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A COMPREHENSIVE REVIEW OF THE VERSATILE ROLES OF *PONGAMIA PINNATA* (L.) PIERRE: ENVIRONMENTAL IMPACTS, MEDICINAL APPLICATIONS AND ECONOMIC POTENTIAL

Sonam Chaudhary, Amit Yadav, Ghanshyam Sharma and Indu Singh Sankhla*
Department of Botany University of Rajasthan, Jaipur, Rajasthan, India
*Corresponding author E-mail: induiitkgp@gmail.com
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ABSTRACT

Pongamia pinnata, a leguminous tree native to the Indian subcontinent and Southeast Asia, is gaining increasing recognition for its ecological, medicinal, and economic value. *P. pinnata* is a resilient, nitrogen-fixing species capable of thriving in arid, saline, and degraded environments, making it an ideal candidate for ecological restoration and sustainable biofuel production. This review provides a comprehensive overview of the multifaceted roles of *P. pinnata*, emphasizing its potential in enhancing soil fertility through symbiosis with rhizobia, mitigating land degradation, sequestering atmospheric carbon, and adapting to climate-induced abiotic stressors. *Pongamia pinnata* forms symbiotic nodules with diverse rhizobial strains from genera *Bradyrhizobium* and *Rhizobium*, enhancing nitrogen fixation and supporting sustainable agriculture. Its region-specific rhizobial diversity highlights the need for further genomic research to optimize biofertilizer use. Additionally, its strong root system aids in soil stabilization, erosion control, and land reclamation. From a medicinal perspective, *P. pinnata* exhibits broad-spectrum pharmacological activities, including antimicrobial, anti-inflammatory, antidiabetic, hepatoprotective, and anticancer properties. Its bioactive compounds, particularly karanjin and pongamol, have demonstrated promising therapeutic potential in both traditional and modern medicine. The plant's phytochemical richness also supports its application in herbal cosmetics and pharmaceutical formulations. Economically, *P. pinnata* is an emerging source of non-edible oil with high potential for biodiesel production. Its oil-rich seeds and adaptability to marginal lands make it an attractive option for renewable energy, reducing dependence on fossil fuels while offering income-generating opportunities in rural areas. The plant is also being utilized in agroforestry systems to improve crop productivity and soil health, thereby supporting sustainable livelihoods. This review underscores the necessity of integrative research on *P. pinnata* across ecological, molecular, and industrial domains. Harnessing its full potential could address pressing challenges in environmental sustainability, renewable energy, and natural resource management.
***Keywords* :** *Pongamia pinnata,* nitrogen fixation, biodiesel production, karanjin**.**

Introduction

Fabaceae is a major plant family with over 714 genera, known for its economic importance as a food source and forage. *Pongamia pinnata* (L.) Pierre, a key species in this family, is a multipurpose, drought and salt resistant legume tree native to the Indian subcontinent and Southeast Asia, now grown in humid tropical regions worldwide. It is recognized for its high seed yield and potential as a biodiesel source, and is well adapted to adverse environmental conditions. The species is also known by various names, including *Millettia pinnata* and *Derris indica* (Al *et al*., 2013).

The name *Pongamia* is derived from the Tamil word, 'Pinnata' referring to its pinnate leaves. *Pongamia pinnata* belongs to the family Leguminosae and the subfamily Papilionaceae (Ghumare *et al.*, 2014). *Pongamia* is a versatile species, with each part of the tree, including flowers, fruits, seeds, leaves, bark, and roots, serving distinct and valuable purposes. The flowers are used for medicinal purposes, while the fruits and seeds provide oil and biofuel. Oil content in *Pongamia pinnata* seeds is around 40% (Sangwan *et al*., 2010). The leaves and bark have applications in traditional medicine, and the roots form symbiotic relationships with *Rhizobium*, enhancing soil fertility (Shankar *et al*., 2017). The aim of this study is to provide a comprehensive review of the diverse roles of *Pongamia pinnata*, highlighting its environmental, medicinal, and economic significance. This review explores the plant's potential in ecological restoration, biofuel production, and carbon sequestration, emphasizing its contribution to environmental sustainability. Additionally, it examines the medicinal properties of *Pongamia pinnata*, including its pharmacological activities and traditional therapeutic uses. Furthermore, the study assesses its economic viability by analyzing its applications in agriculture, industry, and alternative energy sectors. By integrating these perspectives, this review aims to underscore the plant's multifaceted benefits and promote its wider utilization in various fields. The role of *Pongamia pinnata* can be explored in the following aspects:

1. Environmental Impacts

(i) Nitrogen Fixation and Soil Fertility Improvement

Legume plants are nodulated by diverse rhizobia, a group of gram-negative, genetically diverse, and physiologically heterogeneous soil bacteria. This legume-rhizobia symbiosis is crucial for nitrogen fixation and plays a vital role in the nitrogen cycle on the Earth (Sankhla *et al*., 2015). Biological nitrogen fixation (BNF) is a microbial process that transforms atmospheric nitrogen into a bioavailable form for plants, and plays a role in supplying 25–30% of the global protein intake (Bohlool *et al*., 1992). The symbiotic relationship between legumes and rhizobia improves soil fertility and plant growth naturally, providing an eco-friendly alternative to chemical fertilizers. Besides nitrogen fixation, rhizobia also promote plant growth through activities like phosphate solubilization, IAA production and ammonia production making them key to sustainable agriculture (Yadav *et al*., 2022). Approximately 25% of the Earth's newly fixed nitrogen (N_2) originates from the industrial fixation of dinitrogen (N_2) for chemical fertilizer production, while biological nitrogen fixation processes contribute around 60% (Zahran, 1999).

