forests

MDPI

Article

Pongamia: A Possible Option for Degraded Land Restoration and Bioenergy Production in Indonesia

Budi Leksono [1], Syed Ajijur Rahman [2,3,*], Markku Larjavaara [2], Deki A. Purbaya [4], Ni Luh Arpiwi [5], Yusuf B. Samsudin [3], Yustina Artati [3], Eritrina Windyarini [1], Dede J. Sudrajat [6], Aam Aminah [6], Agus Muhamad Maulana [3], Kishor Prasad Bhatta [7], Jino Kwon [3,8] and Himlal Baral [3,9]

[1] Center for Forest Biotechnology and Tree Improvement Research and Development (BIOTIFOR), Ministry of Environment and Forestry, Yogyakarta 55582, Indonesia; boedyleksono@yahoo.com (B.L.); e_windyarini@yahoo.com (E.W.)
[2] Institute of Ecology and Key Laboratory for Earth Surface Processes of the Ministry of Education, College of Urban and Environmental Science, Peking University, Beijing 100871, China; markku@pku.edu.cn
[3] Center for International Forestry Research (CIFOR), Bogor 16115, Indonesia; Y.Samsudin@cgiar.org (Y.B.S.); y.artati@cgiar.org (Y.A.); a.maulana@cigar.org (A.M.M.); alp96jk@korea.kr (J.K.); H.Baral@cgiar.org (H.B.)
[4] Center for Climate Change and Forest and Land Fire Control Sumatra Region Office, Ministry of Environment and Forestry, Palembang 30151, Indonesia; andikadeki100@yahoo.com
[5] Department of Biology, Faculty of Mathematics and Natural Sciences, Udayana University, Bali 80361, Indonesia; arpiwi@unud.ac.id
[6] Forest Tree Seed Technology Research and Development Center, Ministry of Environment and Forestry, Bogor 16129, Indonesia; djsudrajatbtp@yahoo.com (D.J.S.); aamaminah515@yahoo.com (A.A.)
[7] Faculty of Forest Science and Forest Ecology, Georg-August-Universität, 37077 Göttingen, Germany; k.bhatta@stud.uni-goettingen.de
[8] National Institute of Forest Sciences, 57 Hoegi-ro, Seoul 02455, Korea
[9] School of Ecosystem and Forest Sciences, University of Melbourne, Parkville, VIC 3010, Australia
* Correspondence: sumonsociology@yahoo.com

Citation: Leksono, B.; Rahman, S.A.; Larjavaara, M.; Purbaya, D.A.; Arpiwi, N.L.; Samsudin, Y.B.; Artati, Y.; Windyarini, E.; Sudrajat, D.J.; Aminah, A.; et al. Pongamia: A Possible Option for Degraded Land Restoration and Bioenergy Production in Indonesia. *Forests* **2021**, *12*, 1468. https://doi.org/10.3390/f12111468

Received: 4 October 2021
Accepted: 22 October 2021
Published: 27 October 2021

Abstract: Indonesia has 14 million ha of degraded and marginal land, which provides very few benefits for human wellbeing or biodiversity. This degraded land may require restoration. The leguminous tree *Pongamia pinnata* syn. *Miletttia pinnata* (pongamia) has potential for producing biofuel while simultaneously restoring degraded land. However, there is limited information on this potential for consideration. This paper aims to address the scientific knowledge gap on pongamia by exploring its potential as a biofuel and for restoring degraded land in Indonesia. We applied a literature review to collect relevant information of pongamia, which we analyzed through narrative qualitative and narrative comparative methods with careful compilation and scientific interpretation of retrieved information. The review revealed that pongamia occurs naturally across Indonesia, in Sumatra, Java, Bali, Nusa Tenggara and Maluku. It can grow to a height of 15–20 m and thrive in a range of harsh environmental conditions. Its seeds can generate up to 40% crude pongamia oil by weight. It is a nitrogen-fixing tree that can help restore degraded land and improve soil properties. Pongamia also provides wood, fodder, medicine, fertilizer and biogas. As a multipurpose species, pongamia holds great potential for combating Indonesia's energy demand and restoring much of the degraded land. However, the potential competition for land and for raw material with other biomass uses must be carefully managed.

Keywords: Indonesia; pongamia; renewable energy; land restoration

1. Introduction

An ever-growing demand for energy has increased the importance of new and renewable sources of energy [1,2]. Petroleum fuel is the primary source of energy used by communities in Indonesia to run their vehicles, generators and other apparatus with combustion engines [1]. In recent years, Indonesia has switched from being a petroleum-exporting to a petroleum-importing country, and its own natural reserves are expected to be depleted by 2030 [2]. This realization has highlighted the need to seek and develop alternative energy sources. Biofuel is considered an important alternative source of energy [2]. Therefore, the Government of Indonesia's national energy policy supports new and renewable energy, which could provide up to 23% of national energy needs by 2025 and 31% by 2050 [3].

Globally, most biofuels are currently produced from oil palm, coconut, cassava, corn, sorghum and other edible food crops and are known as first-generation biofuels [4]. Second-generation biofuels use non-food crops as feedstocks and involve more advanced technologies in their production [5,6]. Some non-food crops, e.g., jatropha (*Jatropha curcas*), have biofuel potential but require fertile land to achieve high yields and the resulting competition with subsistence and cash crops limits their overall production prospects [7]. Therefore, there is an urgent need to identify suitable plant species that can be used as energy sources and can grow on abandoned lands, i.e., marginal or degraded lands. Pongamia (*Pongamia pinnata* syn. *Milettia pinnata*) is one such species. Its seeds are valued for their biofuel properties and it can grow on marginal and degraded land [8].

As biofuels are produced from renewable feedstocks via photosynthesis using atmospheric CO_2 , their combustion is less harmful to the atmosphere [9,10]. Biofuels have received much attention because, with the exception of a few unhealthy compounds found in oil cakes, they are non-toxic, renewable and more biodegradable in nature than petroleum-derived fuels [11–13]. Toxic pollutants, such as carbon monoxide (CO), unburned hydrocarbons (UHC), and particulate matter (PM) are also significantly lower when biofuels rather than petroleum fuels are burned in compression ignition (CI) engines [14]. Further, an important consideration for biofuel-producing crops is their ability to grow on degraded land, as they can present a sustainable solution to the bioenergy land-use perplexity [15].

Indonesia has around 14 million ha of degraded and marginal land, which is of limited benefit for food production and environmental services [16]. The Government of Indonesia has committed to restoring 12 million ha of this degraded land in an effort to achieve climate resilience in the food, water and energy sectors [17,18]. In relation to energy production, a scientific study has revealed that 3 million ha of severely and critically degraded land is suitable for biofuel and biomass plantations [19]. Several Government agencies have land restoration targets. These include the Peatland Restoration Agency or *Badan Restorasi Gambut*, which aims to restore more than 2 million ha of degraded peatlands in Riau, Jambi, South Sumatra, West Kalimantan, Central Kalimantan, South Kalimantan and Papua provinces [20] (see Figure 1). As a potential bioenergy species, pongamia could provide an opportunity to restore degraded lands while enhancing ecosystem services [21] and supporting local economies [22–24]. (The restoration of degraded areas covered with *Imperata cylindrica* (alang-alang) in Indonesia may also requires crops like pongamia that can shade out such areas and enhance ecosystem services and financial benefits).

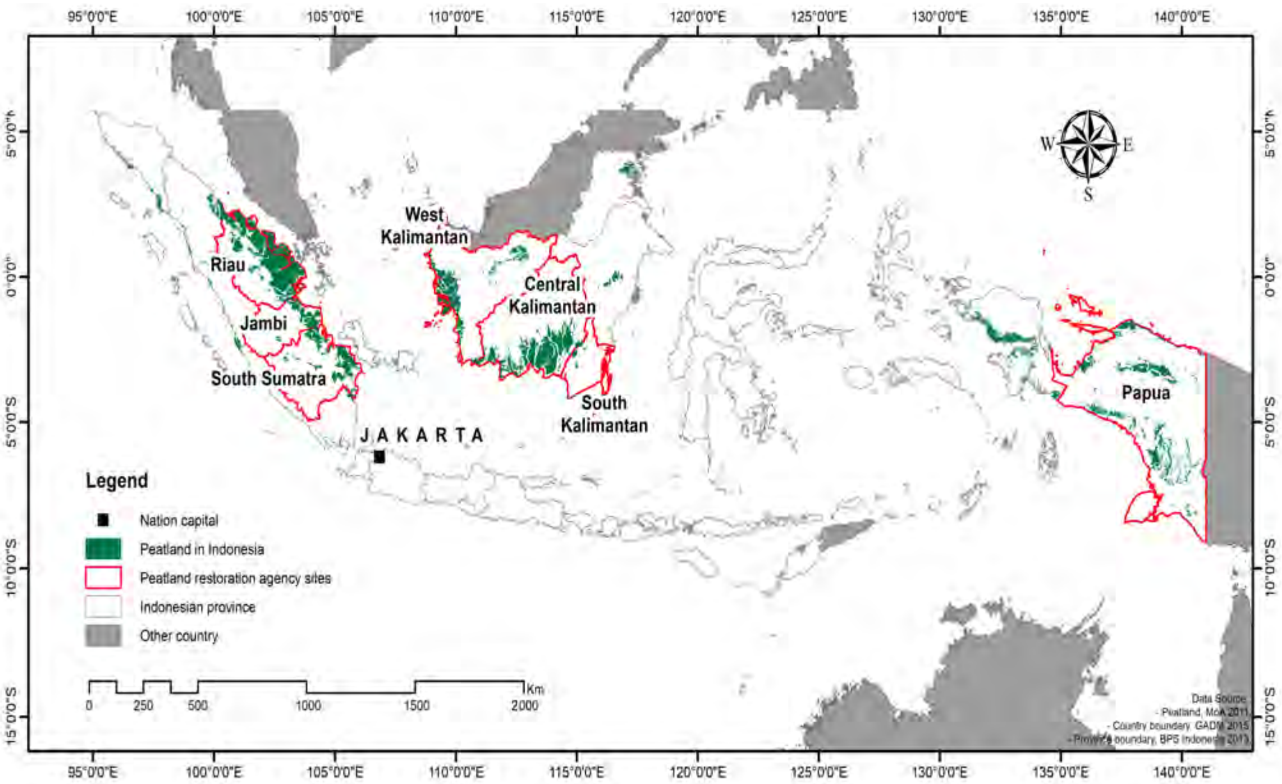

Figure 1. Distribution of peatlands and peatland restoration areas in Indonesia, Source: [25].

