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A Common View of the Opportunities, Challenges, and Research Actions for Pongamia in Australia

**Helen T. Murphy · Deborah A. O'Connell ·
Gary Seaton · R. John Raison · Luis C. Rodriguez ·
Andrew L. Braid · Darren J. Kriticos · Tom Jovanovic ·
Amir Abadi · Michael Betar · Heather Brodie ·
Malcolm Lamont · Marshall McKay ·
George Muirhead · Julie Plummer · Ni Luh Arpiwi ·
Brian Ruddle · Sagun Saxena · Paul T. Scott ·
Colin Stucley · Bob Thistlethwaite · Bradley Wheaton ·
Peter Wylie · Peter M. Gresshoff**

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Abstract Interest in biofuels is increasing in Australia due to volatile and rising oil prices, the need to reduce GHG emissions, and the recent introduction of a price on carbon. The seeds of Pongamia (*Millettia pinnata*) contain oils rich in C18:1 fatty acid, making it useful for the manufacture of biodiesel and other liquid fuels. Preliminary assessments of growth and seed yield in Australia have been promising. However, there is a pressing need to synthesise practical experience and existing fragmented research and to use this to underpin a well-founded and co-ordinated research strategy to support industry development, including better management of the risks associated with investment. This comprehensive review identifies opportunities for Pongamia in Australia and provides a snapshot of what is already known and the risks,

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H. T. Murphy (✉)
CSIRO Ecosystem Sciences, Tropical Forest Research Centre,
PO Box 780, Atherton, QLD 4883, Australia
e-mail: Helen.Murphy@csiro.au

D. A. O'Connell · R. J. Raison · L. C. Rodriguez · A. L. Braid ·
D. J. Kriticos · T. Jovanovic
CSIRO Ecosystem Sciences,
GPO Box 1600, Canberra, ACT 2601, Australia

G. Seaton · G. Muirhead
Bioenergy Plantations Australia,
PO Box 1127, Caboolture, QLD 4510, Australia

A. Abadi
CRC Future Farm Industries, University of Western Australia,
Nedlands, WA 6907, Australia

M. Betar
Standard Commodities Group,
Suite 101, 274-290 Victoria Street,
Darlinghurst, NSW 2010, Australia

H. Brodie
Biofuels Association of Australia,
28 Elaroo Street,
Morningside, QLD 4170, Australia

M. Lamont · B. Thistlethwaite
PolyGenomX Ltd,
Level 4, 130 Bundall Road,
Bundall, QLD 4217, Australia

M. McKay
Australian PhytoFuel Company,
95 Simpsons Road,
Bardon, QLD 4065, Australia

J. Plummer · N. L. Arpiwi
Plant Biology, Faculty of Natural & Agricultural Sciences,
University of Western Australia,
35 Stirling Hwy,
Crawley, WA 6009, Australia

B. Ruddle
Rudco Pty Ltd,
Level 1, 686 Sherwood Road,
Sherwood, QLD 4075, Australia

S. Saxena · B. Wheaton
CleanStar Ventures,
Level 29, The Chifley Tower, 2 Chifley Square,
Sydney, NSW 2000, Australia

uncertainties, and challenges based on published research, expert knowledge, and industry experience. We conclude that whilst there are major gaps in fundamental understanding of the limitations to growth of Pongamia in Australia, there is sufficient evidence indicating the potential of Pongamia as a feedstock for production of biofuel to warrant investment into a structured research and development program over the next decade. We identify ten critical research elements and propose a comprehensive research approach that links molecular level genetic research, paddock scale agronomic studies, landscape scale investigations, and new production systems and value chains into a range of aspects of sustainability.

Keywords Oil seed · Pongamia · *Millettia* · Karanja · Yield · Growth

Introduction

Interest in use of biomass for liquid fuels, electricity, and other products is increasing in Australia due to volatile and increasing oil prices, the pressing need to reduce GHG emissions, and the introduction of a price on carbon. Current production of plant-based oils in Australia is relatively small and could only make a very small contribution to demand for liquid fuels [21, 44]. Many options are being explored to develop new capacity to produce plant-based oils, including those based on algae and oilseed.

Pongamia (*Millettia pinnata,* formerly known as *Pongamia pinnata)* is an arboreal legume belonging to the family Papilionoideae. The Pongamia tree has traditionally been utilised for medicines, fodder, beautification, and shade. Pongamia oil has long been used for lanterns and cooking stove fuel and is currently of major interest for biofuel production [30, 41, 59]. The seeds contain about 40% extractable oil depending on the extraction method, i.e., either solvent (hexane) extraction or cold pressing [4, 40, 66]. The oil is rich in C18:1 fatty acid (oleic acid) and has relatively low amounts of palmitic and stearic acid, making it useful for the manufacture of biodiesel [30, 61]. The presence of toxic flavonoids makes the oil non-edible [38].

Preliminary research on the potential for Pongamia cultivation in Australia has been promising [30, 59], but research and development effort is highly fragmented, operating at small scales, and usually underfunded [53]. Recent attempts to estimate the production potential of Pongamia at a national scale [21, 34, 46] have found that whilst suitable growing areas for Pongamia could be broadly modelled using a climate matching approach, there is insufficient published or reliable information relevant to Australia to provide quantitative relationships between genetics, growing environment, seed set, and oil yield. The recent failure of *Jatropha* spp., another oilseed candidate [29] widely planted in Asia and Africa for biodiesel, clearly demonstrates the risks of embarking upon a large-scale investment and planting program without first conducting the sort of R&D program described in this paper. Widespread optimism over potential oil yields (which have mostly not been realised), and massive investment in planting programs without a solid R&D foundation, has resulted in enormous economic losses to investors in the Jatropha industry. In particular, a lack of knowledge about the environment × genetic × yield relationship in Jatropha is considered a key driver of widespread crop failure [6, 29]. There is a clear need to consolidate current knowledge and attract the requisite quantum of investment in research and development to underpin industry development for Pongamia in Australia.

This paper has been prepared by the representatives of 14 industry and research groups working together to synthesise published information, industry experience, and other expert knowledge to reach a consensus about the future opportunities and challenges for Pongamia in Australia. In some cases, particularly for data pertaining to oil yield from seeds, much higher and unsubstantiated estimates can be sourced from the websites of some companies promoting Pongamia in Australia. For the purpose of this paper, we take a conservative approach and report figures that have been reported in peer-reviewed literature, data collected in field trials conducted by the industry, and research stakeholders contributing to this paper, or where there was wide consensus among the group.

In summary, this review describes the opportunities for Pongamia in Australia, a snapshot of what is already known, the risks, uncertainties and challenges, and key priorities for new research and development. This synthesis can be used to underpin a well-founded and co-ordinated research strategy to support industry development.

Pongamia and its Distribution

Pongamia (*M. pinnata* (L.) Panigraphi) [26] is a medium-sized (10 to 15 m), leguminous tree; general features are shown in Fig. 1. Common names include Indian-beech, ponga-oil-tree, Karanja tree, karum, and kanji, and the plant has been synonymously known as *Pongamia pinnata* Merr.,

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P. T. Scott · P. M. Gresshoff
ARC Centre of Excellence for Integrative Legume Research,
University of Queensland,
St Lucia,
Brisbane, QLD 4072, Australia

C. Stucley
Enecon Pty Ltd,
PO Box 175, Surrey Hills, VIC 3127, Australia

P. Wylie
Origin Energy,
GPO Box 148, Brisbane, QLD 4001, Australia

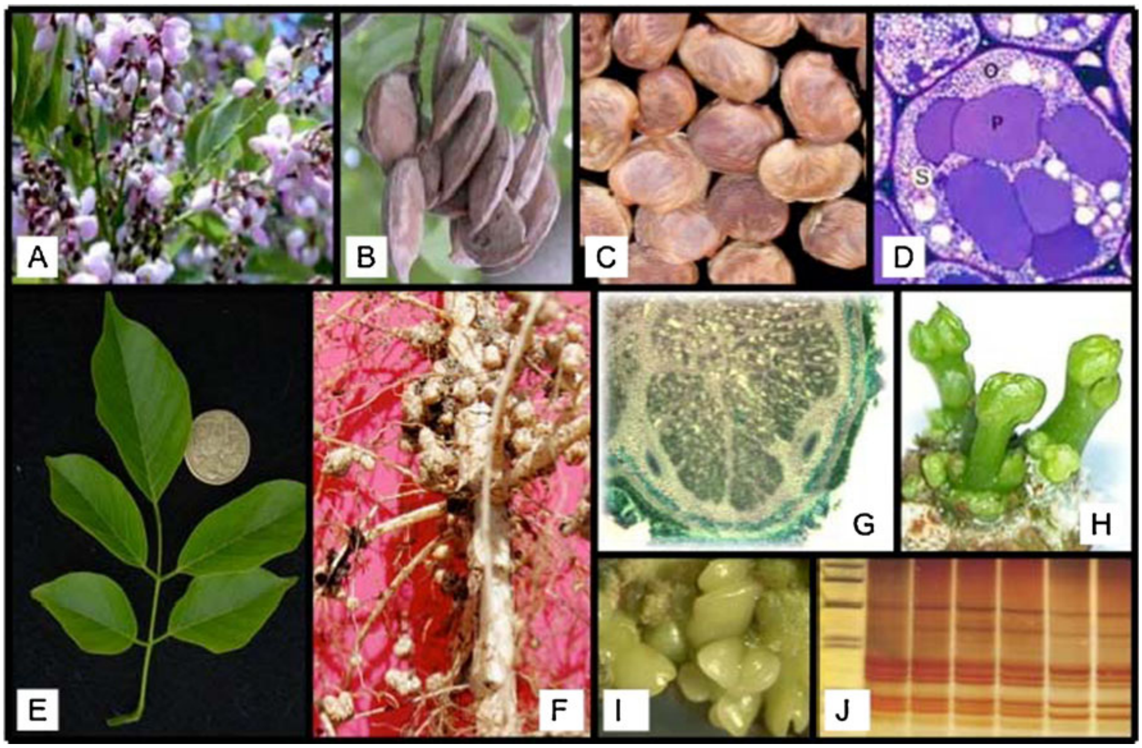


Fig. 1 *Millettia pinnata*: **a** abundant flowers in November/December (southern hemisphere), pea-like flowers are clustered and pink to mauve; **b** clustered seed pods in August/September (southern hemisphere) appear on about 15–35% of flowers and are gray/brownish with either single or double seeds; **c** mature seeds (1.6 g average); **d** seed storage cell showing large protein bodies (P), oil vesicles (O), and starch grains (S) (photograph courtesy of Prof. Ray Rose, Univ. of Newcastle); **e** pinnate foliage, leaves are waxy, dark-green, and arranged in 5 or 7 leaflet pinnate leaves; **f** well-nodulated root system showing determinate nodules (which in later stages may develop branched structures); **g** microscopic section of a Pongamia nodule showing infected central tissues, interstitial cells, and vascular bundles in the periphery; **h** multiple bud culture leading to clonal regenerants (Q. Jiang, CILR, unpublished data); **i** early stages of somatic embryogenesis from Pongamia immature cotyledons (B. Biswas, CILR, UQ, unpublished data); **j** DNA profiling of clonal Pongamia plants using Pongamia-derived Interstitial Single Sequence Repeat (PISSR) amplification and DNA silver staining ([7, 28])

Pongamia glabra Vent., *Derris indica* (Lam) Bennett, and *Millettia novo-guineensis* [59]. The extent of Pongamia's native range is uncertain due to a long history of cultivation and transport, but the species is generally considered native to the Indian sub-continent through central and south-east Asia to northern Australia [17]. Pongamia is reported as naturalised in China, Malaysia, Indonesia, Japan, Vietnam, and the United States (Fig. 2).

