounts for nearly 12% of the global vegetable production ^[3]. Despite India's significant role in global agriculture, small and marginal farmers who make up the majority of the farming population continue to depend on traditional planting methods like broadcasting, dibbling, or sowing behind the plough. While these techniques are cost-effective, they often result in uneven seed depth, inconsistent spacing, and lower germination rates (Atwal and Jaswal, 2024; Saqib *et al.*, 2025) ^[4, 5]. Mechanizing vegetable seed sowing presents an effective way to overcome these challenges by delivering precise control over seed placement and depth. This precision helps optimize plant populations and enhances the overall quality of the yield.

Evolution of Vegetable Planting Technologies

The successful establishment of vegetable crops largely hinges on how evenly seeds are placed in terms of both spacing and depth.

Below is a brief summary of commonly used planting methods along with their practical advantages and limitations.

- **Broadcasting:** Broadcast seeding is a fast and inexpensive technique where seeds are spread across the soil surface. However, it often results in uneven seed distribution and inconsistent planting depth, which can cause patchy germination, overcrowded plants, and ineffective weed control. This method is mainly used for crops like wheat and rice, where precise planting is not as crucial ^[4, 5].
- **Dibbling:** Dibbling involves placing seeds individually into holes at consistent spacing and depth, which supports uniform germination and efficient use of soil, water, and sunlight. This precise method encourages healthy plant growth and higher yields, while also minimizing seed wastage and simplifying maintenance tasks like weeding. However, dibbling is labor-intensive and time-consuming, making it less practical for very small seeds or large-scale farming operations (Atwal and Jaswal, 2024; Saqib *et al.*, 2025) ^[4, 5].
- **Sowing Behind the Plough:** In this traditional method, seeds are placed either by hand or mechanically into furrows created by ploughs. As the plough moves forward, the seeds are covered with soil. Commonly used on farms with animal- or tractor-drawn ploughs, this approach improves seed-to-soil contact, which enhances germination and helps protect seeds from birds and moisture loss. While more effective than broadcasting, it still demands a considerable amount of labor ^[4].
- **Drilling:** Drilling involves using a seed drill machine to plant seeds in straight rows with uniform depth and spacing, ensuring accurate placement and minimizing seed loss. This technique enhances germination, supports better root development, and improves weed control, making it a preferred choice for crops like wheat, rice, and pulses. Some advanced drills also allow simultaneous fertilizer application. However, the equipment is costly and requires regular maintenance, which can make it less accessible for small-scale farmers ^[4].
- **Transplanting:** Transplanting involves growing seeds in a nursery or greenhouse and later relocating the seedlings to the main field once they are strong enough. This approach allows farmers to select the healthiest plants, promoting uniform growth and higher yields. It is widely used for crops such as rice, tomatoes, and cabbages. While effective, transplanting is labor-intensive, expensive, and time-consuming ^[4].

Need for Battery-Operated Planters

Conventional tractor-operated planters work well on large farms, but they aren't suitable for small-scale vegetable cultivation. Their high cost, bulky design, and reliance on fossil fuels make them impractical for smallholder farmers ^[6] (Dave and Aviral 2016). Their operational inefficiency, along with increasing fuel prices and growing environmental concerns, limits their use among farmers with limited resources. Vacuum seeders, while offering high precision, are also expensive and require frequent maintenance ^[7].

In contrast, battery-operated solutions provide a sustainable and affordable alternative. They are lightweight, portable, and energy-efficient, allowing smallholder farmers to adopt mechanization without depending on costly tractors or fossil fuels ^[8]. Moreover, battery-operated machines can be powered using renewable energy sources like solar power, making them a strong fit for global sustainability efforts ^[9]. Lead-acid batteries,

while having a limited lifespan, offer a dependable and budget-friendly power source, helping to reduce the barriers to entry for smallholder farmers ^[10]. Importantly, these systems can maintain consistent seed placement and spacing, offering precision on par with larger mechanized planters while greatly cutting down on labor costs ^[11].

Significance of Belt-Type Seed Metering Mechanisms

Seed metering plays a key role in a planter's efficiency, with systems ranging from vacuum-based mechanisms for fine seeds to finger pick-up systems for larger grains. Belt-type metering is especially suitable for vegetable crops, as it delivers precise seed placement, reduces seed damage, and ensures consistent spacing ^[12, 13]. Studies show that belt-type planters can reach placement accuracies of up to 93%, greatly enhancing uniformity and minimizing errors like skips or doubles ^[14]. Additionally, the relatively simple design of belt-type systems lowers maintenance costs and improves durability, making them a practical choice for smallholder use.

Problem Statement and Research Objectives

Despite the clear benefits of mechanized planting systems, their uptake among smallholder farmers in India remains low due to financial limitations, technical challenges, and lack of supporting infrastructure. Most available mechanized options are either too costly, depend on fossil fuels, or are too complicated for effective use on small farms. As a result, many farmers still depend on manual planting methods, which often lead to uneven plant spacing, higher labor costs, and reduced crop yields ^[15, 16]. This underscores the urgent need for a planting system that is affordable, energy-efficient, and easy to use—specifically designed for vegetable farmers working on small plots.

To bridge this gap, the present study centers on developing and standardizing a battery-powered belt-type seed planter. This innovative system aims to blend the cost-effectiveness and sustainability of electric power with the precision and dependability of belt-type seed metering. The research focuses on determining the power requirements of a single-row belt metering mechanism, creating a suitable battery-operated drive system, and fine-tuning operational settings to ensure accurate seed placement under varying field conditions. Additionally, the planter's performance will be evaluated based on accuracy, efficiency, and real-world usability.

By addressing the shortcomings of both manual and conventional tractor-operated planters, this study supports sustainable mechanization in vegetable farming. It helps reduce labor requirements and operating costs while aligning with global shifts toward electrification and climate-resilient agricultural practices.

Materials and Methods

Scope and Design Considerations

This study focused on designing, prototyping, and standardizing a battery-operated, single-row belt-type vegetable seed planter for crops like okra, onion, and cabbage. Designed with smallholder needs in mind, the machine prioritizes portability, affordability, ease of use and maintenance, and consistent accuracy in seed placement and depth. Key features include gentle seed handling, uniform metering, and ergonomic design elements such as adjustable depth settings and easy battery access. To accommodate different seed sizes, the planter uses an interchangeable belt with calibrated pockets, while battery power allows for cordless, quiet, and environmentally friendly operation ^[17]. The single-row design was maintained to improve

maneuverability and minimize both capital investment and maintenance demands, making it ideal for small plots. The

design of the battery-operated belt-type vegetable seed planter is shown in Figure 1.



Fig 1: Design of battery-operated belt-type vegetable seed planter assembly with labeled components

Seed Material and Physical Properties

Representative seeds of okra (Phule Utkarsha), onion (Phule Samarth), and cabbage (Green Flash) were used to cover a range of sizes and shapes typical in vegetable planting studies, with uniformity prioritized to reduce metering variability. Measurements of length (L), width (W), and thickness (T) were taken on random samples using a digital vernier caliper (0.01 mm resolution) to determine hole sizing and pocket geometry [18].

- **Sphericity (ϕ):** Computed from L, W, T to describe shape roundness affecting hopper flow and pocket release; seeds with higher ϕ flow more smoothly through metering systems [18].
- **Thousand-seed weight (TSW):** Determined using an analytical balance to support seed-rate calibration and pocket sizing; TSW variation informs belt hole area and seed spacing settings [17, 19].
- **Bulk density (kg m^{-3}):** Measured by filling a container of known volume without compacting the contents and then weighing it; this data helps determine hopper size and feeding behavior [18].
- **Angle of repose (θ):** Estimated based on the height and base diameter of a seed pile; this measurement helps determine hopper wall angles to minimize bridging [20].

Planter Architecture and Fabrication

The prototype includes the following components: (i) seed hopper, (ii) belt-type metering mechanism, (iii) seed delivery tube, (iv) furrow opener and closer, (v) drive wheels, (vi) DC motor with electronic speed controller (ESC), and (vii) a steel frame. Components were first modeled in CAD and then fabricated from locally serviceable materials for durability and ease of repair [21].

- **Hopper:** A trapezoidal sheet-metal hopper with sloped walls and a rectangular outlet was sized from bulk density and flow tests to minimize bridging; the outlet aligns directly above the belt to ensure consistent pickup. (Design narrative per CAD is provided in the source file.)
- **Belt-type metering unit:** An endless belt with equidistant, crop-specific holes meters single seeds by gravity pickup and pocket conveyance. Hole diameters and pitch were

tuned to seed size/shape (ϕ , TSW) and agronomic spacing targets for the three crops [22].

- **Seed tube:** A straight, smooth-wall descent positioned under belt discharge limits rebound and loss, guiding seeds into the opener trench.
- **Furrow opener and closer:** Mild-steel shovel openers form a shallow furrow; a paired closer/press mechanism covers and lightly compacts soil over the seed. Dimensions and geometry were selected to promote consistent placement and gentle coverage in tilled soil.
- **Drive wheels and ground contact:** A 250 mm $\text{Ø} \times 80$ mm mild-steel wheel with spokes and lugs provides traction while limiting compaction. Circumference (~ 785 mm) supported calibration of travel per revolution; lugging improves grip and self-cleaning [23].
- **Frame and handle:** A welded mild-steel frame supports subsystems with provisions for depth adjustment and service access; the single-row footprint favors small-plot maneuvering.

