Journal of Forests
2025 Vol. 12, No. 2, pp. 81-93
ISSN(e): 2409-3807
ISSN(p): 2413-8398
DOI: 10.18488/jof.v12i2.4397

Optimizing reforestation: Investigating the efficacy of 3D printed biomimicry seed pod shapes in enhancing seed dispersal

Muhammad Syazani Irfan Jeffri[1]
Cohen Riley Ong Yu[2]
Omar Faruqi Marzuki[3,4+]
Ellie Yi Lih Teo[5,6]
Norzaliza Johan[7]

[1,2,3,5]*Department of Science and Technology, Universiti Putra Malaysia, 97008 Bintulu, Sarawak, Malaysia.*
[1]*Email: syazaniirfan1@gmail.com*
[2]*Email: yujikirishima420@gmail.com*
[3,4]*Email: omar_faruqi@upm.edu.my*
[5,6]*Email: ellie_teo@upm.edu.my*
[4,6]*Institut EkoSains Borneo, Universiti Putra Malaysia, Jalan Nyabau, 97008 Bintulu, Sarawak, Malaysia.*
[7]*Jabatan Hutan Sarawak, Aras 12, Sayap Kiri (East Wing), Bangunan Baitul Makmur II, Medan Raya, Petra Jaya, 93050 Kuching, Sarawak, Malaysia.*
[7]*Email: norzaliza@sarawak.gov.my*

(+ Corresponding author)

Article History
Received: 2 June 2025
Revised: 11 August 2025
Accepted: 26 August 2025
Published: 8 September 2025

Keywords
3D-printing
Biomimicry
Design
Reforestation
Seed pod
Drone.

ABSTRACT

This paper addresses the crucial challenge in reforestation of effectively distributing seeds over large and often inaccessible areas. Traditional methods, limited in cost, reach, and efficiency, are contrasted with innovative solutions that leverage 3D printing technology and biomimicry principles. The research aims to develop seed pods that emulate natural seed dispersal mechanisms, offering a potential revolution in reforestation practices. These 3D printed seed pods, inspired by natural dispersers like gliding maple seeds and parachuting dandelion seeds, are designed to optimize travel distance, thus maximizing seed dispersal. Methodologically, the study employs SolidWorks and PrusaSlicer for designing, with drop tests conducted from a three-level building to evaluate the travel distance performance of various seed pod types. The results indicate significant variability in travel and bounce characteristics based on seed pod design, highlighting the design with wing-like features as particularly effective in achieving longer travel distances. These findings emphasize the crucial role of shape design in seed pod performance, presenting a novel approach to enhance seed dispersal efficiency in reforestation efforts. The research contributes not only to environmental science and technological ingenuity but also serves as a first step for future interdisciplinary studies. For environmental scientists, ecologists, and practitioners involved in reforestation interventions, the findings have important implications for sustainable, cost-effective interventions with the potential to improve livelihoods, support biodiversity, and aid climate regulation. Future research directions include trials in field situations across varying ecological contexts, investigation of environmentally friendly materials, and expansion of biomimetic designs for greater efficacy in seed dispersing.

Contribution/Originality: This study is the first to empirically evaluate and compare 3D-printed biomimetic seed pod designs inspired by natural dispersal mechanisms through systematic drop tests. It uniquely integrates aerodynamic analysis, bounce dynamics, and drone-deployment suitability to optimize reforestation efficiency using biodegradable, cost-effective pods.

1. INTRODUCTION

Reforestation is an important aspect of environmental restoration, yet the distribution of seeds across large inaccessible areas remains an issue. Planting trees by hand through conventional methods is labor-intensive and expensive. Cost estimates for reforestation can be extremely variable; costs range from USD 788 to 2,098 per hectare, depending on the area of the world and particular practices [1]. The labor-intensive and slow nature of manual tree planting, however, can be alleviated by drone-assisted reforestation, particularly as organizations like Flash Forest make advancements in drone technology and secure new funding sources to support reforestation practices. For example, Flash Forest, a Canadian start-up, uses drones to plant trees about 10 times faster than traditional methods and is still able to plant roughly 100,000 seed pods in one day [2]. This increased speed of planting and overall efficiency means fewer labor hours, more trees, and reduced time, in the context of large-scale reforestation projects. Although the widely used methods for seed dispersal, including manual planting or aerial seed bombing, can be restrictive in terms of cost, reach, and efficiency. Nonetheless, seed dispersal remains an important part of ecological restoration, as dispersion will affect the survival and spread of plant species. Consequently, the improvement of seed dispersal methods and mechanisms represents fundamental components of environmental conservation and reforestation efforts [2, 3].

The significance of this research can be understood through the lens of investigating new and better ways to solve the limitations imposed by current reforestation techniques. Through the incorporation of 3D printing technology and biomimicry [4], this research will produce seed pods that mimic those of natural dispersal mechanisms. These developments could lead to a transformational approach to reforestation so that it is more efficient, cost-effective, and ecologically sound.

This research responds to the need for new methods of incorporating natural seed dispersal systems into reforestation efforts and specifically aims to employ 3D printing technology and principles of biomimicry to imitate natural dispersal mechanisms, namely, anemochory. Anemochory (wind-assisted seed dispersal) is a natural process that provides a highly efficient system for seeds to utilize wind and air currents to travel vast distances. Many anemochorous seeds demonstrate the ability to travel long distances by having structural features, such as wings, hairs, or feathers, that are adapted to facilitate flight [5]. This efficiency is important for dispersal due to the many structural forms and functions of some wind-assisted seeds, which allow seeds to travel far from their parent plants, increasing the probability of finding suitable growing conditions [6]. The goal of the research is to emulate the efficiency of seeds that disperse through the use of wind-assisted mechanisms, which include glider, parachute, and helicopter-like features, and encapsulate the structure and function of seed pods from nature through the fabrication of 3D-printed biomimetic pods. The project seeks to investigate wind-mediated dispersal by exploring the variety of strategies plants use to disperse their seeds and fruits, and to design biomimetic seed pods, which should result in higher spreading efficiency in reforestation efforts.

Specifically, the project aims to assess how different 3D-printed biomimetic seed pod shapes impact travel distance and bounce capacity. This will help in understanding which designs are most effective for maximizing seed dispersal in reforestation projects. A secondary objective is to bridge the gap between ecological science and technological innovation, showcasing the potential of 3D printing in environmental applications.

