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Design of a Novel Automated Machine for Roll Towel-Based Seed Germination Analysis

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ABSTRACT

Seed germination testing is a crucial procedure in agriculture, ensuring both seed viability and quality for large-scale production. Conventional roll towel methods, although effective, are labor-intensive, inconsistent, and susceptible to human error. The proposed system introduces an automated precision-embedded machine designed to enhance the evaluation of seed germination using a rolled towel. The novel automated system incorporates cutting-edge automation technologies, such as programmable controls, motorized mechanisms, and real-time monitoring, to streamline seed placement, towel folding, rolling, and securing processes with remarkable accuracy and consistency. By removing human reliance, the framework significantly decreases error rates, enhances throughput, and ensures reproducibility in large-scale testing operations. In addition, the incorporation of real-time data monitoring provides actionable insights into germination performance, positioning it as a potent tool for agricultural research, seed quality assurance, and production optimization. This groundbreaking approach transforms the roll towel test, providing a scalable, efficient, and precise solution to contemporary agricultural challenges.

Keywords: Seed Germination; Automated System; Roll Towel Test; Embedded System

1. INTRODUCTION

Seed constitutes a fundamental element in the dynamics of plant populations and ecosystem functioning by exerting influence on the distribution of species, the composition of communities, and ecological adaptation. This intricate process is modulated by a multitude of ecological and physiological determinants, which subsequently influence the dynamics of plant communities and ecosystems. Functional traits and population dynamics of germination and population processes: The traits associated with germination, including the base, optimal, and maximum temperature thresholds, the thermal time requirements, and the levels of water potential, are integral in defining the population dynamics of various plant species [1].

These traits exert influence over germination fractions, survival probabilities, and reproductive output, which are indispensable to understand long-term demographic changes in plant populations [2]. Species-Specific Responses: Different species demonstrate differential responses to germination under varying environmental conditions, which can substantially affect their population dynamics [3]. Seedlings, in their most vulnerable stage of development, face considerable mortality rates, which can affect the stability and composition of plant populations. Environmental Influences on Germination Temperature and Climate Change: Temperature regimes, which includestant and diurnal variations, play a crucial role in the the formation of germination patterns [4]. The process of seed germination is integral to the ecological dynamics of plant communities, influencing reproductive strategies, mechanisms of seed dispersal, and the establishment of seedlings. Seedlings, being at their most vulnerable developmental stage, encounter considerable mortality rates, which can affect the stability

and composition of plant populations [5].

Traditional methodologies for seed germination typically involve positioning seeds on a substrate, such as absorbent paper or granular sand, with in carefully controlled environmental parameters. The germination process is then monitored over a designated period. These methods are simple and commonly used because they are easy to implement and cost-effective. The Standard Germination Test (SGT) represents a widely accepted traditional technique that entails the positioning of seeds on adequately moistened paper towels or within sand while ensuring the maintenance of optimal temperature and humidity parameters [6].

Seed germination techniques, demonstrated by the conventional germination assay, are widely used due to their simplicity and reliability. An investigation concerning camelina seeds (Camelina sativa) revealed that such traditional germination techniques yielded precise outcomes for evaluating seed viability; however, they may not invariably identify nuanced variations in seed vigor [7]. Similarly, traditional methods have been effectively used for evaluating the germination of rice seeds (Oryza sativa) under low-temperature conditions [8].

The roll towel test is a modified version of the traditional germination method. In this method, seeds are strategically placed between layers of hydrated paper towels, which are subsequently rolled and subjected to incubation under meticulously regulated environmental conditions. This method is beneficial for large-scale germination testing due to its efficiency in handling multiple seed samples simultaneously [9].

The roll towel test is efficient for certain types of seeds, such as those with high water imbibition rates. In a study on five orthodox species, including agricultural seeds like Pisum sativum and Cucurbita pepo, the roll towel test demonstrated consistent germination rates, with water uptake completing between 15 and 25 hours [9]. This method is also advantageous for species that require uniform moisture conditions during germination

Cereal crops like maize (Zea mays), traditional germination methods are highly effective, with germination rates reaching 100% for hybrid seeds [10]. However, the roll towel test has also been successfully used for maize seeds, particularly in studies evaluating seed vigor and field emergence.
Oilseeds, such as camelina (Camelina sativa), have consistently demonstrated high germination rates using traditional methods; however, these methods may not always detect differences in seed vigor. The roll towel test has been practical for oilseeds with high water imbibition rates, such as Cucurbita pepo.
Grass species like Siberian wild rye (Elymus sibiricus), traditional methods have been used to evaluate germination under diverse environmental conditions. The roll towel test has also been applied to these species, particularly for assessing seed vigor and predicting field emergence [11].

Vegetable seeds, such as cucumber (Cucumis sativus) and onion (Allium cepa), have shown high germination rates using both traditional and roll towel methods. However, the roll towel test has been efficient for evaluating the germination of onion seeds under controlled deterioration conditions [12].

The choice between the roll towel test and traditional germination methods depends on the specific requirements of the seeds being tested, including their water imbibition rates, environmental preferences, and the scale of the study. While traditional methods are reliable and adaptable, the roll towel test offers advantages in terms of efficiency and uniformity for certain seed types. The roll towel test offers advantages in terms of scalability and uniformity of moisture, making it suitable for high-throughput germination testing.

The automation of germination assessments has undergone considerable progress in contemporary years, propelling the incorporation of sensors, robotics, and artificial intelligence (AI). These technologies have transformed traditional labor-intensive and error-prone methods into efficient, high-throughput, and accurate systems.

Sensors are crucial for measuring environmental factors essential for seed germination. They facilitate the immediate acquisition of data, which is critical for optimizing germination conditions and predicting outcomes. A system developed for orchid seed germination uses humidity sensors connected to an IoT platform to collect real-time data, which is then analyzed using Convolutional Neural Networks (CNNs) to predict germination efficiency [13]. This integration of IoT and AI ensures precise control over humidity levels, a critical factor for orchid seeds, and can be adapted for other crops with minimal parameter adjustments.

