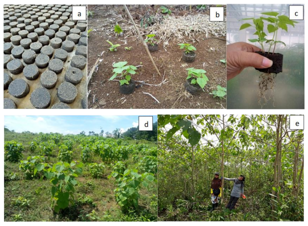

Seeding of tropical tree species in Indonesia

Dede J Sudrajat✉**, Yulianti, Evayusvita Rustam**

Research Center for Applied Botany, National Research and Innovation Agency, Jl. Raya Jakarta-Bogor Km. 46, Cibinong, Bogor, West Java, Indonesia

✉djsudrajatbtp@yahoo.com

ARTICLE INFO

Citation:
Sudrajat D, Yulianti, Rustam E (2026) Seeding of tropical tree species in Indonesia. Reforesta 21: 87-104.
DOI: https://dx.doi.org/10.21750/REFOR.21.06.136

Editors: Gardiner Emile, Stanturf John
Received: 15.11.2025
Accepted: 15.12.2025
Published: 20.01.2026

CrossMark

Note
This paper is a part of a Special issue on International Practices for Regenerating and Restoring Forest Trees by Seeding, edited by Emile S Gardiner and John A Stanturf

Abstract

Indonesia's more than 120 million ha of forest are considered a global biodiversity hotspot. Over-exploitation, land conversion, fires, and natural disasters have degraded almost 13 million ha. In response, the government has launched various restoration programs, aiming to reduce greenhouse gas emissions and decrease vulnerability to disasters like floods, landslides, and droughts. Indonesia aims to restore 12 million ha of forests and 2 million ha of peatlands by 2030. Seeding is a cost-effective alternative to planting seedlings, suitable for large-scale restoration, especially in remote or labor-limited areas. Success depends on species selection, seed quality, land preparation, timing, and maintenance. Seed encapsulation in briquettes or balls can be adapted for aerial seeding using drones or helicopters. Biofertilizers and hydrogels can improve germination and survival. Medium- to large-seeded species generally perform better in seeding applications. Land preparation (clearing and soil loosening at the sowing point or plot) and optimal sowing time (early-mid rainy season) are critical for success. Weeds are controlled around seedlings typically for up to three years until plants are established. Seeding costs about half as much as planting polybag seedlings for the same number of surviving plants. Further research is needed to optimize seeding practices for various species and site conditions.

Keywords

tropical rain forest, seed traits, seed briquettes, biofertilizer, aerial seeding, cost comparison

Contents

1 The Indonesian forest

Indonesia is a tropical country with a large forest area of about 120.47 million ha (MoEF 2022), or around 64% of the total land base of the country. Most forests in Indonesia are categorized as evergreen tropical rainforests that grow wherever rainfall exceeds evapotranspiration (annual rainfall is more than 2,000 mm). The dry season is no longer than 2 months (Elliott et al. 2013). These forest areas are managed based on their function, i.e., production forests (68.8 million ha), protection forests (29.6 million ha), conservation forests (22.1 million ha), and additionally forests associated with marine conservation areas (5.3 million ha) (MoEF 2020). Indonesian forests are one of the significant forest areas recognized for maintaining global climate balance, including the Amazon forests in South America and tropical forests of the Congo Basin in Africa, and are popularly known as the lungs of the world. Indonesia has more than 17,000 islands, which makes Indonesian forests one of the greatest reservoirs of biodiversity after Brazil and Colombia and is included as a "Global Biodiversity Hotspot" (Butler 2016). A total of 1605 bird species, 720 mammal species, 723 reptile species, 5137 arthropod (spider) species, 248 freshwater fish species, 15,1847 insect species, and 197,964 invertebrate species have been documented as living in Indonesian forests. Indonesian forests also grow 120 species of gymnosperms and an estimated 30,000 to 40,000 species of angiosperms, and to date, only 19,112 plants species have been identified (MoEF 2020a).

Over-exploitation, forest encroachment, land conversion, forest fires, and the impact of natural disasters have increased forest and land degradation (MoEF 2024). The existence of degraded forests and lands often trigger forest fires, the release of large amounts of greenhouse gases, changes in microclimate and weather patterns (Ayres and Lombardero 2000, CIFOR 2013), and increased vulnerability to disasters, especially hydrometeorological disasters (BNPB 2016). To overcome forest destruction, the Indonesian government has attempted to reduce the area of degraded forests and landscapes through various restoration programs such as Social Forestry (2002), the National Movement for Forest and Land Rehabilitation (2003), the construction of 57 permanent nurseries (2011), the KPH (Forest Management Unit) nursery (2015), community nurseries (2016), village nurseries (2020), and the construction of six nursery centers (2021) to provide seedlings on a large scale. However, according to data from the Ministry of Environment and Forestry (MoEF 2022), the area of degraded forest and land in Indonesia is still large, i.e., 12.74 million ha, consisting of 8.70 million ha categorized as critical and 4.04 million ha designated as very critical. The parameters determining critical and very critical land are based on Forestry Ministerial Regulation Number P.32/Menhut-II/2009, including land cover, slope gradient, erosion hazard level, and management. Each parameter determining critical land is given a specific score (land cover, slope gradient, and management ranges from 1 to 5; erosion ranges from 2 to 5) and weighting (land cover = 50%, slope gradient = 20%, erosion = 20%, and management = 10%). The sum of each score is then classified to determine the level of critical land. Based on these calculations, the level of land criticality is classified into 5 classes, i.e., very critical (score 120-180), critical (score 181-270), somewhat critical (score 271-360), potentially critical (score 361-450), and not critical (score 450-500).

Forest degradation and deforestation are major factors affecting biodiversity decline and climate change (MoEF 2024). Forests and lands that have been degraded and identified as critical are generally overgrown with brush, reeds, and grasses (Order Poales), have low fertility, and are prone to erosion. Meanwhile, severely degraded land (very critical land) is often grassland or barren land that is severely eroded (gully erosion) with loss of soil, including the entire A horizon and part of the B horizon (Wahyunto and Dariah 2014). Increasing temperatures and shifting rainfall patterns are increasing the area of land noted as critically degraded because of their impacts on ecological, hydrological, and production functions (MoEF 2024). This crisis has encouraged the Indonesian government to prioritize land and forest restoration activities.

Through the Nationally Determined Contribution (NDC) program as a commitment to the United Nations Framework Convention on Climate Change (UNFCCC), the Government of Indonesia (GoI) plans to restore 12 million ha of forests and 2 million ha of peatlands by 2030 (MoEF 2021). The GoI has also set a target for restoring 600,000 ha of degraded mangrove (*Avicennia* spp. L.) forests (Murdiyarso and Ambo-Rappe 2022). As part of the implementation of the NDC, the GoI through the National Program "Indonesia's FOLU Net Sink 2030" as stipulated in Presidential Regulation Number 98 of 2021, targets to achieve net zero emissions in the forestry and land sector by 2030. The success of this forest and landscape restoration (FLR) program will determine whether these targets are achieved. Apart from that, FLR will also contribute to meeting other governmental commitments to sustainable development goals (SDGs), the Paris Agreement on Climate Change, Aichi Biodiversity Targets, Control of Land Degradation (UNCCD), and various other international conventions.

2 Impacts of deforestation and forest degradation

Massive exploitation of the natural forest in Indonesia began in 1975 with the issuance of Forest Tenure Rights (HPH) permits that aimed to increase state income and human welfare (Nawir et al. 2017). Apart from that, forest areas have also experienced pressure due to widespread land conversion to crop estates, settlements, and other non-forestry interests (Frastien 2017; Juniyanti et al. 2021). These licensing policies are often not balanced with an optimal monitoring and control system, increasing the area of degraded forests and lands. In 2000, the area of degraded forests and lands in Indonesia was estimated at around 23.2 million ha, and this continued to increase until 2007 to 77.8 million ha. With intensive forest landscape restoration (FLR) efforts, the area of forest and degraded land had declined to about 14 million ha in 2020 (MoEF 2020b). In 2022, the area of degraded forests and land remained around 12.77 million ha (MoEF 2022).