The immediate beneficiaries of this research are environmental scientists, ecologists, and reforestation practitioners. Indirectly, this research benefits communities and ecosystems affected by deforestation and climate change. Improved reforestation techniques can lead to healthier ecosystems, which in turn support biodiversity, climate regulation, and community livelihoods [7, 8].

So far, various studies have explored the use of technology in reforestation, including drone planting and biodegradable planting capsules [3]. However, research on using 3D printing for creating biomimetic seed pods is still in its nascent stages [9, 10]. This research builds upon existing knowledge in biomimicry and ecological restoration [2, 11] and integrates it with the latest advancements in 3D printing technology.

This study contributes to the knowledge base by demonstrating the practical application of 3D-printed biomimicry in ecological restoration. It adds value by providing empirical evidence on the effectiveness of different seed pod designs, offering a new perspective on integrating technology with natural seed dispersal mechanisms. The research also sets a precedent for future interdisciplinary studies combining environmental science with emerging technologies.

Following this introduction, including background information and context, the paper is structured into several sections. The 'Methodology' section details the experimental setup and procedures. 'Results and Discussion' presents the data and findings from the experiments, interprets these findings, evaluates their implications, and acknowledges limitations. Finally, the 'Conclusion' summarizes the study's key points, its contributions to the field, and suggestions for future research.

2. METHODOLOGY

This research involves the fabrication of 3D-printed seed pods, utilizing SolidWorks and PrusaSlicer for design. A minimum thickness of 1 mm was selected for each seed pod, a decision influenced by the 3D printer's capabilities and the desired pod weight. The designs draw inspiration from natural seed dispersal methods, such as the gliding of maple seeds and the parachuting of dandelion seeds, with a focus on mimicking the efficiency of these natural shapes. In PrusaSlicer, the settings for each seed pod were standardized, including a print layer height of 0.2 mm to optimize print quality and an infill density of 5%. To ensure reliability in the results, each seed pod design was printed three times using the Original Prusa i3 MK3S+. The time taken to print each seed pod varied, averaging about 30 minutes, contingent on the design's complexity (as shown in Figure 1).

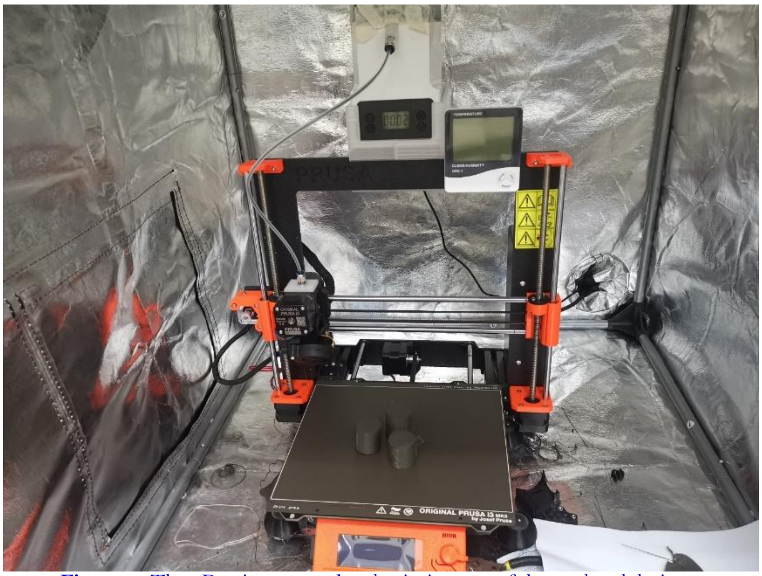


Figure 1. The 3D printer completed printing one of the seed pod designs.

The expense of manufacturing each 3D-printed seed pod in this investigation is quite reasonable, approximately USD 0.2 per pod. The low cost is achieved using polylactic acid (PLA) filament, which is readily accessible and biodegradable for sustainable purposes. Each seed pod weighs about 4 grams, thus minimizing material usage and creating good aerodynamic characteristics for the pod itself. Since it is both low-cost and lightweight, this technique is an efficient, scalable approach to reforestation projects that may be cost- or logistically burdensome in traditional forms, especially in remote or large areas.

The topsoil was intentionally selected as the main growth medium because it is recognized for supporting the establishment and regeneration of native plants. Hamberg et al. [12] found that transferring topsoil significantly enhances the establishment of native woody plants by introducing a viable native seed bank and native microbial communities that are necessary for ecosystem recovery. Likewise, Ferreira and Vieira [13] found that topsoil from natural forests has a greater density and diversity of viable seeds than soils from degraded or plantation sites, which creates increased potential for regeneration to occur passively. The addition of topsoil to seed pods mimics these natural events and creates a microhabitat with organic matter, nutrients, and microbes. This improves seed germination potential and early root establishment, and enhances seedling longevity, supporting a more efficient and ecologically appropriate mechanism for larger-scale reforestation.

The design inspiration for the seed pod shapes encompassed in this study draws from a combination of nature's elegance and function. The five base pod shapes: cylinder, short and long cone, hemisphere, and ellipse were selected to represent a spectrum of simple geometric forms that are common in the natural world. These shapes served as the foundation for the biomimicry-inspired designs.

The biomimetic variations, derived from hemispheres and cones, took inspiration from different seed dispersal mechanisms found in nature (Figure 2). The Glider seed shape was inspired by seeds that exhibit gliding or soaring flight, such as those of maple trees. The Parachutes encompass seeds designed to draw from seeds that use parachute-like structures to achieve a slow, controlled descent, similar to dandelion seeds. The Helicopter seeds were influenced by those that employ spinning or whirling motion during descent, as seen in certain tree seeds like those from the maple family [14, 15]. In the Types A, B, C, D, and E designs, the dimension reference involves measuring the diameter in the horizontal position and the height in the vertical position of the seed pod. Conversely, for Types F, G, H, and I designs, which include seed pods with wings, the dimension reference includes the wingspan parameter in Table 1.