Pongamia is a leguminous species native to Bangladesh, India, China, Pakistan, Sri Lanka, Vietnam, Malaysia, Indonesia, Japan, Fiji and Australia and has been introduced to the United States, Puerto Rico and many African countries, including Egypt [26]. The species occurs naturally in humid and sub-tropical regions and grows well in a wide range of agro-climatic conditions [2] (common names for the species include Indian beech, karum tree (English); pongam (Gujarati); dalkaramch (Tamil); karanj, karanja, kanji (Hindi); kanuga oil tree (Telugu); honge (Kannada); shuihuang pi (Chinese); day mau (Vietnamese); kranji, malapari (Indonesian); mempari (Malay) [27,28]). Pongamia has been utilized traditionally as a pharmaceutical plant [26]. It is a preferred species for controlling soil erosion and binding sand dunes because of its dense network of lateral roots. It can also be productive on degraded land [29].

This paper compiles information on pongamia, including its natural distribution, growth, yields, biofuel potential and land restoration capacity, to corroborate scientific understanding. It may provide a valuable resource for practitioners in planning bioenergy and restoration projects.

Section 1 of this paper comprises the motivation of this research; Section 2 contains data collection and analysis methods used for this work; Section 3, which is divided into ten sub-sections, is results and consequent discussion of the analysis following the focus area of pongamia, as stated in the paragraph above; and the last, Section 4, summarizes the results and provides suggestions for ways forward.

2. Materials and Methods

This study is based on a literature review of both peer-reviewed and grey literature. The review mainly focused on four scientific areas of interest, i.e., distribution and growth, potential yield, potential biofuel, and landscape restoration capacity of pongamia. A preliminary scoping study was conducted based on a Google Scholar search targeted at finalizing key words and search phrases, and contributing to the framing of the manuscript. After finalizing key words and phrases, as well as inclusion criteria (Table 1), relevant literature was gathered using scientific research search sites, i.e., Google Scholar, Mendeley, Scopus and Web of Science. In our literature search, we only considered published scientific papers available online. At the outset of the study, we conducted a quick review of the abstracts and contents of the retrieved literature to evaluate their relevance for inclusion in further extensive reviews. After removing any duplicates, and considering the timeframe for this study, we selected 84 of the 770 pieces of literature for thorough review by considering their relevance. A basic checklist of quality criteria (i.e., clear aim and replicable methodology, accurately and reliably measured outcomes, and consistently reported findings with methodologies and empirical data provided) was used to select these 84 pieces of literature. A total of nine months from January 2018 to September 2019 (and again from June to September 2021 for revision) was required for four reviewers (one full-time and three part-time) to extract relevant data. Further supporting data was gathered from the Indonesian Ministry of Environment and Forestry (MoEF) and is presented in Annex 1 of this paper.

Table 1. Search sites, key words and inclusion criteria to generate targeted information from the literature review used in this study.

Search Sites	Key Words and Search Phrases	Inclusion Criteria
Google Scholar Mendeley Scopus Web of Science	'pongamia' OR 'bioenergy' OR 'biofuel' OR 'jet fuel', 'pongamia' AND 'bioenergy', 'pongamia' AND 'biofuel', 'pongamia' AND 'jet fuel', 'pongamia' AND 'oil', 'pongamia' AND 'yield', ' pongamia' AND 'growth', 'bioenergy' AND 'Indonesia', 'biofuel' AND 'Indonesia', 'pongamia' AND 'Indonesia', 'biofuel' AND 'Indonesia', 'pongamia' AND 'land restoration', 'pongamia' OR 'land restoration' AND 'Indonesia', 'pongamia' AND 'nitrogen', 'pongamia' OR 'land restoration' AND 'nitrogen', 'pongamia' AND 'benefit', 'pongamia' AND 'potential', 'pongamia' AND 'wood', 'pongamia' AND 'medicine', 'pongamia' AND 'landscape', 'land tenure' AND 'Indonesia', 'land tenure' AND 'tree planting', 'land tenure' AND 'pongamia plantation'.	Evidence-based information on pongamia, i.e., distribution, growth, yields, biofuel potential, land restoration capacity

Note: as 'Millettia' is a synonym of 'Pongamia', and mistakenly overlooked as a search word, may cause excluding some relevant articles.

Relevant information was carefully compiled point-by-point, and scientific interpretations were made by using narrative qualitative and narrative comparative analysis methods, including tables and figures [30–32]. (Narrative analysis methods are characterized by perspective and context, which deal with points of view regarding what has happened, and describing what may be significant in the near future [33]. They simply provide meaning and coherence to, and perspective on, experience and knowledge [34].) The analysis process was designed to scrutinize relevant concepts in a transparent and subjective way, following the objective of this paper and the inclusion criteria (Table 1), i.e., the growth, distribution, yield and biofuel production potential, and landscape restoration capacity of pongamia. Careful attention was paid to a more discursive interpretation and to represent a view of reality through a process of decontextualization and recontextualization with appropriate scientific order as presented in Section 3 below. It is also important to mention that some terms in this manuscript are stated in general without having precise quantification (e.g., pongamia growth rates), which reflects the original literature source.

3. Results and Discussion

3.1. Potential of Pongamia as a Biofuel Species

3.1.1. Distribution

Pongamia grows naturally across the Indonesian archipelago, mostly in Berbak National Park in Jambi province, Sembilang National Park in South Sumatra province; Berikat Gulf in Bangka Belitung province; Ujung Kulon in Banten province; Batu Karas, Pangandaran in West Java province; Alas Purwo National Park and Baluran National Park in East Java province; Senipah, Samboja, Sekerat and Tanjung Batu in East Kalimantan province; Lovina in Bali province; and Sembelia in East Lombok, West Nusa Tenggara province. It can also be found in the western part of Seram island, Maluku province (Figure 2) [28,35–37]. Pongamia has many local names in Indonesia, including malapari (Simeulue), mabai (Bangka), kipahanglaut (East Java), bangkongan and kepik (Java), kranji (Madura), marauwen (Minahasa, Sulawesi), hate hira (Ternate) and butis and sikam (Timor) [35].

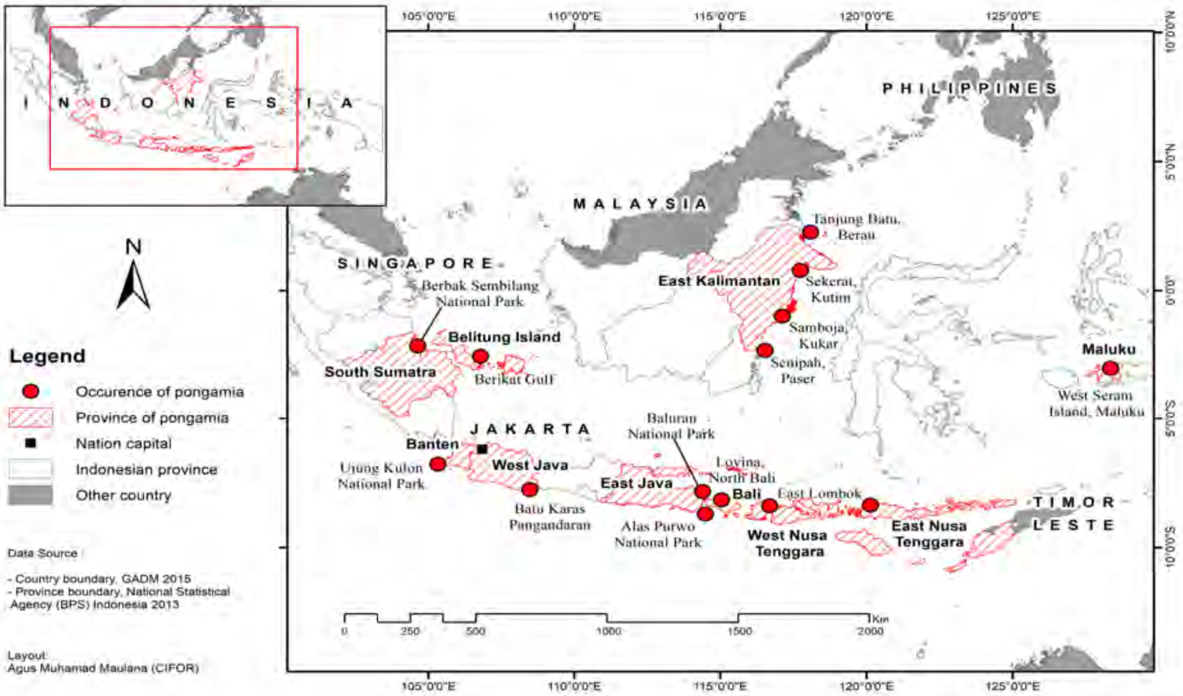

Figure 2. Natural distribution of pongamia in Indonesia, Sources: [28,35–37].