Powertrain and Control

Power Requirement

Draft force was measured in tilled, sandy-loam conditions and used with operating speed to estimate power by the IS 6316:1993 approach. Including a safety margin, the requirement was 327 W, guiding motor/battery sizing.

Motor and Gearing

A 24 V, 350 W DC geared motor was selected (rated 324 rpm after reduction; ≤ 19.2 A). Final sprocket selection and overall ratio were tuned so the drive wheel speed matches target ground speeds with torque headroom.

Speed Control (ESC)

A PWM controller (12-40 V, 8 A, 13 kHz) using TL494 regulated motor speed with linear response across knob positions; this provided stable ground-speed control and consistent metering under variable load.

Battery and Converter Specification

To meet a 350 Wh (1 h $\times$ 350 W) energy budget, a 24 V pack

with ≈ 15 Ah usable capacity was targeted [24, 25]. The solution used two 12 V, 35 Ah lead-acid batteries (type 34B19LMF; ≈ 10.1 kg each), supported by a compact DC-DC step-up module for transient higher-load demands.

Experimental Design and Operating Levels

A factorial completely randomized design (FCRD) assessed the effects of forward speed and sowing depth on metering accuracy. Three speeds (0.8, 1.2, 1.5 km h⁻¹) and three depths (10, 20, 30 mm) produced nine treatment combinations (S₁D₁ ... S₃D₃) as shown in Table 1 and Table 2, consistent with agronomic ranges reported in recent studies [26].

Table 1: Levels of Independent Variables for Mechanism

Independent Variables	Forward Speed (kmh ⁻¹)	Depth of Operation (mm)
	S ₁ = 0.8	D ₁ = 10
	S ₂ = 1.2	D ₂ = 20
	S ₃ = 1.5	D ₃ = 30

Table 2: Combination of Levels (L) of Independent Variables

S ₁ D ₁	S ₁ D ₂	S ₁ D ₃
S ₂ D ₁	S ₂ D ₂	S ₂ D ₃
S ₃ D ₁	S ₃ D ₂	S ₃ D ₃

Calibration and laboratory procedures

- **Planter calibration:** Following IS 6316:1993, ground-wheel circumference was measured and the revolutions for 1/25 ha were computed. With the planter raised, a fixed number of wheel turns were executed and discharged seeds were collected and weighed to verify seed-rate delivery against theoretical values; belt speed was adjusted accordingly (BIS IS 6316:1993).
- **Uniformity (sand-bed) test:** The IS 6316:1993 sand-bed method was used to quantify seed spacing uniformity (misses, multiples, and precision index) under controlled conditions that mimic field travel.
- **Germination test:** To ensure metering did not compromise viability, seeds were soaked 24 h (pre-hydration) and then placed on moist tissue in a closed container; germination (%) was computed as germinated/total $\times 100$ after observation [17, 27].

Result and Discussion

This section deals with designing, fabricating, and testing a battery-operated vegetable seed planter under laboratory and actual field conditions. It also conducts and systematically gives the preliminary test for seed planter design considerations. The section studies the physical characteristics of seeds under consideration, testing results, evaluation, and field performance of the prototype-developed machine. The present study also considered cost economics and its utility in farmer's fields.

Laboratory Test

Physical Properties of Seeds

The physical properties of seeds are crucial for designing the belt and determining the size of the seed-dropping holes along its edge. These characteristics play a key role in shaping and optimizing the seed metering mechanism. Factors such as seed size, shape, sphericity, thousand seed weight, bulk density, and angle of repose directly impact how efficiently seeds are handled, metered, and placed. To ensure precise calibration of the belt-type metering system, the physical dimensions of the selected seeds Okra (Phule Utkarsha), Onion (Phule Samarth), and Cabbage (Green Flash) were carefully analyzed.

Seed dimensions and sphericity: As illustrated in Figure 2, okra seeds had the largest dimensions, with an average length of about 5.30 mm, width of 4.71 mm, thickness of 3.99 mm, and a sphericity (ϕ) of approximately 0.87. Their geometric mean diameter (GMD) was around 4.47 mm. In contrast, onion seeds were the smallest and least spherical, measuring roughly 2.86 mm in length, 2.50 mm in width, and 1.08 mm in thickness, with a sphericity of about 0.69 and a GMD of approximately 1.57 mm. Cabbage seeds were relatively round (length ≈ 2.15 mm, width ≈ 1.99 mm, thickness ≈ 1.53 mm, $\phi \approx 0.87$) and their GMD was around 1.86 mm.

Overall variability was modest, but the highest was observed in okra thickness (CV $\approx 12\%$) and cabbage width (CV $\approx 14\%$). This suggested that the belt's pocket diameter and chamfer required slight safety margins to prevent seed jams and doubles.

Design takeaway: The use of interchangeable belts is well justified okra requires larger, more forgiving pockets, while onion and cabbage need tighter holes to avoid double seeding.

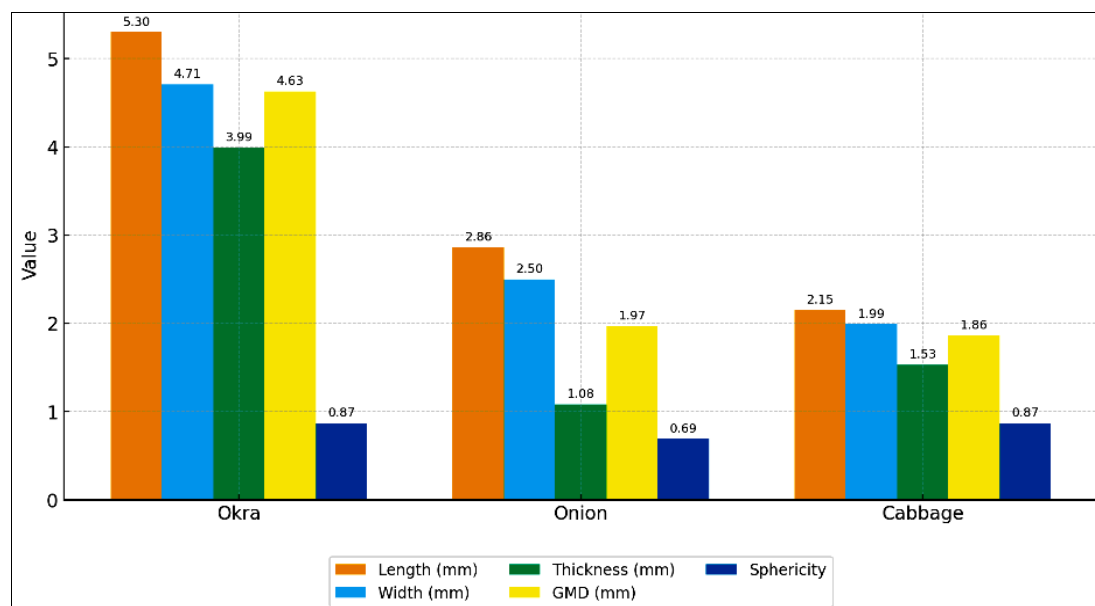


Fig 2: Physical Properties of Vegetable Seeds

Thousand-seed weight (TSW): T SW was ~43 g (okra), 4 g (onion), and 5 g (cabbage) as shown in Figure 3. This nine to ten-fold spread explains the different kinetic responses in metering: heavier okra benefits from slightly deeper pockets and a gentler pocket-release slope; onion/cabbage allow smaller

pockets and closer pitch without increasing doubles.

Design takeaway: pocket volume and pitch should be crop-specific; okra belts must prioritize single-seed capture without bounce-out, while onion/cabbage belts can prioritize throughput.

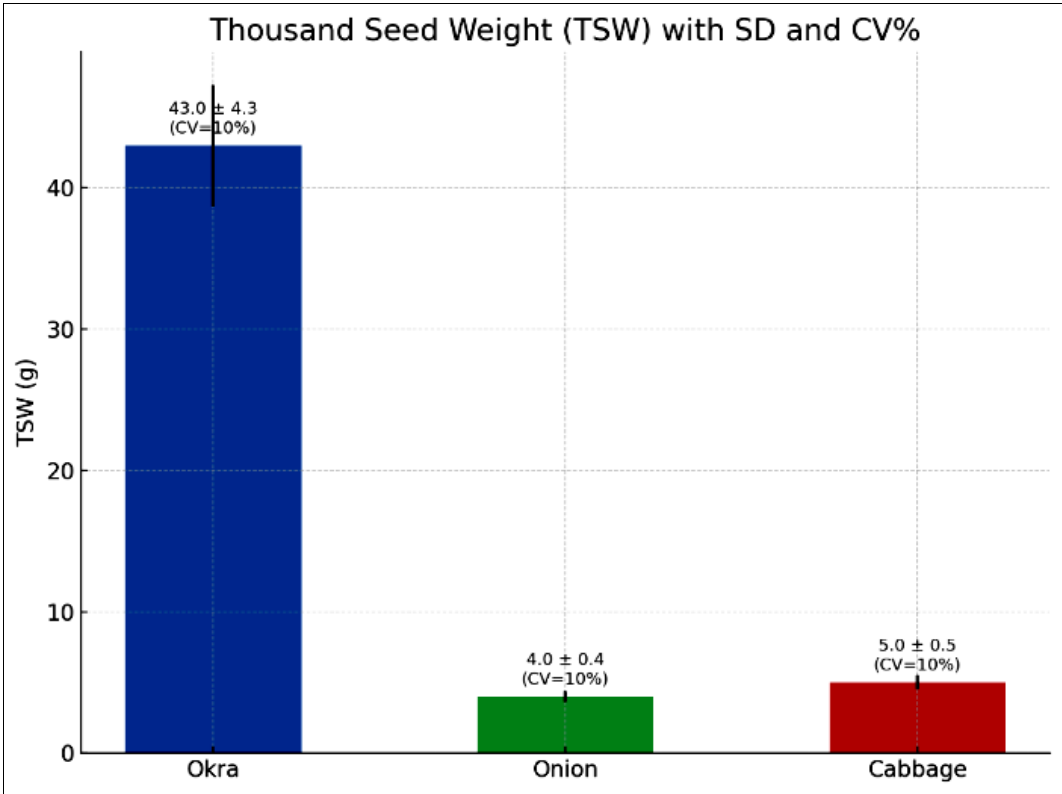


Fig 3: Average TSW of Okra, Onion and Cabbage seeds in grams

Bulk density and angle of repose: As shown in Figure 4 bulk density trended highest for okra (~0.54 g cm⁻³) and lower for onion/cabbage; the angle of repose was greatest for onion (~39°), indicating a higher bridging risk at the hopper outlet.