With the rising population, improving crop productivity is crucial. Characterization of native rhizobia helps to develop biofertilizers suited to local climates, boosting crop yields naturally while reducing the need for chemical fertilizers (Sharma *et al*., 2024).

Pongamia pinnata exhibits a distinct advantage due to its nitrogen-fixing capability which is enhanced tolerance to abiotic stress conditions and improves soil fertility that making it superior to other biodiesel crops. It can grow on low-fertility soils due to its extensive nodulation and effective nitrogen-fixing symbiosis with rhizobia, which reduces competition for fertilizers, water, and land with food crops. *Pongamia* has the potential to restore soil fertility, particularly in degraded soils, through its nitrogen-fixing capacity. Authentic and effective rhizobia strains need to be isolated and identified to assist *P. pinnata* plantations in nitrogen-deficient soils (Kesari *et al*., 2013). Many researchers isolated and reported the rhizobial strains that have ability to form symbiotic relationships with *Pongamia pinnata*.

Pongamia is known to associate with various species from the genera *Bradyrhizobium* and *Rhizobium* exhibiting a typical legume nodulation response. Various authors have reported the ability of these rhizobial strains to form symbiotic relationships with *Pongamia pinnata*. Several rhizobial strains associated with *Pongamia pinnata* have been identified based on 16S rRNA, *recA*, *dnaK*, and *atpD* gene sequences across different geographical regions.

Rasul *et al*. (2012) reported various rhizobial strains associated with *Pongamia pinnata* from the southern regions of India. These strains were identified as species of *Bradyrhizobium* and *Rhizobium* (Table 1). Expanding on diversity, Kesari *et al*. (2013) identified a novel species, *Rhizobium Pongamiae* sp. nov., from *Pongamia pinnata* in North Guwahati (Assam). Similarly, Arpiwi *et al*. (2013) reported effective rhizobial isolates for *Millettia pinnata* from soils in Kununurra, Australia, where the dominant microsymbiont was the slow-growing *Bradyrhizobium yuanmingense*, along with other slow-growing species of *Bradyrhizobium*. In addition, fast-growing isolates were identified as species of *Rhizobium*. Similarly, in Australia, Nemenzo-Calica *et al*. (2016) identified the fast-growing rhizobia as species of *Rhizobium mesoamericanum*, while the slow-growing isolates were closely related to *Bradyrhizobium elkanii* and *B. pachyrhizi*. Shen *et al*. (2023) studied *P. pinnata*-associated rhizobia in China and found that *Bradyrhizobium* isolates were 100% similar to *Bradyrhizobium pachyrhizi* PAC 48^T. Meanwhile, *Rhizobium* isolates showed high similarity to *Rhizobium nepotum* Pulawska 39/7^T (99.12%) and *Rhizobium leguminosarum* NBRC14778^T (99.47%).

Table 1: Identified rhizobial strains associated with *P. pinnata* based on 16S rRNA, *recA*, *dnaK* and *atpD* gene sequences

Isolates	Closest type Strains	Source	Origin
VKLR-01	*Rhizobium Pongamiae* sp. nov.	Kesari *et al.* (2013)	North Guwahati, Assam (India)
NA (4 & 7)	*Bradyrhizobium yuanmingense* M11, *B. yuanmingense* TTC4	Arpiwi *et al.* (2013)	Kununurra (Australia)
NA (15, 26 & 38)	*B. yuanmingense* CCBAU 10071^T		
NA (31, 35 & 36)	*Bradyrhizobium* sp. M16, *Bradyrhizobium* sp. DOA10		
NA (1 & 28)	*Rhizobium miluonense* CC-B-L1, *Rhizobium* sp. CCBAU51330		
PRNB (1-3, 5-11, 16, 26-34)	*Bradyrhizobium* sp. GX5	Rasul *et al.* (2012)	Southern regions of India
PRNB (4, 12-15, 25)	*Rhizobium* sp. TANU 14 (AJ971481)		
PRNB (21, 24)	*Bradyrhizobium* sp. SEMIA 6434		
PRNB (22 & 23)	*Bradyrhizobium elkanii* SEMIA 5002 (FJ390895)		
PP (29 ,40, 47, 56, 57, 69, 76, 80, 90, 98, 99 and 111)	*B. pachyrhizi* PAC 48^T	Shen *et al.* (2023)	China
PP (1, 6 & 18)	*Rhizobium nepotum* Pulawska 39/7^T		
PP15	*Rhizobium leguminosarum* NBRC14778^T		
PR-UQ (01 & 04)	*B. elkanii*, *B.pachyrizi*	Nemenzo-Calica *et al.* (2016)	Australia
PR-UQ (03 & 05)	*R. mesoamericanum*		