In another study, a cartesian robotic system was equipped with multiple sensors, including humidity, temperature, luminosity, and soil moisture sensors, to monitor agricultural parameters during germination [14]. These sensors provide comprehensive data, which can be used to create optimal growing conditions for seeds. A paddy seed germination system utilizes sensors for uniform soil distribution and precise seed placement, achieving a 94% germination rate in optimal conditions [15].
The integration of sensors, robotics, and AI has enabled the development of comprehensive systems for germination testing. These systems integrate real-time data acquisition, automated seed management, and sophisticated data analysis to yield precise and practical insights.

A framework combining IoT and AI was developed to predict germination rates in real time [16]. This system uses soil sensors to collect environmental data, which is analyzed by machine learning models to predict germination patterns. The system is cloud-based, allowing for customization and scalability across different agricultural settings.

An automatic monitoring system based on deep learning was developed to track seed germination in real-time [17]. The system includes a modified germination thermostat and a three-dimensional movable camera bin. It uses a Densely Distributed Small Target detection algorithm (DDST-CenterNet) to detect and classify seeds with high accuracy, even in dense populations.

A novel 4D morphological phenotyping system called phenoTest uses X-ray technology and AI to analyze seedling growth over time [18]. This system captures 3D volume data and automatically segments plant organs, providing quantitative and objective assessments of seedling traits.
The integration of sensors, robotics, and AI has revolutionized germination testing, offering high-

throughput, accurate, and efficient solutions. These technologies not only reduce manual labor and errors but also provide valuable insights into seed biology and the environmental factors that affect germination.

Automation in seed testing laboratories has significantly advanced, leveraging technologies such as image analysis, 3D scanning, and machine learning to enhance efficiency, accuracy, and throughput. These innovations address traditional challenges in seed testing, such as labor-intensive processes and subjective measurements, by providing automated solutions that are both scalable and precise.

The traditional roll towel test begins with manually placing seeds on a pre-moistened paper towel in a grid pattern, ensuring proper spacing but often lacking precision. Next, the towel is rolled manually, requiring care to maintain alignment and uniform tension, but this step is prone to inconsistencies. Once rolled, rubber bands are secured at both ends to hold the towel in place, though uneven application can affect seed compression and moisture retention. Finally, the prepared rolls are placed inside a germination chamber for controlled testing, but the manual process limits scalability and precision for large-scale seed testing.

The existing systems has several disadvantages in traditional roll towel-based seed germination methods, including time inefficiency, high error rates, inconsistent seed placement, and labor-intensive processes. The novel automated embedded machine addresses these challenges by integrating advanced precision mechanisms, programmable controls, real-time monitoring, ensuring accuracy, consistency, and scalability. This innovative approach significantly improves operational efficiency while overcoming the limitations faced in conventional seed testing laboratories.

The contribution of the study is summarised as follows.

- To automate the roll towel seed germination test by designing an automation system for precise seed placement, uniform rolling, and accurate banding.
- To enhance efficiency, accuracy, and scalability in seed testing laboratories by reducing manual intervention and improving reproducibility.

2. MATERIALS AND METHODS

This study introduces an automated roll towel system that significantly reduces processing time while ensuring precision, consistency, and scalability. By integrating motorized mechanisms, programmable controls, and real-time monitoring, it enhances efficiency and reliability for large-scale agricultural research and seed quality assurance in seed testing laboratories.

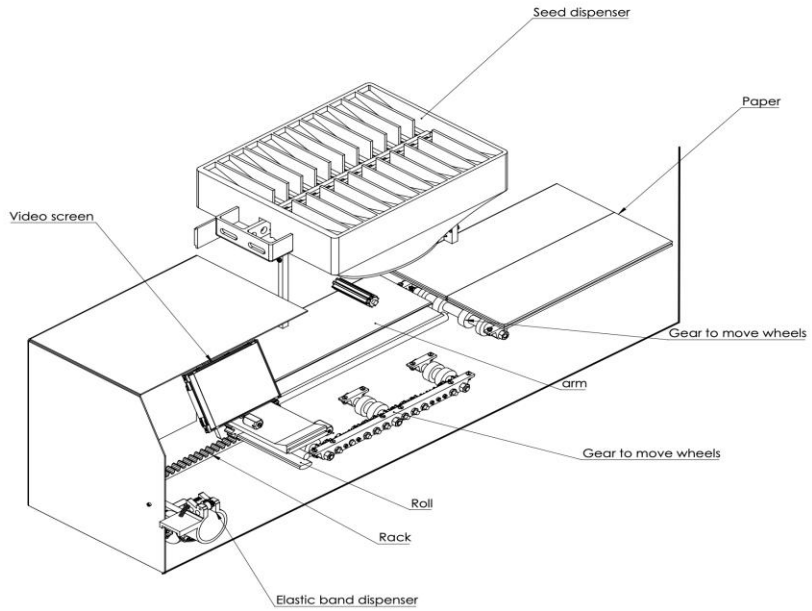


Fig. 1. Novel Automated Machine for Roll Towel-Based Seed Germination.

2.1 Proposed Automated Roll Towel Seed Germination Test

The proposed automated roll towel-based seed germination system as shown in Fig. 1 comprises several key components. At the top, a seed dispenser ensures uniform distribution of seeds onto the paper towel placed on the feed platform. The paper feed area provides the surface where the towel is initially positioned for seed placement. A mechanical arm assists in folding or guiding the towel during the rolling process. The roller system, comprising a roll, rack, and gear mechanism, enables the smooth and consistent rolling of the towel. A gear system connected to wheels ensures precise movement of the towel through different stages. To secure the rolled towel, an elastic band dispenser automatically applies bands at both ends. Finally, a video screen is integrated into the setup, likely for real-time monitoring and displaying the system's operational status. The key components in the proposed system are listed in Table 1. There are several other small components required for the system's complete functionality; the detailed list is provided in Table 5. The Element IDs mentioned correspond to the component numbers listed in the master components list provided in Table 5. This modular and automated configuration significantly reduces manual intervention while enhancing consistency and efficiency. The automated roll towel test involves four key steps: preparing the towel for seed placement, controlled seed dispensing, uniform rolling of the towel, and final securing using an automated banding mechanism.

