CHAPTER 13

Pongamia

A possible option for degraded land restoration and bioenergy production in Indonesia

Budi Leksono, Syed Ajijur Rahman, Markku Larjavaara, Deki A Purbaya, Ni Luh Arpiwi, Yusuf B Samsudin, Yustina Artati, Eritrina Windyarini, Dede J Sudrajat, Aam Aminah, Agus Muhamad Maulana, Kishor Prasad Bhatta, Jino Kwon and Himlal Baral

Abstract: Indonesia has 14 million ha of degraded and marginal land, which provides very few benefits for human well-being or biodiversity. This degraded land may require restoration. The leguminous tree *Pongamia pinnata* syn. *Milettia 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 on pongamia, which we analysed 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 thrives 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 country's degraded land. However, the potential competition for land and for raw materials with other biomass uses must be carefully managed.

Keywords: Indonesia, pongamia, renewable energy, land restoration
Link: https://www.mdpi.com/1999-4907/12/11/1468
This is an edited version of an article previously published in MDPI (Leksono et al. 2021).

13.1 Introduction

An ever-growing demand for energy has increased the importance of new and renewable sources of energy (Hidayat 2005; Kotarumalos 2009). Petroleum fuel is the primary source of energy used by communities in Indonesia to run their vehicles, generators and other machinery powered by combustion engines (Hidayat 2005). In recent years, Indonesia has switched from being a petroleum-exporting to a petroleum-importing country, and its own natural reserves are expected to provide alternative energy sources. As biofuel is considered an important alternative source of energy (Kotarumalos 2009), 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 (Republic of Indonesia 2014).

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 (Hassan et al. 2013). Second generation biofuels use non-food crops as feedstocks and involve more advanced technologies in their production (Antizar-Ladislao et al. 2008; Pena et al. 2016). 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 (Pena et al. 2016). 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 (Kesari et al. 2010). As biofuels are produced from renewable feedstocks via photosynthesis using atmospheric CO_2, their combustion is less harmful to the atmosphere (IPCC 2012; IEA 2021). 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 [Pandey et al. 2011; Leksono et al. 2014, 2017). 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 (Ogunkule et al. 2021). 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 (Lewis et al. 2014).

Indonesia has around 14 million ha of degraded and marginal lands, which is of limited benefit for food production and environmental services (Ministry of Environment and Forestry 2019). 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 (Ministry of Environment and Forestry 2016, 2018). 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 (Jaung et al. 2018). 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 (Lamb et al. 2010) (see Figure 1). As a potential bioenergy species, pongamia could provide an opportunity to restore degraded lands while enhancing ecosystem services (Baral and Lee 2016) and supporting local economies (Casillas and Kammen 2010; Malla 2013; Lynd et al. 2015). (The restoration of degraded areas covered with *Imperata cylindrica* (*alang-alang*) grass in Indonesia may also requires crops like pongamia that can shade out such areas and enhance ecosystem services and financial benefits.

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 (Orwa et al. 2009). The species occurs naturally in humid and sub-tropical regions and grows well in a wide range of agro-climatic conditions (Hidayat 2005). 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); and *mempari* (Malay) (Bobade et al. 2012; Aminah 2017). Pongamia has been utilized traditionally as a pharmaceutical plant (Orwa et al. 2009). 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 (Sangwan et al. 2010).

This chapter 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.

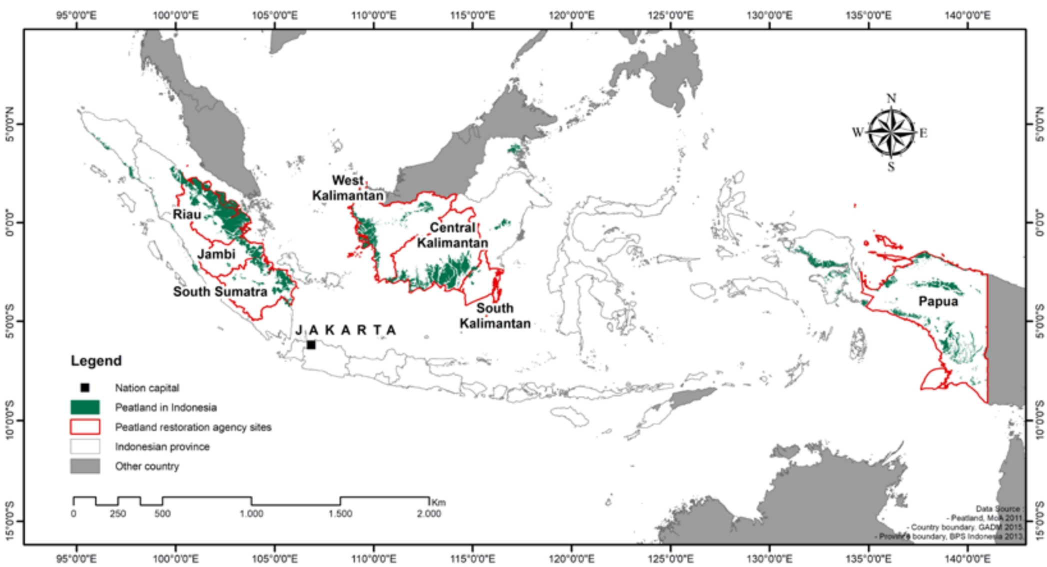

Figure 1. Distribution of peatlands and peatland restoration areas in Indonesia

Source: *Badan Restorasi Gambut* 2016

13.2 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: ‘Millettia’ is a synonym of ‘Pongamia’, and was mistakenly overlooked as a search word. This may have resulted in the omission of 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 (Riessman 1993; Smith 2000; Samsudin et al. 2020). (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 (Gee 2021). They simply provide meaning and coherence to, and perspective on, experience and knowledge (Bruner 2020). 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 representing 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

13.3 Results and discussion

13.3.1 Potential of pongamia as a biofuel species

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) (Djam'an 2009; Sidiyasa et al. 2012; Aminah et al. 2017; Jayusman 2017). 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) (Djam'an 2009).