(ii) Soil Erosion Control

Pongamia pinnata trees are commonly grown along highways, roads, and canals as a soil stabilizer agent. Their lateral root system helps to stabilize the soil and bind sand dunes (Usharani *et al.*, 2019). *Pongamia* trees grow in challenging environments, growing in various soils, sunlight, and temperatures. They have the ability to generate bio-energy on degraded, non-arable land that is not suitable for the crop plants, making them a sustainable and environmentally friendly alternative for renewable energy production *Pongamia* restoring degraded land through cultivation could enhance ecosystem services and support biodiversity. Compared to other biofuel crops like oil palm, coconut, and jatropha, *Pongamia* stands out as a prime candidate for bioenergy feedstock on degraded land due to its multiple benefits (Leksono *et al.*, 2021).

(iii) Carbon Sequestration

Carbon sequestration is the process of capturing CO_2 from the atmosphere (source) and storing it in green plants (sink) for long-term storage. According to Kyoto Protocol 2011, global warming is increasingly evident, driven by rising atmospheric CO_2 levels from 280 ppm in 1850 to 394 ppm in 2012. *Pongamia* plantations on previously cleared land can provide carbon sequestration benefits by storing carbon in long-lived tree biomass, enhancing soil carbon stocks, and producing biochar from husks and prunings (Murphy *et al.*, 2012; Soni *et al.*, 2013). Tall trees with high biomass and many leaves sequester more carbon, acting as long-term carbon sinks and helping mitigate climate change.

(iv) Drought and Salt Tolerance

Environmental stress during growth causes biochemical and morphological changes in plants (Oshunsanya *et al.*, 2019). Abiotic stress, like salinity and drought, limits plant growth and yield. Drought stress affects global food security by disrupting normal physiological processes of plants, leading to reduced yields. Abscisic acid (ABA) plays a key role in controlling plant responses to stress through various molecular mechanisms. *Pongamia* is a semimangrove species with high stress tolerance, capable of growing in both freshwater and seawater. The *MpAITR1*, an ABA-induced gene in *Pongamia*, encodes a transcription factor localized in the nucleus. Its expression is significantly upregulated by Abscisic acid and salt treatments (Yang *et al.*, 2023).

As reported by Rajarajan *et al.* (2022), four *Pongamia* genotypes exhibited varying responses to drought stress at morphological, physiological, biochemical, and transcriptional levels. The genotype NRCP25 showed superior drought tolerance, with better root growth, photosystem function, stable leaf chlorophyll content, and a stronger antioxidant system. It also had higher malondialdehyde, soluble protein, and proline accumulation, aiding osmotic balance under drought. Up-regulation of drought-responsive genes in NRCP25 enhanced root water uptake, solute accumulation, and osmotic adjustment. These traits suggest NRCP25's potential in breeding programs for improved drought tolerance in arid regions. *Pongamia pinnata* exhibits salt tolerance through several mechanisms. Salinity-induced Ca^{2+} levels mitigate Na^+ toxicity and activate signaling pathways, particularly involving jasmonic acid (JAs). Key phytohormones including jasmonic acid (JAs), salicylic acid (SA), and abscisic acid (ABA) are vital for salinity adaptation. Additionally, metabolites like sugars, amino acids, and polyols support nutrient supply and osmotic balance. These pathways influence antioxidant and transporter gene expression, promoting redox homeostasis and facilitating Na^+ exclusion and sequestration in apoplasmic regions under salinity stress. In their study, Marriboina *et al.* (2017) employed the leaves and roots of *Pongamia* exhibit distinct physiological responses to salt stress, with the roots demonstrating superior efficacy in Na^+ ion sequestration. The roots of *P. pinnata* are crucial for enhancing its salt tolerance. They achieve this by sequestering Na^+ in vacuoles, which reduces the amount of Na^+ that moves to the shoots. Additionally, the absorption of K^+ in the leaves may play a role in preserving leaf water potential and optimizing photosynthesis. On a molecular level, various components of the SOS pathway, along with essential salt-responsive genes related to ABA biosynthesis and receptors, as well as peroxidase (POD), actively contribute to the plant's resilience against high salinity. Marriboina *et al.* (2022) reported that *Pongamia* adapts to salt stress by activating proteins involved in key regulatory and metabolic pathways. It induces root proteins association with phytohormones and some GTP binding proteins, facilitating long-distance signaling between roots and shoots. Ultimately this response supports to maintain cell turgidity and redox homeostasis through various physiological and metabolic processes. Stable leaf photosynthesis under salt-induced water stress indicates effective signaling between roots and shoots, ensuring resilience and adaptive water management. Research has shown that C_2H_2 zinc finger proteins (ZFPs) play a role in mediating responses to abiotic stress across various plant species. In their study, Yu *et al.* (2021) identified and functionally characterized MpZFP1, a nucleus-localized C_2H_2 ZFP, which contributes to salt tolerance in *Pongamia*. Zhang *et al.* (2021) isolated and characterized MpCML40, a calmodulin like protein gene from *Pongamia*, demonstrating that *Arabidopsis* plants expressing 35S:: MpCML40 showed increased proline levels and enhanced tolerance to salt and osmotic stress compared to wild types. Importantly, these transgenic plants thrived under normal conditions, MpCML40 as a key positive regulator of salt stress responses and a potential target for genetic modification in crop breeding.