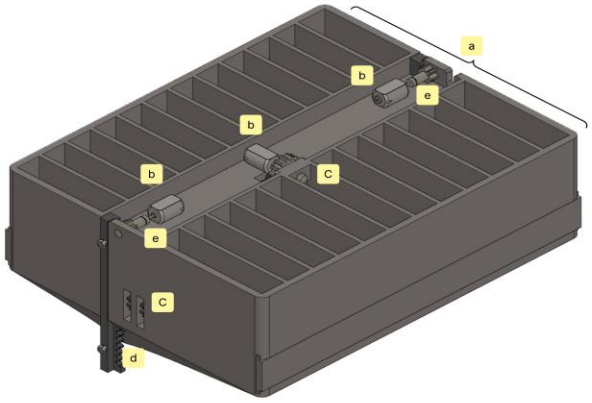


Fig. 2. Seed dispenser: (a) seed compartment, (b) motor, (c) helices, (d) rotating shaft, and (e) wheel grip.

2.1.1 Step 1: Preparing the towel for seed placement

The process begins with the roll towel (Element ID 4), which is placed inside the roller unit. The area of the germination towel, as shown in Eq. (1), is critical in determining the available space for seed placement. For a towel with dimensions and, the total area helps in calculating the spacing for seeds. Ensures that seeds are evenly distributed without overcrowding, maintaining proper conditions for germination. To move the towel forward, an electric motor (Element ID 9) provides the necessary rotation. This motor drives a set of gears, including the small gear to roll (Element ID 10), gear to roll (Element ID 37), and gears with connectors (Element IDs 21–24) which transmit power to the rollers. The double roller (Element ID 11) and the big roller (Element ID 12) are then used to grip the rolled towel and gently slide it forward from the tray. These rollers are supported by a combination of medium gears (Element ID 27) to ensure synchronized rotation. Finally, the top-to-roll part (Element ID 36) guides the towel smoothly and in alignment with the seed dispensing area. This entire system works as shown in Fig. 3 together to automate the first critical step of the Roll Towel Test preparing the towel surface where seeds will placed using a seed dispensing system.

$$A_t = L \times W \tag{1}$$

Table 1. Key Components for Towel Sliding Mechanism in Roll Towel Test

Element ID	Component Description	Process	Quantity
4	Roll	3D printed	1
9	Electric Motor	Commercial Piece	9
10	Small gear to Roll	3D printed	2
11	Double Roller	3D printed	2
12	Roller big	3D printed	2
21–24	Gear with connector	3D printed	Various
27	Medium Gear	3D printed	8
36	Top to Roll	3D printed	1
37	Gear to Roll	3D printed	1

2.1.2 Step 2: Controlled seed dispensing

The seed dispenser assembly shown in Fig. 2 features multiple seed compartments to segregate individual seeds and utilizes geared DC motors for the controlled rotation of dispensing helices. Seed spacing, both along the length (S^L) and width (S^W) of the towel, is calculated by dividing the towel dimensions by the number of rows (R) and columns (C) as shown in Eq. (4). For example, if 100 seeds are placed in a 10x10 grid, this equation ensures the precise positioning of seeds for uniform germination testing. The helices, mounted on rotating shafts, guide the seeds downward with precision. Additionally, structural components such as the roof roll, left and right sliders, and the support frame, along with fastening screws and nuts, ensure stability and smooth linear motion. Several parts are fabricated using 3D printing, while standard fasteners and motors are sourced commercially. A complete seed dispenser list of components is detailed in Table 2.

The programmable seed dispenser calculates the steps required for dispensing (S_t) based on the number of seeds (N_s) and the linear movement per step. Accurate control ensures uniform seed placement for each towel shown in Eqs. (2) and (3).

$$S_s = \text{Pitch} \,/\, \text{Linear Movement per Step} \tag{2}$$

$$S_t = N_s \times S_s \tag{3}$$

$$S^L = L \,/\, R, \quad S^W = W \,/\, C \tag{4}$$

Table 2. Seed Dispenser Components

Component	Process	Quantity
Seed Supplier (Element ID 2)	3D Printed	1
Helice (Element ID 3)	3D Printed	1
Zipper (Element ID 6)	3D Printed	1
Electric Motor (Element ID 9)	Commercial Piece	9
Gear with Connector (Element IDs 21–24)	3D Printed	Various
Small Gear (Element ID 25)	3D Printed	8
Wheel Grip (Element IDs 19–20, 26, 30)	3D Printed	Perforated, Various

2.1.3 Step 3: Uniform rolling of the towel

After the seeds are placed on the first roll towel, a second towel is layered on top to complete the setup. To roll this Towel–Seed–Towel layer uniformly, a motorized mechanism is used as shown in Fig. 3 and Fig 4. This rolling mechanism starts with the electric motor (Element ID 9), which provides the necessary power to drive the system. The motor is connected to a set of gears, including the gear for rolling (Element ID 37), a small gear for rolling (Element ID 10), and a medium gear (Element ID 27). These gears are interconnected using gear connectors (Element IDs 21–24), which ensure the smooth transfer of rotation throughout the system. Once the motor starts, it rotates the gear to roll, which then transfers the motion to the other gears and ultimately drives the big rollers (Element ID 12) and the roll shaft (Element ID 4).