Deforestation and degradation release large amounts of greenhouse gases (GHG) that contribute to climate change (Hansen et al. 2001). In turn, global climate change influences regional and local climate conditions that impact weather patterns (Ayres and Lombardero 2000; CIFOR 2013). Tropical forests such as those in Indonesia are carbon sinks that help to mitigate climate change. However, forest destruction, conversion to other land uses, and escaped agricultural fires once caused Indonesia to be the third-largest emitting country in the world. Of the GHG emissions produced by

Indonesia, 85% comes from deforestation and peatland conversion (Wijaya et al. 2017). In 2015 and 2016, fires in the forestry and peat sectors contributed 66% and 43% of emissions (BPS 2019).

The existence of degraded forests and land has also increased the vulnerability of several regions in Indonesia to various natural disasters, such as floods, landslides, and droughts, which cause loss of life and extremely high property losses. According to the Indonesian Disaster Information Data (DIBI)-BNPB, of the more than 1,800 disaster events in the period 2005 to 2015, more than 78% (11,648) were hydrometeorological disasters, and only around 22% (3,810) were geological disasters. Hydrometeorological disasters include extreme weather (cyclones and tropical storms), extreme ocean waves, floods, drought, and land and forest wildfires. The incidence of these disasters is tending to increase (BNPB 2016). Geological hazards include tsunamis, landslides, and volcanic activities. The severity of most disasters, such as floods, landslides, droughts, and tsunamis, are closely related to land cover conditions (FAO 2005; Maginnis and Elliott 2005). For example, because forests can increase infiltration and reduce runoff, they reduce the threat or severity of floods, droughts, and other hydrometeorological disasters (FAO 2005; Bonell and Bruijnzeel 2005). Forested areas tend to be more resistant to landslides (Schmaltz et al. 2017), and mangrove forests provide physical protection during extreme wave and tsunami events (Maginnis and Elliot 2005).

Deforestation and forest degradation have also threatened the biodiversity of flora and fauna in Indonesia (Budiharta et al. 2011). IUCN Red List data (2021) show that 1 Indonesian tree species is Extinct, 3 species are Extinct in the Wild, and 856 species are threatened with extinction (170 Critically Endangered, 279 Endangered, and 407 Vulnerable tree species). Threats to several species of flora and fauna are caused by over-exploitation and habitat loss. Many of these threatened species could be sustainably used by humans if effective and comprehensive conservation efforts were established to ensure species viability.

3 Initiating seeding in Indonesia

FLR is one means of mitigating climate change and reducing the area of deforested and degraded forests. Conventional seedling planting programs have been used to reduce the area of deforested and degraded land. In 2020, the area that could be planted through the FLR program of the Ministry of Environment and Forestry was estimated at 207,650 ha (MoEF 2020b), so if all currently planned efforts are carried out, it will require many years to restore this area of degraded forest. For this reason, alternative methods capable of quickly afforesting/reforesting land on a large scale are needed; seeding is one such alternative (Sudrajat et al. 2023).

Seeding is a long-standing forestation practice being considered for FLR because of its relatively lower cost and labor requirements compared to conventional seedling planting (Sudrajat et al. 2018; Louhaichi et al. 2021; Downer et al. 2024; Sudrajat et al. 2024). Though potentially useful, this technique is often less dependable than planting seedlings (Brown and Lugo 1990). Several obstacles to its application include competition from surrounding plants (weeds) (Holl 1998; Nurhasybi and Sudrajat 2009), lack of precise microsite conditions for germination (Doust et al. 2006), and occurrence of seed predators and seedling herbivores (Holl et al. 2000; Nurhasybi and Sudrajat 2013). Weather conditions also play a significant role in determining the success of seeding (Sudrajat et al. 2023). Apart from these general obstacles, selecting species suitable for seeding on particular sites has not yet been widely determined (Figueiredo et al. 2021; Naruangsri et al. 2024). Further study is necessary to identify the characteristics of tropical forest tree species that are suitable for seeding (Doust et al. 2008; Naruangsri et al. 2024).

4 Seed procurement and preparation

4.1 Species selection

Species vary in suitability for seeding applications; generally, species with medium- to large-sized seeds show better seedling establishment. They have large nutrient reserves, resulting in better germination and more vigorous seedlings (Hossain et al. 2014; Ceccon et al. 2016; De Sousa and Engel 2018). In addition, suitable species must produce seedlings that grow quickly, fast enough to compete with weeds early in their development. In general, pioneer species have faster initial growth, but species with very small seed (e.g., *Neolamarckia* spp. Bosser and *Eucalyptus* spp. L'Hér.), that require a more open site to germinate, have early seedling growth that is very susceptible to biotic and abiotic stress (Camargo et al. 2002). Several tropical trees have the potential to be used in seeding, such as *Anacardium occidentale* L., *Calophyllum inophyllum* L., *Gmelina arborea* Roxb., *Acacia* spp. Mill., *Enterolobium cyclocarpum* (Jacq.) Griseb., and *Intsia bijuga* (Colebr.) Kuntze among other species (Engel and Parrotta 2001; Hobert et al. 2020).

Apart from the need for species to be suited to seeding, the seeds used must be of good quality. Results of trials on 24 tropical tree species show that large (heavy) seeds tend to produce higher seedling survival. Likewise, seeds with high germination capacity (laboratory test results) show a positive correlation with seedling survival in the field (Figure 1).

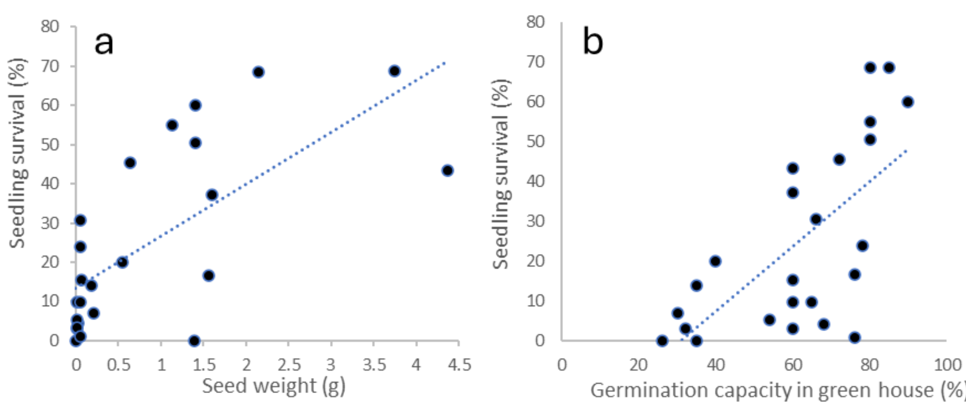

Figure 1. Correlation trends between seedling survival at 12 months and seed traits for some tropical trees: a) seed weight, b) germination capacity.

4.2 Delivery systems

Different delivery systems have been developed to improve the success of seeding. Encapsulating seeds in rooting media, often supplemented with nutrients, protectants, and inoculants, singly or in combination, have been developed. The method was developed in Scandinavia in the 1930s (Heiberg 1934) using forest soil or peat and paraffin. Fukuoka (1973) described the use of seed balls, which are a mixture of seeds, soil, water, and clay. Seed balls contain a basic unit of media for plant growth and can provide the ingredients plants need for unique site situations. Clay, which is a mixing medium, also functions to reduce water loss by increasing water potential and reducing seed predation. Seed pellets or briquettes can be placed on the soil surface or planted in the soil (Sudrajat et al. 2018); seed balls have been adapted for delivery by drone (Stanturf et al. 2024).