3.1.2. Growth

Pongamia grows well naturally in lowland forests on calcareous soils, in rocky coastal areas, along the edges of mangrove forests, and along streams and estuaries. It is a hardy woody plant and can survive temperatures ranging 5 to 50 °C and elevations up to 1200 m [36,38]. It grows well in both full sunlight and partial shade and can grow in most soil types from stony through sandy to clay. Although it is salinity tolerant, it does not survive well in dry sands [39]. Studies have found pongamia to have potential for growing as a restoration species in highly degraded forest areas [38] and on land which has been degraded physically, chemically and biologically due to mining operations [40]. Pongamia plantation trials in a hot, dry area with limestone soil at Bukit Jimbaran, Bali showed 100% survivability of plants two months after planting without irrigation. Trial plants also showed vigorous growth in height (7.5–13.60 m), stem diameter (20.70–63.69 cm at breast height) and numbers of compound leaves (crown width 6.00–20.0 m) [41], indicating pongamia's adaptability to the hot, dry conditions associated with marginal land. Similarly, another study [42] observed survival rates ranging 88 to 100% with average height of 83.75 cm and diameter of 0.85 cm six months after planting in Java. In a trial plot on degraded peatland in Buntoi village, Pulang Pisau district, Central Kalimantan province, pongamia trees started flowering 1.5 years after planting (Figure 3) [43]. Another study showed four-month-old pongamia seedlings demonstrating tolerance to 200 and 150 mM NaCl saline drain and saline waterlogged conditions respectively [44].

Pongamia is a semi-deciduous tree the seeds of which contain non-edible oil, which can be processed into biodiesel. However, recent technological advances have allowed the seeds to be processed as food. It is a forest tree, demands only low levels of moisture and is therefore drought resistant, and needs only minimum input and management to grow well [27,45]. It can reach heights of 15–20 m and has a large and wide crown [27]. It grows very rapidly and reaches its full height and maturity within 4–5 years [46]. Pongamia can be propagated by generative or vegetative means. It can be propagated vegetatively from cuttings and root suckers (with new plants growing from lateral roots of the parent tree) [26]. Pongamia is also propagated from seeds in nursery beds or polybags and via in-situ sowing of seeds in plantations [8,47]. It has also been reported that seeds stored for three months or more result in lower germination and plant vigor [47]. Seeds take approximately one week to germinate and around 85% of seeds do so with appropriate nursery management. Study findings have also indicated a direct relationship between seed size and germination efficiency but only for fresh seeds [8]. The long-term viability of pongamia trees also depends on appropriate pruning practices. Information on pongamia growth rates from four trial sites is presented in Annex 1.

Figure 3. Pongamia tree flowering 1.5 years after planting in a trial plot in Buntoi, Pulang Pisau, Central Kalimantan.

3.1.3. Yields

Pongamia produces large quantities of seeds. However, yields vary according to soil and climatic conditions, as well as management practices [27,39,48–51]. There is limited information on pongamia seed yields in Indonesia, with most literature coming from India and Australia [48,50–52]. This is because pongamia grows naturally or in plantations in a wide range of regions in India, while pongamia is cultivated extensively in Queensland, Australia [8,50].

Pongamia can produce 9 to 90 kg of seeds annually per adult tree in India, equivalent to a potential yield of between 900 kg and 9000 kg per hectare [27,48]. This differs slightly from yields of between 20 and 80 kg per tree reported in Australia [52]. Another report noted average annual seed production of 20 kg per tree in Australia [50]. Another study [53] reported seed yield of pongamia trees improving significantly in the northern part of Western Australia after the introduction of *Apis mellifera* beehives (up to 4.9 kg per 1-year-old tree), as bees are effective pollinators for pongamia. Incorporating *Apis mellifera* bees into pongamia plantations could be a win–win solution for successful pongamia pollination and honey production.

In Bangladesh, young pongamia (15 years old or younger) produced more than 25 kg of seeds per tree annually. However, yields increased as trees grew older, i.e., annual yields of more than 100 kg for 20-year-old trees [54]. A trial plot in Parung Panjang, West Java, Indonesia showed that pongamia trees as young as 8 years old cultivated in an agroforestry system can provide 3.80 kg of seeds per year (Figure 4, Appendix A). Pongamia trees can live for up to 100 years, can produce seeds every year, and require minimal maintenance once they reach 30 years old [54].

Figure 4. A pongamia-based agroforestry system in Parung Panjang, West Java, Indonesia.

3.1.4. Biofuel Production Potential

The most useful product from pongamia is biodiesel. Biodiesel is produced by the transesterification of vegetable oils or animal fats using alcohol (methanol or ethanol) and a catalyst (e.g., potassium hydroxide (KOH) or sodium hydroxide (NaOH) [54]. The biodiesel produced is a clean burning fuel that has no sulfur emissions and is non-corrosive [55]. At low pressures and temperatures, transesterification produces 80% methyl ester, and 20% glycerin as by-products [27]. The major fatty acids in crude pongamia oil are oleic (51%), linoleic (19%), palmitic (11%), stearic (6%), linolenic (4.5%) and behenic (4.5%) [44]. Pongamia oil extracts exhibit good chemical properties and could be used as good biodiesel feedstock [27]. Fatty acid methyl ester from pongamia and other potential biodiesel plants such as *Azadirachta indica*, *Calophyllum inophyllum* and *Jatropha curcas* meet the major specifications of biodiesel standards required by American and European standards organizations [56].

During the past few decades, pongamia oil has attracted considerable attention as a potential renewable, biodegradable, eco-friendly, non-toxic fuel [27] and as being economically viable [52]. Studies have determined oil yield and properties with 1000 kg of pongamia seeds yielding 270–300 kg of crude pongamia oil [49]. In other studies, oil yield was reported to reach up to 35% by weight [27,57], with some reports showing yields of up to 40% [50,58]. Crude pongamia oil needs further processing (transesterification) to give methyl esters. Around 85–90 L of biodiesel and 15–16 L of glycerin (considered a by-product) can be obtained from 100 L of crude pongamia oil by transesterification [49].

Meanwhile, other studies have found approximately 4 kg of pongamia seeds being required to produce one liter of crude pongamia oil, which in turn could yield 0.896 L of biodiesel [59]. The major cost of biodiesel production from pongamia is the feed stock, which can account for 60% of total production costs, followed by chemical costs for transesterification at 17%, and operating costs at 10% [60]. Therefore, high seed yield is the key to successful pongamia biodiesel production. A study on the economic viability of pongamia biodiesel production in Fiji [61] showed the levelized cost of biodiesel to be USD 1.44 per liter and the benefit–cost ratio to be 1:06. Tables 2–4 below detail properties of crude pongamia oil. It is worth noting that pongamia can yield a considerable volume of biodiesel in comparison with other biofuel-producing species (see Figure 5). However, the oil content of pongamia may vary depending on seed source, processing methods (i.e., hydraulic press, mechanical press or solvent extraction) and equipment used (Table 5).

Table 2. Physio-chemical properties of crude pongamia oil.

Property	Unit	Value
Color	-	Yellowish red
Density	g/cc	0.924
Viscosity	mm^2/s	40.2
Acid value	mgKOH/g	5.40
Iodine value	-	87
Saponification value	-	184
Calorific value	Kcal/kg	8742
Specific gravity	-	0.925
Unsaponifiable matter	-	2.9
Flash point	°C	225
Fire point	°C	230
Cloud point	°C	3.5
Pour point	°C	−3
Boiling point	°C	316
Cetane number	-	42
Copper strip corrosion	-	No corrosion observed
Ash Content	%	0.07

Source: [27].

Table 3. Fatty acid composition of crude pongamia oil.

Fatty Acid (%)	Molecular Formula	Percentage	Structure
Palmitic acid	$C_{16}H_{32}O_2$	11.65	$CH_3(CH_{2)14}COOH$
Stearic acid	$C_{18}H_{36}O_2$	7.50	$CH_3(CH_2)_{16}COOH$
Oleic acid	$C_{18}H_{34}O_2$	51.59	$CH_3(CH_2)_{14}(CH{=}CH)COOH$
Linoleic acid	$C_{18}H_{32}O_2$	16.64	$CH_3(CH_2)_{12}(CH{=}CH)_2COOH$
Eicosanoic acid	$C_{20}H_{40}O_2$	1.53	$CH_3(CH_2)_{18}COOH$
Dosocasnoic acid	$C_{22}H_{44}O_2$	4.45	$CH_3(CH_2)_{20}COOH$
Tetracosanoic acid	$C_{24}H_{48}O_2$	1.09	$CH_3(CH_2)_{22}COOH$

Source: [27].

Table 4. Properties of pongamia methyl ester.

Property	Unit	ASTM Test Method	Pongamia Biodiesel	Diesel
Density	g cc^{-1}	D1498	0.860	0.824
Calorific value	Kcal kg^{-1}	D240/D4868	3700	4285
Cetane number	Number	D613	41.7	49
Acid value	mg $KOHg^{-1}$	D664	0.46	0.36
Iodine value	Number	D1510	91	-
Water and sediments	% vol, max	D2709	0.005	-

Source: [27].