These rollers physically pull the towels and roll the layered structure forward. The Top to Roll

part (Element ID 36) helps guide the second towel properly and ensures that the layering remains aligned during the rolling process and sent for banding in the next stage to secure the rolled structure in place for further processing. The force required to roll the germination towel is influenced by the coefficient of friction (μ) and the towel's weight (W) as shown in Eq. (5). By minimizing this force, the roller system can operate smoothly and consistently, ensuring proper tension during the rolling process. Together, these components shown in Table 3 work in coordination to roll the entire layered setup tightly and evenly, ensuring proper seed coverage between the two towels for germination.

$$F_r = \mu \times W \tag{5}$$

Table 3. Components Used in Top Paper Rolling Mechanism

Element ID	Description	Process	Quantity
4	Roll	3D printed	1
9	Electric Motor	Commercial Piece	9
10	Small gear to Roll	3D printed	2
12	Roller big	3D printed	2
27	Medium gear	3D printed	8
36	Top to Roll	3D printed	1
37	Gear to Roll	3D printed	1
21–24	Gear, with connector	3D printed	Various

2.1.4 Step 4: Securing using an automated banding mechanism

After the rolled towel is prepared by placing the seeds inside the towel layers and rolling them up, the next essential step is to band it. This process ensures that the rolled towel stays intact and compact during germination testing or incubation. To perform this task, the system utilizes a combination of 3D-printed and commercial components, precisely coordinated to apply a rubber band around the towel roll. The Element ID 30 serves as the rubber band feeder. It is a commercial unit that holds and dispenses rubber bands for application. Once the towel is rolled and moved into position, the Hook (Element ID 31) has one end of the rubber band firmly. At the same time, the Gear (Element ID 32), a 3D-printed drive gear, engages with the feeder mechanism to stretch the rubber band to the required size. To ensure the rolled towel remains in place during this procedure, the system employs two sliders: the Left Slider (Element ID 34) and the Right Slider (Element ID 35). Both components are 3D printed and positioned on either side of the roll to stabilize and align it during the banding process. These sliders gently grip the towel roll, allowing the rubber band to be wrapped evenly and securely. The elastic bands secure the rolled towels by storing energy when stretched. The energy (E_β) is determined by the elastic constant (k) and the stretch length (ΔL) in Eq. (6). Proper tension prevents seed displacement during testing. Together, these components shown in Table 4 work in coordination to secure the roll towel.

Once the rubber band is successfully placed around the towel roll, the sliders disengage, and the roll is ready for incubation or testing. This automated banding step significantly improves uniformity and efficiency in the roll towel method by eliminating manual errors and ensuring proper closure of

each sample.

$$E_\beta = ½\, k(\Delta L)^2 \quad (6)$$

Table 4. Components Involved in Rubber Banding Mechanism

Element ID	Description	Process	Quantity
30	Elastic band feeder	Commercial Piece	1
31	Hook	3D printed	1
32	Gear	3D printed	1
34	Left slider	3D printed	1
35	Right slider	3D printed	1

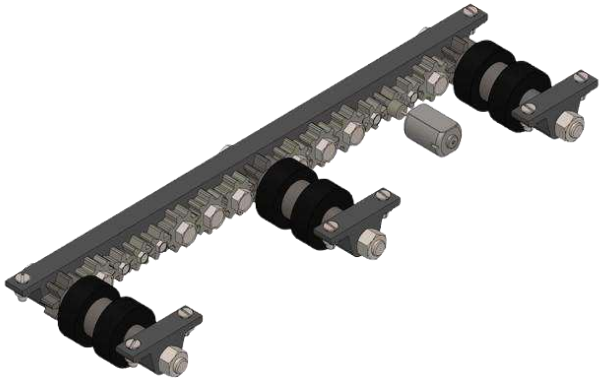


Fig. 3. Gear mechanism to roll germination towels used in the proposed Automated Roll Towel Test.

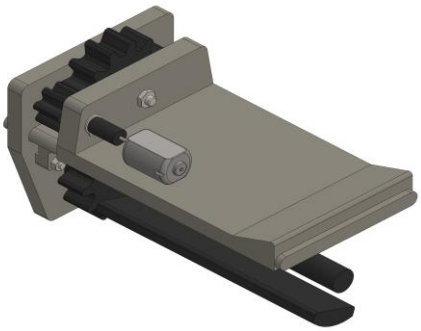


Fig. 4. Roller mechanism used in the proposed Automated Roll Towel Test.

Table 5. Component Details for the Proposed Automated Roll Towel Test System

Element ID	Description	Process	Quantity
1	Folded sheet metal body	Laser cut. SAE 1020, metal h: 2.4mm. Epoxi Pinter.	1
2	Seed supplier	3D printed	1
3	Helice	3D printed	24
4	Roll	3D printed	1
5	Roof Roll	3D printed	1
6	Zipper	3D printed	1
7	Arm	3D printed	1

8	Big gear to Roll	3D printed	1
9	Electric Motor	Commercial Piece	9
10	Small gear to Roll	3D printed	2
11	Double Roller	3D printed	3
12	Roller big	3D printed	2
13	FLATCKT 6x16x10.2-slot-D-N	Commercial Piece	22
14	FLATCKT 4x20x15.5-slot-D-N	Commercial Piece	4
15	B18.2.4.5M - Hex jam nut, M6 x 1 –D-N	Commercial Piece	22
16	B18.2.4.5M - Hex jam nut, M5 x 0.8 –D-N	Commercial Piece	4
17	B18.2.4.5M - Hex jam nut, M8 x 1.25 –D-N	Commercial Piece	8
18	B18.2.4.5M - Hex jam nut, M10 x 1.5, with 16mm WAF –D-N	Commercial Piece	2
19	Wheel grip, 1 perforation	3D printed	4
20	Wheel grip - 5 perforations	3D printed	2
21	Gear, With connector	3D printed	5
22	Gear, With connector	3D printed	1
23	Gear, With connector	3D printed	1
24	Gear, With connector	3D printed	1
25	Small gear	3D printed	8
26	Wheel grip - 5 perforations	3D printed	1
27	Medium gear	3D printed	8
28	Long roller	3D printed	1
29	Wheel grip - 3 perforations	3D printed	1
30	Surtidor de Bandas Elasticas	3D printed	1
31	Hook	3D printed	1
32	Gear	3D printed	1
33	Gear	3D printed	1
34	Left slider	3D printed	1
35	Right slider	3D printed	1
36	Top to Roll	3D printed	1
37	Gear to Roll	3D printed	1
38	B27.7M - 3AM1-46	Commercial Piece	1
39	B27.7M - 3AM1-8	Commercial Piece	1
40	B18.2.3.5M - Hex bolt M6 x 1.0 x 50 –18N	Commercial Piece	1
41	B18.3.1M - 6 x 1.0 x 16 Hex SHCS – 16NHX	Commercial Piece	3
42	B18.3.1M - 4 x 0.7 x 6 Hex SHCS – 6NHX	Commercial Piece	3
43	B18.3.1M - 4 x 0.7 x 45 Hex SHCS – 20NHX	Commercial Piece	1
44	B18.6.7M - M4 x 0.7 x 30 Indented HHMS – 30N	Commercial Piece	8
45	B18.6.7M - M8 x 1.25 x 35 Indented HHMS – 35N	Commercial Piece	8
46	B18.6.7M - M10 x 1.5 x 55 Indented HHMS – 38N	Commercial Piece	2
47	B18.2.4.1M - Hex nut, Style 1, M4 x 0.7 –D-N	Commercial Piece	9
48	AM A M10X120-N	Commercial Piece	3