Using seed briquettes or seed pellets can increase seeding success by reducing risks (Sudrajat et al. 2018; Nuhasybi and Sudrajat 2018; Sudrajat et al. 2023). Apart from protecting seeds from seed predators, seed briquettes also function as a delivery system for biological and chemical treatments to increase seed germination and seedling growth (Taylor et al. 2004; Gevrek et al. 2012; Sudrajat et al. 2023). For example, seed briquettes increased the germination of *Lycopersicon esculentum* Mill. seed, and the effect was like a priming treatment (Govinden-Soulange and Levantard 2008). The use of seed briquettes for seeding is also thought to improve biological control capacity (Choong et al. 2006), increase germination capacity and speed (Podlaski and Wyszkowska 2003; Tamilarasan et al. 2021), and increase resistance to drought stress (Abusuwar and Eldin 2013; Sudrajat et al. 2023).

Seed briquettes can be used with orthodox and intermediate recalcitrant seeds. For orthodox seed, a briquette can be made with 20% soil, 40% compost, 25% rice (*Oryza sativa* L.) husk charcoal, 10% lime, 5% tapioca, and 2 g mycorrhiza inoculum. For intermediate seed, a slightly different mixture is used: 10% soil, 40% compost, 30% rice husk charcoal, 15% lime, 5% tapioca, and 2 g mycorrhiza (Sudrajat and Rustam 2020). Briquette size must be adjusted to the size of the seed. Small seeds will have difficulty germinating in a large briquette. For small seeds, such as *Acacia* spp. and *Calliandra* spp. Benth., briquettes that are 2-3 cm in diameter are best, particularly round or flat briquettes (Sudrajat et al. 2019). In contrast, for *G. arborea*, a round, flat briquette of 5 cm diameter and 3 cm thickness is quite effective in increasing germination and growth of seedlings when sown directly in the field (Sudrajat and Rustam 2020).

4.3 Biofertilizer application

The addition of mycorrhizae to seed briquettes can improve seedling survival through the first month of growth (Sudrajat and Rustam 2020). Mycorrhizae tend to increase plant growth (Bayozen and Yildiz 2009), favorably change the biochemical composition of cells (Jaiti et al. 2008; Neeraj and Singh 2011), and reduce incidence of plant disease (Zachee et al. 2008; Neeraj et al. 2011). Mycorrhizae may also increase plant resistance to drought stress (Manoharan et al. 2010). Dark septate endophytes (DSE) are another biofertilizer that can improve seedling survival and growth (Widyani et al. 2024). Inoculations of mycorrhizae and DSE can increase absorption of water and nutrients, support disease prevention, and remove toxic metals from soil (Brady and Weil 1999; Widyani et al. 2024).

Seeding trials using briquettes with the addition of arbuscular mycorrhizal fungi (AMF) and DSE resulted in a better survival rate of *Ceiba pentandra* (L.) Gaertn. and *Leucaena leucocephala* (Lam.) de Wit 12 months after sowing. In *C. pentandra*, AMF and DSE inoculations had a significant effect on the percentage of colonization, while in *L. leucocephala*, inoculation had no significant effect on the percentage of AMF and DSE colonization. Most seeds and seed briquettes infected with AMF and DSE had higher seedling survival than the control (Widyani et al. 2024).

5 Land preparation

Land preparation that provides an optimal germination environment for seeding typically improves success. Land preparation involves creating a strip cleared of undergrowth and bushes 80-100 cm wide to facilitate sowing. On this strip, plots are made for sowing seeds or seed briquettes cleared of grass and other vegetation with a 40-50 cm radius to provide optimal germination conditions. Site (plot) clearing with burial of large seed briquettes (diameter 5 cm) in soil gave better seedling survival for *G. arborea* (57%) than for medium-sized seed briquettes with a diameter 3 cm (38%) or small seed briquettes with a diameter 2 cm (29%) briquettes; burial, however, did not improve germination and seedling survival for seed sown in medium or small briquettes. Similarly, for *E. cyclocarpum*, seed briquettes buried on cleared land gave the best germination and survival (52.5%), while those sown on unprepared sites showed germination and survival of only 3.7%. Additionally, land prepared with clearing and soil loosening provided the best height growth (Sudrajat et al. 2019).

6 Plant establishment

6.1 Sowing season

The success of plant establishment with seeding is largely determined by the sowing time. Determining the right time to sow seed can affect the survival and growth of seedlings such as *Acacia pycnantha* Benth., *A. acinacea* Lindl., and *Eucalyptus microcarpa* (Maiden) Maiden (Carr at el. 2007). For example, seeding briquettes of several tropical tree species that were sown on four dates in the Parung Panjang Forest Area in Bogor showed the best results for an early-mid rainy season sowing (mid-December). At that time, the frequency of rain had stabilized, which is important because sowing at the beginning or before the rainy season adds risk of drought if the rain stops for 1 to 3 weeks. Likewise, sowing toward the end of the rainy season resulted in high mortality due to the lack of daily rainfall (Sudrajat et al. 2023). The best germination and seedling survival of C. *pentandra, E. cyclocarpum*, and *C. inophyllum* were respectively, 23.9%, 55.0%, and 68.7% in December for seed encapsulated in briquettes and treated with Aquasorb, compared to briquettes or Aquasorb alone (Sudrajat et al. 2023). Aquasorb is a hydrogel or hydrophilic polymer that can absorb and store water up to hundreds of times its weight when it rains and slowly release it when the surrounding soil dries, thus improving germination and early growth of seedlings by reducing effects of drought (Tongo et al. 2014).

6.2 Sowing techniques

Sowing seed or seed briquettes on the surface of the soil is quite efficient and saves labor, but there is a risk that the seed will be washed away by rainwater or predated by animals. According to Johnson (1980), seeding depth will affect germination capacity. Seeding depth must be adjusted to the size of the seed. For example, the best germination of *I. bijuga*, which has a seed length and width of around 2-3 cm, was observed for seeds buried 3 cm deep (Nurhasybi and Sudrajat 2009);

likewise, seed briquettes (with a thickness of 3 cm) supported best germination when buried 3 cm deep (Sudrajat et al. 2018). Seed sowing is generally done manually using a hoe to make placing the seeds or seed briquettes easier. The number of seeds sown per ha is adjusted to the quality of the seeds (results of laboratory germination tests) and the adaptation of the species. For *Swietenia macrophylla* King, with a germination test result of 80%, the target of 1000 plants per ha in the first year is achieved by sowing 1,838 seed briquettes, or 3,906 seed without briquettes (Sudrajat et al. 2024). For *C. inophyllum* with a germination rate of 80%, the target of 1000 plants in the first year is achieved by sowing 1,613 seed briquettes or 5,000 seeds (Sudrajat et al. 2018). Using mixed species can reduce the risk of failure due to attacks by seed and seedling predators and increase biodiversity.

Aerial seeding using helicopters or drones has been conducted at large and remote areas in Indonesia (Andrio 2018). Helicopters were used in several remote areas of Indonesia, such as South Kalimantan, South Sulawesi, and West Java. Drones are being tested for aerial seeding applications to restore degraded mangrove forests—3 cm diameter seed balls of *Avicennia* spp. coated with a biofertilizer are being used in these tests. The drone can sow 600 seeds in 20 minutes from an altitude of 5 m. Given a 1 m x 2 m sowing spacing, one drone can sow 3 ha day^{-1}. As a complement to conventional community-based mangrove planting, this drone technology is suitable for establishing mangroves in areas that are difficult to access, sparsely populated, and remote (Syukra 2021).

7 Post-sowing practices and maintenance

Maintenance of seeded stands is conducted in a minimalist manner, i.e., controlling weeds around seedlings to provide space for growth and free the plants from vining weeds. Weed control is done manually with a machete or other tools by freeing plants from weeds in a radius of 0.5 m around the plant. Weeding is done twice yearly, at the beginning of seedling growth, until the plant is vigorous enough to compete with weeds. Weed control continues for fast-growing trees, typically for three years.