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 1,200 m (Sidiyasa et al. 2012; Ramachandran and Radhapriya 2016). 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 (Csurhes et al. 2016). Studies have found pongamia to have potential for growing as a restoration species in highly degraded forest areas (Ramachandran and Radhapriya 2016) and on land which

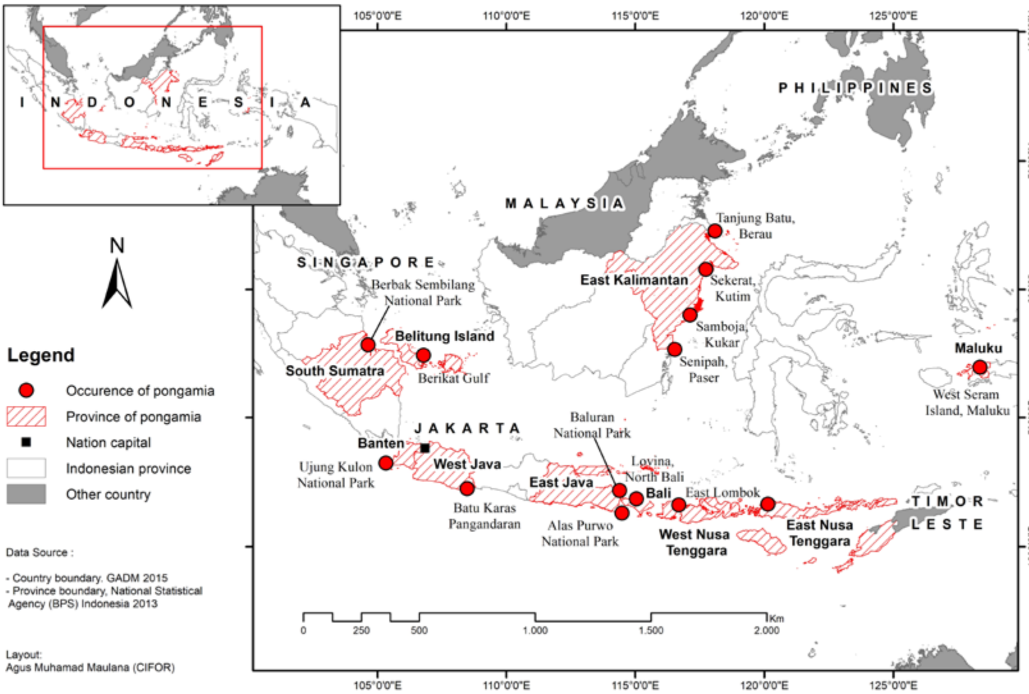

Figure 2. Natural distribution of pongamia in Indonesia

Sources: (Djam'an 2009; Sidiyasa et al. 2012; Aminah et al. 2017; Jayusman 2017)

has been degraded physically, chemically and biologically due to mining operations (Agus et al. 2017). 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) (Arpiwi et al. 2018), indicating pongamia's adaptability to the hot, dry conditions associated with marginal land. Similarly, another study (Aminah and Syamsuwida 2017) 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) (Maimunah et al. 2018). Another study showed four-month-old pongamia seedlings demonstrating tolerance to 200 and 150 mM NaCl saline drain and saline waterlogged conditions respectively (Arpiwi et al. 2013).

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

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 (Bobade and Khyade 2012; Dwivedi and Sharma 2014) . It can reach heights of 15–20 m and has a large and wide crown (Bobade and Khyade 2012). It grows very rapidly and reaches its full height and maturity within 4–5 years (Duke 1983). 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) (Orwa et al. 2009). Pongamia is also propagated from seeds in nursery beds or polybags and via in-situ sowing of seeds in plantations (Scott 2008; Kesari and Rangan 2010). It has also been reported that seeds stored for three months or more result in lower germination and plant vigour (Scott 2008). 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 (Kesari and Rangan 2010). 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.

Yields

Pongamia produces large quantities of seeds. However, yields vary according to soil and climatic conditions, as well as management practices (Dwivedi et al. 2011; Chandrashekar et al. 2012; Murphy et al. 2012; Bobade and Khyade 2012; Csurhes and Hankamer 2016; Garg et al. 2017). There is limited information on pongamia seed yields in Indonesia, with most literature coming from India and Australia [Dwivedi et al. 2011; Murphy et al. 2012; Abadi et al. 2016; Garg et al. 2017). 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 (Kesari and Rangan 2010; Murphy et al. 2012).

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 9,000 kg per hectare (Dwivedi et al. 2011; Bobade and Khyade 2012). This differs slightly from yields of between 20 kg and 80 kg per tree reported in Australia (Abadi et al. 2016). Another report noted average annual seed production of 20 kg per tree in Australia (Murphy et al. 2012). Another study (Arpiwi et al. 2014) 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 one-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 (Rahman et al. 2014). A trial plot in Parung Panjang,

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

West Java, Indonesia showed that pongamia trees as young as eight 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 (Rahman et al. 2014).

