IIETA International Information and Engineering Technology Association
Advancing the World of Information and Engineering

International Journal of Design & Nature and Ecodynamics
Vol. 21, No. 5, May, 2026, pp. 1323-1330
Journal homepage: http://iieta.org/journals/ijdne

The Effect of Various Media on Growth of *Hopea odorata* Seedlings Based on Seed Balls

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https://doi.org/10.18280/ijdne.210509

Received: 15 March 2026
Revised: 28 April 2026
Accepted: 8 May 2026
Available online: 31 May 2026

Keywords:
enrichment planting, native species, natural forest, seed balls

ABSTRACT

Enrichment planting is needed to restore degrading Indonesian forests, and seed ball technology is a promising solution. This study evaluated the growth of *Hopea odorata* seedlings using various seed balls and media. The study employed a completely randomized design (CRD) with two factors—the first factor comprised two media: sand (M1) and soil (M2). The second factor consisted of three seed-ball media: clay (S1), clay and compost (S2), and clay, compost, and hydrogel (S3). The results showed that the soil medium (M2) resulted in greater increases in root length, diameter, and height compared to the sand medium (M1), with increases of 31%, 48%, and 58%, respectively. Meanwhile, the seed ball medium containing clay, compost, and hydrogel (S3) was the most effective treatment for improving seedling survival by approximately 55%. Additionally, the highest seedling growth observed in the S3 treatment reached 20.9 cm ± 2.68 in height, 3.6 mm ± 0.88 in diameter, and 2.08 mm ± 0.21 in diameter increment. However, no significant interaction was found between seed-ball composition and planting medium. Our findings suggest that the seed-ball composition containing clay, compost, and hydrogel (S3) is the most suitable medium for improving the growth of *Hopea odorata* seedlings in soil-based planting conditions (M2).

1. INTRODUCTION

Indonesia contains the world's third-largest area of tropical forests, following Brazil and the Democratic Republic of the Congo [1]. These forests deliver essential ecosystem services by supporting livelihoods, economic resilience, and human well-being, while also sustaining high biodiversity and contributing to global sustainability [2].

Lowland dipterocarp forests, a major tropical rainforest type in Southeast Asia, are dominated by climax tree species of the family Dipterocarpaceae. Within this family, 510 species are distributed across 16 genera, of which 470 species (92.1%) occur in Asia [3]. Borneo serves as the centre of dipterocarp diversity, containing 13 genera and 269 species, whereas Sumatra hosts 12 genera and 113 species [4].

In Indonesia, dipterocarp species are also distributed across Papua, Maluku, Java, and Sulawesi [4]. Within lowland tropical rainforests, dipterocarps account for approximately 15.6–21.9% of total tree abundance [5], yet they dominate forest structure by contributing 41.7% of the basal area, 50–80% of emergent trees, and around 40% of understory individuals [3, 6].

Although deforestation rates in Indonesia have fluctuated over time, recent trends indicate a significant decline [7]. Annual net deforestation decreased from approximately 1.9 million hectares during 1990–1996 to about 121,000 hectares in 2022–2023 [7]. Nevertheless, forest degradation remains a critical issue, driven by factors such as illegal logging and forest fires [8]. This degradation results in substantial ecological consequences, including biodiversity loss and climate-related impacts such as increased CO_2 emissions, changes in temperature and humidity, reduced carbon sequestration, and lower evapotranspiration rates [9]. Consequently, strategies to mitigate the impacts of natural forest degradation must involve forest restoration with native species and the development of silvicultural techniques to enhance canopy cover and improve environmental conditions. Restoration aims to restore the structure of forest stands and enhance forest ecosystems to achieve ecological and socio-economic benefits [10]. Restoration with native species enhances ecosystem functions and biodiversity, improves resilience against environmental changes, and supports local livelihoods [11]. Native species are generally better adapted to local environmental conditions, resulting in higher survival and growth rates [12].

Selecting native species is crucial for restoring forest structure, function, and diversity to support accelerating forest restoration [13]. One Dipterocarpaceae species, *Hopea*, can be used for forest restoration in degraded tropical rainforests. *Hopea*, a genus with 104 species, is found worldwide. These plants are known for their high-quality wood, large size, and evergreen leaves, which are characteristics of tropical rainforest trees [14]. *Hopea odorata* is a protected species in the family Dipterocarpaceae and is classified as Vulnerable (VU) on the IUCN Red List because its population continues to decline globally [15]. *Hopea odorata*, a shade-tolerant dipterocarp, shows promising growth and physiological responses, indicating its potential as a native species for forest rehabilitation and restoration efforts in tropical environments [16].