In Australia, Pongamia occurs in the northern tropics and subtropical east coast ranging from the coastal fringe around Darwin through Cape York and as far south as northern NSW. Records further inland are from locations along major rivers including the Wenlock, Archer, and Holroyd Rivers in the Cape York area, and the Norman River in the Gulf of Carpentaria. The attractive architecture of Pongamia has seen it become a common street tree in and around Brisbane and smaller towns and cities along the east coast of Queensland.

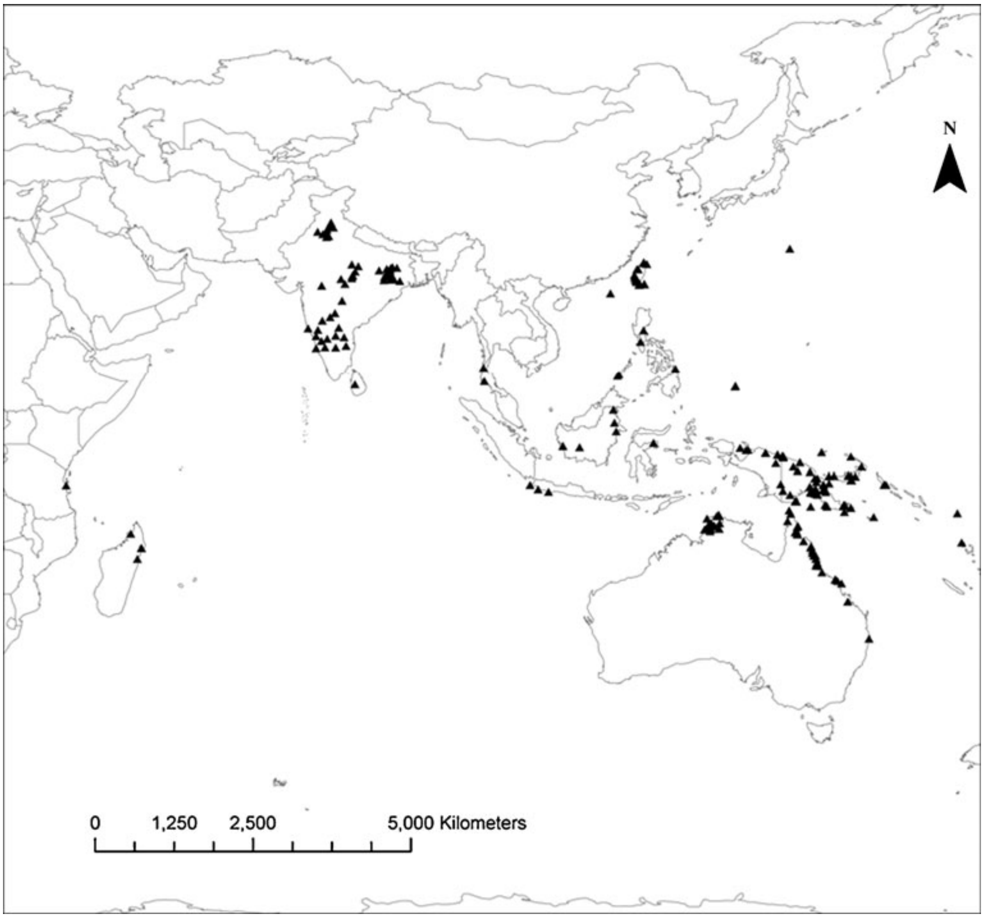
A number of trial plantations have been established throughout Queensland, in the Northern Territory, and in Western Australia (Fig. 3). The largest commercial trial site (300 ha) was established near Roma in central Queensland in 2010 on a coal seam gas site; the longest running trial plantations were established in Western Australia in 1999 by the Forest Products Commission at the Frank Wise Institute in Kununurra and in Queensland near Caboolture in 2007/8. Seeds for the Western Australian collection were purportedly sourced from India but details have been lost. Most Queensland seed material is derived from trees growing on Brisbane streets which may have been originally sourced from the Indian subcontinent.

The Opportunities

Regional Power Generation/Opportunities

A number of opportunities exist for regional power generation either via biomass conversion to electricity or by running diesel generators with Pongamia oil either as raw oil or after conversion to biodiesel. For example, Ergon Energy runs and operates 33 diesel-fired generators that service remote communities in Queensland and the Torres Strait (http://www.ergon.com.au/community–and–our-network/network-management-and-

Fig. 2 Distribution of *Millettia pinnata*; not shown are several records from the USA (Florida and Hawaii) and central America. Source: GBIF (accessed through GBIF Data Portal, data.gbif.org, 2011-06-01) and records from India extracted from [20, 25, 48, 56, 57]



projects/isolated-and-remote-power-stations). In large part, these areas are also climatically suitable for Pongamia growth [34]. A number of mining companies in northern Australia also generate their own power using diesel generators that could be fuelled by Pongamia oil.

Transport Fuels in Australia

About 41 % of energy use in Australia is by the transport sector. Most domestic passenger and freight trips are undertaken in road vehicles, which account for 75 % of transport fuel use. Air

Fig. 3 A 28-month-old trial plantation site near Caboolture, southern Queensland

transport is the second highest consumer (16%) followed by water (4%) and rail transport (2%) [15]. The demand for transport energy is growing at about 2.4% per year [15].

Forecasts by the International Energy Agency (IEA) and many other energy forecasting organisations indicate a future real oil price range of US$100 per barrel between 2015 and 2020, increasing to US$160 per barrel by 2050 [15]. Australian petroleum net imports in 2009–10 were valued at A$14 billion [1], and Australia's petroleum self sufficiency (2009–10) is currently 59%. This is expected to decline to 24% by 2030 [1, 2, 23]. If oil production declines and oil prices increase as expected, by 2029–2030, net oil imports could cost Australia almost A$70 billion per annum in real terms [16].

The Future Fuels Forum [15] modelled Australia's future fuel mix and projected that there will be a more diverse fuel mix in road, rail, air, and sea passenger and freight travel. Electricity, liquefied petroleum gas (LPG), natural gas, and advanced biofuels are expected to increase in use once production infrastructure has had sufficient time to scale up [15]. The extent of their use will depend on primary fuel prices and government greenhouse gas emission targets. The CSIRO study [15] did not consider biodiesel or aviation fuel from Pongamia due to the limited information on which to make reliable projections.

Passenger vehicles powered by diesel engines are gaining greater acceptance, and most heavy machinery as well as marine and rail transport depends on high powered diesel engines. In addition, mining companies are realising the benefit of using bio-based diesel in their underground mines because biodiesel fuels generally emit lower particulates in comparison to fossil-based fuels [8], thus improving the health and safety outcomes for air quality in underground mines.

Aviation

The aviation industry has recognised that bio-derived jet fuels are an essential part of the industry's future greenhouse gas emission reduction strategy. Biofuel blends have been used in numerous test flights of commercial aeroplanes and military jets, using oils from *Camelina sativa*, *Jatropha* spp, algae, and oil palm. Pongamia oil has not been tested but with increasing seed supply, chemical and engine testing is being planned for the near future.

There are a number of ways that jet fuel can be produced from bio-based oil or from lignocellulosic feedstocks. The conversion pathway to convert plant-based oils using hydrodeoxygenation is more efficient (65%) than for other pathways based on lignocellulosic feedstocks and can potentially be conducted with some modification of modern oil refineries [16]. Therefore, this pathway to jet fuel has a lower capital intensity and is very attractive to the aviation industry [16]. However, due to the very low production of plant oils in Australia, new non-food sources of oil would be required to realise this pathway to jet fuel. Unlike the Future Fuels Forum [15], the CSIRO Sustainable Aviation Fuel Road Map study [16] did include the potential for Pongamia, but the information used was extremely uncertain [21] and therefore the estimates were very conservative. However, the study specifically recommended that production of plant-based oils be further assessed.

GHG Mitigation and Carbon Sequestration

Pongamia plantations and biodiesel production have the potential to reduce GHG emissions by displacing fossil fuels consumption and combustion. If Pongamia plantations are established on previously cleared land, there may also be a sequestration benefit through storage of carbon (C) in long-lived tree biomass, possible increase in soil C stocks, and use of husks and prunings to create biochar. In addition, because Pongamia is a legume, there are likely to be lower GHG emissions in comparison to non-legume oil production because the need for nitrogen fertilisers may be reduced. The opportunity may present under future policy developments (for example, the Carbon Farming Initiative Australian Government 2011 [5]) for the grower to be able to access carbon payments for Pongamia plantations).

Realising the Opportunities

There are many overarching challenges to be addressed to assess whether, how, where, and when the opportunities outlined above could be realised. Pongamia is in the very early stages of development as a commercial species. Investors in R&D and implementation, governments, industry developers, and communities of interest will benefit from a review of the knowledge base and gaps and a cohesive national research strategy.

In the following sections, we outline ten key elements of a comprehensive research strategy, briefly review the existing knowledge about those elements, and identify important knowledge gaps and the actions needed to fill the gaps.

Element 1: Growth, Survival, and Reproduction in Contrasting Biophysical Environments

Growth

Pongamia growth potential is being assessed in several field trials in south-east Queensland, Western Australia, and the Northern Territory. However, only a small number of plantings have been designed to capture quantitative data on growth and seed yield. Here, we report on some preliminary observations from a few plantations in southern Queensland (Gatton in Brisbane, Yandina, Eudlo and Caboolture on the Sunshine

Coast and Hinterland, and Roma in south-central Queensland) and from a plantation at Kununurra in the east Kimberley area in northern Western Australia.

The University of Queensland, through the ARC Centre of Excellence for Integrative Legume Research (CILR), planted sapling material at the University of Queensland, Gatton Campus in December 2008. The seeds were derived from street trees under licence from Brisbane City Council. Plantings were monitored for tree failure and replacement seedlings were planted after 1 year. Growth results (Fig. 4) indicate rapid biomass increases for both root and above-ground tissues. Above-ground biomass increased to over 3 kg per tree (above-ground mass) after 2 years.

Rainfall

Experts agreed that average annual minimum rainfall between 500 and 800 mm was required for persistence of Pongamia, with a further requirement for irrigation during the establishment stage (discussed in more detail under "Element 7: Agronomy"). Roots are generally fast growing and thick. Within 2 years, plants appear to have reached deeper soil layers and trees are able to tolerate periods of water deficit without wilting. Established trees (6–10 years) survived 4 months without rain in Brisbane during the 2007–8 drought.

Pongamia seed yield is severely affected by heavy rain periods during the time of flowering. Heavy rain occurred in south-east Queensland in November/December 2010, leading to floods in Brisbane and surrounding districts. Extensive flowering occurred in Brisbane, the Lockyer Valley and Caboolture, but flowers collapsed either because of rain or absence of insect pollination. Less than 5% of flowers yielded a seed-bearing pod. Pongamia develops flowers of different maturity stages along each florescence, which may be an adaptation to adverse conditions. However, prolonged adverse conditions nullify this reproductive strategy. Plants severely affected by spring rain are observed to re-flower in early March (as the photoperiod matches that of the spring period). It is unknown whether the late summer flowers will carry seed which will mature in time for harvest.

