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Designing a Drone-based System for Optimized Seed Ball Deployment in Reforestation Applications

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Abstract

Drone-based system for seed ball deployment in aerial reforestation offer an innovative and efficient approach for restoring degraded ecosystems sustainably. This study primarily focuses on the design and development of a drone equipped with an automated seed ball dispensing mechanism for aerial reforestation applications. The developed drone system has a thrust-to-weight ratio of 1.8, ensuring stable flight performance during the aerial reforestation operations. The system enables controlled seed ball release using a servo-actuated mechanism and GPS-assisted positioning. The second objective of this study is to optimize seed ball parameters and dropping height to enhance aerial delivery and germination performance in reforestation. Taguchi analysis indicated that seed ball composition and dropping height have a greater influence on germination than seed ball weight. A composition, consisting of compost and mud, with a seed ball weight of 40 g, and a dropping height of 2 m, was found to be the optimal. The statistical influence of the parameters on the germination rate was further analysed using ANOVA. Finally, a predictive regression model was developed to estimate germination time based on seed ball composition, weight, and release height, and its accuracy was validated through confirmatory experiments. Thus, this work presents a practical, data-deriven approach for aerial reforestation that integrates optimized seed ball design with drone-based seed ball deployment to enhance ecological restoration outcomes.

Keywords: Aerial reforestation, Unmanned aerial vehicle (UAV), Drone-based seed dispersal, Seed ball optimization, Ecological restoration, Aegle marmelos

1. Introduction

Climate change is exacerbated by ecosystem degradation and distruption to carbon neutrality, mainly resulting from increased wildfires activity. Various forest management methods, including reforestation, sustainable biomass use, and eco-friendly harvesting, can minimize these effects to improve the stability of ecosystem (Cunningham et al., 2024; Gustavsson et al., 2017). A forest landscape after a wildfire is highly prone to erosion due to the loss of vegetation cover and changes in soil properties. Direct reforestation methods are primarily limited by high labor costs and transportation challenges in remote or inaccessible areas (Groen and Woods, 2008).Automated reforestation methods, including drones (Eker et al., 2021; Durgun & Eker, 2025; Buğday, 2018), AI-guided robotic planters (Lloyd et al., 2025), RoboFoR (Sobocki et al., 2023), and Autoplant (Hansson et al., 2024), have advanced features such as path mapping, navigation, afforestation, and surveillance (Spinelli, 2020). It increases the accuracy of the planting mechanism, scalability of reforestation, and reduces labor costs (Rossander & Lideskog, 2023; Li et al., 2025). Seeding in remote forest areas and thereby improving the ecosystem can be achieved by aerial reforestation methods (Xiao et al., 2015; Peppin et al., 2010; Rana & Varshney, 2023).

Unmanned Aerial Vehicles (UAVs), commonly known as drones, have become versatile platforms for precision agriculture, environmental monitoring, logistics, and infrastructure inspection due to their maneuverability, autonomous navigation, and adaptability to modular payload systems (Aydın et al., 2020; Akay et al., 2019; Eker et al., 2017; Türk et al., 2021). Modern multi rotor drones offer vertical take-off and landing (VTOL), hovering stability, waypoint-based navigation, and real-time telemetry, making them well-suited for operations in complex and inaccessible terrain. In engineering applications, UAV systems are increasingly integrated with customized dispensing, spraying, and sensing mechanisms to enable targeted delivery tasks. UAV technologies have increasingly been adopted in forestry engineering for forest road planning,

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terrain modelling, and infrastructure monitoring (Bugday, 2018; Turk et al., 2022; Tas et al., 2023). Drone-based aerial reforestation offers a cost-effective and scalable approach for biodiversity restoration, supporting 'Reducing Emissions from Deforestation and Degradation (REDD)' initiatives (Reyer et al., 2009; Mohan et al., 2021; Novikov and Ersson, 2019) in line with UNFCCC policies (Corbera et al., 2010). These features position drone technology a promising platform for forestry-related seeding operations, where controlled seed deployment, terrain accessibility, and operational efficiency are critical factors. Recent advancements in UAVs-assisted reforestation have demonstrated the feasibility of autonomous seed deployment systems with improved positional accuracy and operational scalability (Stamatopoulos et al., 2024; Castro et al., 2024; Lloyd and Astrup, 2025).