However, the large area of degraded forest land requires technology that can be applied quickly. Additionally, some of the land replanted is hard to reach and cannot be planted using conventional methods. Conventional techniques require more time and money [17, 18]. One approach to restoration is seed ball technology integrated with drones. Seed balls are composed of seeds, clay, compost, and other natural ingredients. The clay shields the seeds from external stress and predation, while the compost offers critical nutrients for seed germination and early plant growth [19, 20]. Seed balls are inexpensive to make and can be disseminated manually or by aerial means, making them ideal for large-scale restoration [21].

Natural forest restoration using seed balls is an innovative technique that uses clay-coated seeds and combinations of them to improve germination and growth in degraded environments [19]. Natural regeneration through waiting for natural succession has a long-term constraint. Additionally, the condition of one of the factors of natural regeneration, the seed bank, is not necessarily the availability of seeds on the forest floor. Degradation significantly changes the composition and density of the seed bank [22]. Tropical forest rehabilitation requires human assistance to speed up recovery. Assisted regeneration enables greater coverage and is cost-effective [23].

Several studies on the use of seed balls—such as in India with *Leucaena leucocephala* and in East Africa with *Sesbania sesban*—have shown that they enhance growth and improve the success of land rehabilitation efforts [20, 24]. The use of seed ball technology in peatland rehabilitation with jelutung (*Dyera polyphylla*) has affected the germination percentage [25]. Research on seed balls with various media compositions has been conducted on various adaptive plants, such as *Artocarpus heterophyllus* and *Intsia bijuga* [26, 27]. However, research on a combination of seed ball media and *H. odorata* plants as native species on land intended for restoration has not been widely studied. Therefore, research is needed to prepare the formula of seed ball media and the site of planting to find the best media composition and site for planting to support the growth of *H. odorata*.

2. METHODS

2.1 Site description

This study was conducted at the Intensive Silviculture Laboratory of the Faculty of Forestry at Universitas Gadjah Mada, Yogyakarta, Indonesia. The research was conducted from January to June 2025. Our study was conducted in a nursery to control environmental variability and allow a clearer evaluation of the treatment effects on seed germination and early seedling establishment. The average relative humidity in the area is 68.6%, with average temperatures of 31.9 °C. The average light intensity is 16,717.78 lux. One limitation of this study is that the experiment was performed in a nursery rather than under open-field conditions. To better simulate field conditions, the seed balls were placed on soil and sand media within the nursery environment. Therefore, we assumed that once the seed balls germinated, the seedlings would be able to adapt to these artificial site conditions.

2.2 Research design

The study was conducted on a completely randomized design (CRD) with two factors. The first factor involved two media: sand (M1) and soil (M2). The second factor consisted of three seed ball media: clay (S1) as a control, clay and compost (v/v) (1:1) (S2), and clay, compost (v/v) (1:1), and hydrogel 0.04 gram per seed ball (S3). This study used *H. odorata* seedlings in which the seed balls were placed in media according to the experimental design and treatment combinations (Figure 1 and Table 1). The study included three replications, each with 10 individual seed balls. So for each treatment combination, there are 30 seedballs, and the total is 180 individuals. The seed balls were prepared with a diameter of 3 cm, which allowed for precise and automated release using the drone system. Each seed ball weighed approximately 42.5 g. In addition, this seed-ball size falls within the recommended range reported in previous studies for improving seed germination and seedling establishment [28].