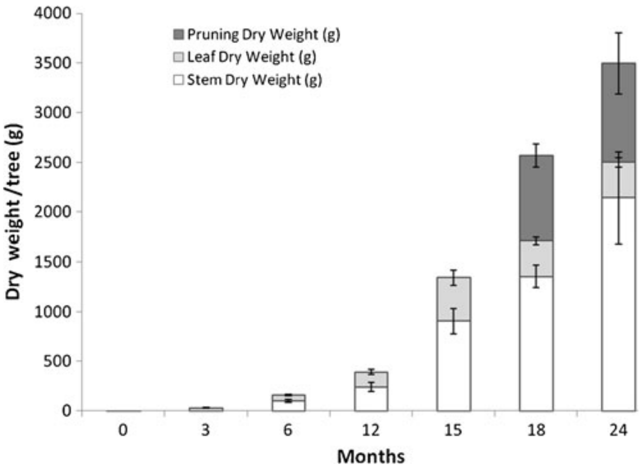


Fig. 4 Above-ground biomass (g dry weight/tree±1 SD) of Pongamia growing at Gatton, south-east Queensland. Plants are irrigated as required and unfertilised. Soil is rich, volcanic loam (P. Scott, CILR, unpublished data)

Mature plants appear to survive moderate water-logging, though some mortality occurs. Trees maintained in polybags during the 2011 Brisbane floods survived inundation for 3 days at a depth of 3–4 m. The same was observed for sapling trees in Yandina (southern Queensland) when the Maroochy River flooded because of heavy rainfall and a king tide. Under controlled glasshouse conditions at the Forest Products Commission nursery in Perth, seedlings survive waterlogging in fresh water; however, waterlogging in saline water (≥250 mM NaCl) causes nearly complete mortality [4, 51].

Temperature

Across the current Australian trial plantation sites, high temperatures are common. For example, in Kununurra (north Western Australia), average monthly maxima range from 30 to 39°C, and maximum temperatures can exceed 45°C [10]. Pongamia saplings and cuttings (60 cm in height) maintained in a greenhouse, the temperature control unit of which failed during the 2011 Brisbane flood, survived 65°C, though ample water was available. While Pongamia appears to tolerate these high temperatures, the impact of extreme heat combined with drought on mature plants is unclear. In India, maximum temperatures throughout Pongamia's distribution range from 27 to 38°C [41]. This agrees in general with Australian observations, though a distinction needs to be made between suitable conditions for tree growth and production of oil, as opposed to suitable conditions for persistence of natural stands. For example, the plantation site near Roma in south-west Queensland appears to be suitable for Pongamia oil production under irrigation (600 mm average rainfall, 2,200 mm evaporation), although it is not within the range of climatic conditions that naturalised populations of the species occur [34].

In Australia, Pongamia is cold- and possibly drought-deciduous, undergoing a winter dormancy period. Night-time temperatures appear critical in regulating Pongamia phenology. Observations suggest that plants do not grow new leaves in spring until minimum temperatures are consistently greater than 15°C, and that at least 6 months of minimum temperatures > 15°C are required for substantial foliage, flower, and seed production.

Pongamia has been observed to survive and recover from frost events. However, experts agreed that the species should not generally be considered 'frost tolerant'. At the Spring Gully coal seam gas plantation site near Roma in Queensland, a late frost occurred in September 2009 after the winter dormancy period (i.e., trees had already put on new leaves).

Leaf blackening and abscission were observed after the frost but trees were able to undergo profuse vegetative growth again in October. Stem mortality occurred primarily in young trees. About 20% of sapling material suffered from stem tip die-back (10–30 cm), which did not appear to result in any negative growth effect during the subsequent season. These observations are generally consistent with reports from India that indicate the tree can withstand ‘slight’ frost [41, 52]. However, experts noted that frosts have been observed to result in sprouting from the base of saplings that suffer stem mortality, which is undesirable from a production efficiency perspective. Ideally, in a commercial setting, frost-damaged saplings are replaced by retained nursery stock; replanting at this early stage (year 1) does not appear to affect final plantation uniformity.

Currently, very little is understood about the effect of extreme weather, including drought, frost, flooding, cyclones, or extreme heat on Pongamia seed production and oil yield. In addition, fire may pose a risk to Pongamia plantations in some areas identified as potentially suitable; the impact of fire on Pongamia has not been assessed.

Action: Field measures of growth and seed production across climatic and soil fertility gradients should be used to calibrate simple models (e.g., CLIMEX [67]) that could be used to provide estimates of plantation performance in Australia. Impacts of extreme events on Pongamia performance need to be assessed.

Phenology and Reproduction

Plants are commonly observed to flower after 4–5 years and usually only once per year. Some precocious flowering has been observed by experts—for example approximately 6% of trees flowered and produced seed in the second year in a trial planting at Gatton in southern Queensland. A very small number of observations have been made of two flowering episodes per year. Individual flowers open for only a single day, though multiple stages of maturity exist along the same florescence. Pongamia requires tripping (i.e., forcing the pistil from its concealed position within the petals of the flower) for pollination to occur, and the main agents are bees [54]. Trials at Kununurra indicated that the peak flowering period varied between trees and that the presence of bee hives substantially improved seed set and yield.

In general, and depending on location and winter dormancy, Pongamia starts producing pods 4–7 years after planting with full production from about 10 years of age. Some plants have been observed producing seed pods after 2 years and data from the trial plantation in Kununurra indicates only 37% of 9-year-old trees and 83% of 14-year-old trees set pods in any 1 year, suggesting considerable variability in these timeframes [51].

The period for full development of the seeds can be as long as 11 months in India [19] and Kununurra [4], and seed pods are often still attached to the tree by the time of flowering the following year. This may have consequences for production as mechanical harvesting may damage these delicate floral organs impacting on the subsequent year's yield (see “Element 7: Agronomy”). Pods do not open naturally, requiring mechanical opening/shattering or allowing the fruit to decay before germinating. Mechanical decorticators are used in India to release seed. The rate of germination of seeds declines quickly (12 months for dry storage; even less when on the ground where fungal attack appears to destroy the seed).

Experts have all noted the high inter-tree variability in phenology, growth, and reproduction and identify this as one of the major impediments to commercial production. For example, anecdotal observations suggest that trees which have a high degree of genetic similarity, planted adjacent to each other, may demonstrate vastly different phenology and seed production. Pongamia has not undergone extensive domestication either in Australia or India, so future development of commercial plantations will first require extensive genetic selection and/or improvement of germplasm followed by clonal propagation to manage the high inter-tree variability.

Action: Activities required regarding genetic selection and clonal propagation are covered in more detail in “Element 2: Strategy for Rapid Selection of Elite Genetic Material” and “Element 4: Propagation and Establishment”, respectively.

Soil–Climate–Growth–Yield Relationships

Recent studies to assess the national production potential for a Pongamia industry in Australia used the simple approach of matching the climatic ‘niche’ of the plant (based on data on current global distribution of Pongamia) to where similar conditions exist in Australia, thus predicting the area potentially suitable for establishment of the tree across Australia at a national scale [33, 34]. Although this provides a useful ‘first cut’ on where the plant might grow and survive under rain-fed conditions, it does not provide useful information on the potential oil yield from Pongamia. It is clear from the literature and from observations by experts that there are complex relationships between genetics, growing conditions, survival, and growth of the tree, flowering, pollination and fruit set, and oil yield.

There is a considerable amount of anecdotal and observational information about Pongamia growth and production for oil in India that could be used to develop climate–growth–oil yield relationships which could then be applied across Australian climates to gain improved predictions of potential performance. For example, the Karnataka State Biofuel Development

Board states that annual harvests of 600,000 t of Pongamia seed are collected by hand in village situations for biofuel production [55]. As interest in Pongamia's potential for biodiesel has grown over the last few years, there has been a significant increase in the published peer-reviewed literature with the mean annual number of published papers (containing '*Pongamia pinnata'* or '*Millettia pinnata'* in the title, abstract or as a keyword) increasing from five in the years up to 2005 (1991–2005) to 26 in the 5 years since (2006–2010), peaking at 36 published papers in 2009. Approximately 75% of this literature is generated in India; less than 2% (four papers) originated in Australia. However, experts who have visited with research and industry agencies in India note that much knowledge has been generated which is currently inaccessible via the peer-reviewed literature.

The experts generally agreed that, whilst valuable as a background source of information, the published Indian observations could not often be directly applied to the Australian context for a number of reasons. Pongamia has not traditionally been established in commercial plantations in India. Rather, either natural stands have been harvested or plants have been cultivated in small lots, on degraded land, along roadsides and railways, and in open farmland and there has to date been very little systematic collection and processing of seeds [32]. As a result, little attempt has been made to optimise production of the plant for harvesting, identify elite genotypes, or investigate propagation methodology, although all these areas are seeing increasing attention in India. Kesari and Rangan [32] listed 28 research organisations in India currently involved in "plus tree" identification, cultivation of Pongamia germplasm, and other research relating to successful cultivation of Pongamia for biofuel. Given the long history of usage, the potential remains to collect vital, long-term data on seed production and oil yield from across climatic gradients in India.

Action: Given the very limited local experience of the performance of Pongamia in plantations, the challenge is to make credible translation of overseas experiences to the biophysical conditions of Australia. Meeting with key Indian research groups and surveying plantations and natural stands with a particular emphasis on understanding the basis for variation in oil yields would assist to calibrate models for Australia in the absence of local data and allow for an interim improved prediction of oil production from Pongamia plantations in Australia.

Element 2: Strategy for Rapid Selection of Elite Genetic Material

Pongamia is an obligate outcrossing species; thus each tree is highly heterozygous as confirmed by DNA fingerprinting carried out at the CILR (UQ) using inter-simple sequence repeats (ISSR) markers [27]. Variation is increased by the heterogenous pollen stemming from other heterozygous 'father' trees. This has been confirmed visually and with molecular markers (ISSR), where all progeny plants derived from one parent differed in DNA 'fingerprint' [27]. As a result, plants raised from seed are genetically diverse and exhibit significant variation in many traits including tree architecture, seed morphology, and yield [60]. Traditional methods for development of 'elite' trees, including cross-breeding high performers, are only feasible if genetic lines can then be maintained through clonal propagation (see "Element 4: Propagation and Establishment").

Pongamia is a diploid legume with $2n=22$. The chromosomes are small at mitosis and resemble those of soybean. An estimate of the genome size is around 600–700 megabase pairs per haploid genome. DNA and RNA have been isolated and analysed from leaf and root material. Modern high through-put DNA sequencing techniques (specifically using Illumina SOLEXA technology) have been applied and created large datafile sets of Pongamia genomic sequence. These databases have been used for gene discovery, especially using alignment with the recently published soybean genome sequence [58]. For example, using this approach, genes for seed fatty acid biosynthesis and stability and seed storage protein have been isolated from Pongamia and characterised for their developmental expression profile during seed maturation (J. Vogt, P. Scott, and P. Gresshoff, CILR, UQ, unpublished data). As an indirect measure of expression, mRNA can be quantified for specific Pongamia genes, different tissues, and growth conditions.

Proteins and oils can be isolated from seed cotyledons. Oil extracted from seeds is found predominantly in the form of triglycerides, with the major fatty acid being C18:1 (oleic acid; a common component of olive and canola oil). Stearic (C18:0) and palmitic (C16:0) acids, which contribute to a rise in the cloud point are minor components, usually measured at between 9% and 17% of the total fatty acids [4, 51, 59, 61].

Action: The tools have been established to assist genetic selection and need to be applied, and then selected material needs to be evaluated by thorough and systematic field assessment of growth and oil yield across potential Australian growing environments.