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) (Rahman et al. 2014). The biodiesel produced is a clean burning fuel that has no sulphur emissions and is non-corrosive (Chincholkar et al. 2005). At low pressures and temperatures, transesterification produces 80% methyl ester, and 20% glycerin as by-products (Bobade and Khyade 2012). The major fatty acids in crude pongamia oil are oleic (51%), linoleic (19%), palmitic (11%), stearic (6%), linolenic (4.5%) and behenic (4.5%) (Arpiwi et al. 2013). Pongamia oil extracts exhibit good chemical properties and could be used as good biodiesel feedstock (Bobade and Khyade 2012). 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 (Azam 2005)

During the past few decades, pongamia oil has attracted considerable attention as a potential renewable, biodegradable, eco-friendly, non-toxic fuel (Bobade and Khyade 2012) and as being economically viable (Abadi et al. 2016). Studies have determined oil yield and properties with 1,000 kg of pongamia seeds yielding 270–300 kg of crude pongamia oil

(Chandrashekar et al. 2012). In other studies, oil yield was reported to reach up to 35% by weight (Ahmad et al. 2009; Bobade and Khyade 2012), with some reports showing yields of up to 40% (Nabi et al. 2009; Murphy et al. 2012). 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 (Chandrashekar et al. 2012).

Meanwhile, other studies have found approximately 4 kg of pongamia seeds being required to produce one litre of crude pongamia oil, which in turn could yield 0.896 L of biodiesel (Patil et al. 2015). 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% (Doddabasawa 2009). Therefore, high seed yield is the key to successful pongamia biodiesel production. A study on the economic viability of pongamia biodiesel production in Fiji (Prasad and Singh 2020) showed the levelized cost of biodiesel to be USD 1.44 per litre 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^{-1}	0.924
Viscosity	mm^2 s^{-1}	40.2
Acid value	mg KOH g^{-1}	5.40
Iodine value	-	87
Saponification value	-	184
Calorific value	Kcal kg^{-1}	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: Bobade and Khyade 2012

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: Bobade and Khyade 2012

Table 4. Properties of pongamia methyl ester

Property	Unit	ATSM Test Method	Pongamia Biodiesel	Diesel
Density	g cc^{-1}	D1498	0.860	0.824
Calorific value	Kcal kg^{-1}	D240 / D4868	3,700	4,285
Cetane number	Number	D613	41.7	49
Acid value	Mg $KOHg^{-1}$	D664	0.46	0.26
Iodine value	Number	D1510	91	-
Water and sediments	% vol. max	D2709	0.005	-

Source: Bobade and Khyade 2012

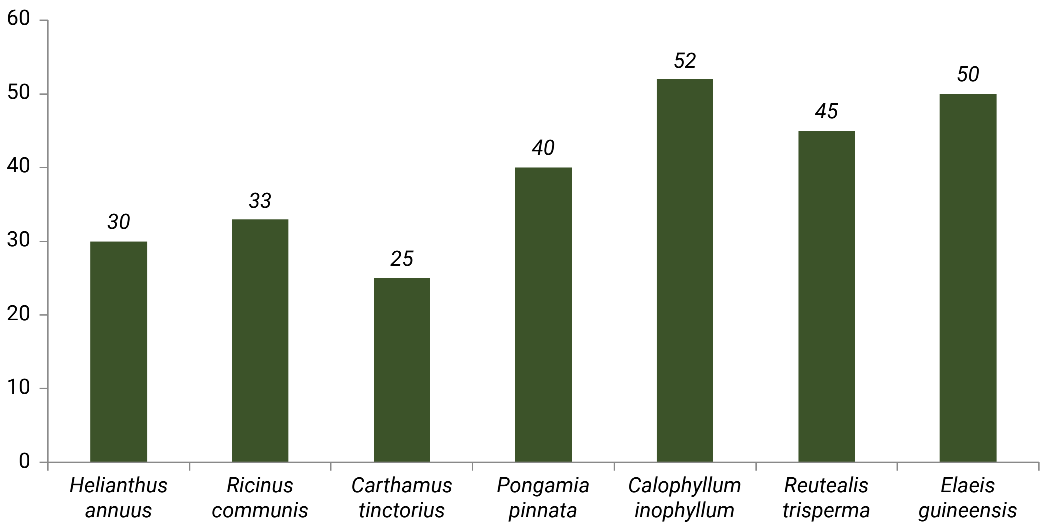

Figure 5. Average percentages of crude oil yielded by pongamia and other biofuel species (Bobade and Khyade 2012)

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	Jayusman 2017
2.	15.92–19.60	Mechanical press	Fabricant screw expeller press	Bulk seed/Banten, Indonesia	Hasnah et al. 2020
3.	14.25–14.67	Mechanical press	Simple screw expeller press	Bulk seed/West Java, Indonesia	Jayusman 2017
4.	13.05–13.23	Mechanical press	Simple screw expeller press	Bulk seed/East Java, Indonesia	Jayusman 2017
5.	24.00–26.00	Mechanical press	Simple screw expeller press	Bulk seed/India	Meher et al. 2008
6.	27.34–39.26	Solvent extraction	Soxhlet extractor	Bulk seed/Banten, Indonesia	Hasnah et al. 2020
7.	26.61–44.68	Solvent extraction	Soxhlet extractor	Individual seed/ Banten, Indonesia	Hasnah et al. 2020
8.	26.30–32.00	Solvent extraction	Soxhlet extractor	Bulk seed/Bali, Indonesia	Arpiwi et al. 2018
9.	28.00–31.00	Solvent extraction	Soxhlet extractor	Bulk seed/Bali, Indonesia	Arpiwi et al. 2017
10.	27.00–39.00	Solvent extraction	Soxhlet extractor	Bulk seed/India	Meher et al. 2008
11.	33.31–39.01	Solvent extraction	Soxhlet extractor	Bulk seed/Madhya Pradesh, India	Rahangdale et al. 2014
12.	28.18–41.32	Solvent extraction	Soxhlet extractor	Bulk seed/Carmen, Philippines	Razal et al. 2012
13.	33.00–40.30	Solvent extraction	Soxhlet extractor	Bulk seed/ Queensland and Northern Territory, Australia	Arpiwi et al. 2013