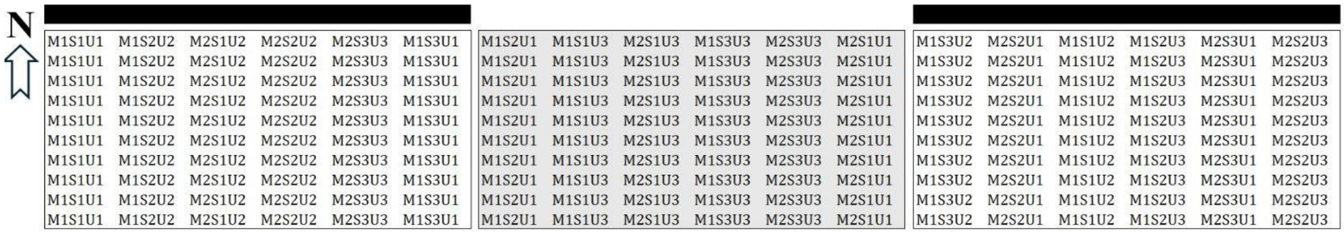


Figure 1. Research layout

where, M1 = sand media, M2 = soil media, S1 = clay seed ball media, S2 = clay seed balls media + compost, S3 = clay seed balls media + compost + hydrogel, U1 = repeat 1, U2 = repeat 2, U3 = repeat 3

2.3 Data collection

The growth parameters measured in *H. odorata* seedlings include survival ability, height, height increment, diameter growth, diameter increment, root length, and aboveground and belowground biomass. The parameters were measured using the following method:

a. Survival ability

$$\text{Survival ability (\%)} = \sum \frac{\text{number of living seedlings}}{\text{number of seed planted}} \times 100\% \tag{1}$$

Table 1. Description of media and seedball media combination treatments, codes of *H. odorata* seedlings

Code	Treatment
M1S1	Sand media (M1) and clay seed ball media (S1)
M1S2	Sand media (M1) and clay seed balls media + compost (S2)
M1S3	Sand media (M1) and clay seed balls media + compost+ hydrogel (S3)
M2S1	Soil media (M2) and clay seed ball media (S1)
M2S2	Soil media (M2) and clay seed balls media + compost (S2)
M2S3	Soil media (M2) and clay seed balls media + compost+ hydrogel (S3)

b. Height and height increment (HI)
Height measured at the final observation.

$$HI\ (cm) = the\ final\ height - the\ initial\ height \quad (2)$$

c. Diameter and diameter increment (DI)
Diameter measured at the final observation.

$$DI\ (cm) = \text{the final diameter-the initial diameter} \quad (3)$$

d. Root length
Root length is measured from the base of the root to the longest tip using a ruler.

e. Aboveground biomass
Aboveground biomass is calculated by drying the upper parts of the plant (leaves and twigs) at 70 ℃ until constant weight is reached.

f. Belowground biomass
Belowground biomass is calculated by drying the plant's lower part (roots) at 70 ℃ until it reaches a constant weight.

2.4 Data analysis

The obtained data were analyzed using analysis of variance (ANOVA). Differences between treatments were tested using Duncan's Multiple Range Test (DMRT) at the 5% and 1% significance levels ($p < 0.05$ and $p < 0.01$). The statistical analysis was performed using Microsoft Excel and SPSS 25.0 [29].

3. RESULT AND DISCUSSION

3.1 Effect of media on *Hopea odorata* growth

The results show that media significantly influenced growth in terms of diameter ($p < 0.01$), diameter increment ($p < 0.01$), height ($p < 0.01$), height increment ($p < 0.01$), and root length ($p < 0.01$) of *H. odorata* seedlings (Table 2). However, the media and seed ball did not significantly affect the above-ground or below-ground biomass of *H. odorata* seedlings (Table 2). Furthermore, combining media and seed balls also had no significant effect on *H. odorata* seedlings (Table 2). The growth and development of a plant are influenced by genetic factors and environmental factors [30]. One of these factors is the planting media. The planting media, as root media, are crucial for plant growth and quality [31].

Table 2. Analysis of variance (ANOVA) for the effects of growth media and seed balls on the growth of *H. odorata*

Source of Variation	df	Diameter (mm)		Diameter Increment (cm)		Height (cm)		Height Increment (cm)	
		MS	F Value	MS	F Value	MS	F Value	MS	F Value
Media	1	67.72	84.43**	57.86	110.68**	3493.21	88.86**	3397.17	169.91**
Seed balls	2	7.14	8.91**	2.23	4.27**	294.30	7.48**	50.00	2.50ns
MediaxSeed balls	2	0.62	0.78ns	0.59	1.14ns	51.42	1.30ns	23.19	1.16ns
Source of Variation	**df**	**Survival Ability (%)**		**Root Length (cm)**		**Aboveground (g)**		**Belowground (g)**	
		MS	**F Value**	**MS**	**F Value**	**MS**	**F Value**	**MS**	**F Value**
Media	1	355,556	1,600ns	479.67	45.30**	5.06	3.26ns	2.09	1.83ns
Seed balls	2	1,372,222	6,175*	11	1.03ns	0.15	0.09ns	0.03	0.02ns
MediaxSeed balls	2	2065,556	0.92ns	20.69	1.95ns	1.47	0.95ns	1.02	0.89ns