8 Successful seeding

8.1 Seedling survival and growth

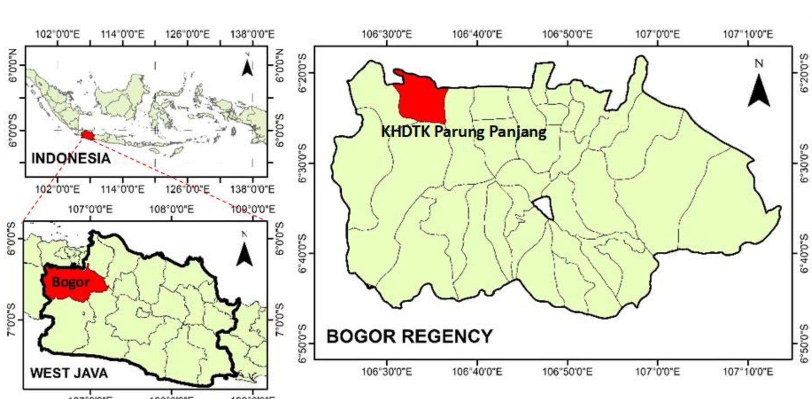

Figure 2. Seeding trial location in Parung Panjang Forest Area (KHDTK Parung Panjang) in Bogor, Indonesia.

Seeding of 24 tropical tree species using seed briquettes in the Parung Panjang Forest Area, Bogor, West Java (Figure 2) showed five species with high germination and first-year seedling survival (>50%) (Figure 3). The species with high survival were *S. macrophylla, C. inophyllum, E. cyclocarpum, Pongamia pinnata* (L.) Pierre, and *Hymenaea verrucosa* Gaertn. (Figure 3). Seedling survival was correlated with seed weight, length, width, and initial germination capacity (r^2 = 0.686, 0.729, 0.762, and 0.670, respectively). Sowing seeds encapsulated in briquettes increased seedling stem diameter compared to sowing unencapsulated seeds.

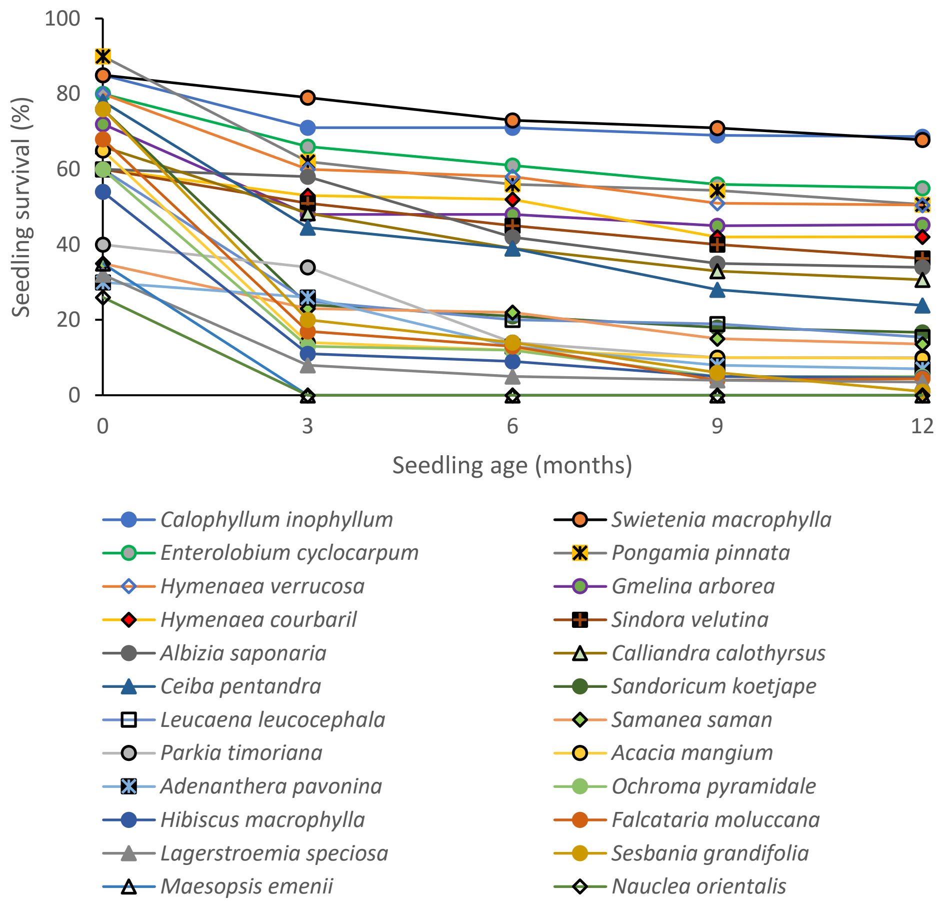

Figure 3. Percentage of normal seedlings based on the germination test (0 month) and seedling survival of seeded trees in the Parung Panjang Forest Area, Bogor, West Java (3, 6, and 12 months) (Sudrajat et al. 2021). Seed were treated prior to the germination test and prior to seeding as follows. 1) Seeds treated by soaking in hot water (80 °C) and letting them cool for 24 hours (*Acacia mangium* Willd., *Adenanthera pavonine* L., *Albizia saponaria* (Lour.) Blume ex Miq., *Calliandra calothyrsus* Meisn., *Enterolobium cyclocarpum* (Jacq.) Griseb., *Falcataria moluccana* (Mic.) Barneby & J.W. Grimes, *Leucaena leucocephala* (Lam.) de Wit, *Parkia timoriana* (DC.) Merr., *Samanea saman* (Jacq.) Merr., and *Sesbania grandifolia* (L.) Poir.). 2) Seeds treated by stripping the exodermis (*Calophyllum inophyllum* L.). 3) Seeds treated by soaking in water for 24 hours (*Ceiba pentandra* (L.) Gaertn., *Gmelina arborea* Roxb., *Lagerstroemia speciosa* (L.) Pers., and *Ochroma pyramidale* (Cav. ex Lam.) Urb.). 4) Seed treated by soaking in H_2SO_4 for 20 minutes (*Hibiscus macrophyllus* Roxb. ex Hornem., *Hymenaea courbaril* L., *Hymenaea verrucosa* Gaertn., *Maesopsis emenii* Engl., and *Sindara velutina* Baker). 5) Seed treated by hydrating in wet straw paper for 24 hours (*Pongamia pinnata* (L.) Pierre, *Sandoricum koetjape* (Burm.f.) Merr., and *Swietenia macrophylla* King). 6) Seed that was not treated (*Nauclea orientalis* (L.) L.) (Sudrajat et al. 2017).

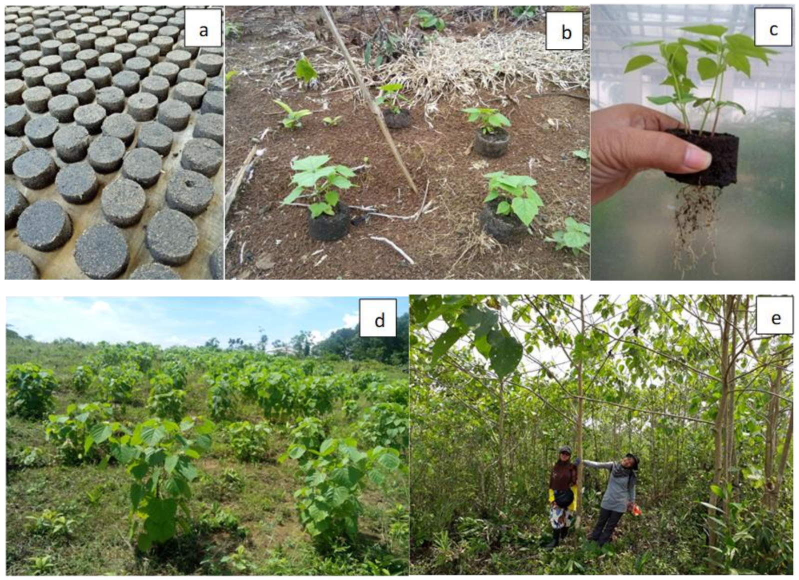

Figure 4. Seeding of *Gmelina arborea* Roxb. encapsulated in seed briquettes: a) seed briquettes, b, c) germinated *G. arborea* in seed briquettes, d) 1-year-old seedlings, e) 2.5-year-old trees (Photo credits: Dede Sudrajat).