Element 3: Exploiting Genotype × Environment Interactions to Maximise Oil Yield

Very little is currently understood about the genotype × environment interaction in Pongamia or the relationship between environmental stress (induced by soil and climatic factors) and oil yield in Pongamia. Seed production across and within trial sites and on street trees in Australia is highly variable. Table 1 summarises reproductive and yield variables based on Australian observations to date. Seed production estimates range from 0 to 30 kg seed/tree/year in an irrigated plantation near Kununurra [51] to an estimated 80 kg seed/year on an approximately 15-year-old tree growing on a street in Brisbane. This high variability, particularly within trials, is currently considered an area requiring considerable further research and development. Accounts of seed yield from India are highly variable but suggest an average range of 8–90 kg/tree/year [31, 57], although seed yields as high as 300 kg/tree have been reported from specially selected high-yielding trees [20]. It should be kept in mind that the Indian yield estimates are sourced from trees identified as high-yielding, rather than averages for trees in plantations; researchers in India note that a large proportion of wild trees do not yield at all and that only a small proportion of trees produce a 'commercially attractive' number of seeds [60]. Scott et al. [59] report a potential yield in Australia of approximately 20,000 seeds from 10-year-old trees/year. Based on their estimate of 1.8 g/seed, this converts to a seed yield of 36 kg/tree or 12.6 t of seed per hectare based on 350/trees/ha, provided all trees were productive.

Seed oil content has been measured from four trees within a 100-km radius in south east Queensland and found to be within the range 35% to 43% (P. Gresshoff, CILR, unpublished data); seeds from a trial plantation in Kununurra had an oil content ranging from 31% to 45% [4, 51]. In India, total oil content has been reported ranging from 15% to 50%, with an average for specially selected 'candidate-plus' trees of 38% (range 34% to 40%) [48] and averages from a random selection of wild trees being between 28% and 34% [32, 41, 66]. Little data is available for seed from other geographic areas, but Arpiwi et al. [4] found Indonesian trees had 28% to 36% oil. The oleic oil (C18:1) component appears relatively consistent at an average of 50% of total oil content for trees from south-east Queensland (P. Gresshoff, CILR, unpublished data) and an average 51% from trees in Kununurra [51], but importantly, some trees had seeds which contained 63% oleic acid [4].

While it is generally thought that larger seeds have higher oil content, research in India suggests that oil content is only very weakly, and not significantly, correlated with a range of seed and pod morphometric traits including weight and size of seeds and pods [48, 66]. Preliminary data from a plantation in Kununurra also indicates that seed size is not related to oil content [4, 51].

Action: Planting 'elite' clonally propagated genotypes across environmental gradients in a systematically designed network of long-term field trials is required, noting that effective cross-pollination of these trees will need to be managed to optimise yield. Comprehensive long-term field studies, consistently measured across the network of trial sites, will assist not only with quantifying genotype×environment yield relationships, but also with gathering agronomic and sustainability datasets (see "Element 7: Agronomy" and "Element 9: Sustainability").

Element 4: Propagation and Establishment

With pollination of Pongamia occurring primarily via bees, a pollen donor could include any tree within the distance a bee is capable of carrying and transferring pollen (approximately 3 km radius). Therefore, once the best performing genetic material is selected, trees must be clonally propagated from stem cuttings or tissue culture, or via grafting to maintain genetic lines. Significant effort is directed at clonal propagation of elite (or 'plus') trees due to the need for uniformity in plantations allowing equal usage of row space, avoidance of shading and competition, uniform flowering period, management and harvesting regimes and predictable quality of products. Methods for cloning have been successfully demonstrated at the laboratory scale but require further work to enable economic scale-up to support plantation

Table 1 Summary of reproductive and yield variables based on Australian observations to date

Variable	Unit	Range based on all observations in Australia	Average	Source
Time to reproductive maturity	Years	4 to >14 years	5 years	Expert observation and [51]
Full development of seeds	Months	10–11 months	10 months	Expert observation and [4]
Flowering episodes/year	Number	1–2	1	Expert observation and [51]
Seed production per tree	kg/year	0–30 kg/year	20 (a)	Expert observation and [51]
Seed oil content	%	31–55%	40	P. Gresshoff (unpublished data) and [4, 51]
Seed viability	Months	<12 months		Expert observation
Tree per hectare	Number	320–500	350 (b)	Expert observation
Yield estimate (if all trees are productive)	Tonnes/ha/year		7	Calculated from (a) and (b)

development. While it may be desirable to maintain uniform genetic stock for commercial plantations, it is important to be mindful of past problems (e.g., insect and plant pathogens) associated with extensive crop monocultures. It is therefore considered that future plantings should incorporate a variety of defined lines or cultivars of trees.

Experts agreed that whilst propagation from elite stock is often promoted, there is very little information on how these elite trees are identified or selected and virtually no data to support the designation of trees as ‘elite’. Kesari et al. [31] report a method for selection of “candidate plus trees” (CPT) in India involving selecting individual trees possessing a range of superior morphological and reproductive characters. Trees in Kununurra, Western Australia, have also been selected using several morphological and physiological traits [4]. However, the heritability of traits in offspring has not been assessed or reported.

The current process for propagation of Pongamia in Australia is labour-intensive, requiring manual extraction of the seed, since commercial decorticators crack the seed during removal from the pod. Seeds are first soaked in warm water and then placed individually for planting to ensure the seed is in the correct orientation for germination. Germination generally occurs within 2 weeks. Propagation from seed is also the most commonly used method for production of large numbers of seedlings in India [42]. Indian researchers have reported a significant positive correlation between germination rate and seed size [71].

Propagation from stem cuttings is a relatively simple procedure; however, it is labour intensive and requires source material at the correct stage of development (i.e., semi-woody). Pongamia twigs can be rooted to form clonal cuttings which establish in soil and develop a deep fibrous root system over time (but slower than tap root development on seedlings). This tendency to develop a fibrous, adventitious root system in cuttings is considered less than optimal, particularly in moisture-deficient soil systems. Classical grafting of elite germplasm onto seedling derived root stock has also been demonstrated (P. Gresshoff, CILR, UQ, unpubl. data).

Propagation via tissue culture can take alternative approaches. For example, dormant buds can be sterilised then cultured to induce multiple buds which can be separated and grown to full scale plants (Q. Jiang, CILR, unpublished data). Sterilisation of dormant buds is difficult to achieve from field grown material, but easier from clonal glasshouse material. This procedure is both labour and infrastructure-intensive and requires optimisation for commercial application to reduce costs. Immature cotyledons have been induced to undergo both organogenesis as well as early stages of somatic embryogenesis (B. Biswas, CILR, unpublished data). Optimally, organogenesis or somatic embryogenesis should be obtained from meristem-derived material assuring clonal propagation of superior germplasm. In India, increasing attention is also being focussed on propagation techniques via tissue culture and a comprehensive review of the current state of the research is given in Mukta and Sreevalli [42].

Propagation via grafting has been conducted with some success in India and is being trialled in some Australian plantations in 2011. In India, wedge grafting has been found to be most successful using 3-month-old seedlings raised in polybags as the stock and semi-hardwood scions of 12–18 cm length from high-yielding trees [42]. The advantage of propagation via grafting, besides the potential for higher productivity due to elite scions, is the earlier time to seed production. Indian trials have shown seed yield within 3 years following grafting [42].

Action: While propagation from tissue culture and micropropagation of Pongamia has proven successful, the methods require much further refinement to be feasible and cost-effective on a commercial scale.

Element 5: Identification of Suitable Land and Water Resources

Soil and Water

In Australia, Pongamia has been observed growing on a wide range of soil types. Trial plantations have been established on sodic acid soils, alkaline soils, and heavy clay soils with a sodic subsoil. Plants have also been observed growing on beach sand near Darwin and on sand levies along rivers in Cape York. In India, Pongamia is also reported to grow on a wide range of soil types from stony to sandy to clay [32], though it is noted that the plant does not do well on dry sands. Trees reportedly grow in coastal, saline habitats [12], but Indian field trials on saline soils have yielded mixed results [68, 70]. Despite tolerance to a wide range of soil types, soil conditions are likely to interact strongly with climate to markedly affect rates of Pongamia growth, but this is currently poorly quantified.

Water requirements for satisfactory rates of seed and oil production by Pongamia are poorly understood, but experts suggested that irrigation is required during the establishment phase of the plantings (first 7 years) in dry tropical and subtropical areas and sometimes subsequently in order to ensure seed set. There are examples of plantings where trees have been successfully established without irrigation. A plantation on the Sunshine Coast hinterland of Queensland was established without irrigation, even surviving the drought period of 2007–2008. These trees have grown to nearly 3 m in height and 10 cm stem diameter within 4 years (this growth is less than the irrigated trial plantation at Gatton in southern Queensland, where plants achieved these measures of growth within 2 years).

Land and water use or allocation issues may arise with Pongamia plantations if they are to be established on a large scale. Kriticos et al. [34] identified zones of productivity for growth, based on rain-fed situations. Areas requiring no irrigation only occur in the very northern and coastal areas of Australia. There may be other competing demands for this land including biodiversity and conservation, high value agriculture, or urban land use. However, relatively small high yielding plantations may be well suited to providing oil for remote communities. There are some irrigated lands in crop and grazing zones that could be used for Pongamia; however, the feasibility of this would be driven at least in part by the economics of, and societal attitude towards, using irrigation water for a dedicated energy crop.

Water availability in northern Australia is highly seasonal and may be limited in many areas. Therefore, if irrigation is required, it may require the use of groundwater. It has been estimated that there is approximately 600 GL year^{-1} of potentially useable groundwater in northern Australia and that this could provide irrigation for 40,000–60,000 ha [36]. There are specific opportunities for irrigation, for example, in association with mining ventures, but these have yet to be systematically investigated and quantified.

Action: A systematic approach to identifying land (within suitable rainfall zones, or with access to irrigation) capable of supporting commercial Pongamia production should be conducted.

Salt Tolerance

Pongamia is promoted as being able to produce oilseeds on low productivity, degraded or salt-affected land thereby lessening competition for higher productivity land used for agricultural production [32, 46]. However, pot and field trials of growth and performance in saline conditions have provided mixed results [63, 69, 70] and in controlled glasshouse trials in Perth, seedlings were not tolerant of waterlogging and salinity levels of 250 mM NaCl [4].

Pongamia could have the benefit of soil rehabilitation through nitrogen fixation; however, recent experiments carried out on Australian seedlings and saplings shows a decrease in nitrogen concentration and total nitrogen of nodulated plants at moderate to high salinity levels (i.e., approximately 10–20 dSm^{-1}) [74]. The reduction in nodulation with increasing salinity in Pongamia is comparable with that shown by *Acacia ampliceps*, another salt-tolerant legume that has been widely used for the purpose of reclaiming salt-affected land in Australia [74]. *A. ampliceps* has improved nodulation and nitrogen fixation in saline environments when inoculated with salt-tolerant strains of rhizobia [74]. The long-term impacts of salinity on mature trees are not understood.

Action: Efforts are required to ascertain whether N-fixation is the primary or only limitation to growing Pongamia in a commercially successful manner on degraded or salt-affected land. Further investigation on the effect of inoculation of Pongamia with salt-tolerant rhizobia is required if this is considered to be a major limitation to production in these landscapes.

Element 6: Development of New Production Systems and Value Chains

New Production Systems

There is potential to develop and establish new types of production systems for Pongamia, as well as the value chains—for example for conversion of oil to aviation fuel. New production systems might combine Pongamia plantations, grazing, and carbon farming which could provide enterprise diversification, reduction of risk, and reduced GHG emissions for the grower. High value co-products may also be a component of an innovative new mixed enterprise model (explored further below).