Pongamia for bio-jet fuel

One potential product from pongamia is bio-jet fuel. Most aircraft are fuelled by conventional jet fuel, which is non-renewable, costly and emits large amounts (80%) of carbon, e.g., one ton of conventional jet fuel emits 0.8 tons of carbon when burned (Hendricks et al. 2011). Therefore, the aviation industry is looking for renewable jet fuels (Hendricks et al. 2011). 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 (Graham et al. 2011). *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 (Murphy et al. 2012), as it can abate 43% of greenhouse gases on a lifecycle basis (Cox et al. 2014).

13.3.2 The potential of pongamia for land restoration

Nutrition enhancement for degraded land

Degraded land is land that has lost its productivity (Lamb 2010). 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 (Ahirwal et al. 2016).

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 (Bohre et al. 2014; Edrisi and Abhilash 2016). 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 (Lal 2010). 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 (Juwarkar and Singh 2010; Singh 2013). Iron, chromium, copper, manganese and magnesium in fly ash dykes have been phytostabilized by establishing pongamia plantations on the dykes (Singh 2013). 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 (Balooni and Singh 2001; Juwarkar and Singh 2010; Lal 2010; Ahirwal 2016).

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 (Kesari et al. 2013). 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 (Chaukiyal et al. 2000; Samuel et al. 2013). 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 (Samuel et al. 2013). Pongamia fixes nitrogen throughout its life (Samuel et al. 2013). 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

(Arpiwi et al. 2013). 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 (Fterich et al. 2014). By using this method, the highest relative effectiveness of rhizobia isolates was 85.9% (Arpiwi et al. 2013).

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 (Biswas and Gresshoff 2014). 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 (Balooni and Singh 2001). Therefore, cultivating pongamia together with agricultural crops has the potential to produce favourable agricultural yields.

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 (Figure 3).

13.3.3 Community involvement

As stakeholders, local communities can be directly affected by fuel shortages, and their potential contributions (Rahman et al. 2017) should be taken into account during pongamia cultivation processes. Such contributions could be overseen through local technical and administrative capacity building (Ostrom 1990; Watts and Colfer 2011) 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 (Nawir and Murniati 2007; Rahman et al. 2017). 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 (Basria and Nabihab 2014).

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.	Islam and Bari 2016
	Pongamia wood is useful for making tool handles, combs, cabinets, cartwheels, posts, agricultural implements and paper pulp	Orwa et al. 2009, Dwivedi et al. 2011
	Pongamia wood is used as fuelwood	Dwivedi et al. 2011
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	Orwa et al. 2009, Sangwan et al. 2010
	A crude decoction of pongamia leaves is used as an antidiarrheal with efficacy against cholera	Brijesh et al. 2006
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, presscake and seedcake contain much protein and are used for poultry feed; but should not exceed 75% of feed as they contain several toxic compounds	Duke 1983, Orwa et al. 2009, Dwivedi et al. 2011
Fertilizer and biogas	The seedcake and leaves are used as fertilizer. Seedcake can generate biogas in household biogas generators	Chandrashekar et al. 2012, Chandrashekar et al. 2017
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)	Kesari and Rangan 2010, Sangwan et al. 2010, Herman 2016, Herman et al. 2013, Modi and Dudani 2013, Shirbhate and Malode 2012, Dutta and Agrawal 2003
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	Kesari and Rangan 2010, Orwa et al. 2009, Dwivedi et al. 2011, Azam et al. 2005, Ahmad et al. 2009, Pranowo and Herman 2016, Herman et al. 2013, Wulandari et al. 2015, Atabani and César 2014, Bridgemohan and Bridgemohan 2014, FAO 2010, Bustomi et al. 2009, Akinerdem and Öztürk 2008, Sumathi et al. 2008

13.4 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 (Rojas 2012). 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 (Scott et al. 2008; Nagarjun and Suryanarayana 2014; Usharan et al. 2019; Kumari et al. 2020). 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 (Angelsen and Kaimowitz 2004; Rojas 2012). Secure land tenure is crucial for the successful implementation of tree-planting activities (Tomich et al. 2002; Rahman et al. 2014). 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 (Ahman et al. 2012). 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 analyse existing conditions, formulate problem-solving strategies, and develop policies for sustainable biofuel (Bappenas 2015). The General National Energy Plan (RUEN) has a number of long- and short-term programmes to support the National Energy Policy (Government Regulation No. 79/2014). RUEN targets to produce 15.6 and 54.2 million kilolitres of biofuel by 2025 and 2050, respectively (Traction Energy Asia 2020). 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 (Maimunah et al. 2018; Rahman et al. 2019).

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 modelling) 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.

13.5 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 (Kharina 2016), has significantly increased the importance of domestic biofuel production (Rahman et al. 2019). 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 (Rahman et al. 2019).

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.