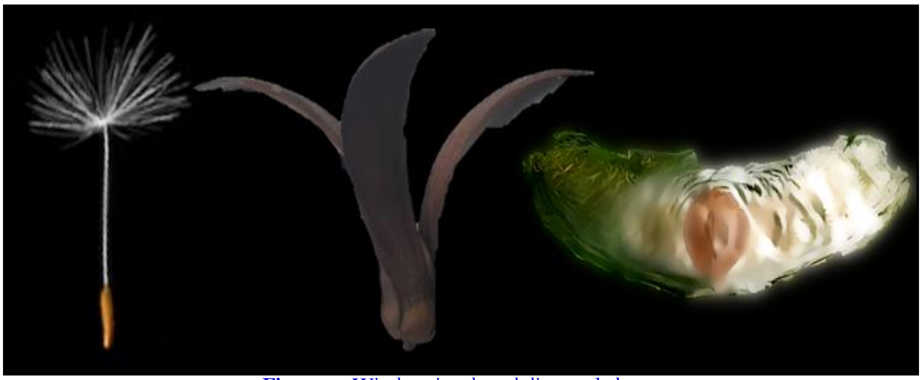
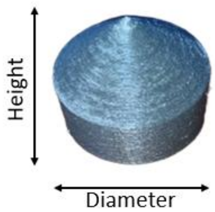
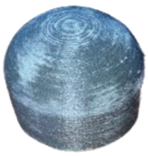
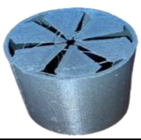
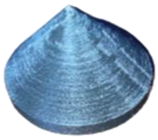
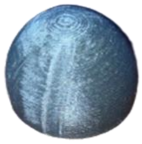
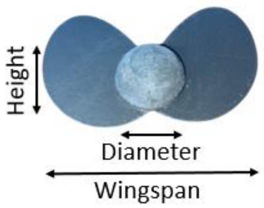
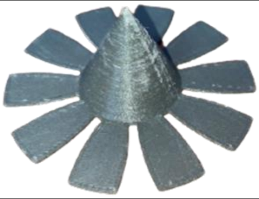
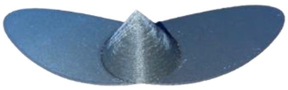


Figure 2. Wind-assisted seed dispersal shape.

Table 1. Specification of 3D-printed seed pod.

Type	3D-Printed shape	Specification
A		Diameter: 30 mm Height: 30 mm Cone length from tip: 15 mm
B		Diameter: 30 mm Height: 30 mm Sphere diameter: 30 mm
C		Diameter: 30 mm Height: 30 mm

Type	3D-Printed shape	Specification
D		Diameter: 30 mm Height: 30 mm Cone length from tip: 25 mm
E		Diameter: 30 mm Height: 30 mm Ellipse length: 30 mm
F		Diameter: 15 mm Height: 15 mm Wingspan: 96 mm Notes: Two large wings with a spherical seed pod
G		Diameter: 30 mm Height: 30 mm Wingspan: 70 mm Notes: Ten wings with cone cone-shaped seed pod
H		Diameter: 30 mm Height: 30 mm Wingspan: 115 mm Notes: Two narrow wings with cone cone-shaped seed pod
I		Diameter: 30 mm Height: 30 mm Cone length from tip: 20 mm Wingspan: 85 mm Notes: Five wings with a low chamber shape and a short cone shape seed pod

The choice of a 3D-printed seed pod that is 30 mm in diameter and 30 mm in height is a thoughtful and optimized design decision, balancing functional performance, manufacturability, and ecological integration. This relatively small option has beneficial weight-to-volume proportionality for drone-assisted reforestation projects, ensuring drones can transport and deploy many seed pods per mission without exceeding payload weight limits [2, 3]. A larger pod will limit the number of pods deployed per mission, decreasing the overall effectiveness and efficiency of the drone. A pod that is too small may not provide adequate internal volume to sufficiently accommodate the seed and essential growing materials like topsoil or nutrients, or moisture-retention gels, which are crucial for initial germination processes in degraded or remote landscape scenarios.

The form factor of the 30 mm pod also improves aerodynamic descent behavior. Less excessive drag and unpredictable flight patterns are observed due to compact proportions and decreased drag during descent [16], which yields a predictable and targetable landing. These effects improve ground coverage and lessen seeding clustering, a common issue with uncontrolled drop methods. The cylindrical symmetry of the pod contributes to stable free-fall characteristics, especially when deployed from moderate heights. The size also contributes to a low impact force upon landing, which lessens the chances of damage to the seed while possessing adequate kinetic energy to partially embed an object into soft soil or light vegetation. This is a positive trait to achieve increased seed-to-soil contact and moisture retention.

From a mass production perspective, the 30 mm × 30 mm size is highly efficient for mass 3D printing. It is the right balance of resolution and speed for large production runs using standard desktop or industrial 3D printers [17]. The quantity of material used is moderate to low, while maintaining structural integrity, making it cost-effective and environmentally efficient, especially when utilizing biodegradable polymers. The pod size also standardizes logistics and loading mechanisms, simplifying handling, packaging, storage, and transport—important factors for efficiency in large-scale ecological restoration.

Additionally, the given pod size is ecological, non-intrusive, and measures 30 mm. The pods are large enough to deter predation from small animals Zhang and Wang [18] while also being small enough to naturally degrade over time without leaving harmful matter or disrupting the microhabitat. Furthermore, both shape and size can accommodate a variety of seed measures, ranging from grasses to small trees, which enhances the potential for biodiversity-centered restoration or seeding practices. Overall, the 30 mm × 30 mm size is a practical, scalable, and ecologically sensitive option for modern, tech-aided restoration strategies.

The experiments involving drop tests were carried out from a building with three levels. This experimental arrangement incorporated digital scales to measure the mass of the seed pods, laser tools for determining the drop heights, and smartphones to capture the trajectory and descent of each seed pod. To ensure uniformity in the testing process, every seed pod underwent three trials at each level. Digital anemometers were also used in the setup to gauge wind speed, a key element affecting the seed pods' travel distance during their free fall. It is important to note that during these experiments, the wind speed was recorded as 0 m/s.