Note: *: significant at $p \leq 0.05$, **: significant at $p \leq 0.01$, ns: non-significant different at $p > 0.05$, MS: Mean Square

The best planting media have a loose, porous soil structure [32], providing optimal conditions for seedling growth. In general, the use of soil significantly increases the root growth of *H. odorata* seedlings (Figures 2 and 3). In soil media (M2), the average root length was approximately 15.74 cm ± 1.23, which was about 31% higher than in sand media. Soil media also significantly increased the diameter, height, and the increment in diameter and height (Figure 4). The diameter growth in soil media (M2) was around 4.33 ± 0.40 mm, and the diameter increment was 2.84 ± 0.14 mm (Figure 4(a)). In addition, the height growth was around 25.89 ± 1.83 cm, and the increment was around 18.38 ± 3.33 cm (Figure 4(b)). This growth in diameter and height was 48% and 58% higher, respectively, than that observed in sand media. Soil provides good aeration, which improves root development and increases water absorption [33]. It improved nutrient adsorption and water use efficiency, facilitating better water and nutrient uptake by roots during the experiment. This is consistent with previous research indicating that soil media is more effective than sand media for seedling growth [34]. Therefore, it has the potential to promote plant growth.

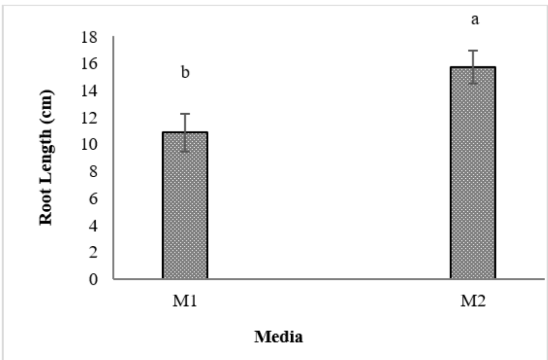


Figure 2. Mean root length of *Hopea odorata* seedling roots in sand media (M1) and soil media (M2) treatments
Note: Different letters indicate significant differences between treatments at $p < 0.05$. The sample size (n): M1 = 33, (n) M2 = 39; error bars represent standard error (SE); The SE is calculated by dividing the standard deviation by the square root of the sample size.

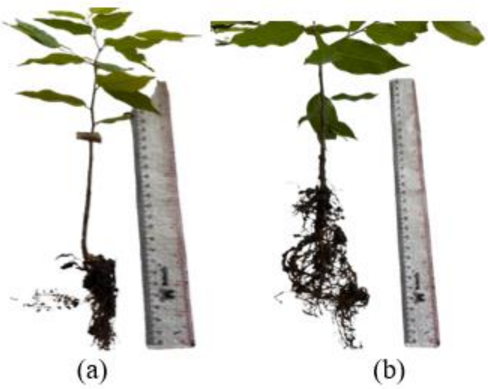
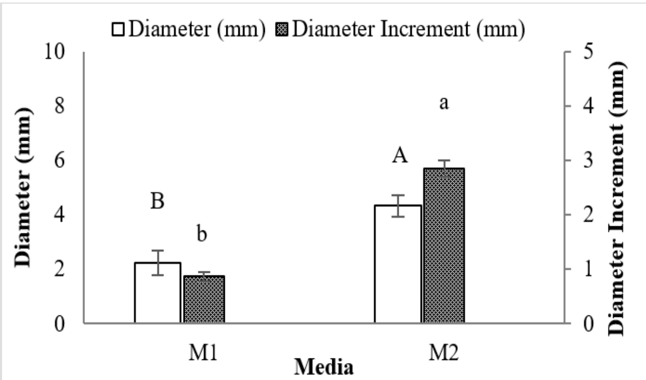
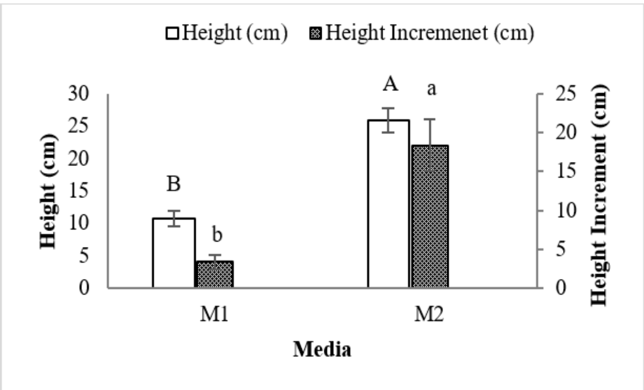