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 x 8	6 x 6	5 x 2	3 x 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

Abadi A et al. 2016. Economics of oil production from Pongamia (*Millettia pinnata*) for biofuel in Australia. *BioEnergy Res* 9: pp. 874–883.

Agus C, Wulandari D, Primananda E and Faridah E. 2017. 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.

Ahirwal J, Maiti SK and Singh AK. 2016. Ecological restoration of coal mine-degraded lands in dry tropical climate: What has been done and what needs to be done? *Environ Qual Manag* 26: pp. 25–36.

Ahmad M, Zafar M, Khan MA and Sultana S. 2009. Biodiesel from *Pongamia pinnata* L. Oil: A promising alternative bioenergy source. *Environ Eff* 31: pp. 1436–1442.

Akinerdem F and Ozturk O. 2008. Safflower and biodiesel quality in Turkey. *In* Proceedings of the 7th International Safflower Conference, New South Wales, Australia, 3–6 November 2008.

Aminah A and Syamsuwida D. 2019. 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. Bristol, UK: IOP Publishing 308, No. 1. pp. 1–8.

Aminah A, Supriyanto S, Suryani A and Siregar IZ. 2017. Genetic diversity of *Pongamia pinnata* (*Millettia pinnata* Aka. *Malapari*) populations in Java Island, Indonesia. *Biodiversitas* 7(18): pp. 677–681.

Angelsen A and Kaimowitz D. 2004. Is agroforestry likely to reduce deforestation? *In* Schroth G, Gustavo AB, Da Fonseca Harvey CA, Gascon C, Vasconcelos HL, Izac AN. eds. *Agroforestry and biodiversity conservation in tropical landscapes.* London, UK: Island Press. pp. 87–106.

Antizar-Ladislao B and Juan LTG. 2008. Second-generation biofuels and local bioenergy systems. *Biofuels Bioprod Biorefining* 2: pp. 455–469.

Arpiwi NL, Negaral MS and Simpen IN. 2017. Selection of high oil yielding trees of *Millettia pinnata* (L.) Panigrahi: Vegetative propagation and growth in the field. *J. Trop. Life Sci*. 7: pp. 258–262.

Arpiwi NL, Wahyuni IGAS, Muksin IK and Sutomo S. 2018. Conservation and selection of plus tree of *Pongamia pinnata* in Bali, Indonesia. *Biodiversitas* 19: pp. 1607–1614.

Arpiwi NL, et al. 2013. Phenotypic and genotypic characterisation of root nodule bacteria nodulating *Millettia pinnata* (L.) Panigrahi: A biodiesel tree. *Plant Soil* 367: pp. 363–377.

Arpiwi NL, Yan G, Elizabeth LB and Julie AP. 2014. Phenology, pollination and seed production of *Milletia pinnata* in Kununurra, Northern Western Australia. *J. Biol. Udayana* 1: pp. 19–23.

Atabani AE and César ADS. 2014. *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.* 37: pp. 644–655.

Azam MM, Waris A and Nahar NM. 2005. Prospects and potential of fatty acid methyl esters of some non-traditional seed oils for use as biodiesel in India. *Biomass Bioenergy* 29: pp. 293–302.

Badan Restorasi Gambut (BRG). 2016. *Penetapan peta indikatif restorasi gambut* (SK. 05/ BRG/KPTS/2016 & lampiran peta indikatif prioritas restorasi). Badan Restorasi Gambut (BRG): Jakarta, Indonesia.

Balooni K and Singh K. 2001. Tree plantations for restoration of degraded lands and greening of India: A case study of tree growers cooperatives. *Nat. Resour. Forum* 25: pp. 21–32.

Bappenas. 2015. Kajian pengembangan bahan bakar nabati (BBN). Government of Indonesia, Jakarta, Indonesia.

Baral H and Lee SM. 2016. Sustainable bioenergy systems to restore and valorize degraded land. Bogor, Indonesia: Center for International Forestry Research (CIFOR).

Basria H and Nabihab AKS. 2014. Accountability of local government: The case of Aceh Province, Indonesia. *Asia Pac. J. Account. Financ*. 3: pp. 1–14.

Biswas B and Gresshoff PM. 2014. The role of symbiotic nitrogen fixation in sustainable production of biofuels. *Int. J. Mol. Sci*. 15: pp. 7380–7397.

Bobade SN and Khyade VB. 2012. Detail study on the properties of *Pongamia pinnata* (*Karanja*) for the production of biofuel. *Res. J. Chem. Sci*. 2: pp. 16–20.

Bohre P, Chaubey OP and Singhal PK. 2014. Biomass production and carbon sequestration by *Pongamia pinnata* (Linn) Pierre in tropical environment. *Int. J. Bio-Sci. Bio-Technol*. 6: pp. 129–140.

Bridgemohan P and Bridgemohan RSH. 2014. Invasive weed risk assessment of three potential bioenergy fuel species. *Int. J. Biodivers. Conserv*. 6: pp. 790–796.

Brijesh S, et al. 2006. Studies on *Pongamia pinnata* (L.) Pierre leaves: Understanding the mechanism(s) of action in infectious diarrhoea. J. Zhejiang Univ. *Sci. B* 7: pp. 665–674.

Bruner J. 2020. Actual minds, possible worlds. Cambridge, MA, USA: Harvard University Press.

Bustomi S, et al. 2009. *Nyamplung (Calopyhllum innopyhllum L.) sumber energi biofuel yang potensial.* Departemen Kehutanan: Jakarta, Indonesia.

Casillas CE and Kammen DM. 2010. The energy-poverty-climate nexus. *Science* 330: pp. 1181–1182.