Action: Little is known about the scale and type of opportunities for Pongamia to be grown in a complementary fashion with other land uses such as grazing or mining and quantifying the location and scale of such opportunities would help to focus efforts in industry development. This is usually an iterative process which starts with pre-experimental or ex-ante modelling analysis on the performance and economics to assess what may be feasible. Promising production systems can then be trialled and evaluated, with progressive refinement over time to fine-tune new systems.

Animal Feed Co-products

The seed of Pongamia consists of an outer hull portion (~6% mass) and an inner kernel portion (~94%). Following oil extraction, approximately two thirds by weight of the original seed is left as a residual meal or cake, containing 28–34% crude protein [73]. The Pongamia meal or cake (also known as karajin cake) has been used as manure, fungicide, and insecticide, and there has been considerable research, mainly in India, on utilisation of this protein meal as animal feed [35, 47, 49, 73]. However, the meal contains karanjin (a fluroflavinoid) and pongamol in the residual oil that make it unpalatable. It also contains anti-nutritional factors such as phytates, tannins, and protease inhibitors that affect rumen metabolites and the digestibility of protein and carbohydrates [73]. Oil extraction carried out by the usual method of expeller pressing, leaves 15–20% oil in the cake (referred to as EKC—expeller pressed karajin cake). Solvent extraction removes more oil and should increase the palatability of the meal and reduce the toxicity, but research indicates that inclusion of solvent extract Pongamia meal (SKC—solvent extracted karajin cake) in mixed diets still reduces feed intake and results in reduced animal growth rates. Researchers have sought additional ways of detoxifying the meal aimed at reducing the anti-nutritional factors through water leaching and the addition of mild acid or alkali. In a laboratory study, Vinay and Kanya [73] use a 2% HCL treatment for 1 h to reduce anti-nutritional factors.

A long-term (34 weeks) performance trial of lambs was undertaken using diets containing either 24% expeller (EKC) or 20% solvent extracted (SKC) Pongamia meal, replacing half of the de-oiled groundnut cake as the source of protein [64]. In this trial, there were no further treatment of the meal to reduce anti-nutritional factors. Dry matter intake, the digestibility of protein and carbohydrates, the growth rate and wool production were all reduced in the lambs subject to each of the diets containing either EKC or SKC. In addition, by the end of the trial, the lambs had lower bone density (osteoporosis), testicular degeneration, and liver and spleen lesions. Growth performance trials with chickens also demonstrate that Pongamia meal may only be useful as animal feed at very low levels of addition [47].

Despite the research that has been undertaken over many years to find ways of utilizing Pongamia meal as livestock feed, the combination of poor palatability, anti-nutritional factors, and the recognition through molecular analysis that the primary proteins in the meal are known to provide low nutritional benefit because of poor amino acid composition, make it unlikely that a co-product stream based on animal feed will be developed. However, there is a benefit from Pongamia containing the unpalatable karanjin and pongamol, as it allows the integration of grazing livestock in Pongamia plantations with minimal risk of the animals grazing and damaging the trees. At a trial plot in southern Queensland, where the trees are 3–4 years old, sheep are grazed in the plantation to control grass and weed growth and to provide some additional income from the land (G. Muirhead pers comms.).

Green Manure Co-products

Pongamia is used as a green manure with some benefits [43], but this is derived from the leaves of the tree rather than the oilseed cake. However, trials have shown that oilseed cake can be used in conjunction with the mycorrhiza *Glomus fascicuatum* in organically enriched soils to reduce the incidence of the plant disease complex caused by the root knot nematode, *Meloidogyne incognita* and the root wilt fungus *Fusarium udum* in pulse crops viz. cowpea, soybean, pigeonpea [24].

Insecticide Co-products

In terms of use as an insecticide, extracts of Pongamia have been reported to be effective against insect pests in stored grains and on crops, acting as a deterrent to oviposition and as antifeedants and larvicides against a wide range of pests [35]. The relevance of this to the use of Pongamia oilseed cake is questionable, as it appears that the oil (as a water–oil suspension of up to 2%) has generally been used as a spray to achieve the desired insect inhibiting effect [49].

The pod shells and woody material from pruning could potentially be used as a form of fertiliser, produce biochar, combusted to produce electricity, or be used as a feedstock for gasification and conversion to a range of products. This requires further investigation.

Action: Avenues for sustainable use or disposal of co-products, including the seed cake, pods, and woody material from pruning, need further investigation.

Element 7: Agronomy

Irrigation

Irrigation has been discussed under “Element 5: Identification of Suitable Land and Water Resources” and is not discussed further here.

Nitrogen Fixation and Fertiliser Management

Relatively little is known regarding nodulation and actual rates of N fixation in Pongamia. Preliminary experiments suggest that Pongamia is able to form functional spherical nodules with a broad range of rhizobia belonging to the Bradyrhizobium tribe [59]. Such bacteria commonly nodulate Australian acacia (wattle) species. Their persistence in Australian soils may present a hurdle to establishing highly effective Bradyrhizobium strains for Pongamia that will persist in field situations, as competition from the ‘local’ rhizobia may be severe. The nodule structure (see Fig. 1f) suggests determinate nodule growth similar to that observed in soybean [22] and the model legume *Lotus japonicus* [27]. However, observations on field-grown Pongamia roots show nodules ranging from spherical (as seen in saplings, [3]) to branched and coralloid nodules (P. Gresshoff and P. Scott, CILR, unpublished data).

Pongamia plants are thought to exhibit the classical legume nodulation response called autoregulation of nodulation (AON; [14, 22]). Nodulation occurs predominantly in the upper regions of the root system as early nodulation events suppress the formation of new nodules. Thus, sapling inoculation with effective bacteria may give the plant sufficient nodule numbers for early plant development, without incurring problems of ‘competition’ from resident rhizobia.

Application of fertiliser at the seedling stage probably enhances establishment success and early growth but expert observations at some trials (with fertile soils) suggest it may not be necessary. However, addition of P, K, and micronutrients may be required over the long term to maintain soil fertility. Experts note that soil and foliar analysis is required at plantation sites to provide a basis for establishing appropriate fertiliser regimes.

Action: Characterisation of the spectrum of rhizobia that can form an effective symbiotic relationship(s) with Pongamia is required. An assessment of whether nitrogen fixation capability at plantation densities is likely to meet the plants' nitrogen requirements needs to be undertaken.

Weed Control

Mechanical and chemical weed control during the first 3 years after planting was identified by the experts as critical for successful establishment. In particular, seedlings <30 cm high are very vulnerable to weed overgrowth. Ideally, weed mat would be used for establishment; however, the cost is significant (approximately $1.40 per tree). Indian and Australian observations suggest planting of seedlings of 50–60 cm in height will greatly improve survival in the field [72]. Intercropping with suitable species during the period of establishment (i.e., first 3–4 years) may also contribute to management of weeds, as well as increase economic returns for the system.

Animals are required to be fenced out for the first 3 years of Pongamia growth because they will pull seedlings out of the ground; after that, stock will only feed on the lower branches if other feed is scarce. The minor ‘pruning’ carried out by stock is likely to be beneficial in controlling root or base sprouting.

Action: Knowledge about effective weed control, fertiliser management, spacing and pruning from Indian plantations in needed to provide some early information to help guide the management of Australian plantations. Systematic evaluation of agronomic practices needs to be conducted under a range of prospective Australian growing environments and management systems.

Harvesting Methods

Mechanical harvesting of Brisbane city trees has been demonstrated with umbrella shakers style machinery [9]. Umbrella shaker style harvesters require a minimum of 7 m spacing between rows. The large trial plantation near Roma has been planted with 8 m spacing between rows and 2.5 m between trees within the row. Another trial plantation at Caboolture utilises a 5/7/5/7 m spacing pattern between rows with 5 m spacing within the row. The optimal arrangement for accommodating a gantry style shaker with maximum trees per hectare is thought to be 7 m spacing between rows and 4 m between trees within the row, which gives approximately 320 trees/ha. Another consideration for optimisation of harvesting is tree shape. Pongamia can tend towards a ‘poplar’ or ‘weeping willow’ shape which cannot be harvested efficiently. Therefore, some pruning of trees is required during the establishment phase (first 3 years) of the plantation to control tree shape. Further pruning is required to adjust for wind effects. Plants are generally pruned following harvest with the aim of maintaining trees at a height of approximately 6 m. The presence of shoots that will develop flowers or flower buds at the time of harvest/pruning needs to be considered. Future genetic selections may focus on semi-dwarf varieties with high yield.

Action: Harvesting methods for plantation scale plantings of Pongamia require considerable further development and testing. Options for further investigation include gantry and umbrella style shakers similar to those used for harvesting in nut and olive plantations. These harvesters have been trialled successfully at a small scale on Pongamia in Australia; however, trial plantations are currently harvested predominantly by hand. The possibility of using abscission chemicals to release mature pods prior to flower development should also be investigated.

Pests and Diseases

In north Queensland, Pongamia has been observed to be infected by a fungus (*Phyllachora yapensis* subsp *pongamiae*) causing a disease known as ‘tar spot’ [62]. The fungus has also been recorded in India and is known as *Phyllachora pongamiae* [11]. The fungus causes a leaf discolouration but does not appear to cause mortality or seriously impact mature trees; however, it may have more serious impacts on seedlings. Also recorded on native Pongamia in north Queensland is the fungus *Asperisporium pongamiae* which causes leaf spot [62]. Other fungi causing leaf spot and blight recorded on Pongamia in India include *Fuscicladium pongamiae*, *Microstroma pongamiae*, *Cercrospora pongamiae* [39], and *Ravenelia hobsoni* (leaf rust) [11].

A number of other potential pests of Pongamia have been observed in trials around Australia (a stem borer, leaf miner, locusts, green ants), but none appear to cause significant damage. The only pest observed to cause mortality in seedlings has been rabbits (ring-barking the lower 20 cm of the stem), and as noted earlier, grazing animals need to be fenced out of Pongamia plantings for the first 3 years. Kangaroo damage has not been observed in plantations in mixed grass-wooded areas, suggesting that macropods avoid the plant, possibly because of a bitter taste.

Action: While there is little evidence that pests and diseases currently cause anything other than minor foliage damage to Pongamia in Australia, establishment of Pongamia as a broad-acre crop will provide increasing opportunity for pest and pathogens to establish and the consequences of this need careful assessment.

Element 8: Economics

The price of biodiesel is inextricably linked to the price of crude oil because it is the main competitor, although the cost of production may be more independent (depending on the level of oil-derived inputs for growing, processing, and transporting the product). In many countries, biodiesel is used primarily as a fuel additive. Commonly, blends range from 2% to 20%. A comparison of the economics of various alternative transportation fuels requires estimation of their total costs of production, from the cost of raw materials for fuel production to the cost of conversion to biodiesel and distribution. Successful development and commercialisation of biodiesel or other fuels of products from oils of farm grown crops depends on (a) their cost competitiveness compared with that of the product they replace (e.g., conventional diesel) and on the amount of fuel that could be supplied annually and (b) on the competitiveness of oil crops compared with alternative land uses. Social and environmental policies may provide incentives that can assist in the development of emerging renewable fuels industries.