Figure 3. Root growth of *H. odorata* seedlings in (a) sand media and (b) soil media

In contrast, *H. odorata* seedlings grown in sand media exhibited lower growth. Sand is highly porous, allowing nutrients, aeration, and drainage to pass easily. It has large pores, so adding organic matter is necessary to retain water and nutrients [32]. Each growing medium has its own advantages and disadvantages, particularly regarding the naturally occurring nutrients available in the media. The structure of the media and their nutrient content are important factors to consider when choosing the right medium for each plant type [35].



(a)



(b)

Figure 4. Mean growth of *Hopea odorata* seedlings: (a) diameter and diameter increment, (b) height and height increment, in sand media (M1) and soil media (M2) treatments
Note: Different letters indicate significant differences between treatments at $p < 0.05$. The sample size (n): M1 = 33, (n) M2 = 39; error bars represent standard error (SE); The SE is calculated by dividing the standard deviation by the square root of the sample size.

3.2 Effect of seed ball media on *Hopea odorata* growth

The results showed that the type of seed ball media significantly affected the survival ability ($p < 0.05$), diameter ($p < 0.01$), diameter increment ($p < 0.01$), and height ($p < 0.01$) of *H. odorata* seedlings (Table 1). Seed ball media containing a mixture of clay, compost, and hydrogel (S3) exhibited the most significant growth (Figure 5, Figure 6). Seed ball media containing clay, compost, and hydrogel (S3) increase survival ability, height, diameter, and diameter increment of *H. odorata* seedlings (Figure 5, Figure 6). The survival rate of *H. odorata* seedlings in the S3 seed ball treatment was around 55 ± 5.00%, which was higher than in treatment S1 (around 36 ± 6.15%) and treatment S2 (around 25 ± 6.32%) (Figure 5). Seed balls protect seeds from biotic and abiotic stressors, increasing their survival and establishment rates [20]. The highest growth of *H. odorata* seedlings in height, diameter, and diameter increment in treatment S3 was 20.9 ± 2.68 cm, 3.6 ± 0.88 mm, and 2.08 ± 0.21 mm, respectively, during the observation period (Figure 6(a, b, c)). This is due to the presence of organic materials, such as compost, which contain the essential nutrients that plants need [36]. Providing compost in the planting media provides additional nutrients to support seedling growth [27, 37].