(v) Land reclamation

Pongamia is recognized for its effectiveness in mitigating soil erosion and stabilizing sand dunes due to its extensive lateral root system. Moreover, it demonstrates strong potential for cultivation on degraded land. Given Indonesia's vast expanses of degraded land that currently offer minimal ecological or economic value, the introduction of *Pongamia* could contribute significantly to ecosystem restoration and biodiversity conservation. While multiple species produce biofuels, *Pongamia*'s multifunctional role makes it an exceptional candidate for sustainable bioenergy production (Leksono *et al.*, 2021). Maimunah *et al.* (2023) reported rapid growth of *Pongamia* on post-mining land, with an average height increase of 184.92 cm and diameter growth of 10.76 cm over three years, and a survival rate of 87.78%. The Simpson index for local tree species was 0.67, indicating enhanced biodiversity, alongside the presence of bird nests in the canopy. The improved soil fertility facilitated the growth of dicotyledonous herbs, demonstrating the role of *Pongamia* in ecosystem recovery.

(vi) Phytoremediation

Soil heavy metal pollution from mining and mineral waste is a growing concern, as these metals are non-biodegradable and can harm human health. While various remediation methods are being explored, physical and chemical approaches are limited due to their high cost, energy use, potential for secondary pollution, and adverse impact on soil microorganisms. Phytoremediation is an eco-friendly, cost-effective method that uses plants and their soil microbes to clean up pollutants and reduce their harmful effects on the environment (Ali *et al*., 2013; Yu *et al*., 2021).

Phytoremediation using *Pongamia pinnata* has demonstrated notable effects on soil properties and microbial communities in both mine tailings and natural topsoil. Over a three-year in-situ study, significant shifts in soil nutrients, metal content, and microbial diversity were observed, with changes in microbial abundance closely tied to alterations in soil function and the availability of nutrients and metals (Yu *et al*., 2021). In hydroponic systems, *P. pinnata* effectively accumulates arsenic, with antioxidant enzymes and mineral elements such as sulfur and non-protein thiols (NP-SH) playing key roles in stress regulation. These findings support the classification of *P. pinnata* as an arsenic hyperaccumulator and a viable candidate for arsenic phytoremediation (Kumar *et al.*, 2017). Additional studies, comparing *Jatropha curcas* and *P. pinnata* on soils contaminated by paper mill and landfill waste revealed that *P. pinnata* removed up to 93% of nickel within 120 days, although zinc removal was less efficient due to root accumulation. Both species exhibited greater phytostabilization than phytoaccumulation, as evidenced by low translocation and bioaccumulation factors (Borah *et al.*, 2023).

Further enhancing its phytoremediation capabilities, *P. pinnata* inoculated with *Bradyrhizobium liaoningense* strain PZHK1 showed elevated metal accumulation in shoots and higher superoxide dismutase (SOD) activity, indicating improved stress tolerance. Field tests on a V–Ti magnetite mine tailing dam demonstrated the strong remediation potential of *P. pinnata*, supported by its natural nodulation ability and adaptability to the dam coverage conditions required by local regulations (Yu *et al.*, 2017). The species has also shown resilience to Cr (VI), tolerating concentrations up to 200 µg/g soil. When paired with the rhizobacterium *Paenibacillus konsidensis* SK3, metal accumulation in the plant's tissues increased significantly, while Cr (VI) levels in the soil decreased by 13.48%, highlighting the effectiveness of this plant-microbe association in large-scale remediation efforts (Das *et al.*, 2022).

A two-year field study using *P. pinnata* on a V–Ti magnetite tailings dam further confirmed its ecological benefits, with improved soil enzyme activities and enhanced microbial diversity, particularly among Proteobacteria. The study noted increased β-diversity and enrichment of rhizobia taxa such as *Rhizobium* and *Nordella*, suggesting a strong symbiotic relationship that supports ecological restoration in degraded environments (Yu *et al.*, 2019). Moreover, *P. pinnata* seedlings have demonstrated the ability to tolerate high concentrations of Cr (100–800 µM) and Cu (50–400 µM), with efficient uptake and translocation of these metals, especially to the roots and leaves. Notably, copper was found to be more toxic than chromium, but stem accumulation was limited, and shoot elongation remained unaffected. The seed coat played a protective role by absorbing significant amounts of metal, thereby shielding the cotyledon (Kumar *et al.*, 2009). Collectively, these findings highlight significant potential of *P. pinnata*'s as a multifunctional species for phytoremediation and ecological restoration.

2. Medicinal Applications

Herbal medicine, also known as phytotherapy, uses plant parts to treat diseases. *Pongamia pinnata* contains alkaloids, glycosides, and other compounds with various medicinal properties. Its roots treat ulcers, strengthen gums, and aid in gonorrhea. The bark is antihelmintic and useful for skin diseases and ulcers. Leaves aid digestion and treat diarrhea and leprosy. Flowers help with diabetes and balance body energies. Seeds are used for inflammation and anemia, while the oil treats eye infections, leprosy, and ulcers (Yadav *et al.*, 2011).