Apart from direct seeding reforestation methods, which are associated with labor costs and limited seedling success rates, researchers have investigated various drone-based seed dispersal mechanisms (Lloyd and Astrup, 2025; Stanturf et al., 2017). Gravity-assisted mechanisms offer cost-effectiveness, but they require a detailed study on the optimization of seed selection and delivery. The shooting mechanism can improve seed-ground contact, though it introduces greater operational complexity (Marzuki et al., 2021). The integration of machine learning and AI algorithms with high-resolution imaging (Hafeez et al., 2023) and drone-mounted sensor, enables monitoring seed viability and sprouting, facilitating accurate evaluations of planting outcomes (Stamatopoulos et al., 2024; Castro et al., 2024). Instead of dispersing seed alone, encasing seeds in clay, soil, or compost to form seed balls provides protection from wildlife, unfavorable weather conditions, thereby increasing germination and growth rates. Optimizing both composition of seed ball and the parameters determining the exact locations is critical for promoting seed balls in remote forest areas, which is necessary for successful reforestation strategies (Xiao et al., 2015, Kannan et al., 2021).

In this study, aerial seeding for reforestation has been conducted using a drone. This work was carried out as a pilot study under the direction of the Department of forests, Kerala, India, as part of annual seed dispersal in the Malampuzha forest terrain, Palakkad. In the first part of the work, a lightweight, heavy-duty drone equipped with user controlled navigation and customized seed-dropping mechanism was designed and manufactured. To maximize seed germination, both selecting terrain-appropriate seed and optimizing the dropping mechanism were prioritized. Seed balls were produced and deployed from the drone to enhance seed germination. This method facilitates the sprouting of multiple seed types across diverse forest terrains. Various parameters influencing seed ball germination, including composition, weight, and dropping altitude, were optimized using the Taguchi method. Finally, a statistical analysis was carried out to assess the impact of these parameters on seed germination rate, yielding a regression equation. The proposed study has been considered a viable method for the reforestation across diverse ecosystems and represents a proactive initiative for climate change mitigation.

2. Materials and Methods

The drone system has been designed and manufactured to deploy seed ball to precise locations selected by the user in remote areas of the forest. The designed drone has six modules, including mechanical structure, power distribution, propulsion, flight control, seed ball delivery mechanism, navigation, and telemetry. The power distribution module consists of a 4S 5200mAh Lithium-Polymer battery that supplies 16.2V. Power is managed through a power module (3DR) and a Universal Battery Eliminator Circuit (UBEC), ensuring a stable 5V output to low-voltage components in the receiver and telemetry system. The flight controller monitors battery health in real-time by analyzing the voltage and current feedback from the power module. The voltage stability across the terminals was confirmed by verifying the ground connection with a digital multimeter. To protect the components and shielded wires from vibration, electromagnetic interference, and dust during flight, all electrical connections are housed within an acrylic compartment. Electrical layout of the various modules of the drone is illustrated in Figure 1.

There are six A2212/13T 1000 KV brushless DC motors to drive the 10 × 4.5" propellers through 30–60 A electronic speed controllers (ESCs) programmed via BLHeli. A digital thrust stand was used to evaluate the static thrust and propeller efficiency. Noise and vibrations are reduced by balancing the propellers with the help of a precision balancer. Surface temperatures were measured, and the durability of the system was also monitored during a load test on each ESC. An STM32F7 microcontroller running at 216 MHz with an ARM Cortex-M7 architecture powers the SpeedyBee F7 flight controller. The flight controller includes dual UART channels, I2C sensors, and eight PWM outputs for configuring the ESC control, sensors, and telemetry. Betaflight software was used calibrate magnetometer, gyroscope and the accelerometer. In case of mission failure during flight, due to loss of user signal and adverse battery health, Return to Home (RTH) protocols are established with a fail-safe mechanism.