A comparison of the commercial viability of production of biodiesel requires estimation of its costs of production, from the cost of oil crops grown on farms, the costs of transport and processing, and the costs of distributing the fuel to users. A full economic analysis for selected production systems is currently being conducted by the Future Farm Industries Cooperative Research Centre for production, harvest and delivery of Pongamia oil including the cost of crushing and refining oil to biodiesel [65]. The analysis takes into account the fixed and variable costs of production of biodiesel from Pongamia oil including:

- Initial capital outlays
  - Establishment and conversion of land to a Pongamia tree plantation
  - Development of irrigation systems (if required)
  - The building and commissioning of crushing plant and its machinery
  - Machinery for harvest and transport of seed
- Fixed costs
  - General repair and maintenance
  - Sundry fuel and oil
  - Electricity
  - Administration
  - Permanent staff wages
  - Manager wages
- Land opportunity cost from livestock on pasture
  - The value of net revenues foregone if farm land is converted to a plantation reducing the stocking rate or carrying capacity of pasture
- Variable costs
  - Machinery operating costs including fuel and oil and additional hired labour
  - Fertiliser, including mulch
  - Weed, pest, and disease control—costs of chemicals and their application
  - Irrigation water—if required and where there is a charge for water or if it has an opportunity cost
  - Labour for pruning
  - Harvest
  - Crushing

The economic analysis requires numerous inputs ranging from growth and yield of trees to the cost of extracting oil from crushing of seeds. Given the lack of an established commercial Pongamia industry, it is not possible to source precise and verifiable estimates of the input parameters for such a model. The lack of reliable data on oil yield (tonnes per hectare per year) over the life of the tree is particularly critical. However, for many of the cost items, it is possible to find estimates from other related agricultural and horticultural industries.

A preliminary analysis was conducted of the cost of establishment and operation of a 500-ha rain-fed Pongamia plantation in sub-tropical coastal Queensland with a rainfall of 1,030 mm per annum (e.g., Rosedale 24.63° S, 151.92° E). The findings of that preliminary analysis are reported here for the purpose of identifying the key economic drivers and to inform priorities for research and development. An exhaustive discussion of the details of all the assumptions and input parameters used in this model is beyond the scope of this paper (but see [65]). It must be emphasised that these are preliminary findings and are subject to change and modification as more reliable information becomes available. The results of this type of preliminary economic analysis, when viewed from the point of view of paucity of data, may be valuable in highlighting the uncertainties about Pongamia that are likely to be economically important and drive its ultimate commercial success and scale of adoption.

The key assumption that was varied in the model was seed yield. Two scenarios were tested for the purpose of illustration in this paper. Both scenarios are based on planting 500 trees per hectare allowing suitable space to manoeuvre a Collossus harvester (a commercially available machine used in large olive and orange orchards internationally, or similar). In scenario A, each tree was assumed to yield an average of 40 kg of pods per year (range 35–50 kg/year) when trees are mature at around 10 years, equating to approximately 20 kg/seed/tree/year. This figure represents the average seed production estimated by industry experts and researchers who contributed to this paper. The growth of the tree and production of seeds follows a sigmoidal curve as shown in Fig. 5 (for scenario A). In scenario B, a lower estimate of pod yield of 10 kg per tree (equating to 5 kg/seed/tree) was used to represent a situation where trees are less productive and is a far more conservative production

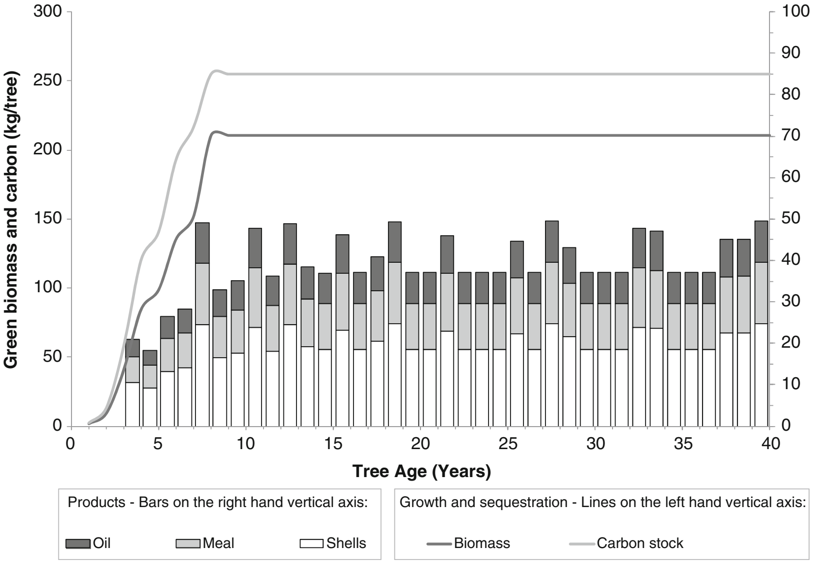


Fig. 5 Pongamia growth (*lines*, left hand axis) and product yield (*bars*, right hand axis) estimates used in the economic model for scenario A with yield at an average of 40 kg pods/tree/year

scenario. Ideally, genetic improvement (as discussed in "Element 2: Strategy for Rapid Selection of Elite Genetic Material" and "Element 3: Exploiting Genotype × Environment Interactions to Maximise Oil Yield") would improve on the upper average yield estimated here of 40 kg/tree; thus even our upper estimate may ultimately be considered conservative.

In this case study, an annual harvest regime is assumed. Industry experts who are actively involved in developing commercial Pongamia plantations expect that it may be possible to harvest in the month or two before flowering (around November) given adequate winter rainfall. This is an area that requires verification with field trials. If winter rainfall is necessary those areas of Australia with highly seasonal rainfall, for example the northern tropics, may not be suitable for growing Pongamia unless supplemented with irrigation in winter. This scenario is not assessed here; however, the model does have provision for inclusion of irrigation infrastructure and costing of capital expenses as well as the variable cost of water charges.

The nutritional requirements of the crop are assumed to be met by a combination of fertilising and mulching with by-products such as seed meal and pod and seed shells returned from the crusher back to the property. Pruned branches and twigs clipped by the harvester are also returned to the plantation to avoid loss of nutrients. The fertiliser costs are assumed to be associated with the use of fertiliser containing nitrogen, phosphate, potassium, and the trace elements exported from the plantation. The fertiliser costs are assumed to ramp up in step with the growth and harvest of trees starting at ~$30 per hectare in the first year when plants are small and increasing to $340 per hectare when trees are mature and being harvested. We stress that these costs are highly uncertain and have a major effect on the economics of production of Pongamia oil.

Harvesting haulage and delivery costs are assumed to be $127 per tonne of seeds in pods or about 5 cents per litre of oil. Harvesting operation is assumed to depend on the purchase and use of the Colossus harvester. This type of harvester and associated gear including bins and trailers is valued at $900,000. Harvesting manually would make the venture unviable by increasing the cost by around tenfold which is in keeping with reported estimates from the olive, macadamia, and almond industries.

Crushing costs are a combination of operating and capital expenses. The crushing plant with a crushing capacity of 12.5 t of seed per 10-h day is assumed to cost around $0.5 million to build. This plant's operating costs are assumed to be $223,912 per annum. Crushing costs amount to less than a third of a cent per litre of oil extruded but it goes up to around 1.5 cent per litre in scenario B in which trees seed yields are only 10 kg/tree per annum.

Land opportunity cost is the net operating surplus in dollars per hectare from grazing that a land holder in that region would forego as a consequence of switching their land use to Pongamia. We assume that some grazing and hay production is possible from the grass and other herbage growing around and under the Pongamia trees in the plantation. However, the competition for light, water, and nutrients from trees is assumed to halve the production of pasture. It is the net loss of grazing potential of the land that is used as the opportunity cost. Here, we assume the long-term average return reported for high rainfall sheep grazing enterprises in similar regions. Pollination services offered by bees supplied by apiarists are assumed to be negligible in cost based on the assumption of mutual benefit between the two enterprises.

Carbon payments are estimated for a hypothetical scenario where a Pongamia plantation may qualify as an activity for removal of carbon from the atmosphere. This analysis considers the possibility that the modelled plantation may satisfy the rules of the Carbon Farming Initiative (CFI) legislation of the Australian Government [18]. Carbon payments are estimated according to an endpoint averaging system. This is because carbon stored in agricultural soils and some forms of vegetation are likely to be susceptible to significant cyclical variations, largely driven by fluctuations in annual average rainfall. These variations can make it difficult to isolate the impact of changes in management practices on carbon stocks. For this reason, estimation methods for sequestration projects must provide for estimates to be adjusted to account for significant variations in carbon stocks that are likely to occur as a result of climatic cycles. The project must be undertaken in accordance with a specified and approved methodology and comply with scheme eligibility requirements. Another key criterion is that the project must be beyond common practice in the relevant industry or part of an industry or in the environment in which the project is to be carried out. Under the CFI legislation, carbon payments may be based on total projected net greenhouse gas removals over the period of scheme obligations less a risk of reversal buffer. If the Pongamia plantation qualifies as a positive carbon sequestration activity and is included on the positive list of CFI, then growers may get credit for voluntary participation in the CFI scheme. The carbon price is assumed to start at $23/t of CO2-e and rises by 2.5% per annum. Carbon revenue is estimated to be $3,346/ha over 40 years or around 2 cents per litre of oil in scenario A. In scenario B, carbon revenues are the same per hectare at $3,346/ha, matching the growth of tree biomass which generates the same amount of sequestered carbon as that in scenario A. However, carbon revenue is higher per litre in scenario B at just over 8 cents per litre since seed yield of each tree is assumed to be four times lower when compared to scenario A. It should be noted that eligibility of Pongamia plantations in relation to CFI legislation and the attendant future carbon revenues are highly uncertain; thus, in Table 2, results are reported with and without carbon revenues.

The preliminary results reported in Table 2 are based on the net present value (NPV) of cashflows. NPV is calculated over the 40 year life of the hypothetical Pongamia project. We use the NPV to provide a dollar per hectare estimate of the cost of production from a Pongamia plantation in present value terms. These results indicate how sensitive the cost of production of oil is to key factors of production. In scenario

Table 2 Cost of production of Pongamia oil for two different yield scenarios over a 40-year life cycle

Cost category	Scenario A		Scenario B	
	Land $/ha over 40 years	Oil Cents/l	Land $/ha over 40 years	Oil Cents/l
Capital (excludes value of land)				
Establishment of site, planting of trees, crushing plant, machinery	9,384	6.00	9,384	24.00
Opportunity cost				
Foregone net ruturns from alternative land use (e.g., grazing)	656	0.42	656	1.68
Variable costs				
Machinery—tractor, implements (fuel, oil, parts, repair and maintenance)	1,128	0.72	1,128	2.88
Fertiliser and mulch	3,975	2.54	3,685	9.42
Control and management of weeds, pests, and diseases	2,237	1.43	2,237	5.72
Prunning labour	2,487	1.59	2,487	6.36
Harvesting	7,977	5.10	6,182	15.81
Crushing seeds for extraction of oil	448	0.29	593	1.52
Fixed costs				
General repair and maintenance	267	0.17	267	0.68
Power, fuel, and oil	347	0.22	347	0.89
Administration and wages of manager and staff	6,786	4.34	6,786	17.35
Total costs	35,691	22.82	33,751	86.31
Carbon revenue	3,246	2.07	3,246	8.30
Total costs less carbon	32,445	20.74	30,506	78.01
Equivalent annual value—total costs ($/ha/year)	2,677		2,532	

Both scenarios are based on a 500-ha plantation with 500 trees/ha. Scenario A assumes 40 kg pods/tree/year when trees are 10 years old; scenario B assumes 10 kg pods/tree/year when trees are 10 years old. Also shown (final row) is the annualised NPV which provides a dollar per hectare per annum estimate of the cost of production in today's dollars (using a discount rate of 7%). For full details of assumptions and input parameters used in this model, see [65]

A, with an annual yield of 40 kg of pods per tree, cost of production is $35,691 per hectare (before carbon credit) over 40 years. This translates to the cost of production of a litre of Pongamia oil of around 23 cents per litre. On the other hand, scenario B, with a yield of 10 kg of pods per tree per annum has a higher cost of production of oil at 86 cents per litre and $33,751 per hectare (before carbon credits) over 40 years.