Traditional medicine uses a wide variety of plants with medicinal and pharmacological value, offering a valuable source of new bioactive compounds. *Pongamia pinnata* is one such widely distributed plant (Arote and Yeole (2010). Its medicinal applications are as follows:

(i) Antimicrobial Activity

Various parts of *Pongamia pinnata* exhibit notable antimicrobial activity against a range of bacterial and fungal pathogens. Seed extracts using petroleum ether and ethyl acetate showed strong inhibition against *Bacillus subtilis* and *Staphylococcus aureus*, and petroleum ether was effective against *Pseudomonas aeruginosa* (Ujwal *et al.*, 2007). Bark extracts exhibited moderate activity against *B. subtilis* and *S. aureus*, with notable inhibition of *E. coli* (Ujwal *et al.*, 2007). Leaf extracts using different solvents (chloroform, ethyl acetate, methanol) demonstrated significant antibacterial effects, in some cases exceeding those of streptomycin, with inhibition zones ranging from 8.1 to 18 mm and MIC values of 125–1000 µg/mL (Bajpai *et al.*, 2009). Methanolic seed extracts showed strong activity against *P. aeruginosa* (20 mm zone), followed by ethanolic extracts (18.5 mm) against multiple pathogens (Rani *et al.*, 2013). Seed oil extracted with n-hexane in DMSO displayed potent antibacterial and antifungal activity, especially against *Yersinia enterocolitica* and *Aspergillus niger* (Kesari *et al.*, 2010). Flower extracts in acetone and petroleum ether also showed broad-spectrum antimicrobial effects, with maximum inhibition against *S. aureus* (24 mm), *B. cereus* (23 mm), and *E. coli* (22 mm) at 1600 µg concentrations (Kagithoju *et al.*, 2012).

Pongamia pinnata seed oil (PSO) tested as a fumigant against sapstain (*Alternaria alternata*) and mould (*Aspergillus niger*) fungi. Fumigation with 15% PSO resulted in complete growth inhibition of both fungi across three bamboo species (*B. tulda*, *B. balcooa*, *D. strictus*) (Samani *et al.*, 2024).

In addition, Silver-doped copper oxide nanoparticles (CuO: Ag NPs) synthesized using *Pongamia pinnata* flower extract exhibited strong antimicrobial activity, with a 26 mm inhibition zone against *Staphylococcus aureus* and *Escherichia coli*, and antifungal effects on *Candida albicans* and *Fusarium oxysporum*. They also demonstrated 99% photocatalytic degradation of Rhodamine B dye, suggesting their potential for both antimicrobial and photocatalytic applications (Saravanakkumar *et al*., 2024). Singh *et al*. (2024) demonstrated that Karanjin (Kar) from *Pongamia pinnata* seeds showed an antiviral activity against Newcastle disease virus (NDV). In vitro, it reduced NDV replication and viral activity. In vivo, it lessened NDV effects in chicken embryos. In silico studies showed strong binding with the NDV, HN (hemagglutinin-neuraminidase) protein. Kar also boosted antiviral responses by upregulating *GLUT1* and *HEX* genes, suggesting its potential for future antiviral treatments.

(ii) Anti-Inflammatory and Analgesic Properties

Inflammation is the body's response to injury, and conventional drugs for it often have side effects. Herbal remedies like *Pongamia pinnata* are safer alternatives. The plant's seeds and oil are used in traditional medicine to treat conditions like leucoderma, leprosy, and rheumatism. The anti-inflammatory effects of methanolic leaf extract of *Pongamia pinnata* using the heat-induced protein denaturation method was compared with diclofenac sodium. The extract showed an IC_{50} value of 82.24 µg/ml, while diclofenac sodium had an IC_{50} of 18.36 µg/ml. The anti-inflammatory activity of the extract is likely due to its flavonoids, tannins, and alkaloids (Bairagi *et al*., 2023).

Pongamol, a bioactive compound in *Pongamia pinnata* seed oil, which efficiently extracted using boron trifluoride etherate ($BF_3{\cdot}OEt_2$), yielding 64% recovery with >95% purity. It showed significant anti-inflammatory activity, inhibiting soy lipoxygenase-1 (LOX-1). Both pongamol and its semi-synthesized form, dihydropongamol (DHP), reduced paw edema (55%) and ear swelling (74%) in rat models, supporting its potential as an anti-inflammatory agent (Rekha *et al*., 2020).

The 70% ethanolic extract of *Pongamia pinnata* leaves showed significant anti-inflammatory effects in rats across acute, subacute, and chronic inflammation models. The extract of leaves reduced edema and inflammation without causing toxicity, mortality, or gastric lesions, indicating its potential as a safe anti-inflammatory treatment (Srinivasan *et al*., 2001).