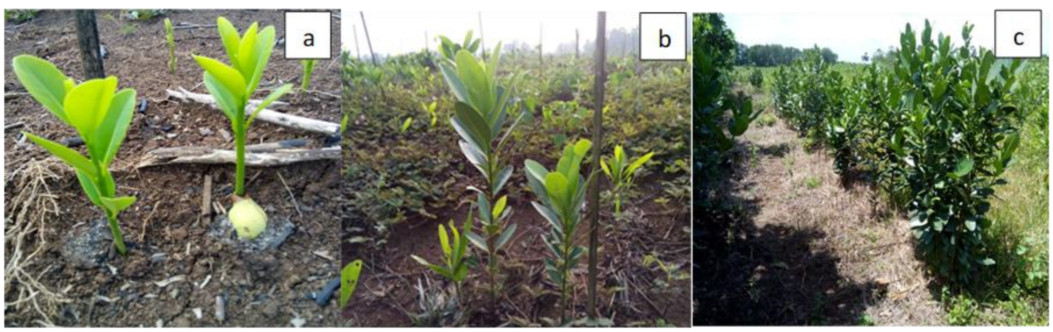

Figure 5. Seeding of *Calophyllum inophyllum* L. using seed briquettes: a) 2-month-old seedlings, b) 6-month-old seedlings, c) 2-year-old saplings. (Photo credits: Dede Sudrajat).

A comparative growth study of plant establishment methods with *C. inophyllum* examined seeding, seeding using seed briquettes, bareroot seedlings, polybag seedlings, and bio-pot seedlings. Bio-pots molded from an organic medium (a mixture of compost (40%), soil (20%), rice husk charcoal (20%), lime (10%), and tapioca (10%) as an adhesive) are used to grow seedlings in a nursery (Sudrajat et al. 2018). Polybag and bio-pot seedlings had the best survival and growth in height and diameter, while seeding without briquettes showed the lowest germination, survival, and growth (Table 1). Sowing seed in briquettes resulted in plants with the longest tap root, tap roots of greatest mass, and the highest overall root dry weight (Figure 6) (Sudrajat et al. 2018).

On the one hand, trees established through conventional seedling planting are more uniform, able to tolerate or avoid environmental or biological stress, and can reach maturity quicker than those established through seeding (Liptay et al. 1982). Sown seed is subject to poor germination and new germinants typically show slower, have more variable growth, and are more susceptible to extreme temperatures, drought stress, heavy rains, or pests and diseases than are planted seedlings (Heydecker and Coolbear 1977). On the other hand, sowing seed in briquettes tends to produce plants with a more balanced root system, a longer tap root, and a greater total root dry weight. The shoot-root ratio of seedlings originating from seeding is 3.8, which is more balanced than the shoot-root ratio of polybag seedlings (4.5) (Sudrajat et al. 2018). Seedlings produced from seeding develop a natural root system that is structured for the prevailing site conditions. Seedlings grown in polybags, common in the tropics, often are stunted or deformed (Tsakaldimi et al. 2009; Haase et al. 2021) and vulnerable to drought (Canadell et al. 1996).

Table 1. Comparison of *Calophyllum inophyllum* L. seedling survival, height, and root collar diameter relative to several plant establishment methods (Sudrajat et al. 2018).

Method	Seedling survival (mean ± SD)[1] (%)	Height (mean ± SD) (cm)	Root collar diameter (mean ± SD) (mm)
Seeding	20 ± 5 d	25.86 ± 9.06 c	4.38 ± 1.54 c
Seeding with briquettes	61 ± 5 c	32.77 ± 0.69 b	6.14 ± 2.10 bc
Bareroot seedling	84 ± 4 b	37.38 ± 9.63 b	6.34 ± 1.43 b
Polybag seedling	98 ± 2 a	46.15 ± 5.40 a	7.79 ± 2.62 ab
Blocked media seedling	98 ± 1 a	48.12 ± 7.85 a	9.26 ± 1.11 a

[1] Different letters in a column denote statistical difference ($P \leq 0.05$) between treatments.

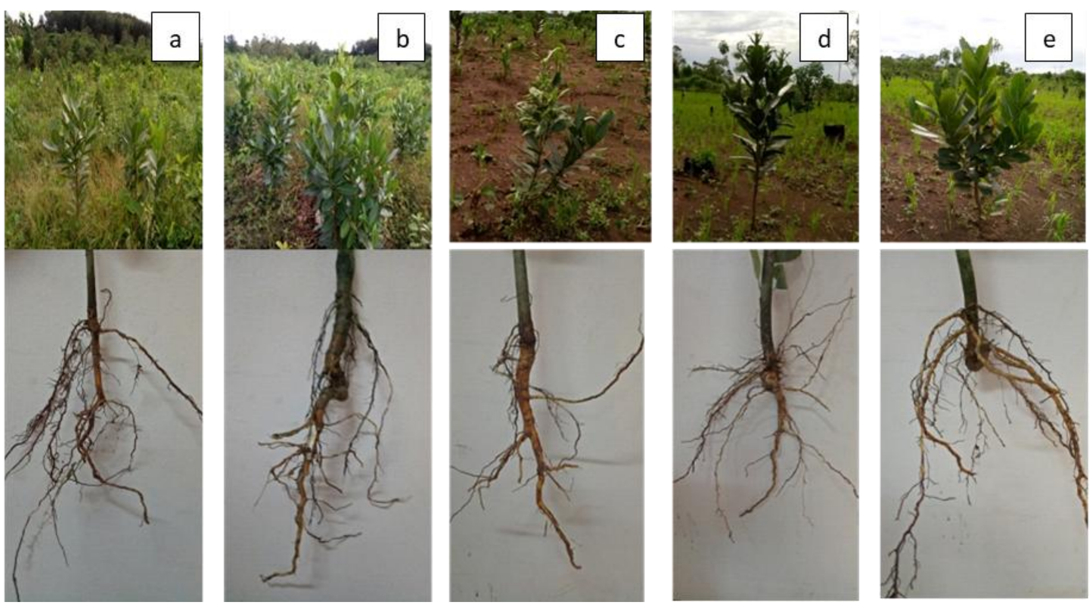

Figure 6. Comparison of growth and root form of 5 plant establishment methods for *Calophyllum inophyllum* L., a) seeding, b) seeding with briquettes, c) bare-root seedlings, d) polybag seedlings, and e) blocked media seedling. (Photo credits: Dede Sudrajat 2018).

8.2 Seedling establishment cost comparison

The costs of producing and establishing trees vary greatly depending on many factors including the materials used in production, size of the target plant, establishment method, survival in the field, and other factors such as transportation and labor. A comparison of plant production costs based on 1000 target plants indicates that seeding is generally the least expensive establishment alternative (Sudrajat et al. 2018; Sudrajat et al. 2024). Cole et al. (2011) reported a similar finding: planting seedlings typically cost 2 to 4 times more than seeding depending on the level of maintenance provided.

One of the biggest uncertainties in calculating the cost of seeding, however, is the percentage germination and survival assumptions, because this depends on the season of sowing, microclimate, seed viability, and other factors. Nevertheless, use of seed encapsulated in briquettes was about half the cost of planting bio-pot or polybag seedlings (based on the calculations in Table 2). Assuming 1000 surviving *C. inophyllum* seedlings at 9 months, seeding with seed encapsulated in briquettes provided the lowest cost (USD 199.80 = IDR 3,167,815), followed by seeding without briquettes, then planting bareroot seedlings (Sudrajat et al. 2018). Establishing seedlings raised in bio-pots had the highest cost, slightly more than seedlings raised in polybags (Table 2).

Table 2. Comparison of establishment costs for *Calophyllum inophyllum* L. plants using seeding, seeding with briquettes, bareroot seedlings, polybag seedlings, or bio-pot seedlings weighted for 1000 surviving seedlings at the Parung Panjang Forest Area, Bogor (Sudrajat et al. 2018).