Design takeaway: hopper wall angles must be steeper for onion and outlet lips should be radiused or polished to reduce stagnation; for okra, capacity can be exploited without compromising flow.

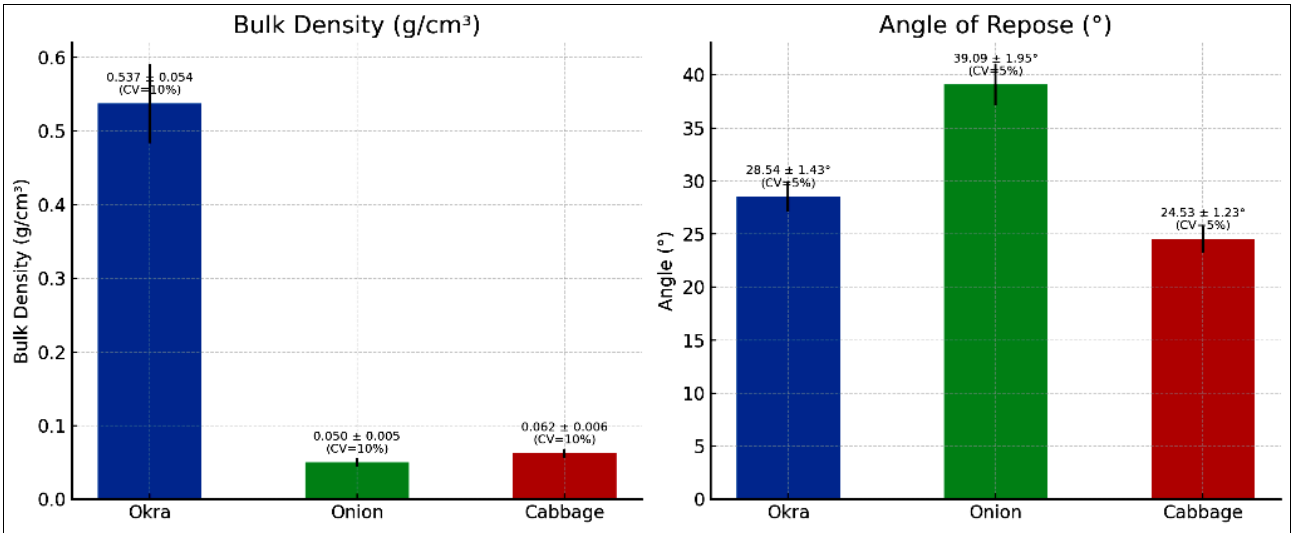


Fig 4: Bulk Density and Angle of Repose of Vegetable Seeds

Germination after metering: As shown in Table 3 the high post-metering germination (~88-93% across crops) confirms that belt pickup and release are non-injurious, validating the gentle-handling objective of the belt mechanism.

Table 3: Germination Test

Seed Type	Okra	Onion	Cabbage
Range (%)	91	88	93

Calibration and sand-bed uniformity (IS 6316)

Calibration (25-rev discharge): As shown in Figure 5 the measured seed rates closely matched agronomic targets: ~6.38 kg ha⁻¹ (okra), 2.23 kg ha⁻¹ (onion), and 0.276 kg ha⁻¹ (cabbage),

with low dispersion across replicates—evidence that the belt, sprocket ratio, and wheel circumference collectively yield repeatable seed rates under quasi-static conditions.

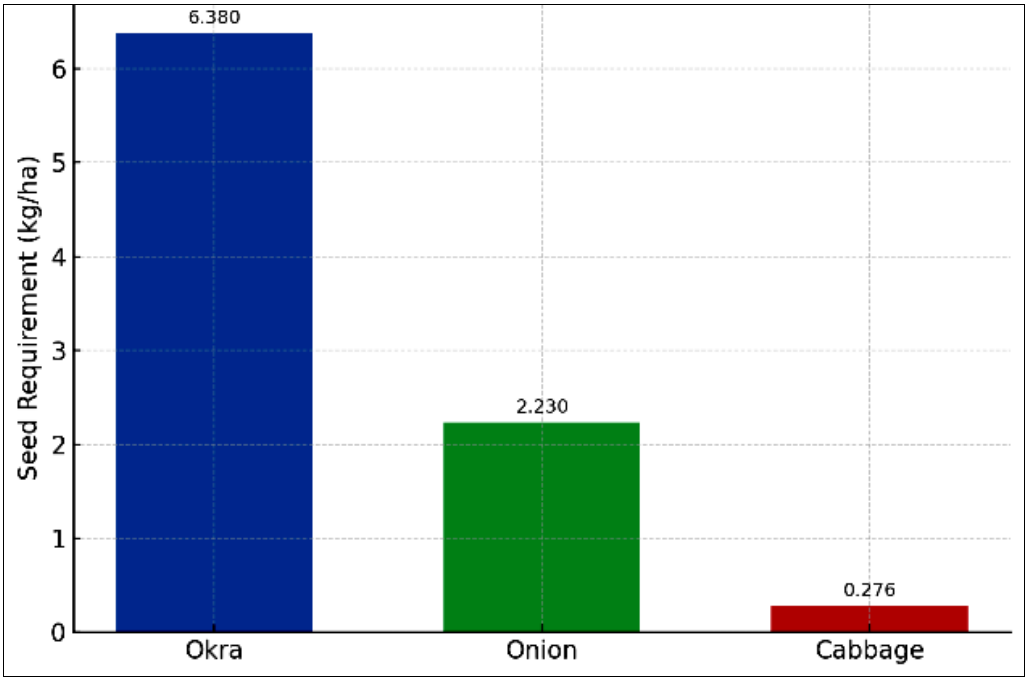


Fig 5: Calibration of Developed Seed Planter

Sand-bed spacing tests: As shown in Figure 6 the average seeds per meter and inter-seed distances aligned with recommended intrarow spacings: okra ~7 seeds m⁻¹ (~154 mm), onion ~8 seeds m⁻¹ (~138 mm), cabbage ~3 seeds m⁻¹ (~344

mm). These outcomes, obtained at the standardized ground speed, show low miss and multiple tendencies prior to field perturbations.

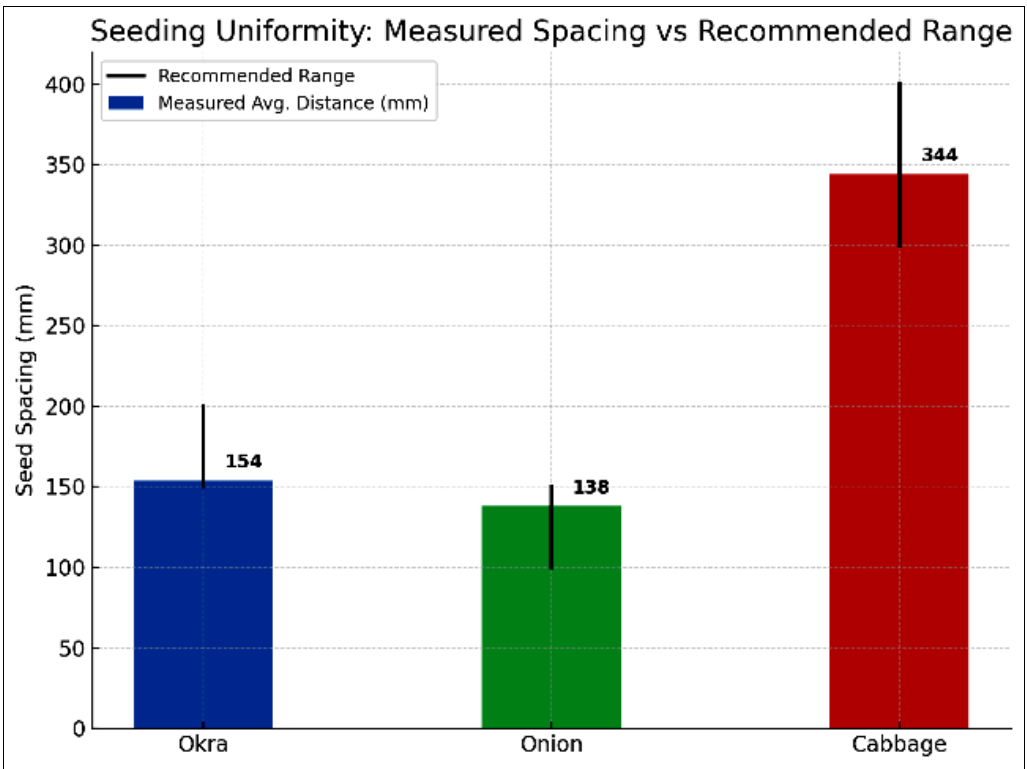


Fig 6: Results of Sand Bed Test

Optimization of operating parameters (RSM/ANOVA)

A 3×3 factorial (speeds: 0.8, 1.2, 1.5 km h⁻¹; depths: 10, 20, 30

mm) was analyzed for Missing Index (MI), Multiple Index (Mull), and Precision Index (PI) using response surface

methods.