Rao *et al*. (2007) established that the leaf extracts of *Pongamia pinnata* (petroleum ether, ethyl alcohol, and aqueous) showed anti-ulcer and anti-inflammatory effects in rats. Ethanol and petroleum ether extracts also showed notable analgesic activity, while the aqueous extract did not. No toxicity was observed at doses up to 2000 mg/kg. These effects are likely due to phytochemicals like alkaloids, flavonoids, and tannins. The methanolic extract of *Pongamia pinnata* stem bark (PSBE) showed considerable anti-inflammatory and analgesic effects in animal models. At doses of 200, 500, and 1000 mg/kg, PSBE reduced inflammation in acute and chronic models without toxicity or gastric irritation (Sagar *et al*., 2010).

(iii) Antidiabetic Activity

The antidiabetic activity of *Pongamia pinnata* leaf extracts (petroleum ether, chloroform, alcohol, and aqueous) assessed in alloxan-induced diabetic rats. Ethanol and aqueous extracts significantly reduced blood glucose to 155.83 ± 11.21 mg/dl and 132.00 ± 4.96 mg/dl, respectively, compared to the diabetic control (413.50 ± 4.75 mg/dl). In glucose tolerance tests, these extract lowered the glucose levels and prevented body weight loss, indicating their antidiabetic potential (Sikarwar and Patil, 2010). The pongamol and karangin, compounds derived from the fruits of *Pongamia pinnata*, exhibit significant antihyperglycemic effects in Streptozotocin-induced diabetic rats and type 2 diabetic db/db mice. These effects are likely due to the inhibition of protein tyrosine phosphatase-1B, a key regulator of blood sugar, which may serve as the primary target for their activity (Tamrakar *et al*., 2008). Cycloart-23-ene-3β, 25-diol (B2), isolated from *Pongamia pinnata* stem bark, demonstrated antidiabetic effects in streptozotocin–nicotinamide-induced diabetic mice. It reduced serum glucose, improved glucose tolerance, and increased insulin levels (Badole and Bodhankar, 2010). The alcohol extract of *Pongamia pinnata* stem bark showed antihyperglycemic activity in diabetic mice, with no toxicity up to 5,000 mg/kg. It reduced serum glucose at doses of 100, 200, and 400 mg/kg, with peak effects at 4 hours. The greatest glucose reduction (305.72 mg/dl) was observed at 400 mg/kg on day 28. The stem bark extract (200 mg/kg) also improved glucose tolerance in non-diabetic mice, suggesting its potential as an antihyperglycemic agent (Badole *et al*., 2008).

(iv) Hepatoprotective effects

Pongamia pinnata hydro-alcoholic leaf extract (400 mg/kg/day) effectively mitigated hepatic ischemia/reperfusion injury by restoring the balance between oxidants and antioxidants, improving liver function and histological damage in rats (Behera *et al*., 2012).

The bark of *P. pinnata* has traditionally been used for treating bronchitis, whooping cough, rheumatism, and diabetes. Phytochemical analysis of the hydro-alcoholic extract of *P. pinnata* revealed flavonoids, phenolics, tannins, alkaloids, and sterols. The extract showed significant hepatoprotective effects by reducing liver enzymes and increasing protein levels in rats. Key compounds, including 3-methoxy-2´´,2´´-dimethylpyrano-flavone and caryophyllene oxide, highlight its potential as a hepatoprotective agent (Battu *et al*., 2019). The ethanolic and aqueous extracts of *Pongamia* showed significant hepatoprotective effects against paracetamol-induced liver damage in albino rats. The extracts helped reduce liver enzyme levels (SGPT, SGOT, ALP) and total bilirubin, suggesting that phenolics and flavonoids in the bark contribute to its protective properties (Kaur *et al*., 2014). Chelvan *et al*. (2008) reported that methanolic extract of *P. pinnata* flowers (300 mg/kg) significantly improved liver function in rats with paracetamol-induced damage, indicating hepatoprotective effects likely due to its antioxidant properties. Derangula *et al.* (2022) reported that an aqueous extract of *Pongamia pinnata* leaves demonstrates liver-protective effects at a dose of 400 mg/kg when compared to a toxic control.

(v) Anticancer Activity

AuNPs synthesized using *Pongamia pinnata* leaf extract have promising selective anticancer properties against HeLa cells, potentially offering a basis for future cancer therapies, while demonstrating minimal toxicity to normal human cells (HEK293) (Khatua *et al*., 2020).

(vi) Antihyperlipidemic Effects

Hyperlipidemia is a metabolic disorder linked to an increased risk of diabetes. Elevated levels of triglycerides, cholesterol, and Low- Density Lipoprotein (LDL) are major contributors to the early development of cardiovascular diseases like atherosclerosis, hypertension, and coronary heart disease (Ansarullah *et al*., 2009). Studies on the stem bark, fruits, and flowers of *P. pinnata* found that they help lower blood sugar. The seed oil also contains fluorescent pyranoflavonoids (Tamrakar *et al*., 2008; Punitha and Manoharan, 2006).