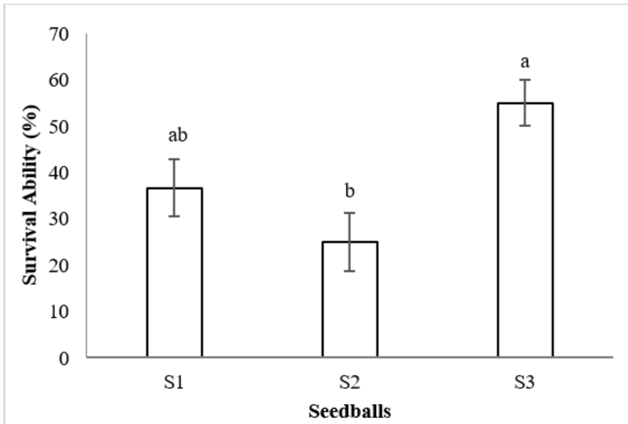
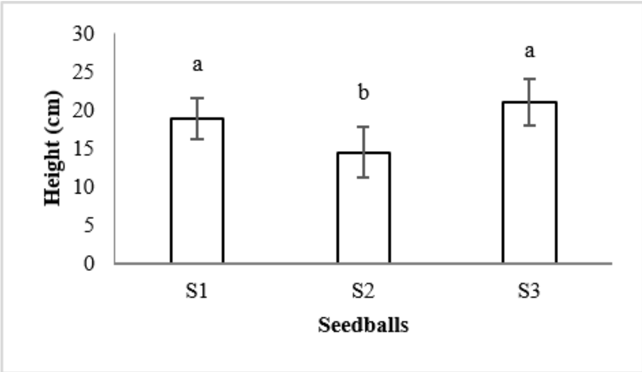
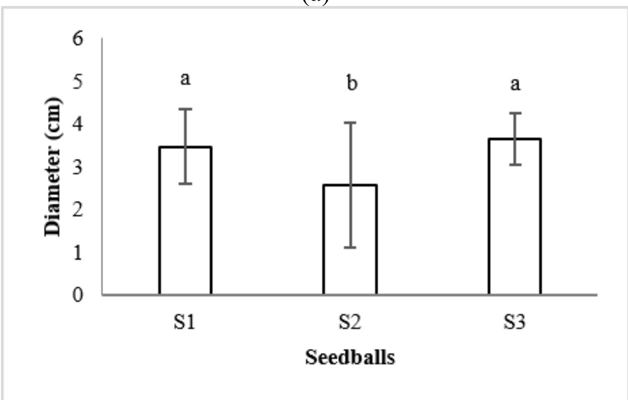


Figure 5. Mean survival rates of *Hopea odorata* seedlings under various seed ball medium treatments (S1: clay; S2: clay and compost; S3: clay, compost, and hydrogel)
Note: Different letters indicate significant differences among treatments at $p < 0.05$. The sample sizes (n): S1 = 24, S2 = 15, S3 = 33; error bars represent standard error (SE); The SE is calculated by dividing the standard deviation by the square root of the sample size.

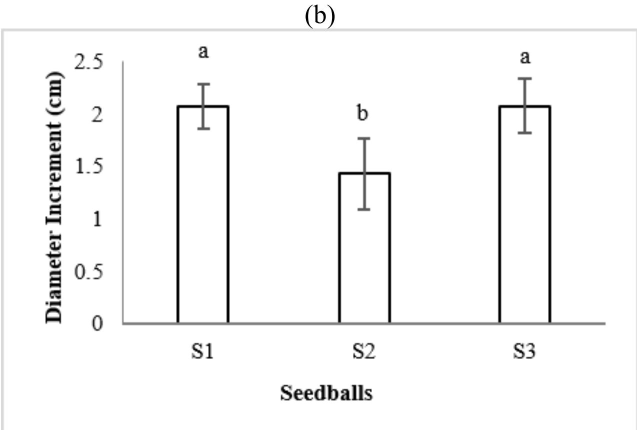
Organic fertilizers, such as compost, increase water absorption and storage capacity, boost organic matter levels, and improve soil physical properties [38]. Furthermore, adding hydrogel helps absorb and store water for optimal growth. Hydrogels help maintain water availability for plants over a longer period [39]. Furthermore, when combined with compost, they can enhance nutrient availability [40], thereby promoting plant growth. Due to its organic matter content and crumbly structure, it is ideal for plant growth as it fulfils their nutrient needs. The integration of these three media types into seed balls is the most effective for increasing height, diameter, and overall growth. The ideal seed ball formulation varies according to the target crop and environmental conditions. To ensure maximum efficiency, seed ball compositions must be adapted to individual environmental conditions. Soil type, moisture availability, and local climate are all important considerations [41]. The right combination of planting media can provide the necessary nutrients for optimal growth, development, and reproduction [32].



(a)



(b)



(c)

Figure 6. Mean growth of *Hopea odorata* seedlings: (a) height, (b) diameter, and (c) diameter increment under various seed ball treatments (S1: clay; S2: clay and compost; S3: clay, compost, and hydrogel)

Note: Different letters indicate significant differences among treatments at the 0.05 significance level. The sample sizes (n): S1 = 24, S2 = 15, S3 = 33; error bars represent standard error (SE). The SE is calculated by dividing the standard deviation by the square root of the sample size.