Okra

Model significance and shape: MI and MullI models were highly significant ($R^2 \approx 0.76-0.81$), with strong quadratic effects of speed and a weaker effect of depth. PI exhibited very high explanatory power ($R^2 \approx 0.92$) with significant quadratic terms for both speed and depth.

Optima: All three indices converged to an operating region near 1.2 km h^{-1} and 20 mm depth—minimum MI and MullI, maximum PI.

Interpretation: Okra's larger, heavier seeds perform best at moderate operating speeds, which help reduce seed bounce, and

at mid-depth furrows that stabilize seed drop and soil coverage resulting in more uniform crop stands. The 3D surface plots in Figures 7, 8, and 9 visually support these trends: Figure 7 shows the lowest missing index at moderate speed and depth, Figure 8 indicates that the multiple index is also minimized in this range, and Figure 9 shows the precision index reaching its peak near the same settings. All three plots MI, MullI, and PI display curved surfaces with valleys or peaks that clearly point to intermediate speeds (around 1.2 km/h) and mid-level depths ($\sim 20 \text{ mm}$) as the optimal conditions for okra seed placement. These results emphasize that operating at a balanced point delivers both minimal misses and doubles, along with high placement precision, which is especially critical for larger-seeded crops like okra.

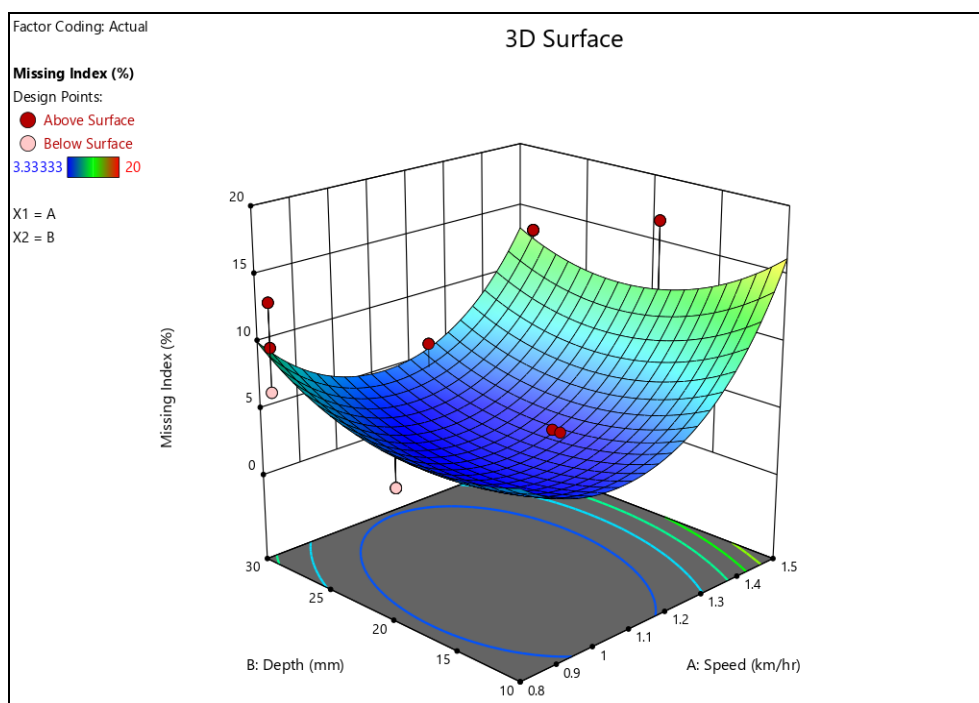


Fig 7: 3D surface plot - effect of speed and depth on missing index of okra

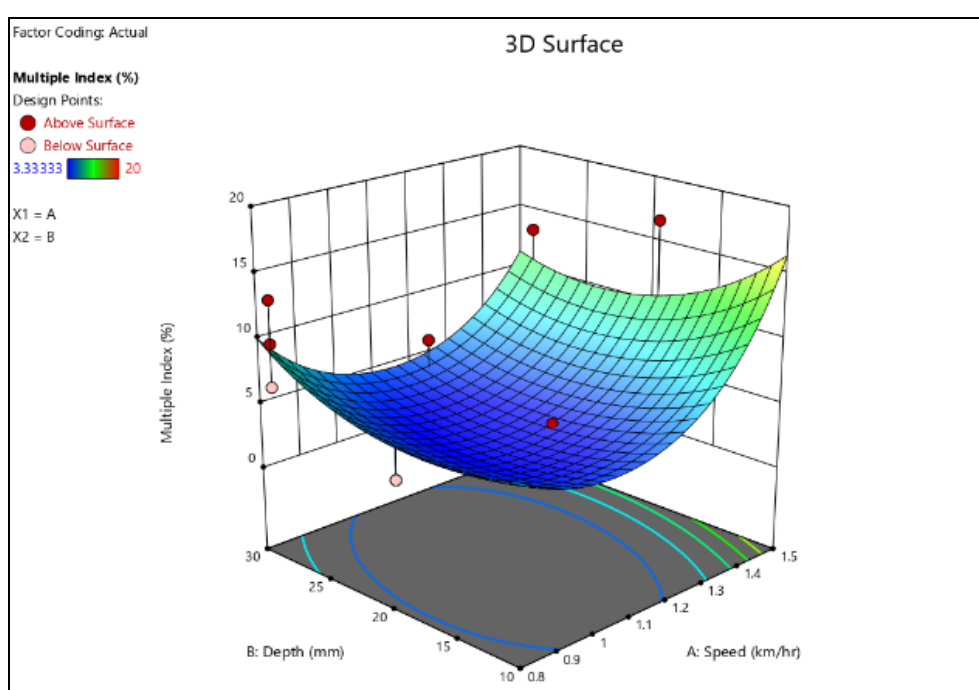


Fig 8: 3D surface plot - effect of speed and depth on multiple index of okra

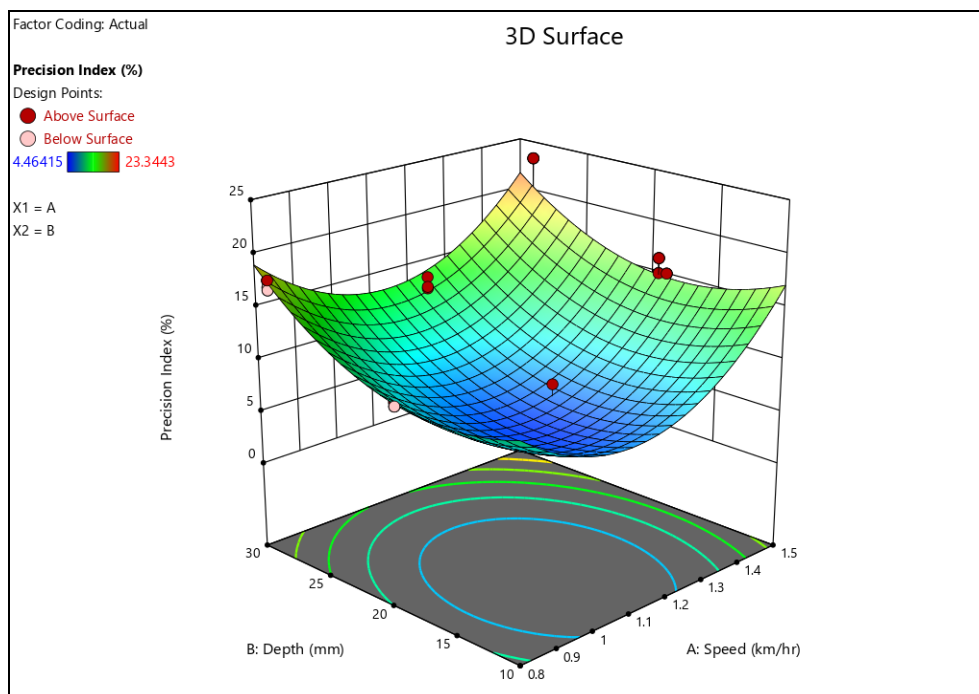


Fig 9: 3D surface plot - effect of speed and depth on precision index of okra

Onion

Model significance and shape: Onion models ($R^2 \approx 0.70-0.78$) also showed dominant quadratic speed effects; depth was less influential on MI and MullI but showed significant speed $\times$ depth interaction for PI.