Sikarwar, and Patil, (2014) investigated the chloroform extract of *Pongamia pinnata* leaves significantly reduced cholesterol, triglycerides and LDL, while increasing High- Density Lipoprotein (HDL) in hyperlipidemic rats, suggesting its potential as a herbal treatment for hyperlipidemia. Similarly, the ethanolic extract of *P. pinnata* flowers reduces hyperglycemia and lipid peroxidation, while boosting antioxidant defenses in diabetic rats. These effects are similar to glibenclamide, suggesting it could be a safe alternative for managing diabetes (Punitha and Manoharan, 2006). *Pongamia pinnata* leaf extract (250 and 500 mg/kg/day for 30 days) improved lipid profiles in high-fat diet-fed rats, reducing body weight, cholesterol, triglycerides, LDL, and VLDL, while increasing HDL. The 500 mg/kg dose was more effective, suggesting heart-protective benefits, whereas the 250 mg/kg dose had no significant effect on HDL (Tenpe *et al*., 2008).

3. Economic Potential

(i) Biofuel Production

Biodiesel, a sustainable alternative fuel, is derived from vegetable oils or animal fats through transesterification with methanol or ethanol to reduce viscosity. It is biodegradable, low in toxicity and sulfur, highly flammable, and has a high cetane number, making it efficient and eco-friendly (Chen *et al*., 2007).

The non edible seeds of *Pongamia pinnata* which contain 30–40% oil, are well-suited for biodiesel production (Dwivedi and Sharma, 2011). Its seed oil has gained recognition as a renewable source for the growing biofuel industry, and its economic feasibility largely depends on the oil content of the seeds (Leksono *et al*., 2024). The increasing demand for petroleum fuels, especially in developing countries, highlights the need for alternative energy sources. Ali *et al.* (2024) optimized the conversion of *Pongamia* oil to biodiesel using acid esterification and alkali transesterification. This study optimized *Pongamia* oil conversion to biodiesel using acid esterification and alkali transesterification. The optimal conditions were 20 mL methanol, 0.8 g KOH, 0.2 mL acid, 60 min, and 55°C. The highest experimental yield was 78.25%, close to the 84.02% simulation yield. The biodiesel met ASTM D 6751 standards and can be blended with petro-diesel, aiding in pollution reduction and climate action.

In India, with rising fossil fuel prices and environmental concerns, non-edible oils including *Jatropha* and *Pongamia* are gaining interest for biodiesel production. *Pongamia pinnata* shows great potential, with seed yields of 9-90 kg/tree and a yield potential of 900-9,000 kg/hectare. Its oil has an annual production potential of 135,000 million tons, though only 6% is currently utilized. *Pongamia* crude oil contains key fatty acids like palmitic, stearic, linoleic, and eicosenoic acids, contributing to its favorable properties for biodiesel and industrial applications. It has a yellowish-red color, density of 0.924 g/cm^3, viscosity of 40.2 mm²/sec, acid value of 5.40 mg KOH, and a calorific value of 8742 kcal/kg. Other important characteristics include specific gravity of 0.925, flash/fire points of 225°C/230°C, cloud/pour points of 3.5°C/-3°C, and cetane number 42. To further reduce biodiesel production costs, utilizing cheaper feedstocks, such as non-edible oils, waste vegetable oils, animal fats, and oil refining byproducts, can be an effective strategy (Bobade and Khyade, 2012).

The Fe_3O_4–SiO_2–PAIL nanocatalyst provides an eco-friendly and effective way to produce biodiesel from *Pongamia pinnata* seed oil. It has strong catalytic performance, magnetic properties, and can be reused multiple times (Sangeetha and Baskar, 2024). Biodiesel from *Pongamia pinnata*, offers a renewable alternative to fossil fuels in India. Fuel properties like density, viscosity, and flash point were tested according to ASTM standards (Bobade and Khyade, 2012). Biodiesel from *Pongamia pinnata* oil, produced with methanol and iron nanoparticles as a catalyst, meets ASTM D6751 standards. Iron nanoparticles offer advantages over traditional catalysts due to high surface area, catalytic activity, and resistance to saponification, making this biodiesel a viable diesel alternative (Rengasamy *et al*., 2014).

Nabi *et al*. (2009) demonstrated that biodiesel from *Pongamia pinnata* oil could be produced via transesterification, achieving a 97% methyl ester yield. They suggested that cultivating karanja on Bangladesh's unused land could reduce diesel imports by 28%. Engine tests revealed that biodiesel blends significantly reduced emissions, including CO by 50%, smoke by 43%, and noise by 2.5 dB, although NOx emissions increased by 15% compared to diesel fuel.

Naik *et al*. (2008) reported that *Pongamia pinnata* oil, often containing high Free Fatty Acids due to seed moisture, is unsuitable for conventional alkali-catalyzed biodiesel production. They employed a dual-step process involving acid-catalyzed esterification to reduce the acid value, followed by alkali-catalyzed transesterification. This approach achieved a biodiesel yield of 96.6–97%. Meher *et al*. (2006) optimized the transesterification of Karanja oil with methanol by adjusting parameters such as catalyst concentration, alcohol/oil molar ratio, temperature, and mixing rate. The process achieved a 97–98% yield of Karanja oil methyl ester (KOME), with fatty acid methyl esters quantified using HPLC and 1H^1H1H NMR.