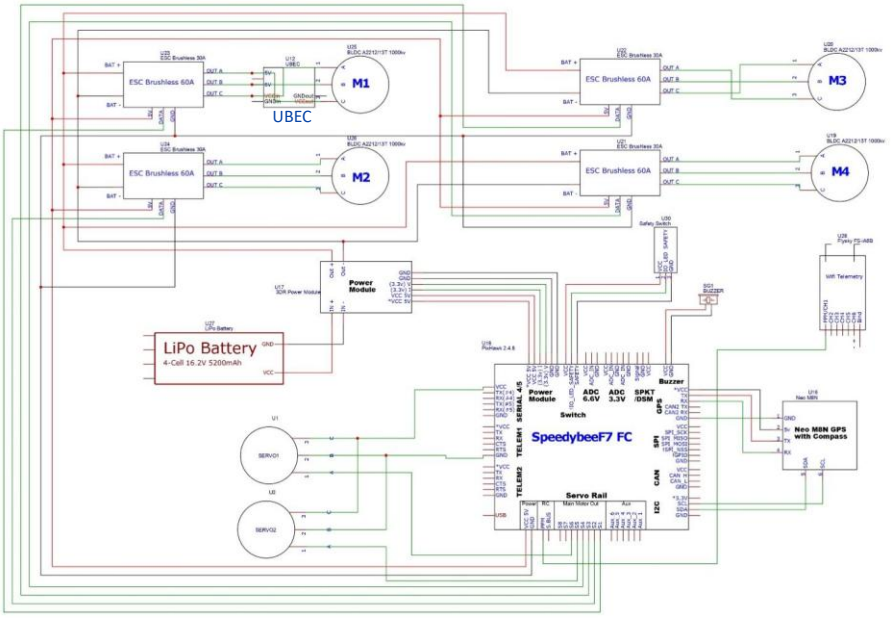


Figure 1. Circuit Diagram of the drone

A GLONASS-supported NEO-M8N GPS module was used to determine coordinates with an accuracy of ±2 m accuracy. The telemetry modules were integrated into the drone for navigation control. The telemetry module transmits data regarding the battery status, velocity, altitude, and geographic coordinates to the control station via Wi-Fi. Mission Planner software was used to upload the flight path, waypoints, and precise seed-dispersal coordinates through telemetry. The system also monitors telemetry feedback and adjusts seed ball drop points during the mission. The drone architecture is shown in Figure 2.

Precise seed ball delivery only possible through accurate altitude control, smooth switching between waypoints, and stable hover via the telemetry module. The seed delivery mechanism uses two servomotors controlled by an ESP32. Each servo motor can take a torque of 1.8 kg·cm. When a PWM signal with a pulse width of more than 1800 µs is received from the RC receiver, the seed ball delivery mechanism will be actuated. The seed balls were dispensed from the smoothly finished holder as one of the programmed servo motors rotated 90° over one second interval. A 100 ms debounce delay and a software flag were also installed to prevent the release of the seed balls during unintended activation.

The drone seed ball dropper housing, frame, and landing gear along with the GPS stand, were designed in TinkerCAD and optimized in Fusion 360 (Autodesk). These components were fabricated using PLA through 3D printing. All the 3D-printed parts were polished to a smooth surface to reduce aerodynamic drag during operation. The landing gear was designed with a honeycomb structure to withstand the impact during landing and take-off. A maximum stress of 28 MPa was observed under a 2 kg load using Finite Element Analysis (FEA) simulations, which is below the yield stress of PLA. Each fabricated structure was weighed to ensure the combined center of gravity was aligned within ±5 mm of the geometric center, which ensures steady flight dynamics. The algorithm for the seed ball dispensing mechanism is depicted in Figure 3.

3. Optimization of Seed Ball Compositions

Since selecting seeds for reforestation suitable for the terrain of Malampuzha, Kerala, India, is important, we have selected Aegle marmelos (Koovalam) for the present study. Before preparing the seed balls, they were soaked in a gibberellic acid solution overnight to ensure sprouting. Seed balls are made by enclosing seeds within a mixture of soil/ clay, water, and organic fertilizer, which is formed into a dough-like consistency. The seed balls are then rolled into 0.5-1” diameter spheres and dried in a shaded area for 24 hours. For this work, the composition of seed balls and the dropping height were optimized for on early seed sprouting and structural integrity using the Taguchi method. Using this method, an L9 orthogonal array was formulated based on the design of experiments. The parameters considered for optimizing dispensing seed balls were the composition of the seed balls, the weight of the seed balls, and the dropping altitude. Various levels of the seed ball compositions include Level 1: a mixture of cotton, compost, and mud; Level 2: a mixture of compost and mud;and the Level 3: mud alone. The three levels of seed ball weight considered for the analysis are 30, 40, and 50 g, respectively. Likewise, three dropping height -2, 4, and 6 m were selected for the study. The lowest germination time and the structural integrity of the seed balls after dropping are considered measures of the success of the experiments. To ensure this, the criterion “Smaller is Better” was applied to of the Signal-to-Noise (S/N) ratio analysis.