The seed pod drop test trials were conducted in Bintulu, Sarawak, Malaysia, at location 3.208331°N, 113.091274°E. Bintulu has a tropical rainforest climate (Köppen-Geiger climate classification: Af) [19]. The tests involved dropping seed pods onto a ground surface of grassy, compacted soil. This type of soil, which is common in Bintulu, consists of tightly packed particles with minimal pore space, affecting the bounce and dispersal of the falling seed pod. The grassy layer acts as a natural cushion, influencing the impact dynamics during the drop test. The interaction between seed pod designs and local ground conditions is crucial for optimizing seed dispersal in reforestation efforts within these tropical environments.

3. RESULTS AND DISCUSSION

Data was collected on key variables such as the height of the drop, type of seed pod, mass (including the soil content within the seed pod), time of fall, distance from a reference point (the X mark on the ground perpendicular to the release drop position), and bounce distance when the seed hit the ground. The data is presented for three different heights: approximately 4.931 meters, 8.569 meters, and 12.015 meters. Not applicable (n/a) for model types H and I as the wings of the seed pods were damaged in a previous test at the 8.569 m drop height (Table 2).

Table 2. Data from the drop test, including uncertainty analysis.

Height (m)		4.931±0.015			8.569±0.009			12.015±0.037		
Type	**Mass (g)**	**Time (s)**	**Distance from X mark (cm)**	**Bouncing Distance (cm)**	**Time (s)**	**Distance from X mark (cm)**	**Bouncing Distance (cm)**	**Time (s)**	**Distance from X mark (cm)**	**Bouncing Distance (cm)**
A	10.31±0.02	1.17± 0.11	17.00±4.89	20.03± 8.165	1.65±0.1	23.67± 2.05	16.67± 4.78	1.77± 0.22	28.00± 6.16	9.331± 3.20
B	13.70±0.02	1.18± 0.08	38.001±4.23	24.67± 11.84	1.50±0.17	28.00± 7.25	11.47± 1.80	1.92± 0.06	27.00± 7.87	7.91± 0.68
C	16.36±0.02	1.21± 0.11	23.67±2.49	23.67± 2.50	1.55±0.17	25.33± 0.47	18.67± 4.50	1.83± 0.13	30.07± 4.35	10.00± 4.08
D	5.54± 0.02	1.24± 0.3	24.33± 6.94	16.00± 4.54	1.67±0.03	27.167±2.09	15.00± 2.16	1.83± 0.07	33.67± 3.39	10.00±8.164
E	11.01±0.02	1.22± 0.11	17.37±5.39	14.67± 3.09	1.68±0.03	28.00± 2.16	12.67± 2.05	1.83±0.09	31.73± 1.96	11.33±8.17
F	11.27±0.02	1.19± 0.06	59.00± 2.94	0.47± 0.08	1.88±0.19	115.00± 24.832	0.37± 0.05	2.36±0.14	255.00±3.52	0.2± 0.14
G	8.97± 0.02	1.22± 0.05	59.00 ±2.94	5.27± 6.16	1.81±0.11	80.70± 4.96	3.67± 4.48	2.73± 0.3	106.10±2.40	0.87± 0.09
H	18.39±0.02	1.23± 0.03	42.67± 7.71	0.67± 0.124	1.55±0.17	99.33± 3.30	0.53± 0.08	n/a	n/a	n/a
I	9.43± 0.02	1.07±0.08	33.33± 3.40	5.6± 6.65	1.37±0.05	53.37± 2.02	3.80± 4.39	n/a	n/a	n/a

Figures 3 and 4 in the study, a detailed comparative analysis of the aerodynamic performance of various seed pod models in relation to drop height. Notably, Figure 3 highlights that the drop test experimental data show that the shape of seed pods is important to aerodynamic performance, specifically horizontal travel distance and bounce. Among the different biomimetic shapes tested, Type F, with large glider-like wings, produced the largest horizontal travel distance (up to 255 cm) from a drop height of 12 meters and exhibited no bounce. This clearly supports the use of biomimicry to improve seed dispersal for reforestation purposes, which is corroborated by broader literature on bioinspired design and engineering. These findings are aligned with the work of Nave Jr et al. [20], who showed that 3D-printed artificial samaras inspired by maple seeds can effectively mimic both the autorotation and wind-dispersal mechanisms of natural samaras. Their findings emphasized how such designs can slow the vertical descent, while also allowing for the wind to create horizontal distance of dispersal, with improved efficiency for the overall dispersal. Their metric of "windage," the effective force acting horizontally, sheds light on the way natural (in this case, maple) samaras and their biomimetic design can be exploited for aerial dispersal [20]. This is parallel to the traveling performance of the Type F design, which further validates it as a more aerodynamic option for drone-based seed spreading. This note highlights the advantage of winged seed pod designs to improve travel distance, an important element that could increase seed germination and lead to more productive reforestation [21].

On the other hand, Figure 4 gives an interesting view of the bounce performance of the seed pods, indicating that the simpler geometric shapes are more effective in this regard. The bounce characteristic has great importance since it informs where the seed pod may land after hitting the ground, which is significant in being able to spread the seed [22]. Additionally, data in Figures 5, 6, and 7 illustrate the differences in performance for each seed pod type (A to I), focusing on the average time to fall, the distance traveled from the predetermined reference point, and the average bounce distance.