49	AM A M10X100-N	Commercial Piece	2
50	AM A M10X240-N	Commercial Piece	1
51	B27.8M - 3DM1-10	Commercial Piece	6
52	B27.8M - 3DM1-16	Commercial Piece	2
53	B18.2.4.2M - Hex nut, Style 2, M10 x 1.5, with 16mm WAF –D-N	Commercial Piece	12
54	Hopper Lid	3D printed	2
55	Camera	Commercial Piece	1
56	LCD screen-Display	Commercial Piece	1
57	Electrical cover	Laser cut. SAE 1020, metal h: 2.4mm. Epoxi Pinter.	1
58	Avoid nut M4	Commercial Piece	3
59	Electric board	Commercial Piece	1

Algorithm 1. Automated Roll Towel Test Process

Require: Germination Towel, Seed Dispenser, Folding Mechanism, Elastic Band Dispenser, Germination Chamber Properly Rolled and Secured Towel with Seeds

Step 1: System Initialization

Power ON the system and perform a hardware check Verify availability of towels, seeds, and elastic bands Position seed dispenser and towel in the starting position

Step 2: Seed Dispensing

While not at end of the process **do**

Detect the towel using sensors

If towel detected **then**

Move the towel to the seed dispensing station Distribute seeds evenly on the towel using a controlled dispenser.

else

Wait for towel placement or alert user

end if

Step 3: Towel Folding and Rolling

Activate the automated rolling mechanism

Roll the towel uniformly while maintaining seed placement

Ensure proper alignment to avoid seed displacement

Step 4: Securing the Roll

Apply elastic bands on both ends using the automated banding system

Check if the towel roll is tightly secured Adjust tension and reapply bands

Step 5: Transfer to Germination Chamber

Move the processed towel roll to the germination chamber Verify chamber conditions (humidity, temperature) Update the system status and log the processed towel

Step 6: Completion

Mark the towel as processed and ready for analysis Repeat for the next towel until all are completed Shut down or await the next batch

Table 6 highlights the integration of mechanical components with their respective electronic control mechanisms in the automated roll towel seed germination system. Electronic components drive each mechanical part to ensure precise, efficient, and automated operations. Key elements include the seed dispenser, controlled by a stepper motor and position sensors for accurate seed placement, and the folding arm, which utilizes a servo motor with torque sensors to ensure proper folding force. The Rollers, responsible for rolling the towel smoothly, are powered by synchronized stepper motors. At the same time, the elastic band dispenser uses a servo motor with load sensors to secure the towels effectively.

This integration of mechanical and electronic components improves the speed, accuracy, and consistency of the roll towel test, making the system more reliable and scalable for seed germination analysis.

Algorithm 1 presents a comprehensive workflow for the automated roll towel test, starting with system initialization and hardware checks, followed by precise seed dispensing, uniform towel folding and rolling, secure banding using elastic dispensers, and final transfer to a controlled germination chamber ensuring a streamlined, consistent, and efficient preparation process for reliable seed germination analysis.

Table 6. Mechanical Components and Their Electronics Control

Mechanical Component	Electronics Control
Seed Dispenser	Stepper motor controlled by a microcontroller; position sensors ensure precise seed placement.
Folding Arm	Servo motor with torque sensors for controlled force during towel folding.
Rollers	Stepper motors synchronized by the microcontroller to roll the towel smoothly.
Elastic Band Dispenser	Servo motor with load sensors to adjust tension while securing towels.

2.2 Mathematical Modeling for Automated Roll Towel System

This section presents the mathematical model for the automated roll towel system, including calculations of the force required for paper rolling, torque needed for folding, motor energy consumption during folding, power required for rolling, as well as battery backup time and current consumption estimations.

The system is divided into four key automation steps. Each step involves motion or control by mechanical components powered by motors or actuators. We estimate the torque, energy, and power requirements for each operation from Eqs. (7) to (16).

Based on observations and component specifications:

- Number of seeds placed (n): 100
- Time per towel (manual), T_m: 4 minutes

- Time per towel (automated), T_a: 1 minute
- Error rate (manual), E_m: 7.5%
- Error rate (automated), E_a: 1%
- Roller radius, r: 0.02 m
- Force required to roll paper with seeds, F_r: 3 N
- Motor power (per motor), P_{motor}: 10 W
- Number of active motors, N_m: 3
- Battery capacity, C_β: 300 Wh
- Motor efficiency, η: 0.85
- Angular speed, ω: 10 rad/s

Torque Required for Rolling

The torque needed to roll the towel with seeds is calculated using:

$$\tau_r = F_r \times r \tag{7}$$

Substituting given values:

$$\tau_r = 3 \times 0.02 = 0.06 \text{ N·m} \tag{8}$$

This torque is provided by components such as the Electric Motor (ID 9) and the rollers (IDs 11, 12).