Table 5. Pongamia oil content from different seed sources and extraction methods.

No.	Oil Content (%)	Method	Equipment	Seed/Seed Source	Reference
1.	15.44–15.82	Mechanical press	Simple screw expeller press	Bulk seed/Banten, Indonesia	[37]
2.	15.92–19.60	Mechanical press	Fabricant screw expeller press	Bulk seed/Banten, Indonesia	[62]
3.	14.25–14.67	Mechanical press	Simple screw expeller press	Bulk seed/West Java, Indonesia	[37]
4.	13.05–13.23	Mechanical press	Simple screw expeller press	Bulk seed/East Java, Indonesia	[37]
5.	24.00–26.00	Mechanical press	Simple screw expeller press	Bulk seed/India	[63]
6.	27.34–39.26	Solvent extraction	Soxhlet extractor	Bulk seed/Banten, Indonesia	[62]
7.	26.61–44.68	Solvent extraction	Soxhlet extractor	Individual seed/Banten, Indonesia	[62]
8.	26.30–32.00	Solvent extraction	Soxhlet extractor	Bulk seed/Bali, Indonesia	[41]
9.	28.00–31.00	Solvent extraction	Soxhlet extractor	Bulk seed/Bali, Indonesia	[64]
10.	27.00–39.00	Solvent extraction	Soxhlet extractor	Bulk seed/India	[63]
11.	33.31–39.01	Solvent extraction	Soxhlet extractor	Bulk seed/Madhya Pradesh, India	[65]
12.	28.18–41.32	Solvent extraction	Soxhlet extractor	Bulk seed/Carmen, Philippines	[66]
13.	33.00–40.30	Solvent extraction	Soxhlet extractor	Bulk seed/Queensland and Northern Territory, Australia	[44]

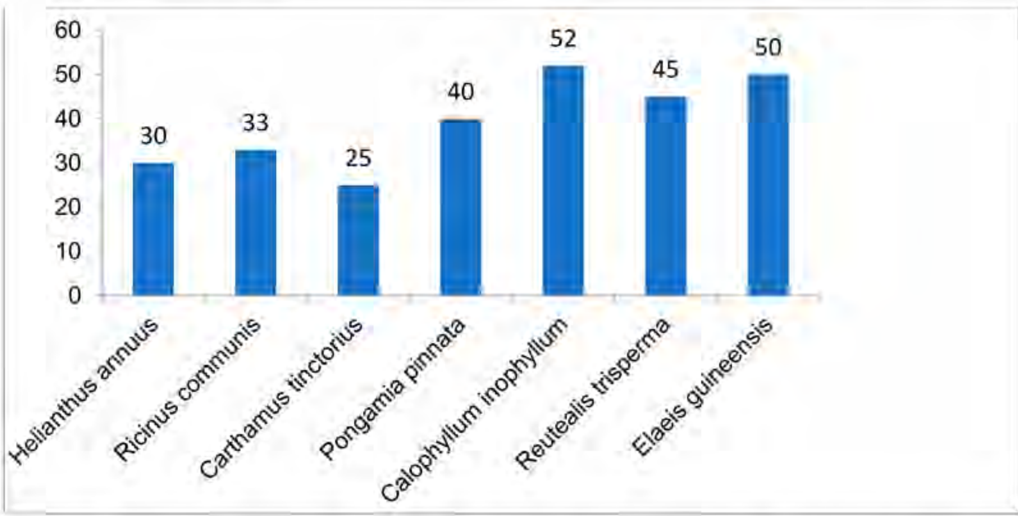

Figure 5. Average percentages of crude oil yielded by pongamia and other biofuel species [27].

3.1.5. Pongamia for Bio-Jet Fuel

One potential product from pongamia is bio-jet fuel. Most aircraft are fueled by conventional jet fuel, which is non-renewable, costly and emits large amounts (80%) of carbon, e.g., one tonne of conventional jet fuel emits 0.8 tonnes of carbon when burned [67]. Therefore, the aviation industry is looking for renewable jet fuels [67]. However, compared to other industries, aviation has a limited range of alternative renewable fuel options that can replace fossil fuels. Bio-derived jet fuel could be a viable alternative for aviation industries [68]. *Camelina sativa*, *Jatropha* spp., *Elaeis guineensis* and algae have already been used to produce fuel for several test flights. Pongamia oil has yet to be tested, but has significant potential [50], as it can abate 43% of greenhouse gases on a lifecycle basis [69].

3.2. The Potential of Pongamia for Land Restoration

3.2.1. Nutrition Enhancement for Degraded Land

Degraded land is land that has lost its productivity [20]. Such land often has low soil nutrient content, low productivity, suffers from erosion, and is unsuitable for growing crops. There are two main ways of restoring degraded land: (i) physical, technical or engineering restoration; or (ii) biological restoration [70].

Pongamia trees have several benefits for restoring degraded land. Studies have shown five-year-old pongamia plantations having carbon sequestration potential of around 13.43 tons per ha [71,72]. Pongamia is capable of withstanding drought stress, can grow on saline soils, and needs little topsoil as it has a dense network of lateral roots and long thick taproots. Pongamia plantations can help alleviate compaction and crusting [73]. It is a sturdy plant with no special nutritional requirements and can grow in extreme environmental conditions. It is tolerant to soil sodicity, pH imbalances, high temperatures, heavy metal contamination, drought and poorly drained soils. Consequently, pongamia can achieve phytostabilization, i.e., the long-term stabilization and containment of pollutants [74,75]. Iron, chromium, copper, manganese and magnesium in fly ash dykes have been phytostabilized by establishing pongamia plantations on the dykes [75]. Therefore, establishing pongamia biofuel plantations on degraded land can be a win–win solution for energy production and land restoration, especially compared to *Elaeis guineensis* (oil palm), where links to deforestation are a worldwide concern [70,73–76].

3.2.2. Nitrogen Fixation

Chemical nitrogen fertilizer is widely used for growing crops. However, it is costly and its production causes high levels of greenhouse gas emissions [77]. The restoration of degraded land also requires the stabilization of its nitrogen content. Pongamia is a leguminous tree that fixes nitrogen, while also producing raw material for biofuel [78,79]. In contrast, other common biofuel crops, such as canola, sugarcane, sweet sorghum, maize and woody trees (e.g., eucalyptus and willow), deprive soils of nitrogen rather than increasing nitrogen content [79]. Pongamia fixes nitrogen throughout its life [79]. A study of the phenotypic characteristics of rhizobia isolates from pongamia showed isolates growing well at temperatures ranging 29 to 39 °C, within pH levels 7 to 9, and tolerating less than 1% salinity. It also showed isolates from Rhizobium and Bradyrhyzobium genera being effective microsymbionts under controlled conditions [44]. Relative effectiveness of the symbiosis between pongamia as a host and rhizobia is determined by dividing shoot dry weight of plants inoculated with rhizobia isolate by shoot dry weight of plants treated with nitrogen fertilizer expressed as a percentage of weight [80]. By using this method, the highest relative effectiveness of rhizobia isolates was 85.9% [44].

Another study showed that nodules of pongamia formed on seed-derived seedlings within four weeks with visible nodulation and established symbioses by eight weeks at 28 °C. The nodules produced by these strains were uniformly filled with bacteroid zones [81]. Pongamia nodules can actively fix nitrogen as demonstrated by quantification by gas chromatography of ethylene in acetylene reduction assays, where C_2H_2 (acetylene) serves as a substrate for bacterially encoded nitrogenase [76]. Therefore, cultivating pongamia together with agricultural crops has the potential to produce favorable agricultural yields.

3.2.3. Other Services Provided by Pongamia

Restoring degraded land using pongamia could also provide a range of services to benefit local communities and nature by enhancing ecosystem functions (see Table 6). Such services could be enhanced with appropriate pongamia plantation design by counting costs and benefits as well as trade-offs and synergies associated with different options in specific locations, e.g., various understory crop combinations considering local economic, cultural and environmental values (e.g., Figure 3).

Table 6. Pongamia tree products and their various uses.