The estimates of costs are included and discussed here in order to indicate a plausible range of values which must be scrutinised and modified over time as the industry develops and future research and development generates the better data. The data in Table 2 is indicative of the important cost items. Oil yield/ha is a critical variable determining the overall economics of the Pongamia plantation project.

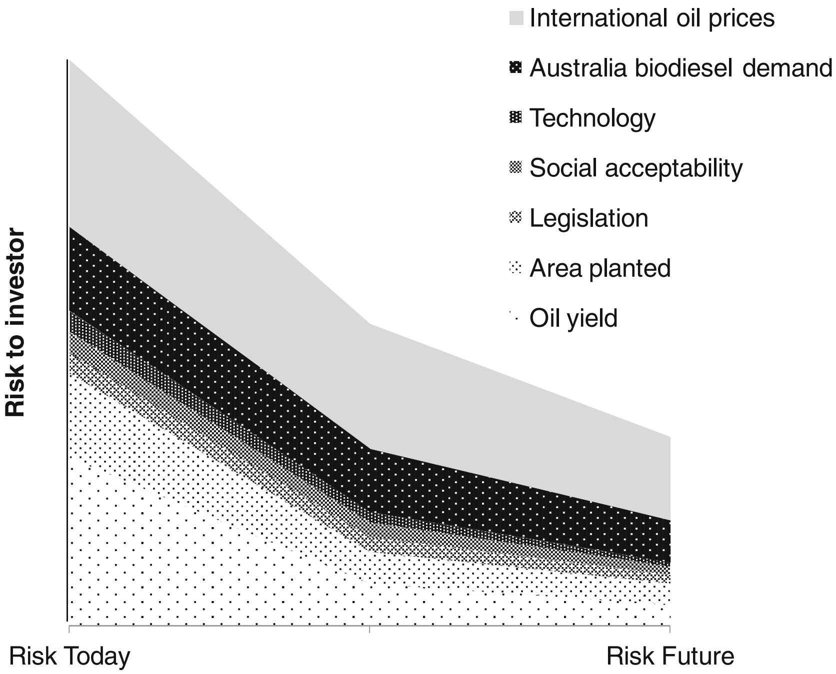
Action: Further certainty is required around many of the parameters influencing the establishment and production costs of Pongamia and many of these have been identified in previous elements including phenological and reproduction parameters ("Element 1: Growth, Survival, and Reproduction in Contrasting Biophysical Environments"), propagation and establishment methods ("Element 4: Propagation and Establishment"), production systems and value chains ("Element 6: Development of New Production Systems and Value Chains") and agronomic parameters ("Element 7: Agronomy"). The economic model provided here will require updating and further sensitivity analysis as new and more precise information becomes available.

Investment Risk and the Pongamia Industry

From an investor's perspective, the risk associated with an Australian Pongamia industry are currently high, but the prospects for reducing risk in the future through a comprehensive research program are good (Fig. 6). High uncertainty is primarily due to the fact that there are large uncertainties about the ability to supply Pongamia oil at competitive cost. These are driven mostly by a lack of knowledge about suitable and available land and water requirements for Pongamia production in Australia, as well as uncertainties with respect to yield and oil content of the seed in the Australian environment. Nevertheless, research aimed at determining the potential land area available for Pongamia, and genetic and technological developments to improve consistency of yield and seed oil content will substantially reduce the future risks associated with supply. Other risks related to the legal environment, technology for oil extraction, and social acceptability of the product are relatively small and are expected to be minor in the future due to Australia's stability and governance, well-known technologies and a highly skilled labour force, as well as the enhanced perception of the need to reduce GHG emissions, and the proposed development of an Australian bioenergy sustainability standard (see "Element 9: Sustainability").

The other risk components associated with the size of the Australian demand for biodiesel and International oil prices are currently high but will likely reduce over time. Forecasted oil prices are higher in the future, improving the competitiveness of biodiesel and increasing demand. Figure 7 summarises how the biological and environmental factors identified

Fig. 6 Schematic indicating current and future risk to investors of an Australian-based Pongamia industry



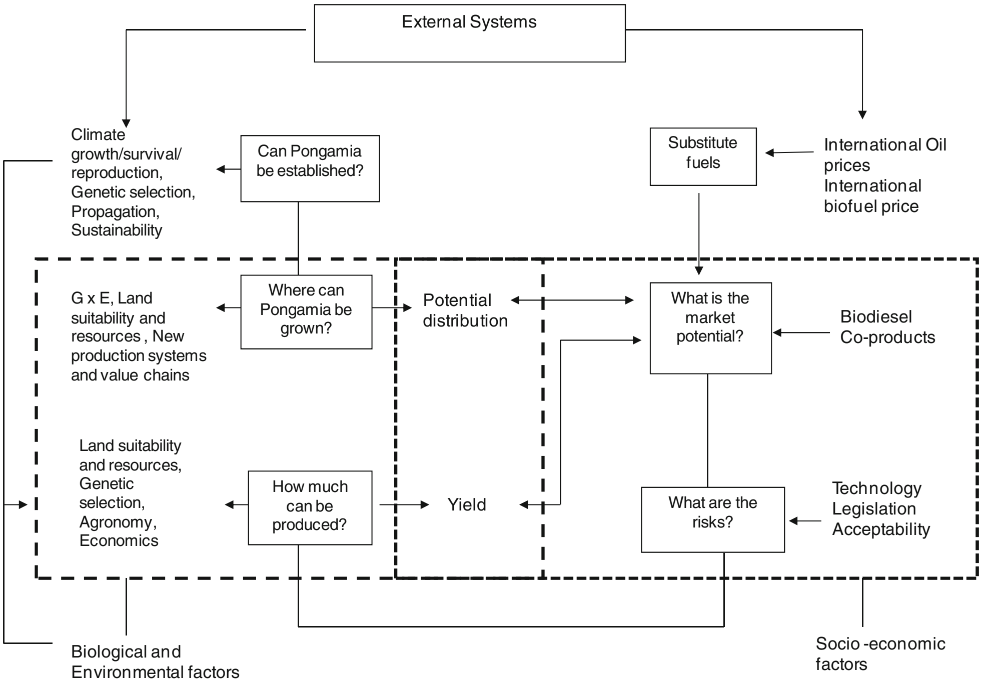


Fig. 7 Interaction of biological and environmental factors and socio-economic factors which determine the market potential and risk for commercial Pongamia production in Australia. The *left-hand side box* indicates the contribution of the integrated research strategy to the two key questions which influence market potential, i.e., potential distribution and yield. The *right-hand side box* outlines those variables that are also influenced by external forces, i.e., international oil and biofuel prices

throughout our review interact with the other external forces to determine market potential and risks associated with a commercial Pongamia production system in Australia.

Element 9: Sustainability

Sustainability issues arise at each stage of the value chain, as well as across the whole value chain and must be addressed at different scales and within different social and environmental contexts. Sustainability issues arising directly from the bioenergy value chain are reasonably well-defined and understood [45]. However, the drivers to expand renewable energy (GHG mitigation, fuel security and regional development) could lead to a rapid expansion of the bioenergy industry, with many associated implications for sustainability. Because Pongamia is not a food crop, diversion of food is not an issue per se, but diversion of arable land or water resources may become one if Pongamia plantations begin to scale-up dramatically.

There are multiple dimensions to achieving ‘sustainability’. Sustainable production requires the maintenance of critical ecosystem function for long term delivery of the full range of values (including the market values of agriculture or energy crops, and the non market values such as ecosystem services) from the land. For Pongamia, important dimensions may include assessment of the potential for invasiveness and effects on biodiversity as well as an ability to play a role in mitigating GHG emissions and in restoring salt-affected lands. However, land and water resources will be increasingly contested and pressured for production of food, fibre, water, biodiversity, carbon storage, and urbanisation. Pongamia and a new biofuel industry could also have benefits for developing regions by opening new market opportunities for biofuel feedstock crops and increasing incomes of farmers. The impacts of an expanded Pongamia industry on the above aspects may be positive or negative. They need to be fully assessed and reported. These issues are discussed in detail in O'Connell et al. [45].

Action: Further investigation is required around the environmental benefits and risks of large-scale Pongamia production—for example potential impacts on land, water and biodiversity resources, and the social acceptance and potential socio-economic benefits at regional to national scales of a new biofuel crop. It is important to have a solid understanding of the likely GHG balance of plantation establishment and management, and the bioenergy production phases of the industry. Both the potential GHG emissions and the potential for carbon storage in biomass, as well as the savings from substitution of fossil fuels by biofuels, require assessment of each aspect per se, as well as an integrated evaluation of the tradeoffs between them.

Demonstration of Sustainability Credentials

Sustainability is a critical issue for the biofuel industry internationally as well as in Australia. Many governments and market segments now consider that quantitative, robust, and independently verified (or certified) sustainability credentials are vital in order for the bioenergy industry to expand globally [45]. This type of approach is already translating to government policies in many countries, including Australia. These policies will limit market access and government support to only those biofuels which meet specified sustainability criteria. The recent Australian legislation to extend the period for excise relief for biofuels requires that in order to qualify, the biofuels must meet ISO sustainability standards. An ISO process for developing sustainability standards for production, supply chain and application of bioenergy is currently in progress (TC248 2011).

Action: The Pongamia industry would benefit from participating in the ISO and any interim process. This will require assisting with adaptation of international criteria and indicators, making the requisite field and other measurements, and making this information available to third parties conducting audits and verification in order to obtain certification.

Many aspects of sustainability have been discussed under Elements 1–8; the issue of biosecurity has not been raised under other elements and is briefly discussed here.

Invasiveness

Large-scale planting of woody species for biofuels in Australia will require further consideration of the potential for weedy growth and invasion of natural or other agricultural areas. Recently, Biosecurity Queensland produced a Weed Risk Assessment (WRA) for Pongamia. The WRA determined that Pongamia poses a low risk to Queensland based primarily on the fact that there is currently no evidence that Pongamia has significant negative impacts as a weed elsewhere in the world and that it is considered naturalised in Queensland [17]. However, in a review on potential weed issues with biofuel crops in Australia, Low and Booth [37] of the Invasive Species Council suggested that "Because this plant has a demonstrated capacity to spread from cultivation, it should not be grown outside its natural range close to national parks or watercourses. It should be declared a restricted plant that should not be grown near sensitive areas." These publications highlight concern by government and non-government agencies in Australia about Pongamia's potential for invasion. In Hawaii, where Pongamia has naturalised, it is considered to be 'high risk' for invasion based on the Australian/New Zealand Weed Risk Assessment criteria, adapted for Hawaii [13, 50]. This high risk score is generated because the species is considered to have naturalised widely and be tolerant of a wide range of soil and climatic conditions, as well as exhibiting other characteristics typical of invasive weeds such as production of a large number of viable seeds and extensive suckering [50].

Several characteristics of the species establishment and survival observed in Australian trials point to low potential for invasiveness under most circumstances; (1) the majority of seeds only remain viable, even when stored with care, for 12 to 18 months, (2) seeds remaining in the pod where they fall are vulnerable to fungal infection which experts have observed to prevent seed germination, (3) seeds and seedlings planted in cultivated or uncultivated ground without subsequent weed control have very low survivorship, (4) very little recruitment from street planted trees in Brisbane, likely originally sourced from Indian stock, has been observed over the last century.