Power Required for Rolling

The power to maintain rolling is:

$$P_{rolling} = (\tau_r \times \omega) / \eta \tag{9}$$

Substituting values:

$$P_{rolling} = (0.06 \times 10) / 0.85 \approx 0.71 \text{ W} \tag{10}$$

Total Power Consumption

Assuming three motors are active during operation:

$$P_{total} = N_m \times P_{motor} \tag{11}$$

$$P_{total} = 3 \times 10 = 30 \text{ W} \tag{12}$$

Battery Backup Time

Given a battery capacity of 300 Wh:

$$B_a = C_\beta / P_{total} \tag{13}$$

$$B_a = 300 / 30 = 10 \text{ hours} \tag{14}$$

Error Rate Reduction

The improvement in error rate achieved by automation is:

$$\Delta E = E_m - E_a \tag{15}$$

$$\Delta E = 7.5\% - 1\% = 6.5\% \tag{16}$$

These calculations illustrate significant advantages of automation. The automated system reduces cycle time by 75% (4 min to 1 min) and improves placement precision, reducing error rates by 6.5%. Torque and power requirements are within feasible ranges for compact motors (ID 9), and energy needs are

compatible with commercially available battery systems offering 10-hour continuous operation. In contrast, the manual process depends entirely on human effort, leading to variable precision and throughput.

In the manual process, preparing a rolled towel with 100 cotton seeds typically takes about 4 minutes, as workers manually align the paper, place seeds by hand, roll the towel, and apply rubber bands. This approach often results in inconsistencies in seed spacing, variable tightness of rolling, and human fatigue, which leads to higher error rates (around 7.5%). The automated system reduces the cycle time to 1 minute by using electric motors, rollers, seed dispensers, and a banding mechanism. The force required to roll the towel with seeds was estimated to be 3 N, primarily due to the weight of the seeds and the friction between the towel and the rollers. Given the roller radius of 0.02 m, the torque required to roll the towel is 0.06 Nm, which is easily provided by the compact motors (Element ID 9) driving the rollers (Element IDs 11, 12). The power needed to perform rolling is approximately 0.71 W, calculated from the torque, angular speed (10 rad/s), and motor efficiency (85%). Because three motors are typically active at different stages (seed dispensing, rolling, and banding), the total power consumption is 30 W. A standard 300 Wh battery can, therefore, operate the system for 10 hours, which is sufficient for continuous lab-scale testing shifts. Notably, the system enhances precision in seed placement by utilizing controlled motors and gears (Element IDs 2, 3, 21–24), thereby significantly reducing error rates from 7.5% to less than 1%. The automated banding process, utilizing components such as the rubber band feeder (ID 30), ensures consistent tension on each towel roll, thereby further improving uniformity across samples. These mathematical models not only quantify system performance but also highlight how automation shifts the process from variable, labor-intensive manual work to reliable, reproducible, and scalable operations — crucial for seed testing laboratories aiming for high throughput and quality assurance. The energy and torque requirements in the proposed system are listed in Table 7. The comparison of Manual vs Automated system with model outputs are given in Table 8.

Table 7. Energy and Torque Requirements in Automated Roll Towel Test

Step	Operation	Energy (J)	Torque (N·m)	Motor ID	Notes
1	Slide towel from tray	0.15	0.024	9	Rollers and gears used
2	Dispense seeds	2.00	0.02	9	100 cotton seeds dispensed
3	Roll top towel	0.75	0.03	9	Uniform seed coverage
4	Apply rubber bands	0.50	–	9	Two bands applied
–	Total per towel	3.4	–	–	Includes all sub-processes

Table 8. Comparison of Manual vs. Automated System with Model Outputs

Feature	Manual	Automated	Equation / Value
Time per Towel	4 min	1 min	Given

Error Rate	7.5%	1%	ΔE = 6.5%
Torque (Rolling)	Manual force	0.06 N·m	Eqs. (7)–(8)
Power (Rolling)	N/A	0.71 W	Eqs. (9)–(10)
Total Power	N/A	30 W	Eqs. (11)–(12)
Battery Backup	N/A	10 h	Eqs. (13)–(14)

3. RESULTS AND DISCUSSION

3.1 Existing Roll Towel Test



Fig. 5. (a) Seed Research Technology Center, (b) seed placement on roll towel, (c) folding and rolling of roll towels, and (d) roll towels placed in germination chamber.

The author and his team visited the Seed Research Technology Center at Professor Jayashankar Telangana Agricultural University, where they measured the time and performance of each step in the roll towel test process using cotton seeds as shown in Fig. 5. They collected data over approximately 1500 towels, focusing on seed placement, folding, rolling, and banding operations. In the manual system, seed placement was labor-intensive and inconsistent, typically taking 3–5 minutes per towel, with a high error rate of 5–10%. Folding and rolling were manual and erratic, and banding required additional effort.

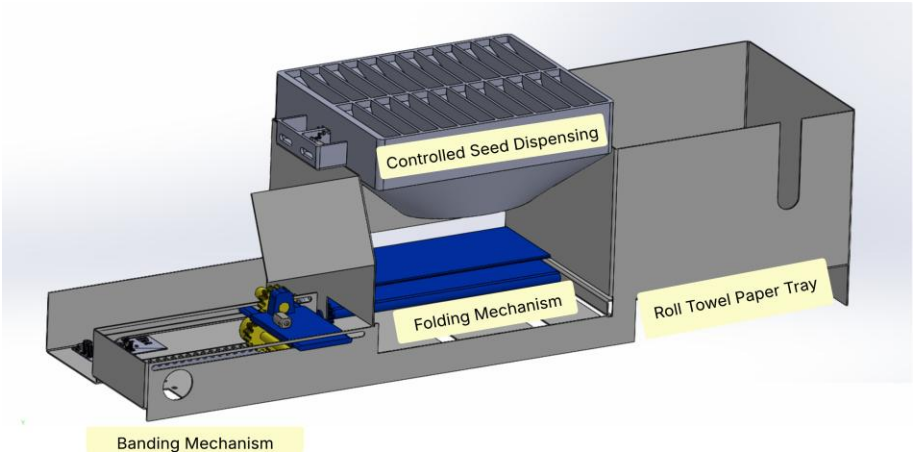


Fig. 6. Novel Automated Machine for Roll Towel-Based Seed Germination.