The seed ball media contains nutrients that support seed growth and the success of planting [20, 42]. It entails encapsulating seeds in a mixture of locally accessible materials to generate seed balls that may easily disseminate in varied conditions [43]. A combination of seeds, clay, and compost creates a protective, nutrient-rich environment for germination [19]. However, the success of seed balls depends on soil quality, climatic conditions, and appropriate dispersal methods, such as drone technology [44]. Additionally, they create conditions conducive to germination and survival until the seeds germinate [45]. A limitation of this study is the absence of additional blank controls, such as untreated seeds or no seed ball treatments. The clay-only treatment was used as the experimental control to evaluate the relative effects of seed ball amendments within the clay matrix. Consequently, the results should be interpreted as comparisons among seed ball formulations rather than absolute effects relative to untreated conditions.

3.3 Opportunity for the seed ball for restoration in the degraded tropical rainforest

The rate of forest degradation in Indonesia is high due to deforestation, forest fires, and land use change [46]. The net deforestation in Indonesia remains hundreds of thousands of hectares per year, while the accumulated deforestation over recent years has reached millions of hectares [7]. Deforestation has a direct impact on declining biodiversity, increased carbon emissions, and disrupted ecosystem stability [47, 48]. Restoring degraded forests is crucial as a climate change mitigation strategy, as forests serve as vital carbon sinks that absorb greenhouse gases [49].

Additionally, forest restoration using native species is an essential measure to address the biodiversity crisis [50]. Such large-scale forest damage requires effective, efficient, and adaptive rehabilitation efforts that take into account various biophysical conditions in the field. Conventional rehabilitation approaches through manual seedling planting have proven to have limitations, including high labour requirements, difficult land access, high planting costs, and limited coverage in remote areas [51]. Furthermore, technological innovation in enrichment planting is necessary to accelerate forest restoration.

One restoration effort involves seed ball technology. Seed balls are a vegetation restoration technology that encases seeds in a soil mixture and protects them from extreme environmental conditions, and increases their chances of germination [20, 26]. Seed ball technology is a cost-effective reforestation approach that is suitable for degraded land and large-scale applications [21]. Using seed balls with native species increases seedling survival by 50-60% [52]. Using seed balls can increase seed mass. This way, they can fall on the target restoration site. Tropical forest restoration efforts can be supported by using drones, which can increase the number of native species individuals. Seed balls can be disseminated manually or by drones to efficiently cover large, inaccessible areas [42, 53]. Drones offer flexibility, low cost, and improved efficiency for seed ball dispersal in large-scale restoration projects [54, 55]. However, obstacles include high seed predation rates, uneven effectiveness, and a paucity of success statistics [44].

The combination of drone technology and seed balls offers an innovative, efficient approach to forest rehabilitation that has the potential to be applied on a large scale. Drones can deliver seeds to targeted microsites with precision, potentially boosting success rates [44]. Meanwhile, seed balls can increase seed viability after dispersal [56]. The integration of drones and seed balls enables accelerated forest restoration at a lower operational cost than traditional methods, while also improving planting accuracy in priority restoration areas [57]. This approach is expected to be a strategic alternative for restoring resilient, sustainable forest ecosystems aligned with national climate change mitigation and biodiversity conservation targets. The novelty of this research lies in the information on the best seed ball media for the native species

Hopea odorata. The implications and benefits of this study's results include selecting the best seed ball media for native species, which can contribute to the success of natural forest restoration and large-scale plantations. It is hoped that further research can be carried out directly in degraded tropical forest areas to determine the germination and growth of *Hopea* seed balls in actual environmental conditions.

4. CONCLUSIONS

The findings of this research indicate that seedball and media significantly affected the survival rate and growth of *H. odorata* seedlings. The best seed ball media combination was soil, compost, and hydrogel (S3), which yielded a survival rate of approximately 55 ± 5.00% and showed the best growth in height (20.9 ± 2.68 cm), diameter (3.6 ± 0.88 cm), and diameter increment (2.08 ± 0.21 cm). Meanwhile, the in-root length, diameter, and seedling height in soil media (M2) were higher than in sand media (M1), by 31%, 48%, and 58%, respectively. However, the combination of media and seed ball did not significantly affect the growth of *H. odorata* seedlings. It suggested that the seed-ball composition containing clay, compost, and hydrogel (S3) is the most suitable medium for improving the growth of *Hopea odorata* seedlings in soil-based planting conditions (M2).

ACKNOWLEDGMENT

The authors sincerely thank Universitas Gadjah Mada for its research grant and financial support for this study.

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