Chandrashekar LA, Mahesh NS, Gowda B and Hall W. 2012. Life cycle assessment of biodiesel production from pongamia oil in rural Karnataka. *Agric. Eng. Int. CIGR J*. 14: pp. 67–77.

Chaukiyal SP, Sheel SK and Pokhriyal TC. 2000. Effects of seasonal variation and nitrogen treatments on nodulation and nitrogen fixation behaviour in *Pongamia pinnata*. *J. Trop. For. Sci*. 12: pp. 357–368.

Chincholkar SP, et al. 2005. Biodiesel as an alternative fuel for pollution control in diesel engine. *Asian J. Exp. Sci*. 19: pp. 13–22.

Cox K, et al. 2014. Environmental Life Cycle Assessment (LCA) of aviation biofuel from microalgae, *Pongamia pinnata*, and Sugarcane molasses. *Biofuels Bioprod. Biorefining* 8: pp. 579–593.

Csurhes S and Hankamer C. 2016. Invasive plant risk assessment: Pongamia (*Millettia pinnata* Syn. *Pongamia pinnata*). Queensland Government: Queensland, Australia.

Demirbas MF. 2009. Biorefineries for biofuel upgrading: A critical review. *Appl. Ecol*. 86: pp. 151–161.

Djam'an DF. 2009. *Penyebaran dan pembibitan tanaman kranji (Pongamia pinnata Merril) di Indonesia.* Majalah Kehutanan Indonesia Edisi VIII; Departemen Kehutanan: Jakarta, Indonesia.

Doddabasawa PR. 2009. Physio-chemical analysis of biodiesel derived glycerin and saponification of crude glycerin with different concentrations of sodium hydroxide ly. *Int. J. Sci. Res*. 3: pp. 210–212.

Duke JA. 1983. Handbook of energy crops. West Lafayette, IN, USA: Purdue University.

Dutta RK and Agrawal M. 2003. Restoration of opencast coal mine spoil by planting exotic tree species: A case study in dry tropical region. *Ecol. Eng*. 21: pp. 143–151.

Dwivedi G, Jain S and Sharma MP. 2011. Pongamia as a source of biodiesel in India. *Smart Grid Renew. Energy* 2: pp. 184–189.

Dwivedi G and Sharma MP. 2014. Prospects of biodiesel from Pongamia in India. *Renew. Sustain. Energy Rev*. 32: pp. 114–122.

Edrisi SA and Abhilash PC. 2016. Exploring marginal and degraded lands for biomass and bioenergy production: An Indian Scenario. *Renew. Sustain. Energy Rev*. 54: pp. 1537–1551.

FAO. 2010. Agribusiness Handbook: Sunflower Refined and Crude Oils. FAO: Rome, Italy.

Fterich A, Mahdhi M and Mars M. 2014. Seasonal changes of microbiological properties in steppe soils from degraded arid area in Tunisia. *Arid Land Res. Manag*. 28: pp. 49–58.

Garg RK, Chaudhari S and Singh R. 2017. In vitro propagation of potential biodiesel plant, *Pongamia pinnata* (L.) Pierre. *Shrinkhla Ek Shodhparak Vaicharik Patrika* 4: pp. 4.

Gee JP. 1991. Memory and myth: A perspective on narrative. Developing narrative structure. pp. 1–25. Available online: https://psycnet.apa.org/record/1991-97747-000 (Accessed 4 October 2021).

Graham PW, Smart A, Tasman A and Graham P. 2011. Possible futures: Scenario modelling of Australian alternative transport fuels to 2050; CSIRO: Newcastle, Australia.

Hasnah T et al. 2020. Pongamia as a potential biofuel crop: Oil content of *Pongamia pinnata* 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.

Hassan MH and Kalam MA. 2013. An overview of biofuel as a renewable energy source: Development and Challenges. *Procedia Eng*. 56: pp. 39–53.

Hendricks RC, Bushnell DM and Shouse DT. 2011. Aviation fuelling: A cleaner, greener approach. *Int. J. Rotating Mach*. pp. 782–969.

Herman M, Syakir M, Pranowo D and Saefudin S. 2013. *Kemiri Sunan (Reutalis trisperma (Blanco) Airy Shaw) tanaman penghasil minyak nabati dan konservasi lahan.* Indonesian Centre for Estate Crops Research and Development: Bogor, Indonesia.

Hidayat AS. 2005. *Konsumsi BBM dan peluang pengembangan energi alternatif. Inovasi* 5: pp. 11–17.

IEA. 2011. Technology Roadmap Biofuels for Transport. Available online: https://www.iea.org/reports/technology-roadmap-biofuels-for-transport (Accessed 4 October 2021).

IPCC. 2012. Renewable energy sources and climate change mitigation. *In* Edenhofer O, Madruga RP, Sokona Y, Seyboth K, Eickemeier P, Matschoss P, Hansen G, Kadner S, Schlomer S, Wickel T, et al. eds. *Special Report of the Intergovernmental Panel on Climate Change.* Cambridge, UK: Cambridge University Press.

Islam MA and Bari R. 2016. Flat pressed *Pongamia pinnata* wood-flour/polypropylene composite loaded with talc: A statistical optimization. J*. Indian Acad. Wood Sci*. 13: pp. 91–100.

Jaung W et al. 2018. Spatial assessment of degraded lands for biofuel production in Indonesia. *Sustainability* 10: pp. 45–95.

Jayusman J. 2017. *Peta sebaran malapari (Pongamia pinnata Merril) di Pulau Jawa dan upaya konservasinya.*Prosiding Seminar Nasional Pendidikan Biologi dan Saintek II. Surakarta, Indonesia: Universitas Muhammadiyah Surakarta (UMS).