Optima: MI minimized near 1.1-1.2 km h⁻¹ and 30 mm depth; MullI and PI favored ~1.2 km h⁻¹ and ~20 mm depth.

Interpretation: The small, less-spherical onion seed benefits from moderate travel speed (to avoid doubles) and slightly deeper placement for MI control, while PI peaks closer to 20

mm. The 3D surface plots (Figures 10, 11, and 12) visually highlight these effects: Figure 10 shows minimum missing index at somewhat deeper depths (around 30 mm) and moderate speed (1.1-1.2 km h⁻¹); Figure 11 indicates the multiple index is minimized under similar speed and depth ranges; and Figure 12 demonstrates that precision index reaches its optimum near 1.2 km h⁻¹ and 20 mm depth. The clear valleys and peaks in these response surfaces confirm that onion requires a practical compromise: opt for moderate speed and controlled, slightly deeper seed placement if reducing misses is a priority, or target 20 mm depth for maximum placement precision.

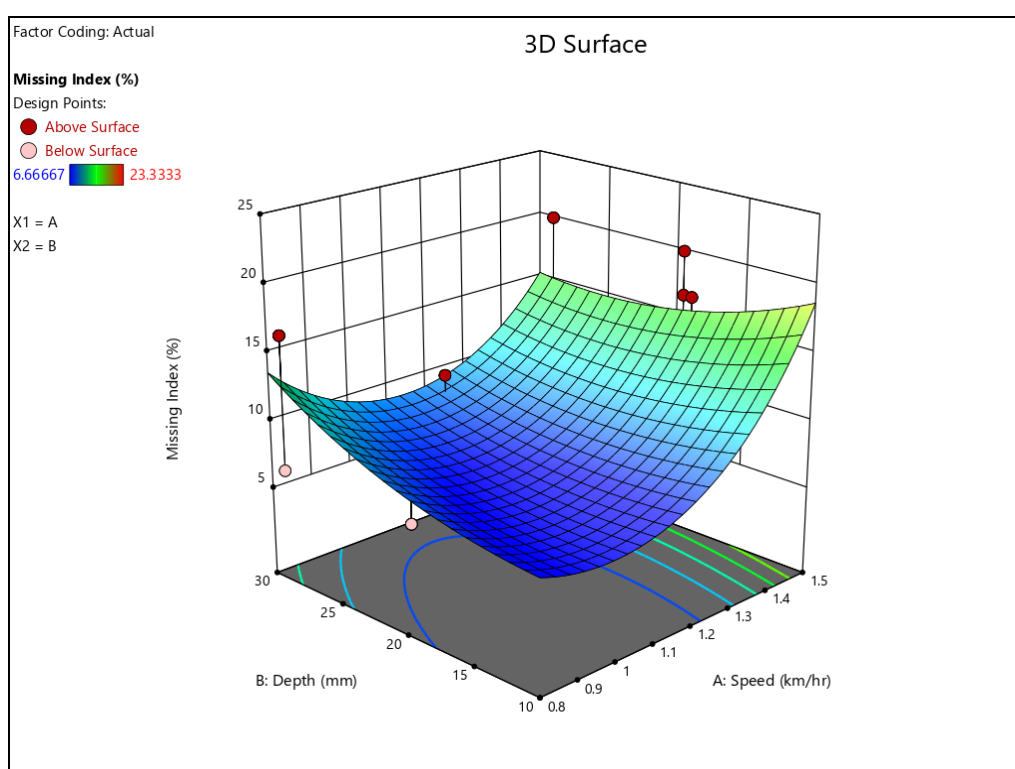


Fig 10: 3D surface plot - effect of speed and depth on missing index of Onion

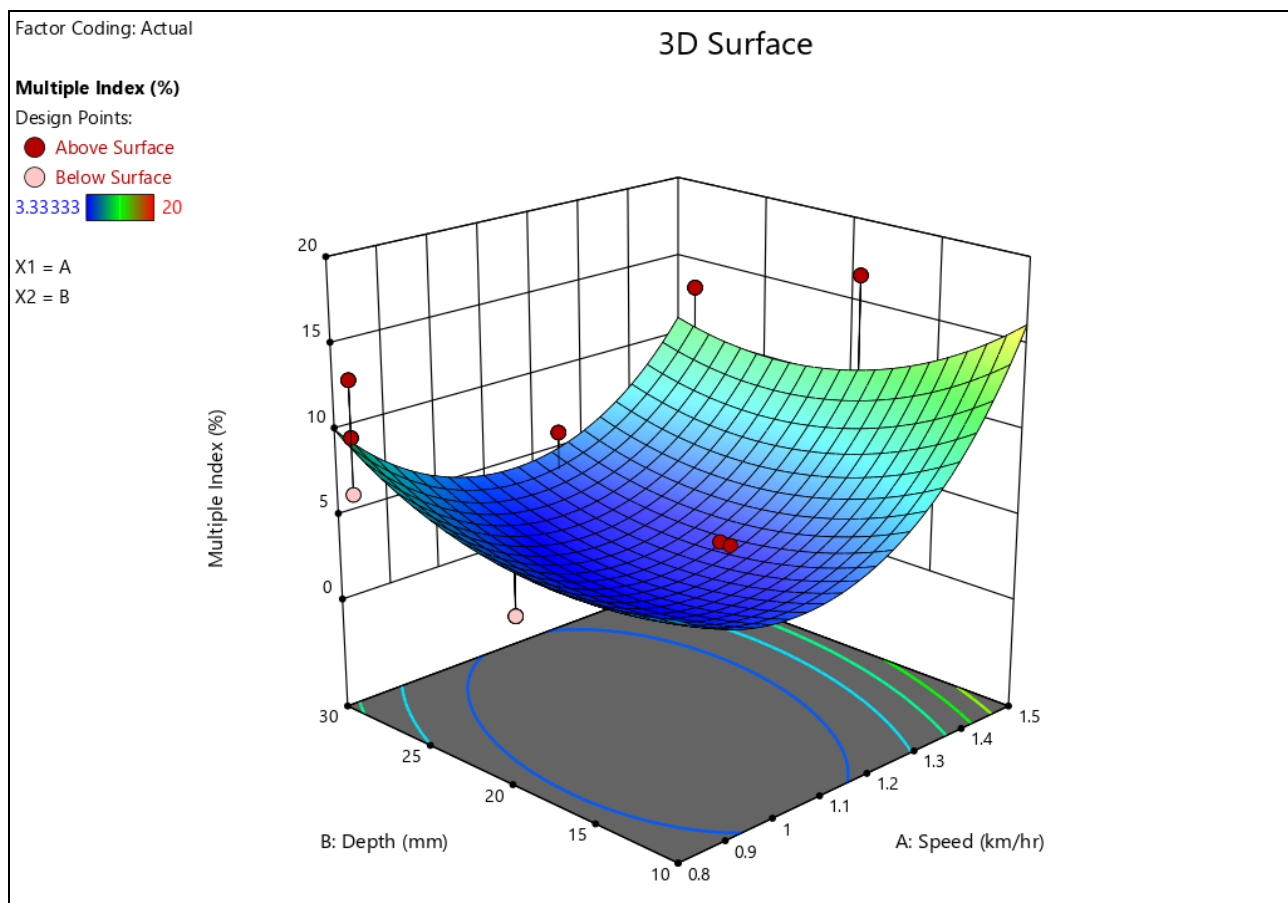


Fig 11: 3D surface plot - effect of speed and depth on multiple index of Onion

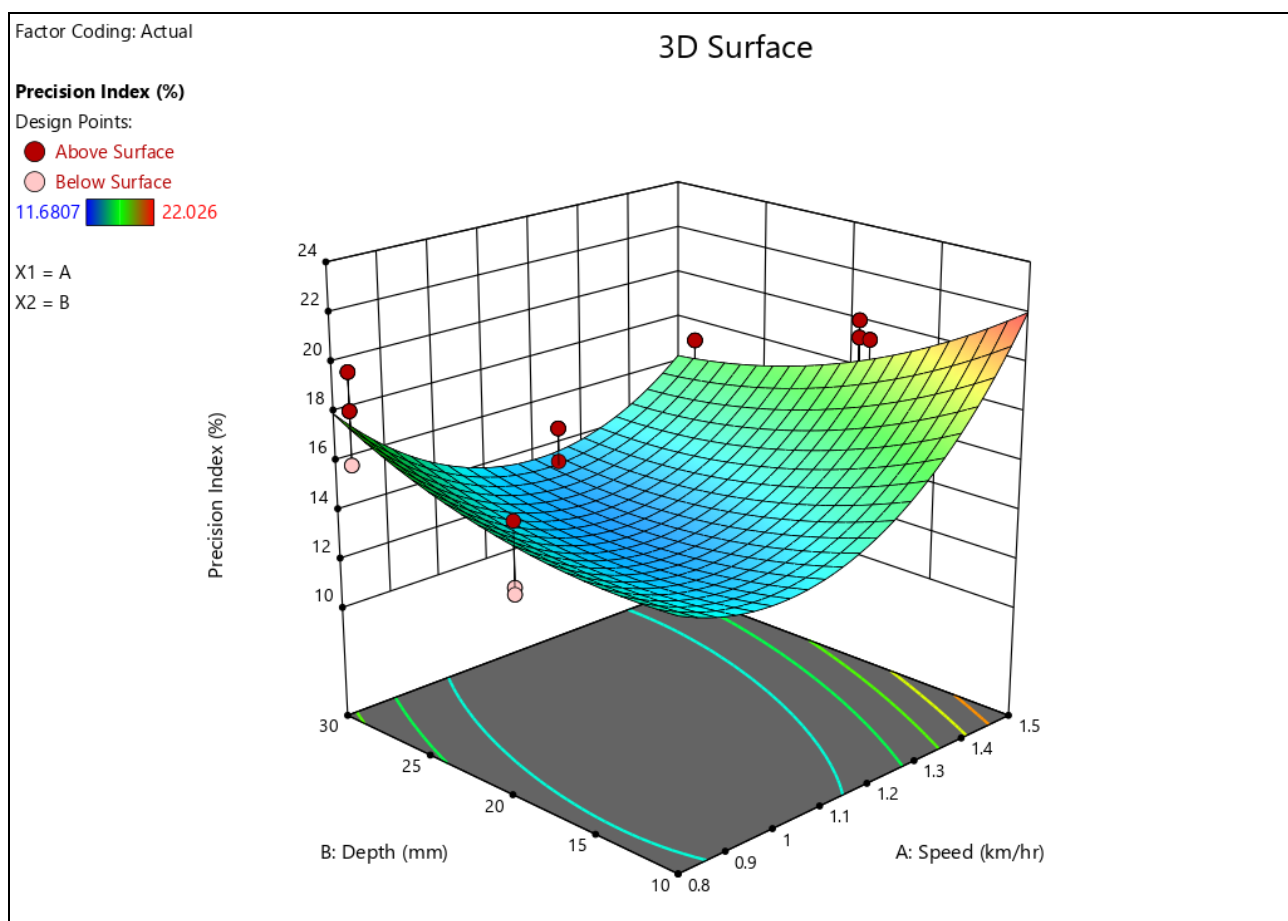


Fig 12: 3D surface plot - effect of speed and depth on precision index of Onion

Cabbage

Model significance and shape: Models were highly significant with very strong speed quadraticity ($R^2 \approx 0.81$ for MI/Mull; $R^2 \approx 0.95$ for PI). Depth showed weaker main effects but significant curvature (B^2).

Optima: MI and Mull minimized near $\sim 1.2 \text{ km h}^{-1}$, 20 mm, while PI likewise peaked at $\sim 1.2 \text{ km h}^{-1}$, 20 mm.

Interpretation: For small, fairly round cabbage seeds, a travel speed of 1.2 km h^{-1} and a depth of 20 mm consistently balanced misses, doubles, and spacing consistency. The 3D surface plots

in Figures 13, 14, and 15 clearly demonstrate these trends: Figure 13 shows the missing index minimized at moderate speed and mid-level depth, Figure 14 shows the multiple index exhibiting similar minimum zones, and Figure 15 displays a responsive peak in precision index near the same operational settings. The valley and peak patterns observed across all response surfaces suggest that cabbage seeds also reach optimal placement and uniformity under conditions similar to those for okra. This highlights the robustness and adaptability of the belt system design, even when handling seeds of varying sizes and shapes.