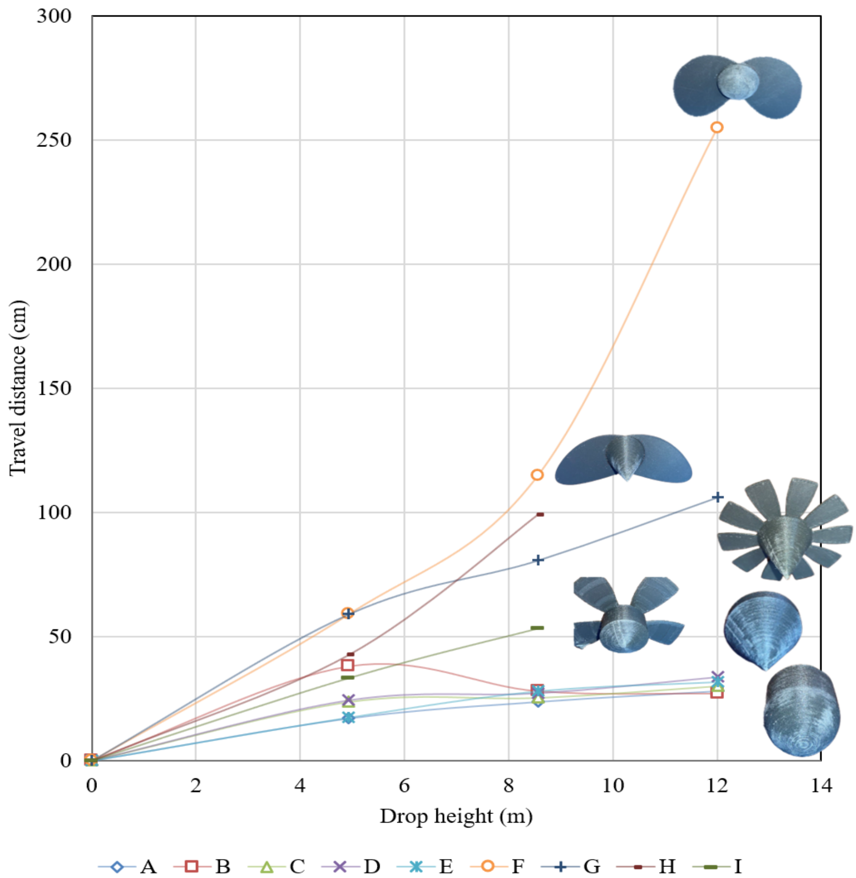


Figure 3. Travel distance versus drop height for each seed pod shape.

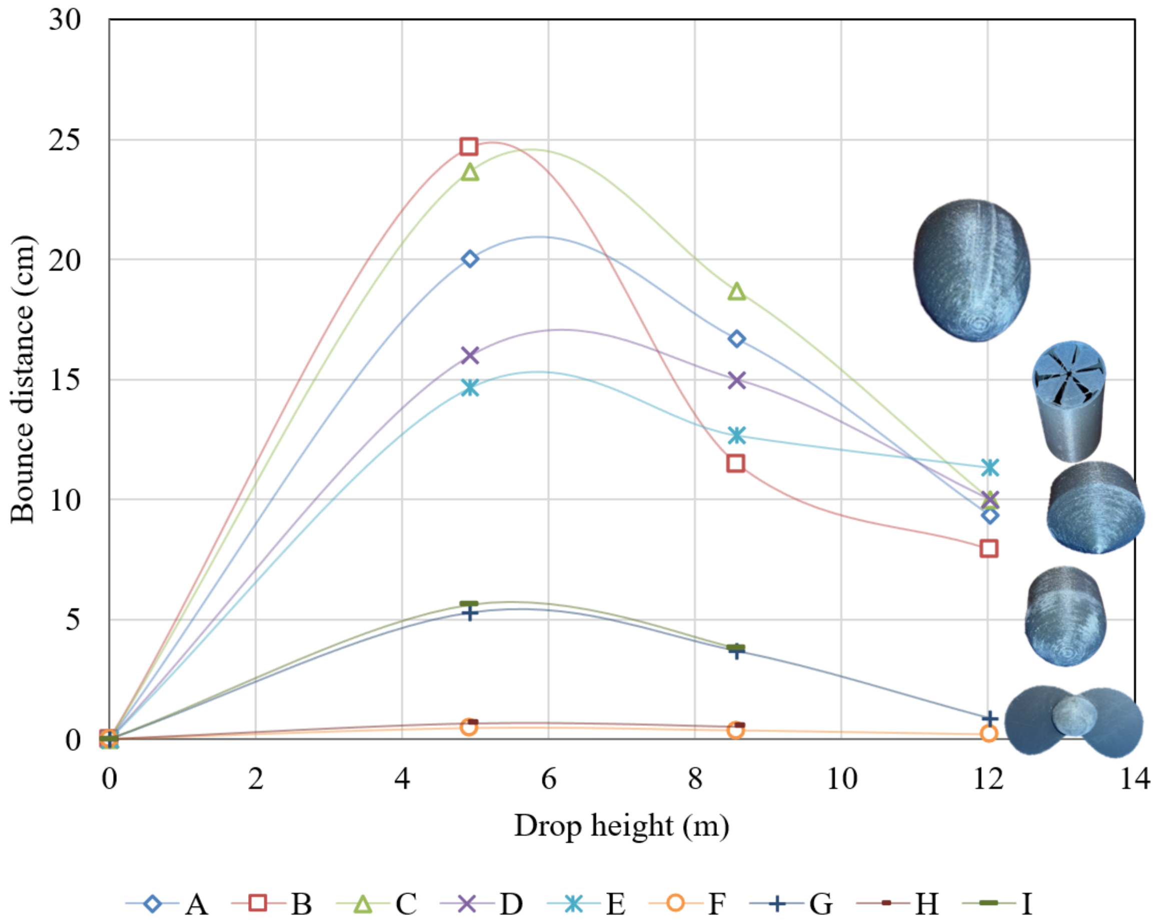


Figure 4. Bounce distance versus drop height for each seed pod shape.