Attributes	Important Uses	References
Wood	Pongamia logs serve as the raw material for wood flour as lignocellulosic filler that can be further processed to produce wood–plastic composites.	[82]
	Pongamia wood is useful for making tool handles, combs, cabinets, cartwheels, posts, agricultural implements and paper pulp.	[26,48]
	Pongamia wood is used as fuelwood.	[48]
Medicine	Almost all parts of pongamia trees are used in folk medicine: Juice from the roots blended with coconut milk is used to treat gonorrhea. Stem bark extract has sedative and antipyretic qualities and reduces enlarged spleens. Juice from the leaves is used to treat diarrhea, colds and coughs, and to relieve rheumatism. The fruits are used to treat abdominal tumors. The seed is used to treat keloid tumors, skin ailments and hypertension, and as an expectorant for bronchitis and whooping cough. The flowers are used to treat certain diabetic conditions. The oil is used to treat leprosy, chronic fever, skin diseases and rheumatism.	[26,29]
	A crude decoction of pongamia leaves is used as an antidiarrheal with efficacy against cholera.	[83]
Fodder	The leaves are commonly used for cattle feed and, less so, for goat feed, and are a valuable source of fodder in arid regions. Seed residue, press cake and seedcake contain much protein and are used for poultry feed; but should not exceed 75% of feed as they contain several toxic compounds.	[26,46,48]
Fertilizer and biogas	Seedcake and leaves are used as fertilizer. Seedcake can generate biogas in household biogas generators.	[49,51]
Biodiversity restoration	Pongamia trees can restore biodiversity by improving soil quality, controlling erosion, and enhancing vegetation cover at the landscape level (including in sandy, heavy clay, rocky and waterlogged areas).	[8,29,84–88]
Other services	Pongamia trees serve as windbreaks, are fire tolerant, and are ornamental trees. The oil is used as a lubricant, as a leather dressing, and for manufacturing soap, varnish and paint. The flowers are a good source of pollen and nectar, yielding a dark honey. The bark is used to make rope. Pounded and roasted seeds used to be utilized as a fish poison. Dried leaves are useful to store with grain to repel insects.	[8,26,29,48,56,57,84,85, 89–95]

3.3. Community Involvement

As stakeholders, local communities can be directly affected by fuel shortages, and their potential contributions [96] should be taken into account during pongamia cultivation processes. Such contributions could be overseen through local technical and administrative capacity building [97,98] to strengthen pongamia cultivation at the landscape level. Community involvement could also enhance local incomes, innovative spirit, technical proficiency and enthusiasm through the distribution of degraded land in areas surrounding settlements to communities for pongamia cultivation, or by villagers using their own degraded land for the same purpose [96,99]. It may also increase transparency and accountability for all parties (local communities, government and investors), foster a sense of responsibility and encourage support and mutual interest for land restoration efforts [100].

3.4. Other Considerations

To restore forestland, it has to be a biodiversity-rich, self-regenerating system, consisting of a microclimate and a wide variety of plants and animals in mutual coexistence [101]. Monoculture plantations may not provide as high levels of biodiversity as forest, and require ongoing human intervention including the use of herbicides and pesticides during land preparation [47,102–104]. Profitable pongamia plantations might also become a new driver of land clearing and an indirect cause of deforestation, especially where land tenure is not clear, as witnessed in various countries [101,105]. Secure land tenure is crucial for the successful implementation of tree-planting activities [106,107]. If local communities have insecure rights to use land and to harvest produce from trees, they are less likely to tend trees. When farmers lack secure land titles, they are deprived of access to the credit essential as initial capital for investing in tree planting [108]. Therefore, policy support to provide secure land titles to local people will be essential to enable pongamia adoption.

Development of the Government of Indonesia's policy on biofuel-based energy is carried out using a SWOT analysis approach to analyze existing conditions, formulate problem-solving strategies, and develop policies for sustainable biofuel [109]. The General National Energy Plan (RUEN) has a number of long- and short-term programs to support the National Energy Policy (Government Regulation No. 79 of 2014). RUEN targets to produce 15.6 and 54.2 million kiloliters of biofuel by 2025 and 2050, respectively [110]. To support government policy, sustainable energy plantations of adaptive and productive species could play a crucial role, especially when implemented on ex-mining and degraded land. Besides growing biofuel, such species can also fertilize soils and provide other benefits, e.g., income generation, improved biodiversity, and provision of multiple ecosystem services [43,111].

Considering the diversity of biofuel production (and system components) across locations, there may be a shortage of specific evidence about variation in contributions to the delivery of various ecosystem services. Improving this knowledge base (e.g., through modeling) can be facilitated by research that produces a more sophisticated approach to incorporate the economic, social and environmental characteristics of biofuel.

Further, through strengthening and socializing biofuels as a strategic industry, increasing productivity and diversification of biofuel-producing plants, providing incentives for investment in biofuel facilities, encouraging market links, and increasing research budgets for the development of biofuel commodities and products can strengthen sustainable biofuel production.

4. Conclusions

Pongamia trees are well suited to growing in adverse environmental conditions. The species can grow in most soil types, in partial shade or full sunlight, and at various temperatures. Pongamia is a multipurpose tree that fixes atmospheric nitrogen, improves soil health and can produce large amounts of oil for biodiesel. It can produce bioenergy on degraded land unsuitable for food production. As Indonesia's large areas of degraded land deliver limited benefits to people and nature, restoring such land through pongamia cultivation could provide an opportunity to enhance ecosystem services and reverse biodiversity loss. Although several other species produce biofuel (e.g., oil palm, coconut or jatropha), with its multiple benefits (see Table 6), pongamia is a prime candidate for planting as a bioenergy feedstock on degraded land.

The Government of Indonesia's initiation of a national policy on new and renewable energy use, which includes biofuel making up 5% of the energy mix by 2025 [112], has significantly increased the importance of domestic biofuel production [111]. As palm oil production is widely questioned, pongamia could be a potential new alternative for cultivation on degraded land. However, it will necessitate long-term monitoring to prevent forest being cleared for biodiesel crop production [111].

It was apparent from our literature review that scientific knowledge gaps remain, i.e., up-to-date pongamia production technology, long-term plantation management, community involvement, various added-value options (e.g., understory crop association), identifying potential biofuel producers and consumers, developing effective business models for various biofuel stakeholders, and the feasibility of building stable biofuel markets.

Therefore, new studies on pongamia focusing on these issues could help to fill knowledge gaps and benefit scientific communities, managers and other stakeholders.

Author Contributions: B.L., S.A.R., D.A.P., Y.B.S., Y.A. and H.B. designed the study. B.L., S.A.R., D.J.S., A.A., D.A.P. and Y.B.S. collected and analyzed the data. B.L., S.A.R., M.L., D.A.P., N.L.A., Y.B.S., Y.A., E.W., D.J.S., A.A., A.M.M., K.P.B., J.K. and H.B. prepared and reviewed the manuscript. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the CGIAR Research Program on Forests, Trees and Agroforestry (CRP-FTA), its donors and the National Institute of Forest Science (NIFOS) of Republic of Korea.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data supporting the results of this paper can be obtained by direct request to the authors.

Acknowledgments: The authors would like to thank colleagues at the Ministry of Environment and Forestry (MoEF), CIFOR, National Institute of Forest Science (NIFOS), and Universitas Muhammadiyah, Palangkaraya, Central Kalimantan, Indonesia, for their assistance, time and valuable scientific support for this paper.

Conflicts of Interest: No conflict of interest.

Appendix A

Table A1. Performance and management of pongamia in four different locations in Indonesia.

Site Information	Location			
	Buntoi, Central Kalimantan	**Kalampangan, Central Kalimantan**	**Wonogiri, Central Java**	**Parung Panjang, West Java**
Altitude (m)	18	12	142	52
Average annual rainfall (mm)	2992	2992	1878	2440
Average temperature (°C)	27.3	27.3	29.0	28.0
Soil type	Peat	Peat	Mineral (alfisol and entisol)	Mineral
Planting date	January 2020	January 2020	January 2020	February 2012
Spacing (m)	8 × 8	6 × 6	5 × 2	3 × 3
Stand density (per ha)	156	278	1000	1111
Planting system	Mixed with nyamplung (*Calophyllum inophyllum*)	Monoculture	Monoculture	Agroforestry with understory crops, i.e., pineapple (*Ananas comosus*), Asian blue ginger (*Alpinia galangal*), Cassava (*Manihot esculenta*)
Tree height (m)	1.26 (1 year old)	1.01 (1 year old)	1.49 (1 year old)	6.62 (8 years old)
Seed yield	N/A	N/A	N/A	3.80 kg per tree (i.e., 4222 kg per ha)

References

1. Hidayat, A.S. Konsumsi BBM Dan Peluang Pengembangan Energi Alternatif. *Inovasi* **2005**, *5*, 11–17.
2. Kotarumalos, N.A. Menuju Ketahanan Energi Indonesia: Belajar Dari Negara Lain. *J. Glob. Dan Strateg.* **2009**, *3*, 1–18.