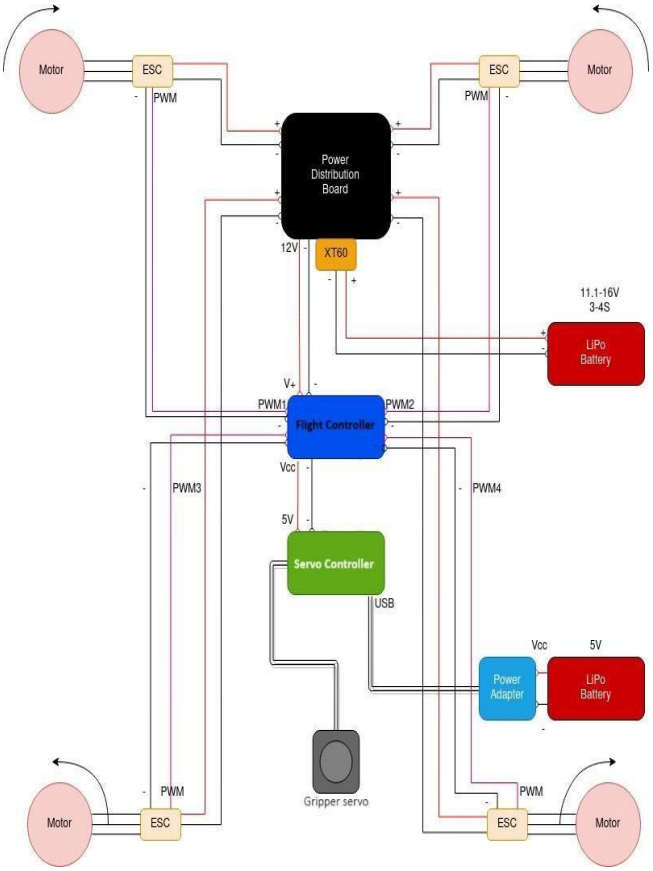


Figure 2. Schematic diagram of the drone architecture

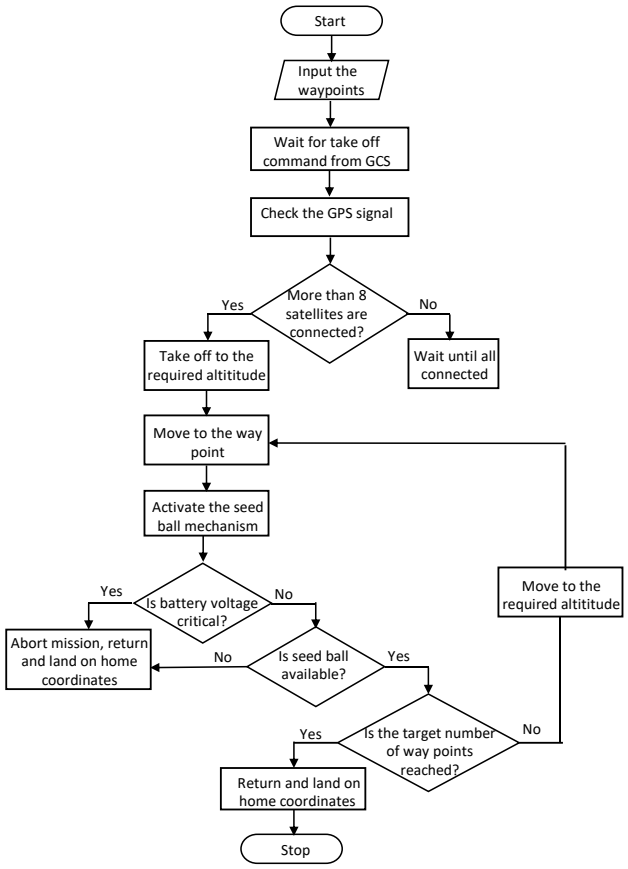


Figure 3. Algorithm of seed ball dropping mechanism.

At the same time to examine the influence of above seed ball parameters on the seeds germination time, a statistical analysis was conducted using an ANOVA test. The primary indicator of statistical significance was the P-value. This will help distinguish actual changes due to experimental conditions from those caused by random fluctuations. After determining significance using the P-value, the F-ratio is calculated for each factor to identify its relative influence on the response variable in ANOVA. Changes in germination time are more substantial for higher F-value. Statistical significance and the magnitude of effect of each experimental factor on seed ball performance can be determined by the P-value and F-ratio.