A low score on a weed risk assessment in Queensland does not negate the need for further consideration of management and ecology aimed at limiting the potential for invasiveness and does not guarantee that Biosecurity agencies will not impose further regulation on its cultivation, particularly if new evidence arises. In particular, the introduction of germplasm from more vigorous individuals and elite stock from India or elsewhere into large-scale plantations significantly increases the risk of invasiveness [17, 37]. The WRA also highlights the risk involved with the importation of Pongamia germplasm that introduce new genetic material into the Australian Pongamia population, possibly enhancing its fecundity, adaptability, and invasion potential. The assessment recommends that genetic material sources from existing Australian naturalised stocks should be used.

Action: Best-practice standards for minimising both the risk of invasion and the introduction of exotic genetic material to the Australian Pongamia population need to be identified and implemented.

Element 10: Integration and Knowledge Management

Australia has an opportunity to deliver the much needed outputs from a comprehensive research program (including maps, spatial and temporal data on resources, technologies, economics, sustainability indicators, GHG emissions) in a synthesised, modern and effective manner. Potential beneficiaries include sectors of government (policy makers and analysts at Australian, state and local levels), industry peak bodies (e.g., Bioenergy Australia), industry (energy producers, recycling corporations, biomass collectors), researchers (scientists working on bioenergy, land-use, sustainability, regional development), and the public.

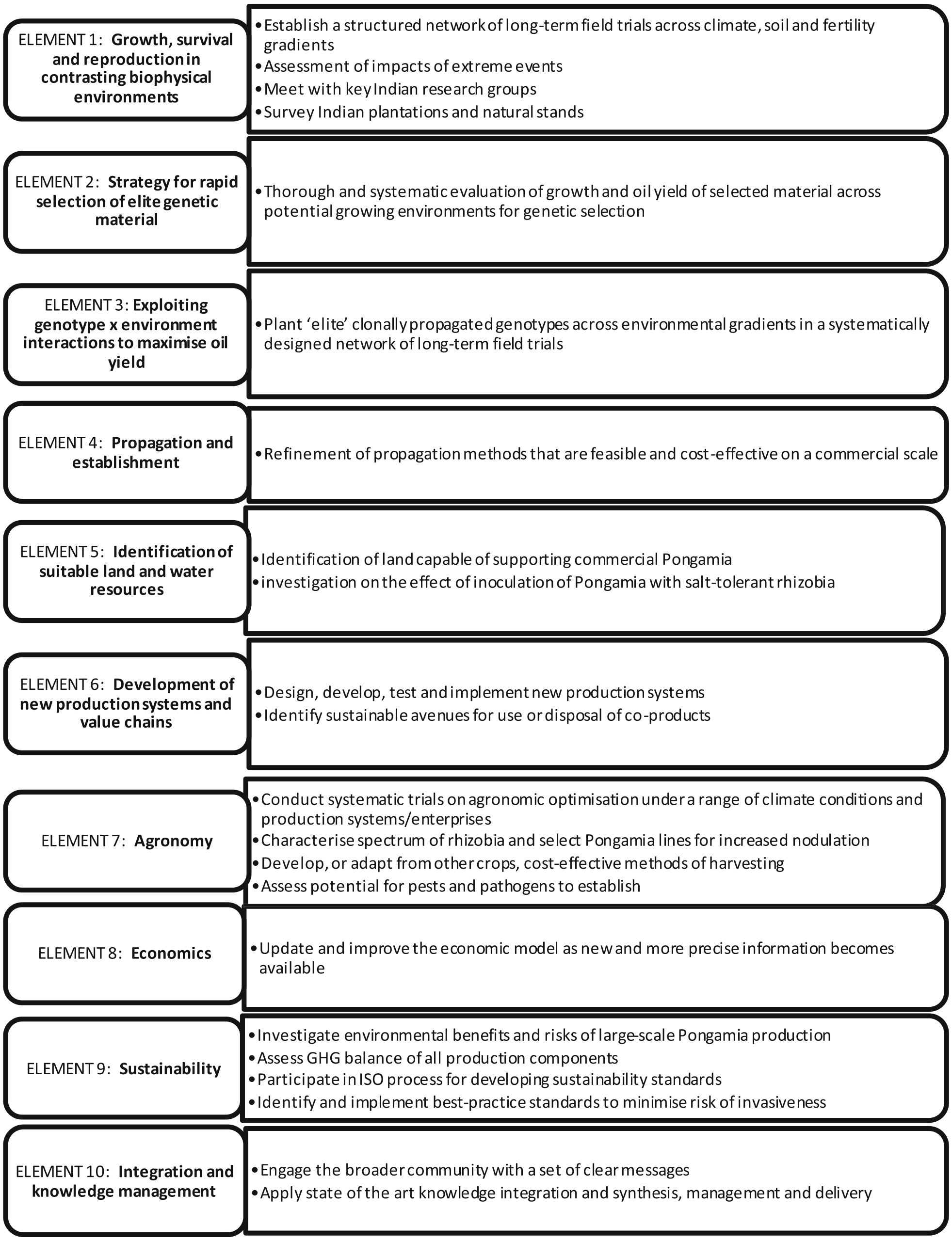
Action: In order to gain a social license to operate, the bioenergy industry will benefit from engaging the broader community with a set of clear messages to explain the different technologies, the opportunities for regions and industries, and the sustainability credentials. These messages, if they are to gain the confidence of the community, need to be demonstrably underpinned by robust science. If the plan as presented here is implemented, there will be a great deal of new knowledge generated and an even greater need to apply state of the art knowledge interpretation and synthesis, management, and delivery.

A Comprehensive Research Strategy

Our review has identified several key areas for future research and development to support the expansion of a Pongamia industry in Australia. Here, we summarise our review and outline a comprehensive research strategy to fill the gaps in knowledge about the potential for Pongamia to be utilised as a biofuel crop in Australia.

Figure 8 synthesises the ten key knowledge gaps and research questions identified by our review and highlights in brief the actions required to address the knowledge gaps. The strategy starts with an element that relates to survival, growth, and reproduction in Australian climates and edaphic conditions. Key to addressing the knowledge gaps in this area is the need to establish a structured network of long-term field trials across climate, soil, and fertility gradients that run long enough to capture year to year variability in climate. Trial plantations established with a sound experimental design are a vital component of the comprehensive research strategy and can be used for collection of data to address many of the knowledge gaps identified in this paper. In addition, the experts agreed that there is still a lot that could be learned from the long history of use of Pongamia for fuel in India and that there is a large amount of research on commercial

Fig. 8 A summary of the ten key research priorities and actions



ELEMENT 1: **Growth, survival and reproduction in contrasting biophysical environments**	• Establish a structured network of long-term field trials across climate, soil and fertility gradients • Assessment of impacts of extreme events • Meet with key Indian research groups • Survey Indian plantations and natural stands
ELEMENT 2: **Strategy for rapid selection of elite genetic material**	• Thorough and systematic evaluation of growth and oil yield of selected material across potential growing environments for genetic selection
ELEMENT 3: **Exploiting genotype x environment interactions to maximise oil yield**	• Plant 'elite' clonally propagated genotypes across environmental gradients in a systematically designed network of long-term field trials
ELEMENT 4: **Propagation and establishment**	• Refinement of propagation methods that are feasible and cost-effective on a commercial scale
ELEMENT 5: **Identification of suitable land and water resources**	• Identification of land capable of supporting commercial Pongamia • investigation on the effect of inoculation of Pongamia with salt-tolerant rhizobia
ELEMENT 6: **Development of new production systems and value chains**	• Design, develop, test and implement new production systems • Identify sustainable avenues for use or disposal of co-products
ELEMENT 7: **Agronomy**	• Conduct systematic trials on agronomic optimisation under a range of climate conditions and production systems/enterprises • Characterise spectrum of rhizobia and select Pongamia lines for increased nodulation • Develop, or adapt from other crops, cost-effective methods of harvesting • Assess potential for pests and pathogens to establish
ELEMENT 8: **Economics**	• Update and improve the economic model as new and more precise information becomes available
ELEMENT 9: **Sustainability**	• Investigate environmental benefits and risks of large-scale Pongamia production • Assess GHG balance of all production components • Participate in ISO process for developing sustainability standards • Identify and implement best-practice standards to minimise risk of invasiveness
ELEMENT 10: **Integration and knowledge management**	• Engage the broader community with a set of clear messages • Apply state of the art knowledge integration and synthesis, management and delivery

production of Pongamia currently being undertaken in India which is difficult to access. An assessment of this research may allow for modification of the scope and methodology of any field trials and further research undertaken in Australia.

The second element involves developing and implementing a strategy for rapid selection of elite genetic material for Pongamia. The ability to select and improve genetic material is considered vital by industry stakeholders for the progression of a Pongamia industry.

The third element combines outputs from the first elements to understand the genotype × environment relationship particularly as it relates to oil yield. This element can only be understood through investment in trial plantations where growth and yield in varying environments can be assessed over the long-term.

The fourth element covers methods for propagation and establishment of Pongamia on a commercial scale. In fact, an inability to successfully propagate clonal material at a commercial scale may be a ‘deal-breaker’ for the viability of the industry.

The fifth element (linked to the first and third elements) involves understanding land suitability across Australia through a systematic analysis. This element also addresses assessing the suitability of land for nitrogen fixation and the ability to grow Pongamia in degraded and salt-affected or salt-irrigated land.

Element 6 deals with identification of opportunities for new production and farming systems and new value chains. Production of Pongamia provides the opportunity to establish novel types of farming systems which integrate production systems taking into account crops, grazing, carbon farming, and renewable energy. This could have many benefits at the ‘grower’ part of the value chain including enterprise diversification, reduction of risk, and reducing GHG emissions.

The seventh element identifies the uncertainties related to agronomy for commercial Pongamia production. These uncertainties can also be addressed partly by data collected from field trials in conjunction with specific experimental methods (e.g., silviculture, pest control) and be further supplemented by modelling approaches.

The economics of Pongamia production, harvest, delivery of Pongamia oil, and refining to biodiesel are covered in the eighth element. A preliminary economic analysis of production costs for Pongamia in Australia is already underway, and the results of this will help identify where further research in understanding the economic viability of a commercial Pongamia production system in needed.

The ninth element identifies questions of sustainability. Robust and independently verified (or certified) sustainability credentials are vital in order for the Pongamia industry to expand in Australia.

The tenth and final element involves integrating, synthesising, managing, and delivering the outputs from this comprehensive research strategy to achieve a clear set of messages with the goal of achieving broad community acceptance

Conclusions

This paper puts forward the combined knowledge, data, and expertise of most of the active research and industry groups working with Pongamia in Australia. It highlights the existing knowledge, the critical knowledge gaps, and suggests a cohesive strategy for national R&D within a risk management framework.

Pongamia shows potential for increasing Australia's current low level of plant oil production, using a non-food crop. The tree is leguminous and does have the potential for high oil yields (perhaps 2–8 t/ha/year). However, there are many challenges to address which could be solved by investing in a significant and structured R&D program. Other challenges, for example, availability of suitable land and water resources which are increasingly contested, or the continued volatility of oil prices, also need to be considered and planned for.

We conclude that there is sufficient evidence about the potential for Pongamia to warrant investment in well structured R&D over the next decade. This R&D would link molecular level genetic research through to paddock scale agronomic research, landscape scale investigation of new production systems and value chains, and system scale research into a range of aspects of sustainability. Addressing the challenges and knowledge gaps as described in this paper may enable the promise of Pongamia as a significant new source of plant based oils in Australia (and potentially many other places in the world) to be realised.

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