3.2 Proposed Roll Towel Test

Fig. 6 shows the proposed automated roll towel test system, which integrates and automates the four main steps of the germination test process. First, it pulls and slides the towel from the paper tray using motorized rollers and gears, ensuring precise alignment and tension. Next, the seed dispenser unit above evenly distributes seeds onto the towel in a controlled manner, guided by sensors and mechanical feed elements. Then, a folding and rolling mechanism precisely folds and wraps the towel with seeds, maintaining uniform pressure and tightness for consistent germination conditions.

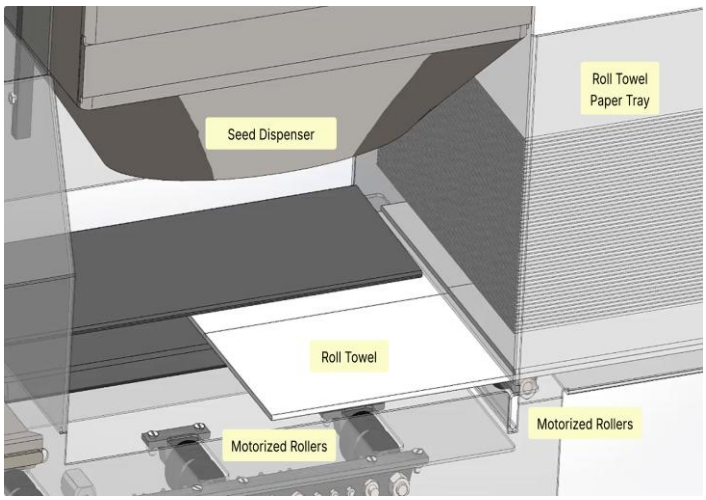


Fig. 7.Automated Paper Folding and Rolling Mechanism for Roll Towel Based Seed Germination Test.

In the next step as shown in Fig. 7, the system initiates the process by detecting the presence of a towel stack in the paper tray. A motorized roller, connected to a set of gears, engages the bottom towel and gently pulls it forward from the stack. This action ensures that the towel moves smoothly onto the next section of the machine where seeds will be dispensed. The roller's speed and torque are precisely controlled by the motor to prevent tearing or misalignment of the towel.

Fig. 8 illustrates the automated seed dispensing mechanism in the Roll Towel Test system. This step reveals a precisely designed seed dispensing unit with multiple aligned seed compartments. Each compartment is equipped with a controlled-release mechanism, likely driven by a motorized system, enabling the accurate and uniform placement of seeds onto the rolled towel beneath. This ensures consistent seed distribution, reducing manual errors and improving test repeatability.

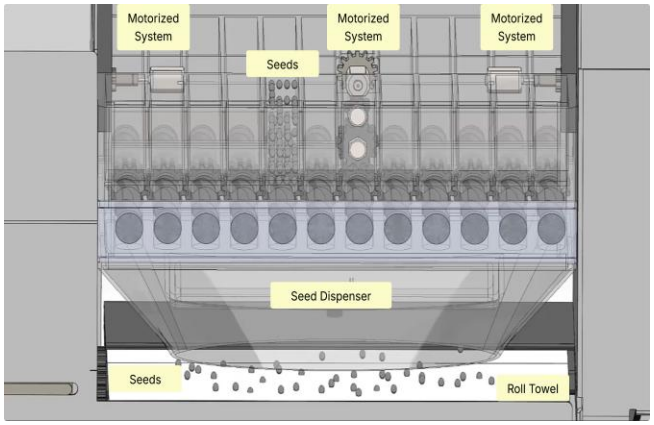


Fig. 8. Automated Paper Folding and Rolling Mechanism for Roll Towel-Based Seed Germination Test.

This step describes the automated paper-folding and rolling mechanism used in the roll-towel-based seed germination test. It automates the folding and wrapping of the seed-laden towel in a consistent and precise manner, using a folding plate, rollers, and a motorized gear system that eliminates manual intervention and improves process efficiency. The Fig. 9 shows the mechanism used in this step.

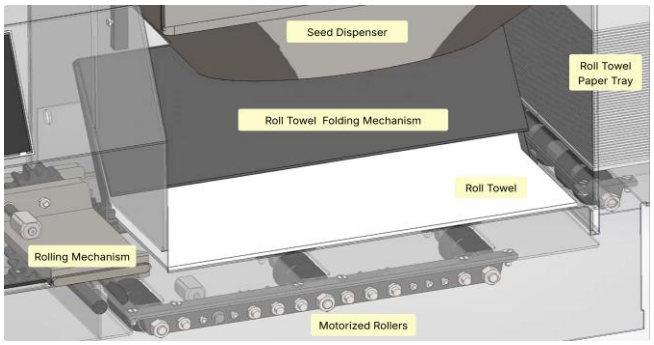


Fig. 9. Automated Paper Folding and Rolling Mechanism for Roll Towel-Based Seed Germination Test.

This step focuses on the automated elastic banding mechanism, which secures the rolled towel containing seeds using elastic bands. This system features a rotating spool of bands, precision gears, and a motorized actuator that evenly applies bands around each towel roll. By automating this process, the system ensures uniform band tension, reduces the chance of seed displacement during incubation, and eliminates the need for manual band tying. This step significantly enhances consistency, efficiency, and throughput in seed germination testing workflows, contributing to greater accuracy and reliability in laboratory analysis, as shown in Fig. 10.