3. Republic of Indonesia. *Peraturan Pemerintah Republik Indonesia Nomor 2014, 79 Tahun 2014*; Republic of Indonesia: Jakrata, Indonesia, 2014.
4. Hassan, M.H.; Kalam, M.A. An Overview of Biofuel as a Renewable Energy Source: Development and Challenges. *Procedia Eng.* **2013**, *56*, 39–53. [CrossRef]
5. Antizar-Ladislao, B.; Juan, L.T.G. Second-Generation Biofuels and Local Bioenergy Systems. *Biofuels Bioprod. Biorefining* **2008**, *2*, 455–469. [CrossRef]
6. Demirbas, M.F. Biorefineries for Biofuel Upgrading: A Critical Review. *Appl. Ecol.* **2009**, *86*, 151–161. [CrossRef]
7. Pena, D.S.; Evangelista, A.W.P.; Júnior, J.A.; Casaroli, D. Agroclimatic Zoning for Jatropha Crop (*Jatropha curcas*, L.) in the State of Goiás. *Acta Sci. Agron.* **2016**, *38*, 329–335. [CrossRef]
8. Kesari, V.; Rangan, L. Development of *Pongamia pinnata* as an Alternative Biofuel Crop—Current Status and Scope of Plantations in India. *J. Crop Sci. Biotechnol.* **2010**, *13*, 127–137. [CrossRef]
9. IEA. Technology Roadmap Biofuels for Transport. Available online: https://www.iea.org/reports/technology-roadmap-biofuels-for-transport (accessed on 4 October 2021).
10. IPCC. Renewable Energy Sources and Climate Change Mitigation. In *Special Report of the Intergovernmental Panel on Climate Change*; Edenhofer, O., Madruga, R.P., Sokona, Y., Seyboth, K., Eickemeier, P., Matschoss, P., Hansen, G., Kadner, S., Schlomer, S., Wickel, T., et al., Eds.; Cambridge University Press: Cambridge, UK, 2012.
11. Pandey, V.C.; Singh, K.; Singh, J.S.; Kumar, A.; Singh, B.; Singh, R.P. *Jatropha curcas*: A Potential Biofuel Plant for Sustainable Environmental Development. *Renew. Sustain. Energy Rev.* **2011**, *16*, 2870–2883. [CrossRef]
12. Leksono, B.; Hendrati, R.L.; Windyarini, E.; Hasnah, T. Variation of Biofuel potential of 12 Calopyllum inophyllum Populations in Indonesia. *Indones. J. For. Res.* **2014**, *1*, 127–138.
13. Leksono, B.; Windyarini, E.; Hasnah, T. Conservation and Zero Waste Concept for Biodiesel Industry Based on *Calophyllum inophyllum* Plantation. In Proceedings of the IUFRO-INAFOR Joint International Conference, Forestry Research, Development and Inovation Agency, Yogyakarta, Indonesia, 24–27 July 2017; pp. 163–174.
14. Ogunkule, O.; Ahmed, N.A. Review Overview of Biodiesel Combustion in Mitigating the Adverse Impacts of Engine Emissions on the Sustainable Human–Environment Scenario. *Sustainability* **2021**, *13*, 5465. [CrossRef]
15. Lewis, S.M.; Kelly, M. Mapping the Potential for Biofuel Production on Marginal Lands: Differences in Definitions, Data and Models across Scales. *ISPRS Int. J. Geo-Inf.* **2014**, *3*, 430–459. [CrossRef]
16. The Ministry of Environment and Forestry. *Statistics of Ministry of Environment and Forestry, 2018*; The Ministry of Environment and Forestry: Jakarta, Indonesia, 2019.
17. The Ministry of Environment and Forestry. *Statistics of Ministry of Environment and Forestry, 2015*; The Ministry of Environment and Forestry: Jakarta, Indonesia, 2016.
18. The Ministry of Environment and Forestry. *Statistics of Ministry of Environment and Forestry, 2017*; The Ministry of Environment and Forestry: Jakarta, Indonesia, 2018.
19. Jaung, W.; Wiraguna, E.; Okarda, B.; Artati, Y.; Goh, C.S.; Syahru, R.; Leksono, B.; Prasetyo, L.B.; Lee, S.M.; Baral, H. Spatial Assessment of Degraded Lands for Biofuel Production in Indonesia. *Sustainability* **2018**, *10*, 4595. [CrossRef]
20. Lamb, D. *Regreening the Bare Hills: Tropical Forest Restoration in the Asia-Pacific Region*; Springer Science and Business Media: London, UK, 2010.
21. Baral, H.; Lee, S.M. *Sustainable Bioenergy Systems to Restore and Valorize Degraded Land*; Center for International Forestry Research (CIFOR): Bogor, Indonesia, 2016.
22. Casillas, C.E.; Kammen, D.M. The Energy-Poverty-Climate Nexus. *Science* **2010**, *330*, 1181–1182. [CrossRef] [PubMed]
23. Malla, S. Household Energy Consumption Patterns and Its Environmental Implications: Assessment of Energy Access and Poverty in Nepal. *Energy Policy* **2013**, *61*, 990–1002. [CrossRef]
24. Lynd, L.R.; Sow, M.; Chimphango, A.F.A.; Cortez, L.A.B.; Cruz, C.H.B.; Elmissiry, M.; Laser, M.; Mayaki, I.A.; Moraes, M.A.F.D.; Nogueira, L.A.H.; et al. Bioenergy and African Transformation. *Biotechnol. Biofuels* **2015**, *8*, 1–8. [CrossRef] [PubMed]
25. Badan Restorasi Gambut (BRG). *Penetapan Peta Indikatif Restorasi Gambut (SK. 05/BRG/KPTS/2016 § Lampiran Peta Indikatif Prioritas Restorasi)*; Badan Restorasi Gambut (BRG): Jakarta, Indonesia, 2016.
26. Orwa, C.; Mutua, A.; Kindt, R.; Jamnadass, R.; Anthony, S. *Agroforestree Database: A Tree Reference and Selection Guide Version 4.0*; ICRAF: Nairobi, Kenya, 2009.
27. Bobade, S.N.; Khyade, V.B. Detail Study on the Properties of *Pongamia pinnata* (Karanja) for the Production of Biofuel. *Res. J. Chem. Sci.* **2012**, *2*, 16–20.
28. Aminah, A.A.M.; Supriyanto, S.; Suryani, A.; Siregar, I.Z. Genetic Diversity of *Pongamia pinnata* (*Millettia pinnata* Aka., Malapari) Populations in Java Island, Indonesia. *Biodiversitas* **2017**, *18*, 677–681. [CrossRef]
29. Sangwan, S.; Rao, D.V.; Sharma, R.A. A Review on *Pongamia pinnata* (L.) Pierre: A Great Versatile Leguminous Plant. *Nat. Sci.* **2010**, *8*, 130–139.
30. Riessman, C.K. *Narrative Analysis*; Sage Publication: London, UK, 1993.
31. Smith, C.P. Content Analysis and Narrative Analysis. In *Handbook of Research Methods in Social and Personality Psychology*; Reis, H.T., Judd, C.M., Eds.; Cambridge University Press: New York, NY, USA, 2000; pp. 313–335.