Item	Seeding		Seeding with briquette		Bareroot seedling		Polybag seedling		Blocked media seedling	
	Unit	Cost (IDR)	Unit	Cost (IDR)	Unit	Cost (IDR)	Unit	Cost (IDR)	Unit	Cost (IDR)
Seed cost [1]	5000	50000	1613	16130	1429	14290	1224	12240	1224	12240
Seed pellet production [2]			1613	233885						
Seedling production [3]					1190	466480	1020	624240	1020	770100
Transportation [4]	5000	50000	1613	50000	1190	100000	1020	400000	1020	400000
Land preparation [5]	1 ha	2706500	1 ha	2706500	1 ha	2706500	1 ha	3721400	1 ha	3721400
Sowing cost [6]	5000	500000	1613	161300						
Planting preparation [7]					1000	500000	1000	500000	1000	500000
Digging planting holes cost [8]					1000	300000	1000	500000	1000	500000
Planting cost [9]					1000	100000	1000	200000	1000	200000
Total (IRD)	3,306,500		3,167,815		4,172,980		5,946,864		6,091,500	
Total (USD)	209		200		263		375		384	

Notes: [1] *C. inophyllum* seed price IDR 3,000 kg^{-1}, germination capacity 80%, seedling survival for each method based on Table 1; [2] Production cost per pellet; [3] Production cost bareroot, polybag, and blocked media seedlings; [4] Pickup charge for blocked media and polybag seedlings and courier charge for seed/seed pellet; [5] Based on standard of Ministry of Forestry, Republic of Indonesia No. P.64/Menhut-II/2009 (Standard biaya pembuatan hutan tanaman industri dan hutan tanaman rakyat), range of land preparation cost IDR 2,706,500-3,721,438; [6] Sowing cost IDR 100 per seed/seed pellet; [7] Planting preparation (making and setting up planting marker/stake in the field) for 1000 seedlings and IDR 500 per stake, seedling stock was prepared for replanting; [8, 9] Planting hole digging and planting cost based on experience of work performance per worker in Parung Panjang, Bogor, IDR 500 per a planting hole, IDR 200 per planting of a seedling; currency in 2018: 1 USD = IDR 15,854

9 Conclusion

Seeding is an alternative afforestation/reforestation method that holds promise for cost effective forest restoration in Indonesia, particularly considering the amount of land designated by the Indonesian government as critical or very critical for FLR. Opportunities to employ seeding practices for forest restoration are most obvious in remote areas, areas with limited access, and regions where funding or labor availability are in short supply. However, there are drawbacks to seeding that can compromise restoration success. Failures are often caused by poor planning and inattentive implementation that does not fully consider the environmental conditions of the restoration site or best technical procedures. Initial research in Indonesia indicates that seeding success can be increased through attention to several factors—these include selecting appropriate species (easily germinating, adapted to critical land, and early competitiveness with weeds), land preparation (soil conditioning to support germination and early seedling growth), use of quality seed (high viability), encapsulating seed in briquettes or balls, application of biofertilizers and hydrogels (mycorrhiza, DSE, aquasorb, and others), sowing at the appropriate time, and plantation maintenance (weed control around established seedlings). Too, the efficiency of seeding operations can be improved with aerial seeding technology (helicopters or drones) in certain situations such as for mangrove forests. Advancing seeding as a conventional forest restoration practice in Indonesia will require additional research broadened to include many important plant species, various site conditions, seeding technologies, and other key factors that impact success.

10 Acknowledgement

The article is an activity within the work of IUFRO Task Force “Transforming Forest Landscapes for Future Climates and Human Well-Being.” We thank the editors and two anonymous reviewers for helpful suggestions.

Disclaimer

The use of trade or firm names in this publication is for reader information and does not imply endorsement by the authors or their respective institutions of any product or service.

Pesticide Precautionary Statement

This paper may include research involving pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All use of pesticides must be registered by appropriate agencies before they can be recommended.

CAUTION

Pesticides can be injurious to humans, domestic animals, desirable plants, and fish or wildlife if they are not handled or applied properly. Use all herbicides selectively and carefully. Follow recommended practices for the disposal of surplus pesticides and their containers.

11 References

Abusuwar AO, Eldin AK (2013) Effect of seed pelleting and water regime on the performance of some forage species under arid conditions. American-Eurasian J Agric Environ Sci 13(5):728-734. https://doi.org/10.5829/idosi.aejaes.2013.13.05.1961

Andrio A (2021) Development of UAV technology in seed dropping for aerial revegetation practices in Indonesia. IOP Conference Series: Earth and Environ Sci 308:012051. https://doi.org/10.1088/1755-1315/308/1/012051

Ayres MP, Lombardero MJ (2000) Assessing the consequences of global change for forest disturbance from herbivores and pathogens. Sci Total Environ 262:263–286. https://doi.org/10.1016/S0048-9697(00)00528-3

Bayozen A, Yildiz A (2009) Determination of mycorrhizae interactions and pathogenicity of *Rhizoctonia solani* Kuhn isolated from strawberry and *Xanthium strumarium*. Turk J Biol 33:53-57. https://doi.org/10.3906/biy-0801-15

Birkedal M, Löf M, Olsson E, Bergsten U (2010) Effects of granivorous rodents on direct seeding of oak and beech in relation to site preparation and sowing date. For Ecol Manag 259:2382-2389. https://doi.org/10.1016/j.foreco.2010.03.014

BNPB (Badan Nasional Penanggulangan Bencana) (2016) Resiko Bencana Indonesia. Badan Nasional Penanggulangan Bencana. Jakarta, Indonesia.

Bonell M, Bruijnzeel LA (2005) Forests, water and people in the humid tropics: past, present and future hydrological research for integrated land and water management. Cambridge University Press, Cambridge, UK.

BPS (Badan Pusat Statistik) (2019) Statistik Lingkungan Hidup 2019 (Environment Statistics of Indonesia 2019). Badan Pusat Statistik. Jakarta, Indonesia.

Brady NC, Weil RR (1999) The nature and properties of soils. 12th Edition, Prentice-Hall, Publishers, London, UK.

Budiharta S, Widyatmoko D, Irawati, Wiriadinata H, Rugayah, Partomihardjo T, Ismail, Ugi T, Keim AP, Wilson K (2011) The processes that threaten Indonesian plants. Oryx 45:172-179. https://doi.org/10.1017/S0030605310001092

Butler RA (2016) The top 10 most biodiverse countries. Mongabay. https://news.mongabay.com/2016/05/top-10-biodiverse-countries (last accessed 13 Dec. 2024).

Camargo JLC, Ferraz DK, Imakawa AM (2002) Rehabilitation of degraded areas of Central Amazonia using direct sowing of forest tree species. Restor Ecol 10(4):636–644. https://doi.org/10.1046/j.1526-100X.2002.01044.x

Canadell J, Jackson RB, Ehleringer JR, Mooney HA, Sala OE, Schulze ED (1996) Maximum rooting depth of vegetation types at the global scale. Oecologia 108:583-595.

Carr D, Bonney N, Millsom D (2007) The effect of sowing season on the reliability of direct seeding. Rural Industries Research and Development Corporation, Publication No. 07/105 Project No. GAL-6A, Kingston, Australia.