Finally, the relationship between the selected seed ball parameters and germination time was analyzed using regression. Multiple linear regression model was developed to predict the germination time T_g as a function of mixture compositions M, weight of the seed ball W and dropping height H. Regression coefficients were determined using the least square method. Positive regression coefficients indicate a proportional relationship, whereas the negative ones represent an inverse relationship. At the same time, the larger regression coefficients also represent a more pronounced factor in determining seed germination. This regression model can be used to predict germination time under varying experimental conditions and identify major seed ball parameters affecting growth.

4. Results and Discussions

4.1. Drone Assembly and Fabrication

The designed components, including landing gear, GPS stand, and the seed ball dropper, are shown in Figure 4. These parts were further fabricated from PLA using a 3D printer, confirming their robustness and light weight. The various drone modules were assembled on the drone architecture, and the electrical connections were properly assembled for aerial reforestation use, as shown in Figure 5.

The total weight of the drone, including the frame, various electrical modules, battery, and payload, is 2 kg. With four 10×4.5” propellers attached to the brushless motors, the drone can produce a total thrust of 3.6 kg. Thus, the thrust-to-weight ratio of the designed drone is 1.8, which is sufficient for aerial reforestation missions. All four motors draw a total current of 40 A from the 4S 5200 mAh LiPo battery, allowing the drone to hover for approximately 7.8 minutes under ideal conditions before requiring a recharge and battery swap. Real-time conditions may reduce this flight duration and affect the efficiency of the propulsion system.

The User Datagram Protocol (UDP) is used to establish communication between the mission planner software and the drone, enabling real-time real-time route correction during flight. Stable communication between the drone and the user is maintained up to 600 m during range validation. The GPS module, configured at 115200 bps and positioned at the top of the main drone frame, minimizes magnetic interference from the power module. Figure 6 illustrates the reforestation mission

route, including waypoints and seed ball dropping locations.

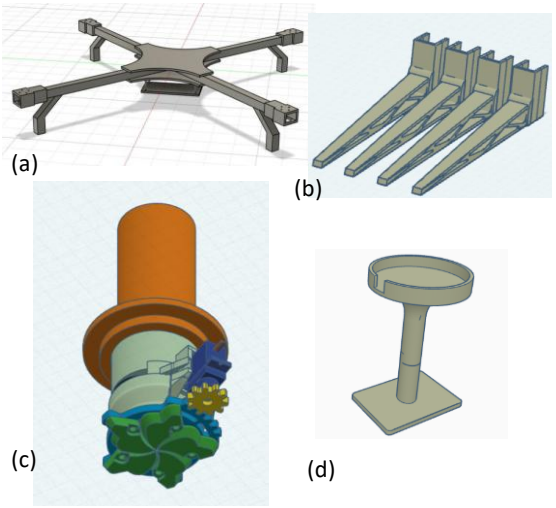


Figure 4. CAD model of the (a) drone frame (b) landing gear (c) seed ball dropper mechanism (d) GPS stand.

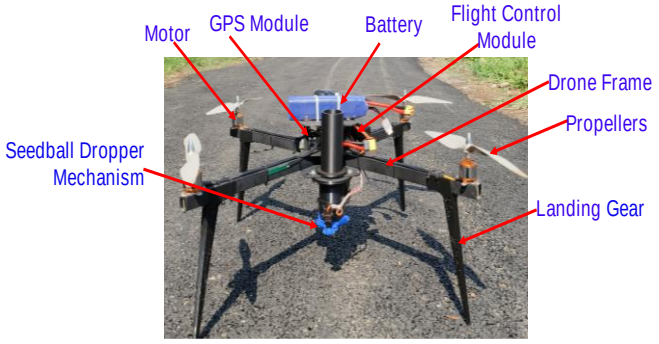


Figure 5. Image of the assembled drone with custom made seed ball dropping mechanism and landing gear



Figure 6. Image of the mission planner software depicting the (a) way points (b) drone navigation files

4.2. Optimization of Seed Ball Delivery Using Taguchi Method

Compared to prior drone-based seeding systems that primarily focused on mechanical dispersal efficiency, this study applies statistical optimization to seed ball parameters, thereby addressing both engineering performance and biological outcomes. Nine experiments were carried out using the Taguchi L9 orthogonal array, with three parameters levels, including composition, weight, and dropping height of the seed balls. Table 1 presents the various parameter combinations defined by the Taguchi L9 orthogonal array and their corresponding germination times. Figure 7 shows the physical condition and germination of seed balls with different compositions after the first bloom. It can be observed that maintaining structural integrity and optimizing seed ball parameters are essential for the early sprouting of seeds.