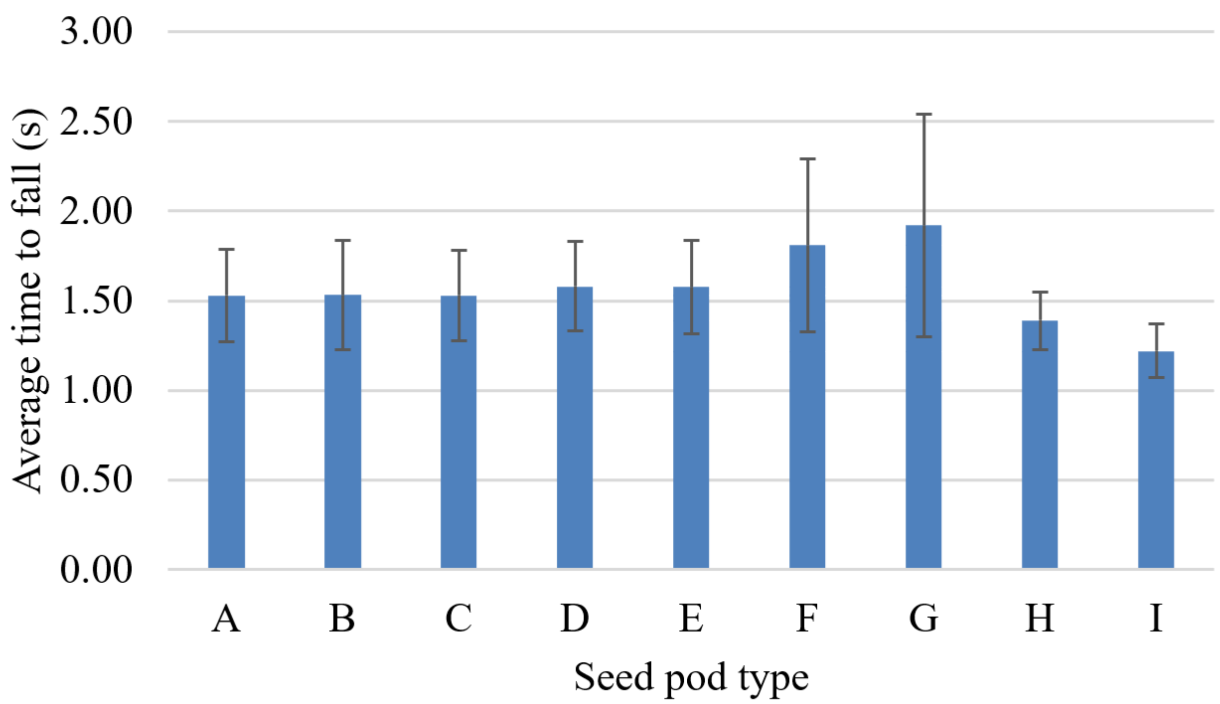


Figure 5. Average time to fall versus seed pod types.

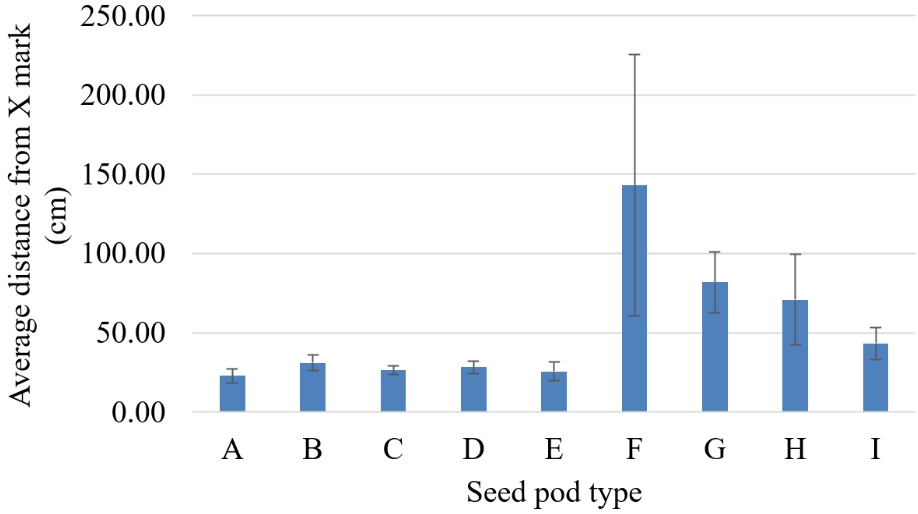


Figure 6. Average distance from reference point (X mark) versus seed pod types.

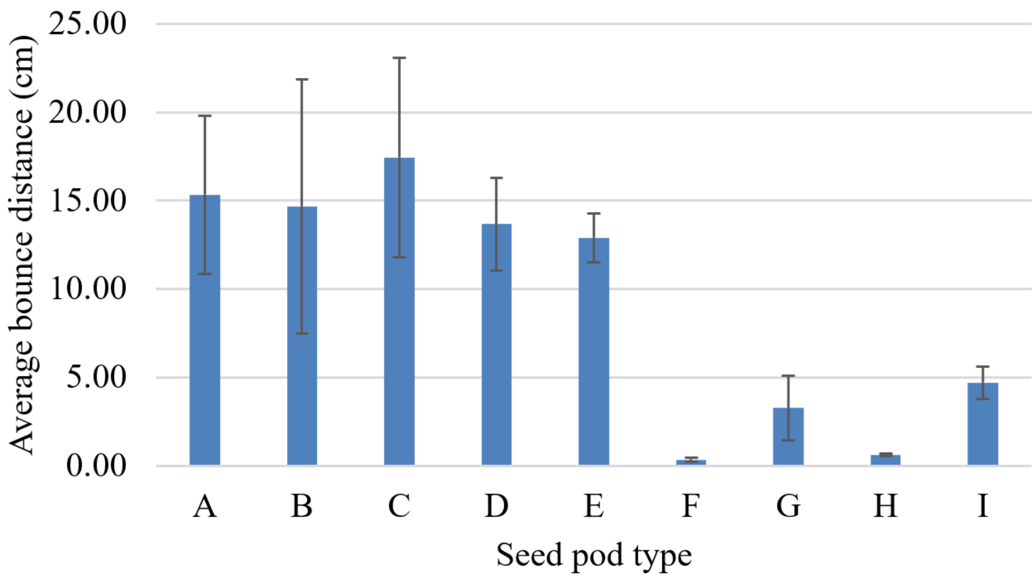


Figure 7. Average bounce distance versus seed pod types.

The mass of the seed pods varied significantly, ranging from 5.54 g for Type D to 18.39 g for Type H. This variation in mass was observed to impact the performance in drop tests, with heavier pods generally exhibiting different descent dynamics compared to lighter ones due to air resistance [23]. Interestingly, the average time to fall was relatively consistent across pod types, with times ranging from 1.22 seconds for Type I to 1.92 seconds for Type G Figure 5.

A noteworthy finding is the substantial variation in the average distance traveled by different seed pod types. Type F, notably the lightest, covered the greatest distance of 143 cm on average, significantly outperforming other types such as A, B, C, D, and E, which traveled between 22.89 cm and 31 cm Figure 6. This suggests that Type F's design, possibly with wing-like features, is more conducive to longer travel distances, offering potential advantages in reforestation efforts where broader seed dispersal is desired [24]. On the other hand, seed pod designs A through E, while having shorter travel distances, may be more applicable in precision situations where the seeds are being dispersed over shorter, more accurately controlled distances [3].