Ceccon E, González EJ, Martorelli C (2016) Is direct seeding a biologically viable strategy for restoring forest ecosystems? Evidence from a meta-analysis. Land Degrad Dev 27(03):511-520. https://doi.org/10.1002/ldr.2421

Chapman CA, Chapman LJ (1999) Forest restoration in abandoned agricultural land: a case study from East Africa. Conserv Biol 13:1301-1311. https://doi.org/10.1046/j.1523-1739.1999.98229.x

CIFOR (2013) Hutan dan Mitigasi Perubahan Iklim, Apa yang Perlu Diketahui oleh Para Pembuat Kebijakan. CIFOR Factsheet No 17, Juni 2013. Center for International Forestry Research. Bogor, Indonesia. http://dx.doi.org/10.17528/cifor/004161

Cole RJ, Holl KD, Keene CL, Zahawi RA (2011) Direct seeding of late-successional trees to restore tropical montane forest. For Ecol Manag 261(10):1590-1597. https://doi.org/10.1016/j.foreco.2010.06.038

De Sousa DC, Engel VL (2018) Direct seeding reduces costs, but it is not promising for restoring tropical seasonal forests. Ecol Eng 116:35–44. https://doi.org/10.1016/j.ecoleng.2018.02.019

De Steven D (1991) Experiments on mechanisms of tree establishment in old-field succession: Seedling emergence. Ecology 72(3):1066–1075. https://doi.org/10.2307/1940606

Doust SJ, Erskine PD, Lamb D (2006) Direct seeding to restore rainforest species: microsite effects on the early establishment and growth of rainforest tree seedlings on degraded land in the wet tropics of Australia. For Ecol Manag 234:333–343. https://doi.org/10.1016/j.foreco.2006.07.014

Downer R, Manteuffel-Ross T, Tymon L, Aghai M (2024) Direct seeding for conifer regeneration in the Pacific Northwest: A past, present, and future of operational practices. J For 122(2):171–184. https://doi.org/10.1093/jofore/fvad050

Elliott S, Blakesley D, Hardwick K (2013) Restoring tropical forests: a practical guide. Royal Botanic Gardens, Kew, UK.

Engel VL, Parrotta JA (2001) An evaluation of direct seeding for reforestation of degraded lands in Central Sao Paulo State, Brazil. For Ecol Manag 152:169–181. https://doi.org/10.1016/S0378-1127(00)00600-9

FAO (2005) Forests and floods - Drowning in fiction or thriving on facts? RAP Publication 2005/03 Forest Perspectives 2. Collaboration of Center for International Forestry Research, Bogor and Food and Agriculture Organization of the United Nations, Rome, Italy.

Figueiredo MA, Messias MCTB, Leite MGP, Kozovits AR (2021) Direct seeding in the restoration of post-mined Campo Rupestre: Germination and establishment of 14 native species. Flora 276-277:151772(1–9). https://doi.org/10.1016/j.flora.2021.151772

Frastien D (2017) Perubahan peruntukan kawasan hutan menjadi bukan kawasan hutan untuk menjamin hak masyarakat atas tanah. University of Bengkulu Law Journal 2(2):151-164. https://doi.org/10.33369/ubelaj.2.2.151-164

Fukuoka M (1978) The one-straw revolution: an introduction to natural farming. Rodale Press, Inc., Emmaus, PA, USA.

Gevrek MN, Atasoy GD, Yigit A (2012) Growth and yield response of rice (*Oryza sativa*) to different seed coating agents. Int J Agric Biol 14(5):826–830.

Govinden-Soulange J, Levantard M (2008) Comparative studies of seed priming and pelleting on percentage and meantime to germination of seeds of tomato (*Lycopersicon esculentum* Mill.). Afr J Agric Res 3(10):725-731.

Haase DL, Bouzza K, Emerton L, Friday JB, Lieberg B, Aldrete A, Davis AS (2021) The high cost of the low-cost polybag system: A review of nursery seedling production systems. Land 10:826(1-19). https://doi.org/10.3390/land10080826

Hansen AJ, Neilson RP, Dale VH, Flather CH, Iverson LR, Currie DJ, Shafer S, Cook R, Bartlein PJ (2001) Global change in forests: Responses of species, communities, and biomes: Interactions between climate change and land use are projected to cause large shifts in biodiversity. BioScience 51(9):765–779. https://doi.org/10.1641/0006-3568(2001)051[0765:GCIFRO]2.0.CO;2

Heiberg SO (1934) Briquette planting. J For 32(3):333-336. https://doi.org/10.1093/jof/32.3.333

Heydecker W, Coolbear P (1977) Seed treatments for improved performance-survey and attempted prognosis. Seed Sci Technol 5:353-425.

Holl KD (1998) Effects of above- and below-ground competition of shrubs and grass on *Calophyllum brasiliense* (Camb.) seedling growth in abandoned tropical pasture. For Ecol Manag 109:187–195. https://doi.org/10.1016/S0378-1127(98)00248-5

Holl KD, Loik ME, Lin EHV, Samuels IA (2000) Tropical montane forest restoration in Costa Rica: Overcoming barriers to dispersal and establishment. Restor Ecol 8(4):339–349. https://doi.org/10.1046/j.1526-100x.2000.80049.x

Hossain F, Elliott S, Chairuangsri S (2014) Effectiveness of direct seeding for forest restoration on severely degraded land in Lampang Province, Thailand. Open J For 4(5):512–519. http://dx.doi.org/10.4236/ojf.2014.45055

Jaiti F, Kassami M, Meddich A, El Hadrami I (2008) Effect of arbuscular mycorrhization on the accumulation of hydroxycinnamic acid derivatives in date palm seedlings challenged with *Fusarium oxysporum* f. sp. albedinis. J Phytopathol 156(11-12):641-646. https://doi.org/10.1111/j.1439-0434.2008.01411.x

Johnson RL (1980) New ideas about regeneration of hardwoods. In: Proceedings of hardwood regeneration symposium, January 29, 1980, Atlanta, GA. Southeastern Lumber Manufacturing Association, Forest Park, GA, USA, pp 17-19.

Juniyanti L, Purnomo H, Kartodihardjo H, Prasetyo LB (2021) Understanding the driving forces and actors of land change due to forestry and agricultural practices in Sumatra and Kalimantan: A systematic review. Land 10(5):463(1-24). https://doi.org/10.3390/land10050463

Jyoti B, Bhandari S (2016) Seed pelleting - A key for enhancing the seed quality. Rashtriya Krishi 11(1): 76-77.

Liptay A, Bolton EF, Dirks VA (1982) A comparison of field seeded and transplanted tomatoes grown on a clay soil. Can J Plant Sci 62(2):483-487. https://doi.org/10.4141/cjps82-068

Louhaichi M, Gamoun M, Ouled Belgacem, A (2021) Direct seeding: a fast and cost-effective method for large-scale restoration of degraded rangelands. R4D Initiatives. Beirut, Lebanon: ICARDA. https://hdl.handle.net/20.500.11766/12231

Maginnis S, Elliott, C (2005) Forests and Natural Disasters. Arborvitae No. 27. The IUCN/WWF Forest Conservation Newsletter. https://iucn.org/sites/default/files/import/downloads/arborvitae27.pdf

Manoharan PT, Shanmugaiah V, Balasubramanian N, Gomathinayagam S, Sharma MP, Muthuchelian K (2010) Influence of AM fungi on the growth and physiological status of *Erythrina variegata* Linn. grown under different water stress conditions. Eur J Soil Biol 46(2):151-156. https://doi.org/10.1016/j.ejsobi.2010.01.001

MoEF (2020a) The state of Indonesia’s forests 2020. Ministry of Environment and Forestry, Republic of Indonesia, Jakarta, Indonesia.

MoEF (2020b) Statistik Kehutanan Indonesia Tahun 2020. Kementerian Lingkungan Hidup dan Kehutanan. Ministry of Environment and Forestry, Republic of Indonesia, Jakarta, Indonesia.

MoEF (2021) Updated nationally determined contribution Republic of Indonesia. Ministry of Environment and Forestry Directorate General of Climate Change, Jakarta, Indonesia.

MoEF (2022) Statistik Lingkungan Hidup dan Kehutanan Indonesia Tahun 2022. Kementerian Lingkungan Hidup dan Kehutanan. Ministry of Environment and Forestry, Republic of Indonesia, Jakarta, Indonesia.

MoEF (2024) The state of Indonesia’s forests 2024 towards sustainability of forest ecosystems in Indonesia. Ministry of Environment and Forestry, Republic of Indonesia. Jakarta, Indonesia.