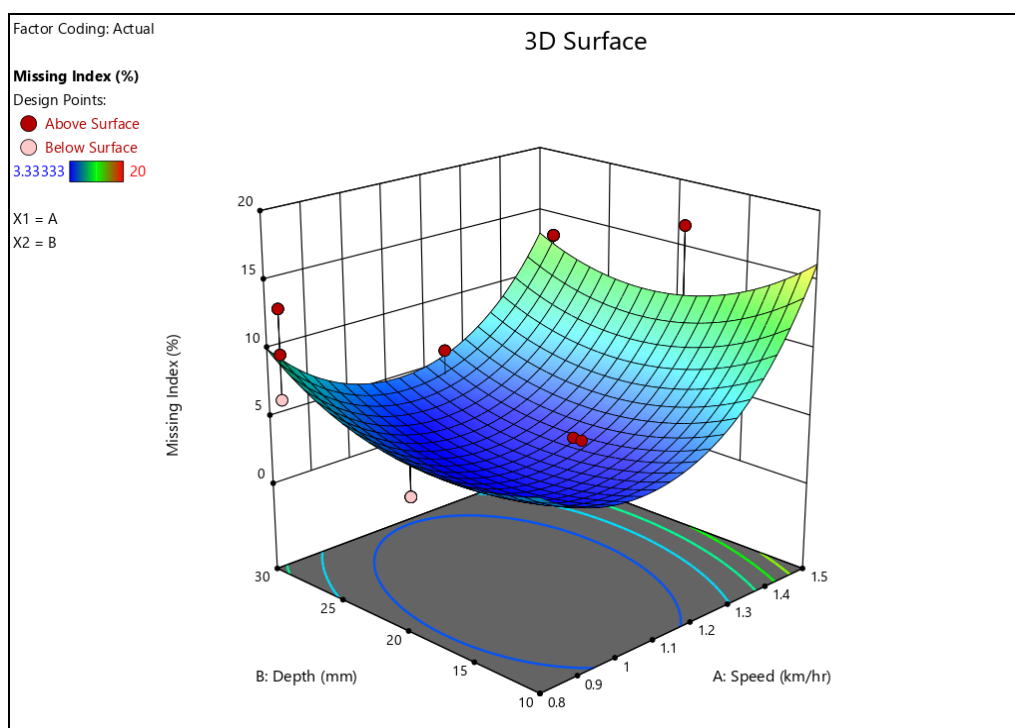


Fig 13: 3D surface plot - effect of speed and depth on missing index of Cabbage

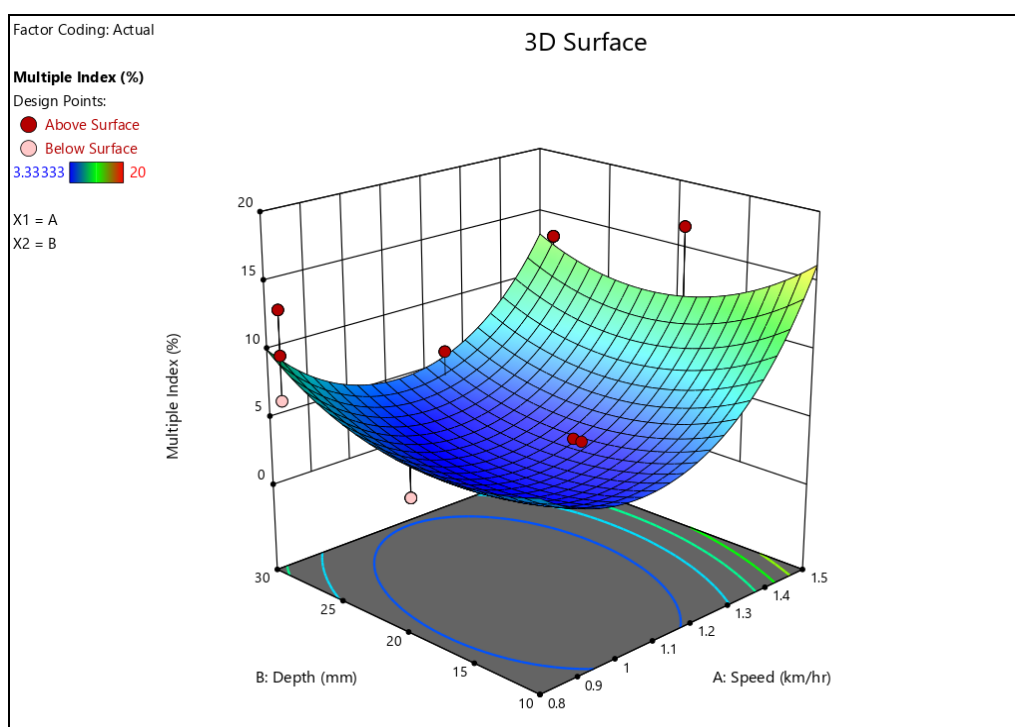


Fig 14: 3D surface plot - effect of speed and depth on multiple index of Cabbage

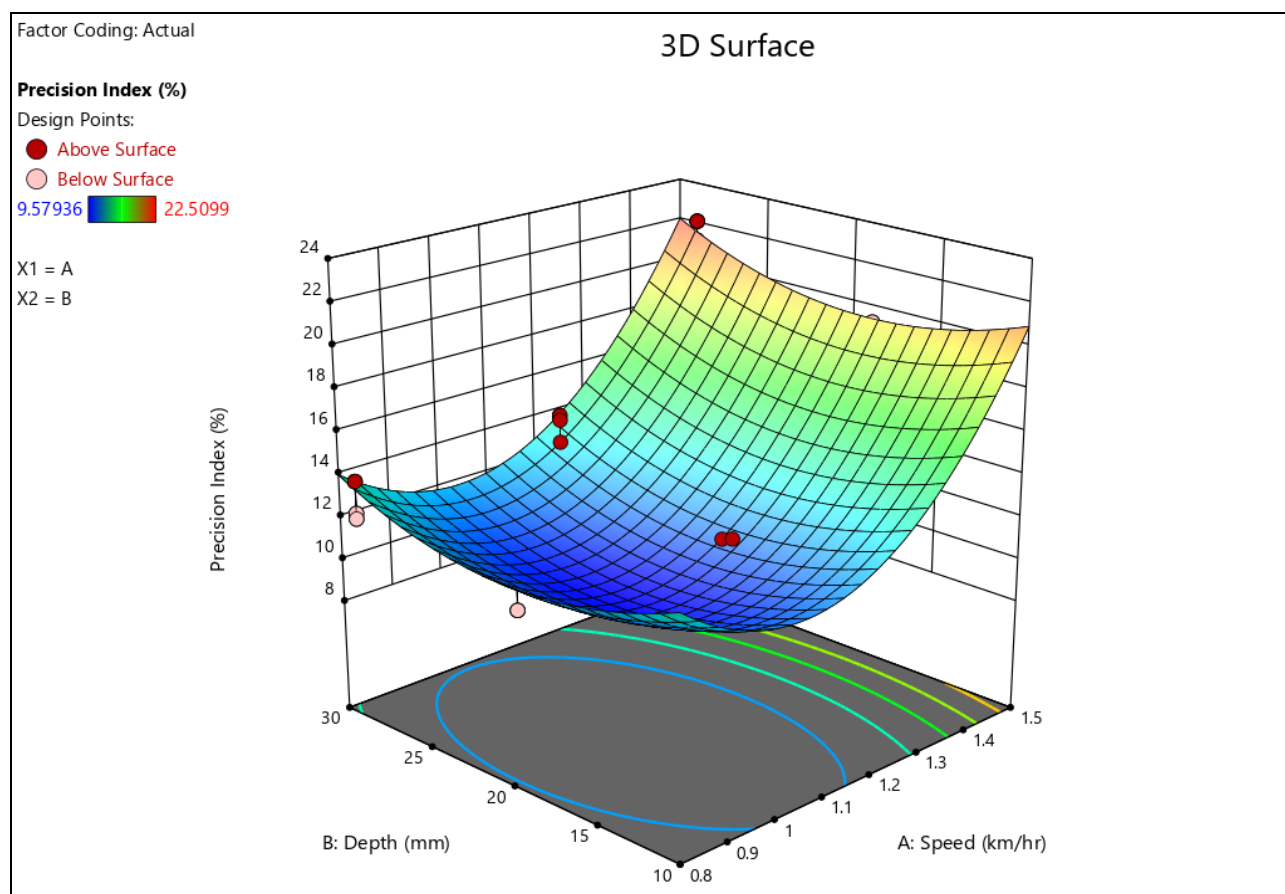


Fig 15: 3D surface plot - effect of speed and depth on precision index of Cabbage

Field performance evaluation

Field trials conducted on sandy-loam soil with moisture levels around 16-17% and bulk density between 1.44-1.45 g/cm³ supported the laboratory results. Operating at the recommended travel speed of 1.2 km/h and standardized planting depths, the prototype achieved field efficiency rates of 81-85% across all crops, with okra performing slightly better, as shown in the field efficiency bar chart. Cabbage recorded the highest theoretical and effective field capacity, indicating faster operation and improved mechanized throughput, as reflected in the corresponding performance plots.

Wheel slip stayed within the acceptable range of 5-6% for all crops, with onion exhibiting the least slip, as shown in the ground wheel slippage chart indicating stable machine operation. Emergence rates were consistently high ($\geq 85\%$), confirming reliable and uniform seed placement.

Power requirements were similar across all crops, with cabbage slightly higher due to its greater field capacity, as shown in the power required plot. Energy consumption was lowest for

cabbage (≈ 4.49 kWh/ha), moderate for onion (≈ 12.2 kWh/ha), and highest for okra (≈ 6.49 kWh/ha), as illustrated in the energy consumption chart. These differences further demonstrate the belt mechanism's adaptability to various seed types.

All miss, multiple, and precision indices stayed within acceptable ranges and matched the settings recommended by the response surface methodology (RSM): okra had a missing index (MI) of about 5.6% and a multiple index (MulI) of 4.5%; onion showed an MI of approximately 7.8% and MulI of 8.9%; cabbage recorded an MI of around 6.7% and MulI of 7.8%. The precision index (PI) remained consistently between 10-11% across all crops.

Figure 16 shows that the planter delivered strong performance under field conditions, with high efficiency, low wheel slip, and competitive energy and power requirements. These results validate the laboratory-identified optimal settings and confirm the practical effectiveness of the belt-type metering system for okra, onion, and cabbage.