The Response Table for the means is depicted in Table 2. In this table, “delta” represents the difference between the maximum and minimum mean response values of a factor's effect across its levels. The highest delta value of 1.333 indicates that the seed ball composition is the strongest influencing factor in seed sprouting. With a delta value of 1.000, the dropping height of the seed ball is the second most influencing parameter; the weight of the seed ball has the least effect, with a delta value of 0.333.

Another crucial measure in the Taguchi method is the Signal-to-Noise (S/N) ratio, which identifies parameters that consistently influence the lower germination times. The Signal-to-Noise (S/N) ratio can be determined from the following Equation,

$$S/N = -10\,log\left(\frac{1}{n}\right)\sum_{i=1}^{n} {y_i}^2 \quad (1)$$

Where y_i is the observed germination time for each trial and n is the number of observations per level. The criterion of 'Smaller is Better' is utilized in this study. The response table for S/N ratios with the delta values is depicted in Table 3. Here, the Delta value is the difference between the highest S/N ratio at any level of a factor and the lowest S/N ratio across its levels. It can be observed that, the highest delta value of 1.16 indicates that the seed ball composition is the highest influencing parameter on the germination time of the seed balls. As observed in the previous sections, dropping height is the second most influencing parameter, followed by the seed

ball weight, as indicated by the S/N delta values. Based on Taguchi experimental designs, the seed ball composition at level 2 (mixture of compost and mud), seed weight at level 2 (40 g), and dropping height at level 1 (2 m) are the optimized parameters for the least germination time and structural integrity.

Table 1. Design of experiment parameters as per the Taguchi L9 orthogonal array.

Seed Ball Composition	Weight of the seed ball (g)	Dropping height of the seed ball (m)	Germination time (days)
Cotton + Compost + Mud	30	2	9
Cotton + Compost + Mud	40	4	10
Cotton + Compost + Mud	50	6	10
Compost + Mud	30	4	10
Compost + Mud	40	6	9
Compost + Mud	50	2	9
Mud	30	6	11
Mud	40	2	10
Mud	50	4	11

Table 2. Response table for means showing delta values and ranking of seed ball parameters.

Level of Experiment	Seed ball composition	Weight of the Seed ball	Dropping height of the seed ball
1	9.667	10.000	9.333
2	9.333	9.667	10.333
3	10.667	10.000	10.000
Delta	1.333	0.333	1.000
Ranking of the parameter	1	3	2

Table 3. Response table for S/N ratios showing delta values and ranking of seed ball parameters.

Level of Experiment	Seed ball composition	Weight of the Seed ball	Dropping height of the seed ball
1	-19.69	-19.97	-19.39
2	-19.39	-19.69	-20.28
3	-20.55	-19.97	-19.97
Delta	1.16	0.28	0.89
Ranking of the parameter	1	3	2

4.3. Optimization of Seed Ball Delivery Using ANOVA

In this section, the statistical significance of the factors affecting seed ball germination was evaluated by Analysis of Variance (ANOVA). The results are summarized in Table 4. It can be observed that all P-values exceed the conventional significance level of 0.05. This may be attributed to the limited number of experimental runs conducted during the pilot study, which reduced degrees of freedom. Therefore, the statistical inference has significant implications for future studies. However, the results clearly indicate a trend in influence, consistent with the Taguchi signal-to-noise ratio analysis.



Figure 7. Image of the sprouted seed balls at different experimental conditions.

The seed ball composition shows the highest influence trend on germination time, with a high F-value of 13 and P-value of 0.071. This is followed by seed ball dropping height with a F-value of 7 and P-value of 0.125. Out of all, the weight of the seed ball had the least influence, with an F-value of 1 and a P-value of 0.15. The residual error, which shows the variation not explained by the studied factors, had a sum of squares of 0.2222 and mean square of 0.1111, and did not have associated F or P-values.