32. Samsudin, Y.B.; Puspitaloka, D.; Rahman, S.A.; Chandran, A.; Baral, H. Community-Based Peat Swamp Restoration through Agroforestry in Indonesia. In *Agroforestry for Degraded Landscapes*; Recent Advances and Emerging Challenges Book Series; Dagar, J.C., Gupta, S.R., Teketay, D., Eds.; Springer: Singapore, 2020; Volume 1, pp. 349–365.
33. Gee, J.P. Memory and Myth: A Perspective on Narrative. *Developing Narrative Structure*. 1991, pp. 1–25. Available online: https://psycnet.apa.org/record/1991-97747-000 (accessed on 4 October 2021).
34. Bruner, J. *Actual Minds, Possible Worlds*; Harvard University Press: Cambridge, MA, USA, 2020.
35. Djam'an, D.F. *Penyebaran dan Pembibitan Tanaman Kranji (Pongamia pinnata Merril) di Indonesia*; Majalah Kehutanan Indonesia Edisi VIII; Departemen Kehutanan: Jakarta, Indonesia, 2009.
36. Sidiyasa, K.; Sitepu, B.S.; Atmoko, T. *Habitat dan Populasi Ki Beusi (Pongamia pinnata (L.) Pierre) dan Kampis (Hernandia Nymphaeifolia Kubitzki) di Kalimantan Timur*; Prosiding Seminar Hasil-Hasil Penelitian BPTKSDA Samboja: Balikpapan, Indonesia, 2012.
37. Jayusman, J. *Peta Sebaran Malapari (Pongamia pinnata Merril) Di Pulau Jawa Dan Upaya Konservasinya*; Prosiding Seminar Nasional Pendidikan Biologi dan Saintek II, Universitas Muhammadiyah Surakarta (UMS): Surakarta, Indonesia, 2017.
38. Ramachandran, A.; Radhapriya, P. Restoration of Degraded Soil in the Nanmangalam Reserve Forest with Native Tree Species: Effect of Indigenous Plant Growth-Promoting Bacteria. *Sci. World J.* **2016**, *2016*, 1–9. [CrossRef]
39. Csurhes, S.; Hankamer, C. *Invasive Plant Risk Assessment: Pongamia (Millettia pinnata Syn. Pongamia pinnata)*; Queensland Government: Queensland, Australia, 2016.
40. Agus, C.; Wulandari, D.; Primananda, E.; Faridah, E. The Role of Organic Pot on the Growth of *Pongamia pinnata* (L.) Pierre Seedling for Rehabilitation of Post Coal Mining Land . In Proceedings of the International Symposium on Bioeconomics of Natural Resources Utilization (ISBINARU), Center for Plant Conservation Botanic Gardens LIPI, Bogor, Indonesia, 12–14 October 2017.
41. Arpiwi, N.L.; Wahyuni, I.G.A.S.; Muksin, I.K.; Sutomo, S. Conservation and Selection of Plus Tree of *Pongamia pinnata* in Bali, Indonesia. *Biodiversitas* **2018**, *19*, 1607–1614. [CrossRef]
42. Aminah, A.; Syamsuwida, D. Natural Growing Site and Cultivation of Pongamia (*Pongamia pinnata* (L.) Pierre) as a Source of Biodiesel Raw Materials. In *IOP Conference Series: Earth and Environmental Science*; IOP Publishing: Bristol, UK, 2019; Volume 308, No. 1, p. 012050.
43. Maimunah, S.; Rahman, S.A.; Samsudin, Y.B.; Artati, Y.; Simamora, T.I.; Andini, S.; Lee, S.M.; Baral, H. Assessment of Suitability of Tree Species for Bioenergy Production on Burned and Degraded Peatlands in Central Kalimantan, Indonesia. *Land* **2018**, *7*, 115. [CrossRef]
44. Arpiwi, N.L.; Yan, G.; Elizabet, L.B.; Julie, A.P.; Elizabeth, W. Phenotypic and Genotypic Characterisation of Root Nodule Bacteria Nodulating *Millettia pinnata* (L.) Panigrahi, A Biodiesel Tree. *Plant Soil* **2013**, *367*, 363–377. [CrossRef]
45. Dwivedi, G.; Sharma, M.P. Prospects of Biodiesel from Pongamia in India. *Renew. Sustain. Energy Rev.* **2014**, *32*, 114–122. [CrossRef]
46. Duke, J.A. *Handbook of Energy Crops*; Purdue University: West Lafayette, IN, USA, 1983.
47. Scott, P.T.; Pregelj, L.; Chen, N.; Hadler, J.S.; Djordjevic, M.A.; Gresshoff, P.M. Pongamia pinnata: An Untapped Resource for the Biofuels Industry of the Future. *BioEnergy Res.* **2008**, *1*, 2–11. [CrossRef]
48. Dwivedi, G.; Jain, S.; Sharma, M.P. Pongamia as a Source of Biodiesel in India. *Smart Grid Renew. Energy* **2011**, *2*, 184–189. [CrossRef]
49. Chandrashekar, L.A.; Mahesh, N.S.; Gowda, B.; Hall, W. Life Cycle Assessment of Biodiesel Production from Pongamia Oil in Rural Karnataka. *Agric. Eng. Int. CIGR J.* **2012**, *14*, 67–77.
50. Murphy, H.T.; O'Connell, D.A.; Seaton, G.; Raison, R.J.; Rodriguez, L.C.; Braid, A.L.; Kriticos, D.J.; Jovanovic, T.; Abadi, A.; Betar, M.; et al. A Common View of the Opportunities, Challenges, and Research Actions for Pongamia in Australia. *Bioenergy Res.* **2012**, *5*, 778–800. [CrossRef]
51. Garg, R.K.; Chaudhari, S.; Singh, R. In Vitro Propagation of Potential Biodiesel Plant, *Pongamia pinnata* (L.) Pierre. *Shrinkhla Ek Shodhparak Vaicharik Patrika* **2017**, *4*, 4.
52. Abadi, A.; Maynard, H.; Arpiwi, N.L.; Stucley, C.; Bartle, J.; Giles, R. Economics of Oil Production from Pongamia (*Millettia pinnata*) for Biofuel in Australia. *BioEnergy Res.* **2016**, *9*, 874–883. [CrossRef]
53. Arpiwi, N.L.; Yan, G.; Elizabeth, L.B.; Julie, A.P. Phenology, Pollination and Seed Production of Milletia pinnata in Kununurra, Norhern Western Australia. *J. Biol. Udayana* **2014**, *1*, 19–23.
54. Rahman, M.M.; Ahiduzzaman, M.; Islam, A.K.M.S.; Blanchard, R. Karoch (*Pongamia pinnata*)—An Alternative Source of Biofuel in Bangladesh. In Proceedings of the 3rd International Conference on the Developments in Renewable Energy Technology (ICDRET), Dhaka, Bangladesh, 29–31 May 2014.
55. Chincholkar, S.P.; Srivastava, S.; Rehman, A.; Dixit, S.; Lanjewar, A. Biodiesel as an Alternative Fuel for Pollution Control inDiesel Engine. *Asian J. Exp. Sci.* **2005**, *19*, 13–22.
56. Azam, M.M.; Waris, A.; Nahar, N.M. Prospects and Potential of Fatty Acid Methyl Esters of Some Nontraditional Seed Oils for Use as Biodiesel in India. *Biomass Bioenergy* **2005**, *29*, 293–302. [CrossRef]
57. Ahmad, M.; Zafar, M.; Khan, M.A.; Sultana, S. Biodiesel from *Pongamia pinnata* L. Oil: A Promising Alternative Bioenergy Source. *Energy Sources Part A Recovery Util. Environ. Eff.* **2009**, *31*, 1436–1442. [CrossRef]
58. Nabi, M.N.; Hoque, S.M.N.; Akhter, M.S. Karanja (*Pongamia pinnata*) Biodiesel Production in Bangladesh, Characterization of Karanja Biodiesel and its Effect on Diesel Emissions. *Fuel Process. Technol.* **2009**, *90*, 1080–1086. [CrossRef]

59. Patil, V.K.; Bhandare, P.; Kulkarni, P.B.; Naik, G.R. Progeny Evaluation of *Jatropha curcas* and *Pongamia pinnata* with Comparison to Bioproductivity and Biodiesel Parameters. *J. For. Res.* **2015**, *26*, 137–142. [CrossRef]
60. Doddabasawa, P.R. Physico-chemical analysis of biodiesel derived Glycerin and saponification of crude glycerin with different concentrations of sodium hydroxide ly. *Int. J. Sci. Res.* **2009**, *3*, 210–212.
61. Prasad, S.S.; Singh, A. Economic Feasibility of Biodiesel Production from Pongamia Oil on the Island of Vanua Levu. *SN Appl. Sci.* **2020**, *2*, 1086. [CrossRef]
62. Hasnah, T.; Leksono, B.; Sumedi, N.; Windyarini, E.; Adinugraha, H.A.; Baral, H.; Artati, Y. Pongamia as a Potential Biofuel Crop: Oil Content of Pongamiapinnata from the Best Provenance in Java, Indonesia. In Proceedings of the International Conference ICUE 2020 on Energy, Environment and Climate Change, Bangkok, Thailand, 20–22 October 2020.
63. Meher, L.C.; Naik, S.N.; Naik, M.K.; Dalai, A.K. *Biodiesel Production using Karanja (Pongamia pinnata) and Jatropha (Jatropha curcas) Seed Oil. Hand Book of Plant-Based Biofuel*; CRC Press: Boca Raton, FL, USA, 2008; pp. 255–266.
64. Arpiwi, N.L.; NegaraI, M.S.; Simpen, I.N. Selection of High Oil Yielding Trees of *Millettia pinnata* (L.) Panigrahi, Vegetative Propagation and Growth in the Field. *J. Trop. Life Sci.* **2017**, *7*, 258–262. [CrossRef]
65. Rahangdale, C.P.; Koshta, L.D.; Patle, N.K. Provenance Variation for Oil Content and Fatty Acid Composition in Seed of *Pongamiapinnata* (L.) Pierre. *Int. J. Proj. Manag.* **2014**, *4*, 1–8.
66. Razal, R.; Daracan, V.; Calapis, R.M.; Angon, C.M.M.; Demafelis, R.B. Solvent Extraction of Oil from Bani (*Pongamia pinnata* (L.) Pierre) Seeds. *Philipp. J. Crop Sci.* **2012**, *37*, 1–7.
67. Hendricks, R.C.; Bushnell, D.M.; Shouse, D.T. Aviation Fueling: A Cleaner, Greener Approach. *Int. J. Rotating Mach.* **2011**, *2011*, 782969. [CrossRef]
68. Graham, P.W.; Smart, A.; Tasman, A.; Graham, P. *Possible Futures: Scenario Modelling of Australian Alternative Transport Fuels to 2050*; CSIRO: Newcastle, Australia, 2011.
69. Cox, K.; Renouf, M.; Dargan, A.; Turner, C.; Klein-Marcuschamer, D. Environmental Life Cycle Assessment (LCA) of Aviation Biofuel from Microalgae, *Pongamia pinnata*, and *Sugarcane olasses*. *Biofuels Bioprod. Biorefining* **2014**, *8*, 579–593. [CrossRef]
70. Ahirwal, J.; Maiti, S.K.; Singh, A.K. Ecological Restoration of Coal Mine-Degraded Lands in Dry Tropical Climate: What Has Been Done and What Needs to Be Done? *Environ. Qual. Manag.* **2016**, *26*, 25–36. [CrossRef]
71. Bohre, P.; Chaubey, O.P.; Singhal, P.K. Biomass Production and Carbon Sequestration by *Pongamia pinnata* (Linn) Pierre in Tropical Environment. *Int. J. Bio-Sci. Bio-Technol.* **2014**, *6*, 129–140. [CrossRef]
72. Edrisi, S.A.; Abhilash, P.C. Exploring Marginal and Degraded Lands for Biomass and Bioenergy Production: An Indian Scenario. *Renew. Sustain. Energy Rev.* **2016**, *54*, 1537–1551. [CrossRef]
73. Lal, R. Land Area for Establishing Biofuel Plantations. *Energy Sustain. Dev.* **2006**, *10*, 67–79. [CrossRef]
74. Juwarkar, A.A.; Singh, S.K. Microbe-assisted Phytoremediation Approach for Ecological Restoration of Zinc Mine Spoil Dump. *Int. J. Environ. Pollut.* **2010**, *43*, 236. [CrossRef]
75. Singh, A. *Comparative Performance and Restoration Potential of Jatropha curcas and Pongamia pinnata on Degraded Soil of North India*; University of Lucknow: Lucknow, India, 2013.
76. Balooni, K.; Singh, K. Tree Plantations for Restoration of Degraded Lands and Greening of India: A Case Study of Tree Growers Cooperatives. *Nat. Resour. Forum* **2001**, *25*, 21–32. [CrossRef]
77. Kesari, V.; Ramesh, A.M.; Rangan, L. *Rhizobium Pongamiae* Sp. Nov. from Root Nodules of *Pongamia pinnata*. *BioMed Res. Int.* **2013**, *2013*, 165198. [CrossRef]
78. Chaukiyal, S.P.; Sheel, S.K.; Pokhriyal, T.C. Effects of Seasonal Variation and Nitrogen Treatments on Nodulation and Nitrogen Fixation Behaviour in *Pongamia pinnata*. *J. Trop. For. Sci.* **2000**, *12*, 357–368.
79. Samuel, S.; Scott, P.T.; Gresshoff, P.M. Nodulation in the Legume Biofuel Feedstock Tree *Pongamia pinnata*. *Agric. Res.* **2013**, *2*, 207–214. [CrossRef]
80. Fterich, A.; Mahdhi, M.; Mars, M. Seasonal Changes of Microbiological Properties in Steppe Soils from Degraded Arid Area in Tunisia. *Arid Land Res. Manag.* **2014**, *28*, 49–58. [CrossRef]
81. Biswas, B.; Gresshoff, P.M. The Role of Symbiotic Nitrogen Fixation in Sustainable Production of Biofuels. *Int. J. Mol. Sci.* **2014**, *15*, 7380–7397. [CrossRef] [PubMed]
82. Islam, M.A.; Bari, R. Flat Pressed *Pongamia pinnata* Wood-flour/Polypropylene Composite Loaded with Talc: A Statistical Optimization. *J. Indian Acad. Wood Sci.* **2016**, *13*, 91–100. [CrossRef]
83. Brijesh, S.; Daswani, P.G.; Tetali, P.; Rojatkar, S.R.; Antia, N.H.; Birdi, T.J. Studies on *Pongamia pinnata* (L.) Pierre Leaves: Understanding the Mechanism(s) of Action in Infectious Diarrhea. *J. Zhejiang Univ. Sci. B* **2006**, *7*, 665–674. [CrossRef] [PubMed]
84. Pranowo, D.; Herman, M. Potensi Pengembangan Kemiri Sunan (*Reutealis Trisperma* (Blanco) Airy Shaw) Di Lahan Terdegredasi. *Perspektif* **2016**, *14*, 87–102. [CrossRef]
85. Herman, M.; Syakir, M.; Pranowo, D.; Saefudin, S. *Kemiri Sunan (Reutalis trisperma (Blanco) Airy Shaw) Tanaman Penghasil Minyak Nabati dan Konservasi Lahan*; Indonesian Center for Estate Crops Research and Development: Bogor, Indonesia, 2013.
86. Modi, N.R.; Dudani, S.N. Biodiversity Conservation through Urban Green Spaces: A Case Study of Gujarat University Campus in Ahmedabad. *Int. J. Conserv. Sci.* **2013**, *4*, 189–196.
87. Shirbhate, N.; Malode, S. Heavy Metals Phytoremediation by *Pongamia pinnata* (L.) Growing in Contaminated Soil from Municipal Solid Waste Landfills and Compost Sukali Depot, Amravati (m.S.). *Int. J. Adv. Biol. Res.* **2012**, *2*, 147–152.