Juwarkar AA and Singh SK. 2010. Microbe-assisted phytoremediation approach for ecological restoration of zinc mine spoil dump. *Int. J. Environ. Pollut*. 43: pp. 236.

Kesari V, Ramesh AM and Rangan L. 2013. Rhizobium Pongamiae Sp. Nov. from root nodules of Pongamia pinnata. *BioMed Res. Int*. 2013: pp. 165–198.

Kesari V and Rangan L. 2010. Development of *Pongamia pinnata* as an alternative biofuel crop—current status and scope of plantations in India. *J. Crop Sci. Biotechnol*. 13: pp. 127–137.

Kharina A, Malins C and Searle S. 2016. Biofuels policy in Indonesia: Overview and status report. The International Council on Clean Transportation: Beijing, China.

Kotarumalos NA. 2009. *Menuju ketahanan energi Indonesia: Belajar dari negara lain. J. Glob. Dan Strateg*. 3: pp. 1–18.

Kumari J, Tripathy MK and Das H. 2020. 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*. 9: pp. 1577–1596.

Lal R. 2006. Land area for establishing biofuel plantations. *Energy Sustain. Dev*. 10: pp. 67–79.

Lamb D. 2010. Regreening the bare hills: Tropical forest restoration in the Asia-Pacific region. London, UK: Springer Science and Business Media.

Leksono B, Hendrati RL, Windyarini E and Hasnah T. 2014. Variation of biofuel potential of 12 *Calopyllum inophyllum* populations in Indonesia. *Indones. J. For. Res*. 1: pp. 127–138.

Leksono B, Windyarini E and Hasnah T. 2017. 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 Innovation Agency, Yogyakarta, Indonesia. 24–27 July 2017. pp. 163–174.

Lewis SM and Kelly M. 2014. Mapping the potential for biofuel production on marginal lands: Differences in definitions, data and models across cales. *ISPRS Int. J. Geo-Inf*. 3: pp. 430–459.

Lynd LR et al. 2015. Bioenergy and African transformation. *Biotechnol. Biofuels* 8: pp. 1–8.

Maimunah S et al. 2018. Assessment of suitability of tree species for bioenergy production on burned and degraded peatlands in Central Kalimantan, Indonesia. *Land* 7: pp. 115.

Malla S. 2013. Household energy consumption patterns and its environmental implications: Assessment of energy access and poverty in Nepal. *Energy Policy* 61: pp. 990–1002.

Meher LC, Naik SN, Naik MK and Dalai AK. 2008. Biodiesel production using Karanja (*Pongamia pinnata*) and Jatropha (*Jatropha curcas*) seed oil. Handbook of Plant-Based Biofuel. pp. 255–266. Boca Raton, FL, USA: CRC Press.

Modi NR and Dudani SN. 2013. Biodiversity conservation through urban green spaces: A case study of Gujarat University Campus in Ahmedabad. *Int. J. Conserv. Sci*. 4: pp. 189–196.

Murphy HT et al. 2012. A common view of the opportunities, challenges, and research actions for Pongamia in Australia. *Bioenergy Res*. 5: pp. 778–800.

Nabi MN, Hoque SMN and Akhter MS. 2009. Karanja (*Pongamia pinnata*) biodiesel production in Bangladesh, characterization of karanja biodiesel and its effect on diesel emissions. *Fuel Process. Technol*. 90: pp. 1080–1086.

Nagarjun N and Suryanarayana V. 2014. Documentation of nursery diseases of *Pongamia pinnata* and developing effective management package in Haveri Forest Division. Available online: http://www.kscst.iisc.ernet.in/spp/37_series/spp37s/synopsis_biofuel/msc/37S_B_MSc_006.pdf (Accessed 15 April 2021).

Nawir AA and Murniati RL. 2007. Forest rehabilitation in Indonesia: Where to after three decades? Bogor, Indonesia: Center for International Forestry Research (CIFOR).

Ogunkule O and Ahmed NA. 2021. Review overview of biodiesel combustion in mitigating the adverse impacts of engine emissions on the sustainable human–environment scenario. *Sustainability* 13: pp. 54–65.

Orwa C et al. 2009. Agroforestree database: A tree reference and selection guide version 4.0. Nairobi, Kenya: ICRAF.

Ostrom E. 1990. Governing the commons: The evaluation of institutions for collective action. Cambridge, UK: Cambridge University Press.

Pandey VC et al. 2012. *Jatropha curcas*: A potential biofuel plant for sustainable environmental development. *Renew. Sustain. Energy Rev*. 16: pp. 2870–2883.

Patil VK, Bhandare P, Kulkarni PB and Naik GR. 2015. Progeny evaluation of *Jatropha curcas* and *Pongamia pinnata* with comparison to bioproductivity and biodiesel parameters. *J. For. Res*. 26: pp. 137–142.

Pena DS, Evangelista AWP, Júnior JA and Casaroli D. 2016. Agroclimatic zoning for Jatropha crop (*Jatropha curcas*, L.) in the State of Goiás. *Acta Sci. Agron*. 38: pp. 329–335.

Pranowo D and Herman M. 2016. *Potensi pengembangan Kemiri Sunan (Reutealis Trisperma (Blanco) Airy Shaw) di lahan terdegradasi. Perspektif* 14: pp. 87–102.

Prasad SS and Singh A. 2020. Economic feasibility of biodiesel production from pongamia oil on the Island of Vanua Levu. *SN Appl. Sci*. 2: pp. 1086.