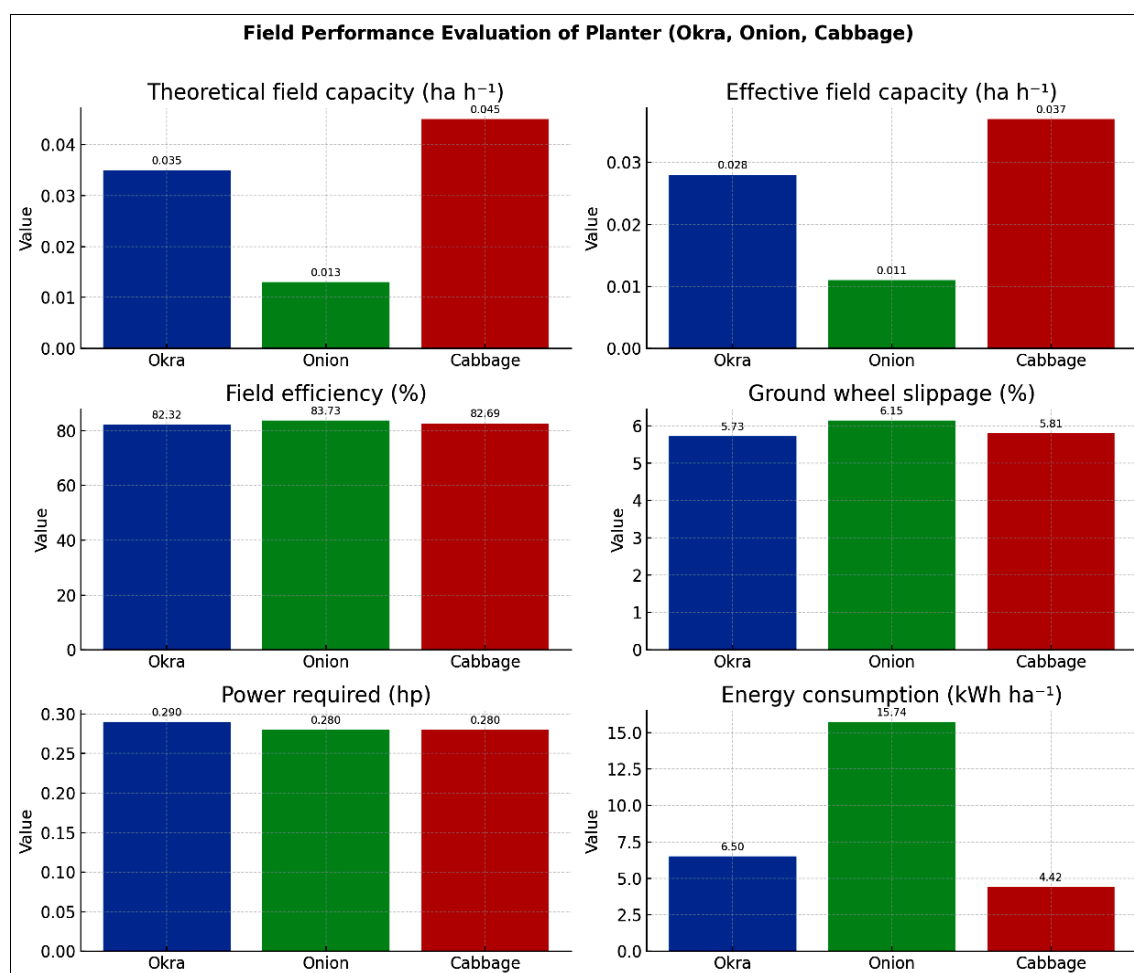


Fig 16: Results of the Field Performance Evaluation of the Planter for Okra, Onion and Cabbage

Discussion

Seed Properties and Design Implications

The physical properties of the seeds especially size, shape, and sphericity played a key role in shaping the design of the seed metering mechanism. Okra's larger size and higher sphericity made it suitable for larger pockets in the metering belt, reducing the risk of picking up multiple seeds at once. In contrast, the smaller and less spherical onion seeds required tighter pockets and carefully spaced pitch to prevent double seeding. Their lower sphericity also increased the likelihood of bridging in the hopper, which led to steeper hopper wall angles to ensure smooth seed flow. Cabbage seeds, though small, had high sphericity, allowing for tighter packing in the metering system without causing jams.

Calibration Performance and Validation

The calibration tests showed that the machine consistently achieved the desired seed rates, with only minor variations that fall within acceptable agricultural standards. For okra, onion, and cabbage, the seed rates stayed close to their theoretical values, indicating accurate performance by the metering system. Additionally, sand-bed testing confirmed uniform seed spacing, which is essential for healthy plant development. The low incidence of skips and doubles further validates the effectiveness of the design features, including the metering belt and seed delivery system.

Optimization Results and Implications for Seed Spacing

The RSM analysis highlighted the significant impact of forward speed and sowing depth on seed placement accuracy. For all

three crops, the optimal conditions were identified as 1.2 km/h forward speed and a 20 mm sowing depth, which minimized both miss and multiple indices while maximizing precision. These results indicate that a moderate speed and a 20 mm depth offer the best compromise between even seed distribution and effective soil coverage. The quadratic shape of the response surfaces suggests that even small changes in speed or depth can greatly influence performance, emphasizing the importance of fine-tuning these settings to match specific field conditions. This also demonstrates the planter's adaptability across different crops with only minor adjustments.