Also, the bounce distance differed considerably from seed pod type to type, with Type C having the highest average bounce (17.45 cm) and Type F having the lowest (0.35 cm) (Figure 7). The change in distance demonstrates how the seed pods' physical properties and design interactively affect their bounce characteristics, which matter when considering the survivability and embedding of seeds when they hit the ground [25]. Additionally, bouncing may assist with seed dispersal as they may travel further from the parent plant, reducing competition for resources and increasing the chance of finding a congenial site for germination [26]. However, substantial bouncing may damage the seeds, particularly those with delicate characteristics, decreasing their viability and germination potential [25].

With respect to material innovations, Cikalleshi et al. [27] further substantiate the potential use of biodegradable and porous cellulose-based materials in the additive manufacturing of artificial seeds. Their Ailanthus-inspired samaras were similar in structure to natural seeds and included humidity-sensitive photonic cellulose nanocrystals for environmental measurements. The use of light, porous structures, as achieved through 3D printing, is important for both this study and theirs for the long-duration, low-velocity descent that enhances seed survival upon impact and expands dispersal distances.

Furthermore, these studies support the combination of design elements of the pods with delivery by drone, which has been reviewed by Mohan et al. [2]. They reviewed UAV-supported reforestation efforts and indicated that an essential element for success in drone-based seeding is the design of the seed pods themselves, with respect to problems faced such as desiccation, damage upon impact, and the risk of not achieving uniform seed spread. They concluded that seed vessels dispersed from UAVs could improve survival rates and efficiency, that, if designed for aerodynamic control and contained nutrient supplements, could lower costs by over 80% compared to traditional seeding methods [2]. This study on biodegradable (~USD 0.20/pod), low-cost PLA pods containing topsoil offers practical solutions to these considerations.

Lastly, from an implementation perspective, the combination of the 3D printed design with biologically inspired design is practical due to the ability to deploy pods with UAV technology. The success of UAVs has been demonstrated by systems such as Flash Forest and DroneSeed, which can plant up to 10,000–40,000 seed pods per day, reforesting at a rate of 6 to 10 times faster than if human-based labor were used [2]. This study improves upon this by providing empirical findings on pod designs that can enhance the precision and success of seed dispersal, particularly applicable in sensitive ecological or remote locations.

4. CONCLUSION

In conclusion, this study sets a foundation for new models of reforestation, integrating biomimicry, 3D printing technology, and ecology. It presents an exciting opportunity for new models of seed dispersal, given that seed dispersal is essential to the success of reforestation and ecological restoration efforts. The particular focus of this study was to examine the travel distance, time to fall, and bounce data of various 3D-printed biomimetic seed pods shaped after natural dispersers that are efficient at dispersing seeds.

Based on this study's findings, it ascertains that both the design and mass of the seed pods are critical to their performance in the drop tests. The seed pods with wing characteristics, specifically Type F seed pods, traveled further, ultimately suggesting they could lead to potentially better seed dispersal in reforestation projects. All average times to fall were consistently similar across the terms of seed pod type; therefore, it may be suggested that gravitational principles primarily influenced the results of fall times. There was a variety of bounce distances; specifically, Type C seed pods had the highest average bounce distance, which indicates that specific pod designs may enhance the probability of seed survival upon impact.

The study supports the proposition that it is feasible to utilize 3D printing technology to construct biomimetic seed pods that can be used to improve the efficacy of seed dispersal in reforestation efforts. Seed pods that travel further and have desirable bounce characteristics are more likely to lead to successful germination and growth; therefore, they produce beneficial outcomes for reforestation and ecological restoration. This proposal is able to merge technology and ecology, demonstrating that this approach would be a sustainable and cost-effective alternative to methods currently used in reforestation.

Moving forward, more study into field testing these 3D printed seed pods in various ecological contexts would be beneficial, as would the examination of the longer-term ecological impacts of biomimetic seed pods on biodiversity, soil health, and ecosystem services. Additionally, the exploration of biodegradable and environmentally friendly materials utilized in 3D printing seed pods would aid future sustainable aims. Finally, further attempts to expand biomimetic design possibilities to include more original forms of seed dispersal can also produce potential models for seed dispersal.

Funding: This research was funded by the Sarawak Forest Research Project Phase 1: Project 1 – Drone Seeding Ecosystem Restoration: Seed Encapsulation and Pod Development under the People's Project allocation, Projek Rakyat, P29 (Grant number: 2022-0099/1407(25598)).
Institutional Review Board Statement: Not applicable.
Transparency: The authors state that the manuscript is honest, truthful, and transparent, that no key aspects of the investigation have been omitted, and that any differences from the study as planned have been clarified. This study followed all writing ethics.
Competing Interests: The authors declare that they have no competing interests.
Authors' Contributions: All authors contributed equally to the conception and design of the study. All authors have read and agreed to the published version of the manuscript.

REFERENCES

[1] J. Fargione *et al.*, "Challenges to the reforestation pipeline in the United States," *Frontiers in Forests and Global Change*, vol. 4, p. 629198, 2021. https://doi.org/10.3389/ffgc.2021.629198

[2] M. Mohan *et al.*, "UAV-supported forest regeneration: Current trends, challenges and implications," *Remote Sensing*, vol. 13, no. 13, p. 2596, 2021. https://doi.org/10.3390/rs13132596

[3] O. F. Marzuki, E. Y. L. Teo, and A. S. M. Rafie, "The mechanism of drone seeding technology: A review," *Malaysian Forester*, vol. 84, pp. 349-358, 2021.