Rahangdale CP, Koshta LD and Patle NK. 2014. Provenance variation for oil content and fatty acid composition in seed of *Pongamia pinnata* (L.) Pierre. *Int. J. Proj. Manag*. 4: pp. 1–8.

Rahman MM, Ahiduzzaman M, Islam AKMS and Blanchard R. 2014. 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.

Rahman SA, et al. 2019. Integrating bioenergy and food production on degraded landscapes in Indonesia for improved socioeconomic and environmental outcomes. *Food Energy Secur*. 8: pp. e00165.

Rahman SA, Rahman MF and Sunderland T. 2012. Causes and consequences of shifting cultivation and its alternative in the hill tracts of Eastern Bangladesh. *Agrofor. Syst*. 84: pp. 141–155.

Rahman SA, Rahman MF and Sunderland T. 2014. Increasing tree cover in degrading landscapes: 'Integration' and 'intensification' of smallholder forest culture in the Alutilla Valley, Matiranga, Bangladesh. *Small-Scale For*. 13: pp. 237–249.

Rahman SA, Sunderland T, Roshetko JM and Healey JR. 2017. Facilitating smallholder tree farming in fragmented tropical landscapes: Challenges and potentials for sustainable land management. *J. Environ. Manag*. 198: pp. 110–121.

Ramachandran A and Radhapriya P. 2016. Restoration of degraded soil in the Nanmangalam Reserve Forest with native tree species: Effect of indigenous plant growth-promoting bacteria. *Sci. World J*: pp. 1–9.

Razal R et al. 2012. Solvent extraction of oil from bani (*Pongamia pinnata* (L.) Pierre) seeds. Philipp. *J. Crop Sci*. 37: pp. 1–7.

Republic of Indonesia. 2014. Peraturan Pemerintah Republik Indonesia Nomor 79 Tahun 2014. Republic of Indonesia: Jakarta, Indonesia.

Riessman CK. 1993. Narrative analysis. London, UK: Sage Publication.

Rojas GI. 2012. What's wrong with tree plantations? Available online: https://news.mongabay.com/2012/09/whats-wrong-with-tree-plantations/ (accessed 18 February 2021).

Samsudin YB et al. 2020. Community-based peat swamp restoration through agroforestry in Indonesia. *In* Dagar JC, Gupta SR, Teketay D. eds. *Agroforestry for degraded landscapes: Recent advances and emerging challenges book series.* Singapore: Springer. pp. 349–365.

Samuel S, Scott PT and Gresshoff PM. 2013. Nodulation in the legume biofuel feedstock tree *Pongamia pinnata*. *Agric. Res*. 2: pp. 207–214.

Sangwan S, Rao DV and Sharma RA. 2010. A review on *Pongamia pinnata* (L.) Pierre: A great versatile leguminous plant. *Nat. Sci*. 8: pp. 130–139.

Scott PT, et al. 2008. *Pongamia pinnata*: An untapped resource for the biofuels industry of the future. *BioEnergy Res*. 1: pp. 2–11.

Shirbhate N and Malode S. 2012. 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*. 2: pp. 147–152.

Sidiyasa K, Sitepu BS and Atmoko T. 2012. *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.

Singh A. 2013. Comparative performance and restoration potential of *Jatropha curcas* and *Pongamia pinnata* on degraded soil of North India. Lucknow, India: University of Lucknow.

Smith CP. 2000. Content analysis and narrative analysis. *In* Reis HT, Judd CM. eds. *Handbook of Research Methods in Social and Personality Psychology.* pp. 313–335. New York, NY, USA: Cambridge University Press.

Sumathi S, Chai SP and Mohamed AR. 2008. Utilization of oil palm as a source of renewable energy in Malaysia. *Renew. Sustain. Energy Rev*. 12: pp. 2404–2421.

The Ministry of Environment and Forestry. 2019. Statistics of Ministry of Environment and Forestry, 2018. The Ministry of Environment and Forestry: Jakarta, Indonesia.

The Ministry of Environment and Forestry. 2016. Statistics of Ministry of Environment and Forestry, 2015. The Ministry of Environment and Forestry: Jakarta, Indonesia.

The Ministry of Environment and Forestry. 2018. Statistics of Ministry of Environment and Forestry, 2017. The Ministry of Environment and Forestry: Jakarta, Indonesia.

Tomich TP, et al. 2002. Carbon offsets for conservation and development in Indonesia? *Am. J. Altern. Agric*. 17: pp. 125–137.

Traction Energy Asia. 2020. *Pemanfaatan dan pengelolaan biofuel (biodiesel): Pembelajaran dan praktik baik dari berbagai negara.* Working Paper 2: Jakarta, Indonesia.

Usharani KV, Naik D and Manjunatha RL. 2019. *Pongamia pinnata* (L.): Composition and advantages in agriculture: A review. *J. Pharmacogn. Phytochem*. 8: pp. 2181–2187.

Watts J and Colfer CJ. 2011. The governance of tropical forested landscape. *In* Colfer CJ, Pfund J. eds. *Collaborative governance of tropical landscapes.* pp. 35–54. London, UK: Earthscan.

Wulandari WS, Darusman D, Kusmana C and Widiatmaka W. 2015. *Kajian finansial pengembangan biodiesel kemiri Sunan (Reutealis Trisperma (Blanco) Airy Shaw) pada lahan tersedia di Jawa Barat. J. Penelit. Sos. Dan Ekon. Kehutan*. 12: pp. 31–42.