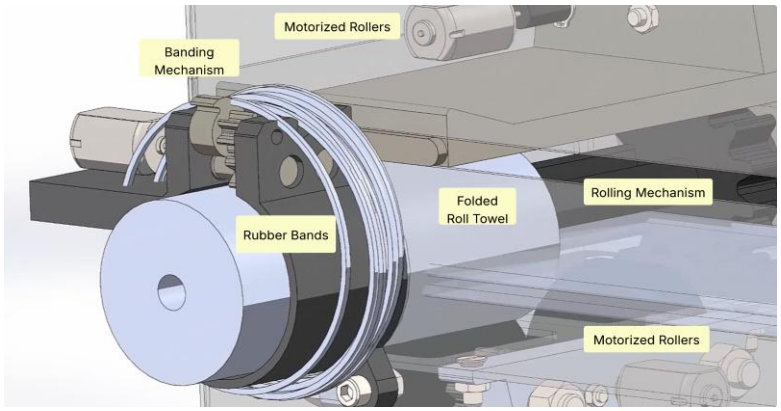


Fig. 10. Elastic Banding Mechanism in Automated Roll Towel Test System.

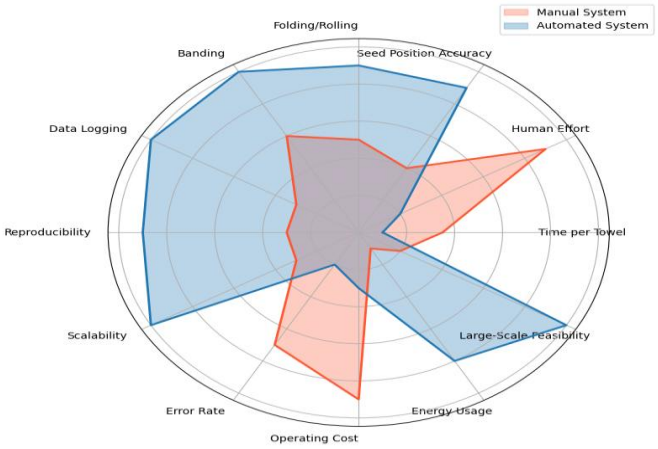


Fig. 11. Comparison of manual and proposed Automated Roll Towel Test Systems.

In contrast, the proposed automated system achieved precise and controlled seed dispensing in under 1 minute per towel, with minimal human effort and less than 1% error rate. The team calcualted the torque and power requirements during folding and rolling, observing improvements in seed position accuracy, reproducibility, and scalability. They also measured the mechanized banding process and energy usage, supporting metrics such as cycle time reduction, operating cost reduction, and large-scale feasibility, as outlined in Fig. 11 and the comparison Table 9.

Table 9. Comparison of Automated vs. Manual Roll Towel Test

Feature	Manual System	Automated System
Seed Placement	Hand-based, inconsistent	Precise, controlled dispensing
Time per Towel	3-5 min	less than 1 min
Human Effort	High	Minimal
Seed Position Accuracy	Low (manual errors)	High (programmed)
Folding/Rolling	Manual, inconsistent	Uniform, automated
Banding	Requires effort	Mechanized
Data Logging	Manual, error-prone	Digital, automated
Reproducibility	Low	High
Scalability	Limited	High
Error Rate	5-10%	Less than 1%
Operating Cost	High (labor costs)	Low (after setup)
Energy Usage	None	Optimized power
Large-Scale Feasibility	Not practical	Designed for mass testing

3.3 System Cost, Maintenance Requirements and Adaptability

The proposed automated roll towel test system includes components like motors, gears, rollers, sensors, and control electronics, leading to a higher initial cost compared to manual methods. Key cost drivers are the motorized rollers, seed dispensing mechanisms, banding actuators, and the microcontroller-based monitoring system, all of which require precise calibration and quality fabrication for consistent operation. Maintenance involves regular lubrication, cleaning seed dispensing parts, checking band

feeders, and calibrating sensors to maintain accuracy and prevent mechanical wear. While the system is optimized for cotton seeds (100 seeds per towel), adapting it to other seed types would need modifications to seed dispensers, roller torque, and banding tension. Though the design allows for such upgrades, additional trials and tuning are needed to maintain accuracy and efficiency across diverse seed varieties.

The cost estimation for the proposed automated roll towel test is shown in Table 10.

- Motors, gears, rollers, mechanical hardware: ₹70,000
- Seed dispenser components (3D printed parts, basic actuators): ₹40,000
- Microcontroller, sensors, basic camera unit: ₹30,000
- Frame fabrication, wiring, assembly: ₹60,000

This estimation assumes using standard-grade components, local fabrication, and minimal custom machining to keep costs within budget.

Table 10. Estimated Cost Breakdown for Automated Roll Towel Test System

Component / Section	Est. Cost (in Rs.)
Motors, Gears, Rollers, Mechanical Hardware	70,000
Seed Dispenser Components (3D Printed Parts, Actuators)	40,000
Microcontroller, Sensors, Basic Camera Unit	30,000
Frame Fabrication, Wiring, Assembly	60,000
Total Estimated Cost	2,00,000

4. CONCLUSIONS

The proposed automatd roll towel system is a novel and first-of-its-kind automated roll towel test system, designed to bring precision and consistency to seed germination analysis. The system combines calibrated motors, torque-controlled rollers, and automated seed dispensing and banding mechanisms, reducing human error and improving throughput. Initial trials with cotton seeds demonstrated reduced error rates and consistent operational parameters, laying the groundwork for broader adoption in seed testing laboratories.

Future enhancements may include additional components, such as integration with germination chambers for improved processing and monitoring. Additionally, the design allows for future adaptations to accommodate various seed types by creating specialized hoppers and dispensing systems. Such advancements will render the system versatile, scalable, and significantly beneficial across diverse agricultural testing applications.

AUTHOR CONTRIBUTIONS

Ramesh Reddy Donapati: Conceptualization, Methodology, System Design, Mechanical and Electronic Integration, Software, Investigation, Experimental Validation, Formal Analysis, Data Curation, Visualization, Writing – Original Draft Preparation, and Writing – Review & Editing. The author has read and approved the final manuscript.

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- AutomtedRollTowelTest.mp4