Table 4. Statistical analysis of the seed ball parameters on the germination time showing Degrees of Freedom, Sum of Squares, Mean Squares, F-Values, and P-Values

Seed ball Parameters	Degrees of Freedom	Adj SS	Adj MS	F-Value	P-Value
Seed ball composition	2	28.889	14.444	13	0.071
Weight of the Seed ball	2	0.2222	0.1111	1	0.15
Dropping height of the seed ball	2	15.556	0.7778	7	0.125
Error	2	0.2222	0.1111		

4.4. Regression Equation for the Germination

Based on the experimental data, the regression equation predicting germination time is as follows:

$$T_g = 9.889 - 0.222\ M_1 - 0.556\ M_2 + 0.778\ M_3 + 0.111\ W_1 - 0.222\ W_2 + 0.111\ W_3 - 0.556\ H_1 + 0.444\ H_2 + 0.111\ H_3 \quad (2)$$

where T_g denotes the predicted days to germination, M_1 M_2 and M_3 are dummy variables for seed ball composition, W_1, W_2 and W_3 represent dummy variables

for seed ball weight in grams, and H_1 H_2 and H_3 correspond to dropping height in meters. Each coefficient reflects the effect of the respective factors on germination time. Coefficients with positive values show an increase in germination duration, while negative coefficients indicate a reduction. This equation allows the prediction of germination days based on specific combinations of seed ball compositions, weight and dropping height. This provides a quantitative tool for optimizing seed ball design for aerial reforestation.

A final confirmation test was conducted on 16th March using the optimal conditions based on the analysis for validation. Composition Level 2 (mixture of compost and mud), Weight Level 2 (40 g) and dropping height of 2.0 m were used to prepare the seed balls. A total of four waypoints were evaluated during the test. Confirming Taguchi results and the statistical analysis one seed ball successfully sprouted within nine days. This result underlined that, as expected, the most significant factors affecting germination success are composition and dropping height. The results are illustrated in Figure 8.



Figure 8. Germinated seed ball from the confirmation test at one of the four evaluated way points, demonstrating successful sprouting within nine days.

5. Conclusions

Degraded landscapes can be restored efficiently and sustainably through drone-based aerial reforestation, and this technology offers a promising solution. A drone equipped with a customized seed ball dispensing mechanism was successfully designed and fabricated in this work. Effective seed deployment, precise navigation, and stable flight ensure the potential of the system for large-scale reforestation. Taguchi analysis revealed that the most significant factors affecting germination time were seed ball composition and dropping height, while seed ball weight had only a minimal effect. Optimal conditions for stable and early germination were confirmed as a mixture of compost and mud, 40 g seed ball weight, and a 2 m dropping height based on the Taguchi response table for means and S/N ratio. During the ANOVA analysis of various seed ball parameters on germination time, the p-values were higher than the conventional significance level of 0.05. This is attributed to the limited number of experimental trials conducted during this pilot study, which limits the statistical power of the analysis. Therefore, a definite conclusion regarding the most influential parameter on germination time cannot be derived from the ANOVA analysis. However, a consistent influence trend can be observed, which consistent with the Taguchi analysis. To predict germination time, a regression equation was developed relating seed ball composition, weight, and dropping height, providing a quantitative method for optimization. The confirmation test validated this model, demonstrating that the identified factors, such as composition and dropping height, are the most critical parameters influencing the effective germination with the least time in aerial reforestation.

Although the developed system demonstrated reliable performance in controlled field conditions, certain limitations must be acknowledged. The present study was conducted under relatively stable weather, and performance in strong wind, heavy rainfall, or highly uneven canopy structures may affect flight stability, seed drop accuracy, and germination outcomes. In particular, wind drift could reduce seed ball landing precision, and excessive rainfall may compromise seed ball structural integrity. Future studies should investigate adaptive flight control strategies and environmental compensation mechanisms to improve robustness across diverse climatic conditions.

Compared to existing UAV-based reforestation approaches that primarily focus on direct seeding or aerial dispersal mechanisms (e.g., Lloyd et al., 2025; Mohan et al., 2021), this study uniquely integrates customized drone system design with statistical optimization of seed ball parameters and predictive regression modelling. This engineering and experimental framework strengthens its practical applicability in forestry restoration programs. The integration of optimized seed ball design with drone-based seed deployment increases the success of ecological restoration efforts.

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