Murdiyarso D, Ambo-Rappe R (2022) Rehabilitasi Kawasan Pesisir untuk Mitigasi Perubahan Iklim: Peranan mangrove dan penurunan emisi tingkat sub-nasional, Working Paper 11. Center for International Forestry Research (CIFOR), Bogor, Indonesia.

Nawir AA, Murniati, Rumboko L (Eds) (2007) Forest rehabilitation in Indonesia: where to after three decades? Center for International Forestry Research (CIFOR), Bogor, Indonesia.

Naruangsri K, Pathom-aree W, Elliott S, Tiansawat, P (2024) Selecting suitable tree species for direct seeding to restore forest ecosystems in Northern Thailand. Forests 15(4):674(1-17). https://doi.org/10.3390/f15040674

Neeraj, Singh K (2011) Organic amendments to soil inoculated arbuscular mycorrhizal fungi and *Pseudomonas fluorescens* treatments reduce the development of root-rot disease and enhance the yield of *Phaseolus vulgaris* L. Eur J Soil Biol 47(5):288-295. https://doi.org/10.1016/j.ejsobi.2011.07.002

Nurhasybi, Sudrajat DJ (2018) Seed pellets of *Calophyllum inophylum* and *Enterolobium cyclocarpum* for direct seeding application on degraded lands. In: IUFRO – INAFOR Joint International Conference 2017, "Promoting Sustainable Resources from Plantations for Economic Growth and Community Benefits"– Poster A7, pp 283-288.

Nurhasybi, Sudrajat DJ (2009) Teknik penaburan benih merbau (*Instia bijuga*) secara langsung di hutan penelitian Parungpanjang, Bogor. Jurnal Penelitian Hutan Tanaman 6(4):209-217. https://doi.org/10.20886/jpht.2009.6.4.209-217

Nurhasybi, Sudrajat DJ (2013) Gained experience through direct seeding of several tree species in degraded land in West Java, Indonesia. In: Proceedings of the 2nd INAFOR International Conference of Indonesia Forestry Researchers-August 27-28, 2013. Forest Research and Development Agency, pp 298-308.

Podlaski S, Chrobak Z, Wyszkowska Z (2003) The effect of parsley seed hydration treatment and pelleting on seed vigor. Plant Soil Environ 49(3):114-118. https://doi.org/10.17221/4099-PSE

Priadi D (2010) Aplikasi teknik enkapsulasi pada benih sengon (*Paraserianthes falcataria*). Teknologi Indonesia 33(2):92–99.

Ryu C-M, Kim J, Choi O, Kim SH, Park CS (2006) Improvement of biological control capacity of *Paenibacillus polymaxa* E681 by seed pelleting on sesame. Biol Control 39(3):282-289. https://doi.org/10.1016/j.biocontrol.2006.04.014

Schmaltz EM, Steger S, Glade T (2017) The influence of forest cover on landslide occurrence explored with spatio-temporal information. Geomorphology 290:250–264. https://doi.org/10.1016/j.geomorph.2017.04.024

Stanturf JA, Dumroese RK, Elliott S, Ivetic V, Khokthong W, Kleine M, Lang M, Löf M, Madsen P, Prescott C, Young T (2024) Advances in forest restoration management and technology. In: Katila P, Colfer CJP, de Jong W, Galloway G, Pacheco P, Winkel G (eds), Restoring forests and trees for sustainable development. Oxford University Press, Oxford, UK, pp 297-334. https://doi.org/10.1093/9780197683958.003.0011

Sudrajat DJ, Rustam E, Widyani N, Nurhasybi, Yulianti, Handayani T, Maharani D, Rosdayanti H, Wawangningrum H, Efendi M, Damaiyani J, Suhaendah E, Salim MA, Yuskianti V (2024) Comparison of direct-seeding, bare-root and polybag methods on early growth, root structure and plant establishment cost of mahogany (*Swietenia macrophylla*). Aust For 87(4):151-160. https://doi.org/10.1080/00049158.2024.2411783

Sudrajat DJ, Rustam E, Nurhasybi, Widyani N, Yulianti, Isnaini Y, Aprilianti P, Primananda E, Zanzibar M, Suhartati, Putri KP, Yuniarti N, Surono, Yuskianti V (2023) Improving the success of direct seeding through the application of seed briquettes, aquasorb, and sowing time: case studies on *Ceiba pentandra, Enterolobium cyclocarpum*, and *Calophyllum inophyllum*. For Sci Technol 19(2):130–137. https://doi.org/10.1080/21580103.2023.2198549

Sudrajat DJ, Rustam E (2020) Reforestation by direct seeding of *Gmelina arborea* using seed briquettes: Composition, size and site preparation, and sowing date. IOP Conference Series: Earth and Environ Sci 533:012014. https://doi.org/10.1088/1755-1315/533/1/012014

Sudrajat DJ, Nurhasybi, Suita E, Rustam E, Sawitri R (2019) Teknologi Alternatif untuk Rehabilitasi Lahan dan Hutan: Biopot dan Briket Benih. In: Sawitri R (Ed), Konservasi Kehati Skala Demo-Plot. IPB Press, Bogor, Indonesia, pp 153-184.

Sudrajat DJ, Nurhasybi, Suita E (2018) Comparison of *Nyamplung* plant establishment: direct seeding, bare-root, blocked media, and containerized seedlings. Jurnal Manajemen Hutan Tropika 24(2):51-59. https://doi.org/10.7226/jtfm.24.2.51

Sukra R (2021) Indonesia Siapkan Teknologi Penanaman Mangrove dengan Teknologi Drone. INVESTOR.ID. https://investor.id/business/259773/indonesia-siapkan-teknologi-penanaman-mangrove-dengan-teknologi-drone (last accessed 18 December 2024).

Tamilarasan C, Jerlin R, Raja, K (2021) Seed ball technique for enhancing the establishment of subabul (*Leucaena leucochepala*) under varied habitats. J Trop For Sci 33*(*3):270–276. https://doi.org/10.26525/jtfs2021.33.3.270

Taylor A, Paine D, Suzuki N, Nault B, McFaul A (2002) Coating technologies for seed treatment applications. In: XXVI International Horticultural Congress: issues and advances in transplant production and stand establishment research 631, pp 49-54. https://doi.org/10.17660/ActaHortic.2004.631.5

Tongo A, Mahdavi A, Sayad E (2014) Effect of super absorbent polymer aquasorb on chlorophyll, antioxidant enzymes and some growth characteristics of *Acacia victoriae* seedlings under drought stress. Ecopersia 2(2):571–583. http://ecopersia.modares.ac.ir/article-24-11798-en.html

Tsakaldimi M, Ganatsas P (2016) A synthesis of results on wastes as potting media substitutes for the production of native plant species. Reforesta 1:147–163. https://doi.org/10.21750/REFOR.1.08.8

Wahyunto, Dariah, A (2014) Degradasi lahan di Indonesia: Kondisi existing, karakteristik, dan penyeragaman definisi mendukung gerakan menuju satu peta. Jurnal Sumberdaya Lahan 8(2):81-93.

Wennström U, Bergsten U, Nilsson JE (2007) Seedling establishment and growth after direct seeding with *Pinus sylvestris*: effects of seed type, seed origin, and seeding year. Silva Fennica 41(2):299-314. https://doi.org/10.14214/sf.298

Widyani N, Surono, Sudrajat DJ, Rustam E, Nurhasybi, Putri KP, Yuskianti V (2024) Direct seeding of *Ceiba pentandra* and *Leucaena leucocephala* using seed briquette with AMF and DSE inoculations to support a green economy. IOP Conference Series: Earth Environ Sci 1302:012027. https://doi.org/10.1088/1755-1315/1302/1/012027

Wijaya A, Chrysolite H, Ge M, Wibowo CK, Pradana A, Utami AF, Austin, K (2017) How can Indonesia achieve its climate change mitigation goal? An analysis of potential emissions reductions from energy and land-use policies. Working Paper, World Resources Institute, Jakarta, Indonesia. Available online at www.wri.org/publication/how-can-indonesia-achieve-itsclimate-goal