88. Dutta, R.K.; Agrawal, M. Restoration of Opencast Coal Mine Spoil by Planting Exotic Tree Species: A Case Study in Dry Tropical Region. *Ecol. Eng.* **2003**, *21*, 143–151. [CrossRef]
89. Wulandari, W.S.; Darusman, D.; Kusmana, C.; Widiatmaka, W. Kajian Finansial Pengembangan Biodiesel Kemiri Sunan (*Reutealis Trisperma* (Blanco) Airy Shaw) Pada Lahan Tersedia di Jawa Barat. *J. Penelit. Sos. Dan Ekon. Kehutan.* **2015**, *12*, 31–42. [CrossRef]
90. Atabani, A.E.; César, A.D.S.; Calophyllum Inophyllum, L.A. Prospective Non-Edible Biodiesel Feedstock. Study of Biodiesel Production, Properties, Fatty Acid Composition, Blending and Engine Performance. *Renew. Sustain. Energy Rev.* **2014**, *37*, 644–655. [CrossRef]
91. Bridgemohan, P.; Bridgemohan, R.S.H. Invasive Weed Risk Assessment of Three Potential Bioenergy Fuel Species. *Int. J. Biodivers. Conserv.* **2014**, *6*, 790–796.
92. FAO. *Agribusiness Handbook: Sunflower Refined and Crude Oils*; FAO: Rome, Italy, 2010.
93. Bustomi, S.; Kurniaty, R.; Rostiwati, T.; Kosasih, A.S.; Irawati, S.; Sudradjat, R.; Illa, A.; Leksono, B. *Nyamplung (Calopyhllum innopyhllum L.) Sumber Energi Biofuel Yang Potensial*; Departemen Kehutanan: Jakarta, Indonesia, 2009.
94. Akinerdem, F.; Öztürk, Ö. Safflower and Biodiesel Quality in Turkey. In Proceedings of the 7th International Safflower Conference, New South Wales, Australia, 3–6 November 2008.
95. Sumathi, S.; Chai, S.P.; Mohamed, A.R. Utilization of Oil Palm as a Source of Renewable Energy in Malaysia. *Renew. Sustain. Energy Rev.* **2008**, *12*, 2404–2421. [CrossRef]
96. Rahman, S.A.; Sunderland, T.; Roshetko, J.M.; Healey, J.R. Facilitating Smallholder Tree Farming in Fragmented Tropical Landscapes: Challenges and Potentials for Sustainable Land Management. *J. Environ. Manag.* **2017**, *198*, 110–121. [CrossRef]
97. Ostrom, E. *Governing the Commons: The Evaluation of Institutions for Collective Action*; Cambridge University Press: Cambridge, UK, 1990.
98. Watts, J.; Colfer, C.J. The Governance of Tropical Forested Landscape. In *Collaborative Governance of Tropical Landscapes*; Colfer, C.J., Pfund, J., Eds.; The Earthscan: London, UK, 2011; pp. 35–54.
99. Nawir, A.A.; Murniati, R.L. *Forest Rehabilitation in Indonesia: Where to after Three Decades?* Center for International Forestry Research (CIFOR): Bogor, Indonesia, 2007.
100. Basria, H.; Nabihab, A.K.S. Accountability of local government: The case of Aceh province, Indonesia. *Asia Pac. J. Account. Financ.* **2014**, *3*, 1–14.
101. Rojas, G.I. What's Wrong with Tree Plantations? 2012. Available online: https://news.mongabay.com/2012/09/whats-wrong-with-tree-plantations/ (accessed on 18 February 2021).
102. Nagarjun, N.; Suryanarayana, V. Documentation of Nursery Diseases of *Pongamia pinnata* and Developing Effective Management Package in Haveri Forest Division. 2014. Available online: http://www.kscst.iisc.ernet.in/spp/37_series/spp37s/synopsis_biofuel/msc/37S_B_MSc_006.pdf (accessed on 15 April 2021).
103. Usharani, K.V.; Naik, D.; Manjunatha, R.L. *Pongamia pinnata* (L.): Composition and Advantages in Agriculture: A Review. *J. Pharmacogn. Phytochem.* **2019**, *8*, 2181–2187.
104. Kumari, J.; Tripathy, M.K.; Das, H. Diversity of Insect and Non Insect Pest Infesting Karanja, *Pongamia pinnata* (L.) Pierre at Bhubaneswar, Odisha, India and their Natural Enemies. *Int. J. Curr. Microbiol. Appl. Sci.* **2020**, *9*, 1577–1596. [CrossRef]
105. Angelsen, A.; Kaimowitz, D. Is Agroforestry Likely to Reduce Deforestation? In *Agroforestry and Biodiversity Conservation in Tropical Landscapes*; Schroth, G., Gustavo, A.B., Da Fonseca Harvey, C.A., Gascon, C., Vasconcelos, H.L., Izac, A.N., Eds.; Island Press: London, UK, 2004; pp. 87–106.
106. Rahman, S.A.; Rahman, M.F.; Sunderland, T. Increasing Tree Cover in Degrading Landscapes: 'Integration' and 'Intensification' of Smallholder Forest Culture in the Alutilla Valley, Matiranga, Bangladesh. *Small-Scale For.* **2014**, *13*, 237–249. [CrossRef]
107. Tomich, T.P.; de Foresta, H.; Dennis, R.; Ketterings, Q.; Murdiyarso, D.; Palm, C.; Stolle, F.; van Noordwijk, M. Carbon Offsets for Conservation and Development in Indonesia? *Am. J. Altern. Agric.* **2002**, *17*, 125–137.
108. Rahman, S.A.; Rahman, M.F.; Sunderland, T. Causes and Consequences of Shifting Cultivation and its Alternative in the Hill Tracts of Eastern Bangladesh. *Agrofor. Syst.* **2012**, *84*, 141–155. [CrossRef]
109. Bappenas. *Kajian Pengembangan Bahan Bakar Nabati (BBN)*; Government of Indonesia: Jakarta, Indonesia, 2015.
110. Traction Energy Asia. *Pemanfaatan dan Pengelolaan Biofuel (Biodiesel): Pembelajaran dan Praktik Baik Dari Berbagai Negara*; Working Paper 2: Jakarta, Indonesia, 2020.
111. Rahman, S.A.; Himlal, B.; Sharma, R.; Samsudin, Y.B.; Meyer, M.; Lo, M.; Artati, Y.; Simamora, T.I.; Andini, S.; Leksono, B.; et al. Integrating Bioenergy and Food Production on Degraded Landscapes in Indonesia for Improved Socioeconomic and Environmental Outcomes. *Food Energy Secur.* **2019**, *8*, e00165. [CrossRef]
112. Kharina, A.; Malins, C.; Searle, S. *Biofuels Policy in Indonesia: Overview and Status Report*; The International Council on Clean Transportation: Beijing, China, 2016.