Field Performance and Efficiency

The field performance results aligned well with the laboratory and calibration tests, confirming the planter's ability to deliver high operational efficiency under real-world conditions. With field efficiency ranging from 81% to 85%, the machine proved effective in both speed and planting accuracy. Low wheel slip and moderate draft force further indicated that the planter was well-suited to the soil conditions encountered during trials. Energy consumption matched expected levels for battery-powered equipment, and emergence rates above 85% across all crops validated the planter's role in supporting healthy plant growth. These results suggest that the machine is a reliable and cost-effective solution for smallholder farmers engaged in vegetable seed planting.

Conclusion

This study successfully designed, developed, and standardized a battery-powered, single-row, belt-type vegetable seed planter

specifically suited for smallholder farming conditions. Based on measured seed characteristics such as size, sphericity, bulk density, and angle of repose, the planter featured interchangeable belt pockets, an optimized hopper design, and a gentle seed delivery system that consistently achieved accurate single-seed pickup and placement across three key vegetable crops okra, onion, and cabbage. The compact powertrain, consisting of a DC geared motor with PWM control and a 24V lead-acid battery pack, enabled quiet, stable, and low-maintenance operation ideal for use in fragmented fields and narrow planting beds.

A structured program of calibration, laboratory sand-bed testing, and field evaluations confirmed that the prototype consistently delivers accurate seed rates and uniform intrarow spacing, with minimal misses and doubles. Response surface analyses of different speed and depth combinations identified a practical operating range that reliably balanced the missing, multiple, and precision indices across all tested crops. In the field, the planter maintained high operational efficiency, exhibited low slip on tilled sandy-loam soil, and supported strong seed emergence demonstrating that uniform seed placement translated into solid agronomic performance. A comparison of drive configurations revealed that front-wheel drive preserved planting accuracy while also reducing draft force and energy consumption. It also improved maneuverability and operator comfort, making it the preferred configuration for standardization.

Contributions: This work contributes: (i) a low-cost, battery-powered precision planting solution tailored for small and marginal farms; (ii) a belt-based metering standard that can be adapted to different crops through pocket sizing and pitch adjustments; and (iii) a clear set of operating guidelines—moderate forward speed combined with shallow-to-moderate sowing depth that apply across various seed types. Together, these outcomes tackle key barriers to mechanized sowing in vegetable farming, including high capital costs, lack of portability, energy demands, and operational complexity, while still delivering the placement accuracy typically found in more advanced and expensive planters.

Future Work

The current standardization was carried out on tilled sandy-loam soil; therefore, further validation is needed across different soil types, moisture conditions, and surface residue levels. Future research should investigate traction performance in wet soils using alternative tread designs, scaling up to multi-row configurations, and developing quick-change belt systems for easier crop switching. Additional opportunities include integrating lightweight lithium-ion battery packs for longer runtime, incorporating solar-assisted charging, and adding affordable sensors (such as wheel RPM or seed-pass counters) for real-time rate monitoring. Large-scale, multi-season field trials that link seed placement metrics to yield and input efficiency will be essential to fully assess the system's whole-farm benefits.

References

1. Anonymous. Horticultural statistics at a glance 2023. New Delhi: Ministry of Agriculture and Farmers Welfare, Government of India; 2023.
2. Verma A, Sahu M, Soni G, Pradhan P. Optimization of operational parameters of pneumatic planter for sunflower seed. *Agricultural Engineering*. 2018;42(1):38-45.
3. Anonymous. Horticulture data: final and first advance estimates. Agritimes; 2024.
4. Atwal AS, Jaswal S. From seed to harvest: modern techniques in crop production. In: *Agriculture in transition*. 2024. p. 55.
5. Saqib M, Haram A, Akbar A, Anjum MA. Methods of open field cultivation of vegetables. In: *Sustainable and innovative vegetable production in times of climate change: concepts of olericulture*. 2025. p. 89-100.
6. Ali RM. Design and development of a multi-crop manual seed drill. *Agricultural Engineering International: CIGR Journal*. 2019;21(3):51-60.
7. Sharma A, Khar S. Current developments in vegetable transplanters in developing countries: a comprehensive review. *International Journal of Vegetable Science*. 2022;28(5):417-440.
8. Chandraker A, Victor VM, Naik RK, Dave AK. Battery powered self-propelled sowing machines: a review. *International Journal of Advanced Biochemistry Research*. 2024;8(4 Suppl):521-524.
9. Anilkumar PR, Aroli RB, Gowada SP, D T, T K. Design and development of battery-powered tiller. *International Journal of Advances in Scientific Research and Engineering*. 2023;9(5).
10. Anonymous. Battery Style [Internet]. 2024 [cited 2024 Sep 11].
11. Zulfikar, Rosa, Alaydrus AZA, Sutihari S, Nanjar A, Hartati H. Utilization of smart agricultural technology to improve resource efficiency in agro-industry. *West Science Agro*. 2024;2(1):28-34.
12. Rajaiah G, Jayan PKV. Development of electronic sticky-belt seed metering mechanism for direct-seeding of paddy. *Indian Journal of Agricultural Sciences*. 2016;86(5):598-604.
13. Muscalu A, Tudora C, Vlăduțoiu L, Vlad C, Dorogan A. Precision sowing of vegetable seeds using electrically operated distribution devices. *E3S Web of Conferences*. 2021.
14. Li Y, Zhou W, Ma C, Feng Z, Wang J, Yi S, *et al*. Design and optimization of the seed conveying system for belt-type high-speed corn seed guiding device. *International Journal of Agricultural and Biological Engineering*. 2024.
15. Solanki M. Design, development and performance evaluation of garlic planter [PhD thesis]. Akola (India): Dr. Panjabrao Deshmukh Krishi Vidyapeeth; 2019.
16. Birlhal SP, Sharma OP, Kumar S. Economics of integrated pest management: evidences and issues. *Indian Journal of Agricultural Economics*. 2000;55(4):644-659.
17. Kumar V, Rani V, Jain M, Kumar A, Kumar S. A study on physical properties of okra seed (*Abelmoschus esculentus* L.). *Advances in Research*. 2018;14:1-7.
18. Mohsenin NN. Physical properties of plant and animal materials: physical characteristics and mechanical properties. Vol. 1. London: Routledge; 2020.
19. Punil G, Yadav R, Zilpilwar S, Dharsenda T. Determination of physical and mechanical properties of onion (Gujarat White Onion-1) seeds. *International Journal of Chemical Studies*. 2019;7(4):3082-3085.
20. Sahay KM, Singh KK. Unit operations of agricultural processing. New Delhi: Vikas Publishing House Pvt Ltd; 1994.
21. Mishra GG, Jain DK. Improving durability of concrete using PVC waste flex banner. *Journal of Emerging Technologies and Innovative Research*. 2019;6:314-318.
22. Khan K, Moses SC, Kumar A. The design and fabrication

- of a manually operated single row multi-crops planter. *IOSR Journal of Agriculture and Veterinary Science*. 2015;8(10):147-158.
23. Verma K. Design, development and evaluation of manual drum seeder for onion seeds [Doctoral dissertation]. Ludhiana (India): Punjab Agricultural University; 2019.
24. Patel SK, Kumar R, Singh V. Design and performance evaluation of a battery-powered semi-automatic vegetable planter. *Journal of Agricultural Engineering*. 2022;59(2):145-156.
25. Sharma A, Gupta C, Tiwari PS. Development of an autonomous robotic weeder for precision agriculture: power system design and validation. *Computers and Electronics in Agriculture*. 2023;210:107892.
26. Shravan S, Jogdand SV. Performance evaluation of manual single row vegetable planter for okra, coriander and cowpea crop. *Journal of Pharmacognosy and Phytochemistry*. 2020;9(3):1255-1258.
27. Singh HJ, Singh HDSBK. Development and field testing of a sowing attachment suitable for hilly areas. *Excellent Publishers*. 2019;8(10):845-852.
28. International Food Policy Research Institute. Global food security and the role of mechanization in agriculture. 2022.
29. Dave AK, Dave SA. Comparative performance of tillage implements for seed-bed preparation of wheat crop in Chhattisgarh state. *Agricultural Engineering Today*. 2016;40(2):24-31.
30. Mishra D, Singh SS. Modified reaper for small-scale farmers: an approach for sustainable agriculture. *Environment, Development and Sustainability*. 2024;26(1):1451-1480.
31. Yan B, Geng D. Design and testing of electric drive system for maize precision seeder. *Agriculture (MDPI)*. 2024;10:14.
32. Anonymous. Next big thing for planters: electric seed meters. *Farm Progress*. 2024.
33. Anonymous. Protected cultivation and precision farming in vegetable crops. Bengaluru (India): ICAR-Indian Institute of Horticultural Research; 2023.
34. Anonymous. Growing with precision: a new era in agriculture. *BCC Research*; 2023.
35. Anonymous. India's fruits and vegetables industry. *India Brand Equity Foundation*; 2022.
36. Singh RB, Paroda RSDM. Science, technology and innovation: Indian agriculture towards 2030. 2022.
37. Anonymous. *AgriExchange*. 2023.
38. Anonymous. 870 belt drill - precision seed drill. *Stanhay*; 2024.