[4] X. Yan *et al.*, "Recent advancements in biomimetic 3D printing materials with enhanced mechanical properties," *Frontiers in Materials*, vol. 8, p. 518886, 2021. https://doi.org/10.3389/fmats.2021.518886

[5] M. Kim *et al.*, "Seed dispersal models for natural regeneration: A review and prospects," *Forests*, vol. 13, no. 5, p. 659, 2022. https://doi.org/10.3390/f13050659

[6] A. L. Wendt, R. L. Chazdon, and O. Vargas Ramirez, "Successional trajectories of seed dispersal mode and seed size of canopy tree species in wet tropical forests," *Frontiers in Forests and Global Change*, vol. 5, p. 946541, 2022. https://doi.org/10.3389/ffgc.2022.946541

[7] S. E. Andres *et al.*, "Defining biodiverse reforestation: Why it matters for climate change mitigation and biodiversity," *Plants, People, Planet*, vol. 5, no. 1, pp. 27-38, 2023. https://doi.org/10.1002/ppp3.10329

[8] N. D. Preece, P. van Oosterzee, and M. J. Lawes, "Reforestation success can be enhanced by improving tree planting methods," *Journal of Environmental Management*, vol. 336, p. 117645, 2023. https://doi.org/10.1016/j.jenvman.2023.117645

[9] Y. Huang, L. Yu, L. Jiang, X. Shi, and H. Qin, "3D printing of hydrogel-based seed planter for in-space seed nursery. In K.-Y. Kim, L. Monplaisir, & J. Rickli (Eds.), Flexible automation and intelligent manufacturing: The human-data-technology nexus (lecture notes in mechanical engineering." Cham: Springer, 2022, pp. 56–63. https://doi.org/10.1016/j.mfglet.2022.07.045

[10] L. Ren *et al.*, "Plant-morphing strategies and plant-inspired soft actuators fabricated by biomimetic four-dimensional printing: A review," *Frontiers in Materials*, vol. 8, p. 651521, 2021. https://doi.org/10.3389/fmats.2021.651521

[11] A. V. Zdeshchyts and V. M. Zdeshchyts, "Seeds on a parachute: The technology of greening," *In IOP Conference Series: Earth and Environmental Science*, vol. 1049, no. 1, p. 012024, 2022. https://doi.org/10.1088/1755-1315/1049/1/012024

[12] J. Hamberg, D. T. Robinson, A. J. Trant, P. J. Richardson, and S. D. Murphy, "Direct topsoil transfer to already planted reforestation sites increases native plant understory and not ruderals," *Restoration Ecology*, vol. 32, no. 3, p. e14076, 2024. https://doi.org/10.1111/rec.14076

[13] M. C. Ferreira and D. L. M. Vieira, "Topsoil for restoration: Resprouting of root fragments and germination of pioneers trigger tropical dry forest regeneration," *Ecological Engineering*, vol. 103, pp. 1-12, 2017. https://doi.org/10.1016/j.ecoleng.2017.03.006

[14] B. Mazzolai *et al.*, "Morphological computation in plant seeds for a new generation of self-burial and flying soft robots," *Frontiers in Robotics and AI*, vol. 8, p. 797556, 2021. https://doi.org/10.3389/frobt.2021.797556

[15] I. M. Viola and N. Nakayama, "Flying seeds," *Current Biology*, vol. 32, no. 5, pp. R204-R205, 2022. https://doi.org/10.1016/j.cub.2022.02.029

[16] N. Ladommatos, "Drag coefficients of air rifle pellets with wide range of geometries," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, vol. 235, no. 21, pp. 5365-5384, 2021. https://doi.org/10.1177/0954406221991190

[17] J. M. Jordan, "Additive manufacturing ("3D printing") and the future of organizational design: Some early notes from the field," *Journal of Organization Design*, vol. 8, no. 1, p. 5, 2019. https://doi.org/10.1186/s41469-019-0044-y

[18] J. Zhang and B. Wang, "Intraspecific variation in seed size is mediated by seed dispersal modes and animal dispersers–evidence from a global-scale dataset," *New Phytologist*, vol. 241, no. 1, pp. 461-470, 2024. https://doi.org/10.1111/nph.19340

[19] S. S. Leong, S. C. Leong, and G. A. Beattie, "Integrated pest management strategies for Asian citrus psyllid Diaphorina citri Kuwayama (Hemiptera: Psyllidae) and huanglongbing in citrus for Sarawak, East Malaysia, Borneo," *Insects*, vol. 13, no. 10, p. 960, 2022. https://doi.org/10.3390/insects13100960

[20] G. K. Nave Jr *et al.*, "Wind dispersal of natural and biomimetic maple samaras," *Biomimetics*, vol. 6, no. 2, p. 23, 2021. https://doi.org/10.3390/biomimetics6020023

[21] S. J. Wright *et al.*, "Understanding strategies for seed dispersal by wind under contrasting atmospheric conditions," *Proceedings of the National Academy of Sciences*, vol. 105, no. 49, pp. 19084-19089, 2008. https://doi.org/10.1073/pnas.0802697105

[22] M. V. Anju, R. R. Warrier, and C. Kunhikannan, "Significance of soil seed bank in forest vegetation—a review," *Seeds*, vol. 1, no. 3, pp. 181-197, 2022. https://doi.org/10.3390/seeds1030016

[23] P. Potvin, P. Chastenay, F. Thibault, M. Riopel, E. Ahr, and L.-M. Brault Foisy, "An understanding of falling bodies across schooling and experience based on the conceptual prevalence framework," *Disciplinary and Interdisciplinary Science Education Research*, vol. 5, no. 1, p. 8, 2023. https://doi.org/10.1186/s43031-023-00075-4

[24] Y. Ren, C. Huang, J. Zhang, Y. Ma, and X. Tian, "Dispersal and germination of winged seeds of Brandisia hancei, a shrub in karst regions of China," *Plant Diversity*, vol. 43, no. 3, pp. 234-238, 2021. https://doi.org/10.1016/j.pld.2020.11.006

[25] R. Shahbazi, F. Shahbazi, M. Nadimi, and J. Paliwal, "Assessing the effects of free fall conditions on damage to corn seeds: A comprehensive examination of contributing factors," *AgriEngineering*, vol. 5, no. 2, pp. 1104-1117, 2023. https://doi.org/10.3390/agriengineering5020070

[26] N. G. Beckman and L. L. Sullivan, "The causes and consequences of seed dispersal," *Annual Review of Ecology, Evolution, and Systematics*, vol. 54, no. 1, pp. 403-427, 2023. https://doi.org/10.1146/annurev-ecolsys-102320-104739

[27] K. Cikalleshi, S. Mariani, and B. Mazzolai, "A 3D-printed biomimetic porous cellulose-based artificial seed with photonic cellulose nanocrystals for colorimetric humidity sensing," in biomimetic and biohybrid systems, F. Meder, A. Hunt, L. Margheri, A. Mura, and B. Mazzolai, Eds." Cham: Springer Nature Switzerland, 2023, pp. 117–129. https://doi.org/10.1007/978-3-031-38857-6_9