(ii) Agroforestry

As the global population nears 11 billion by 2050, ensuring food security with protecting the environment is very essential. Agroforestry, which combines trees with crops or animals, offers sustainable solutions like carbon sequestration and climate mitigation. The interplay of climate and soil conditions significantly influences agricultural productivity, economic viability, and human well-being. *Pongamia pinnata*, a resilient non-food legume, grows well in poor soils, improves soil fertility through nitrogen fixation, and offers biodiesel, medicines, and environmental benefits. Its adaptability to marginal soils, limited water availability, nutrient deficiencies, and high salinity makes it highly suitable for sustainable agriculture, renewable energy, and economic development (Dinesha *et al*., 2023; Sileshi *et al*., 2023; Karada *et al*., 2023).

Agroforestry systems involving *Pongamia pinnata* have shown both potential and challenges for crop productivity. During the 2021–22 Rabi season, Karada *et al*. (2023) found that early sowing improved wheat performance, but the agroforestry system resulted in lower plant growth, yield, and harvest index compared to open systems, highlighting the need for optimization of agroforestry practices to enhance wheat productivity. Inamati and Patil (2019) found that *Pongamia pinnata* enhanced safflower productivity through optimized source selection. These findings emphasize the importance of selecting and optimizing *Pongamia* sources for improved crop yields in agroforestry systems.

According to Ganesha and Inamati (2023), an investigation on the effect of *Pongamia pinnata* seed sources on litter quality and decomposition revealed variations in nutrient concentrations, including nitrogen, potassium, lignin, cellulose, ash, and phosphorus. These findings emphasize role of *Pongamia* in enhancing nutrient cycling, which support soil fertility, moisture retention, and microbial activity for sustainable agroforestry systems. Kiyam, (2020) found that intercropping *Chlorophytum borivilianum* with *Pongamia pinnata* combined with 100% vermicompost (5-ton ha^{-1}), led to improved growth and tuber yield. Without any negative effect on *C. borivilianum*, *Pongamia* fix the nitrogen, enhance soil fertility and provide moderate shade. According to Painkra *et al*. (2020), a field experiment to assess nutrient efficiency for turmeric cultivation under a Karanj-based agroforestry system found that 100% Farm Yard Manure (FYM) led to highest plant growth, followed by various inorganic and FYM combinations. Intercropping Brinjal (Pant Rituraj variety) with *Pongamia pinnata* with 75% N, 75% P, *Azotobacter*, and PSB resulted in the highest flower count, fruit size, weight, and yield in brinjal. while *Pongamia* growth was minimal during the 6-month cropping period (Bhagat, 2017).

(iii) Pharmaceutical and Cosmetics Industries

It was reported that Millettia pinnata produces seeds rich in bioactive compounds such as karanjin and pongamol, which exhibit anticancer, antimicrobial, and antioxidant properties (Devidas *et al*., 2024). Its seed oil, which contains unsaturated fatty acids, also shows antimicrobial effects. The phytochemistry, therapeutic potential, and diverse applications of *Pongamia pinnata* seed and oil, including their uses in agri-food, cosmetics, and medicine, have been widely explored, with particular focus on their bioactive mechanisms and relevance in Ayurveda. Patil *et al*. (2015) confirmed the presence of Karanjin, a flavonoid from *Pongamia pinnata*, in the 10% formulated sunscreen cream. The study highlighted that Karanjin, along with Ellagic acid from *Punica granatum*, contributes to the photoprotective activity of the cream. Shenoy *et al*. (2010) evaluated the photoabsorptive properties of *Pongamia pinnata* leaf extracts, and found that aqueous and methanol extracts absorb UV-B and UV-C rays, while acetone extract is effective in the UV-A region. With increasing concerns about skin cancer, these extracts offer a natural and promising alternative to synthetic sunscreens for broad-spectrum sun protection when combined in herbal sunscreen formulations.

(iv) Antimicrobial Textile

Natural antimicrobial agents offer significant potential for improving the safety of clothing, especially for medical and healthcare textiles, due to their non-toxic and eco-friendly properties. Most studies focus on specific agents and their textile applications. However, there is limited research on their mechanisms and limitations (Mondal, 2021). Researchers explored the use of *Pongamia pinnata* phytochemical extracts as antimicrobial coatings for cotton fabrics (Andra *et al*., 2019). This plant-based solution helps prevent microbial growth in fabrics, reducing the risk of infections. Traditionally, chemical disinfectants were used, but they were found to be toxic to humans, making *Pongamia pinnata* a safer alternative for antimicrobial textile finishes.

Conclusion

Pongamia pinnata emerges as a highly valuable multipurpose tree species with the capacity to address ecological, medicinal, and economic challenges in a sustainable manner. This review highlights the remarkable adaptability of *P. pinnata* to diverse and adverse environmental conditions, including drought, salinity, and nutrient-deficient soils, primarily due to its nitrogen-fixing ability and resilient root system. Its symbiotic relationship with diverse rhizobial strains enhances soil fertility, making it an eco-friendly alternative to chemical fertilizers and a crucial component of sustainable land management practices. Beyond its environmental significance, *P. pinnata* holds vast potential in the medical field. The plant harbors a rich array of phytochemicals such as flavonoids, alkaloids, and terpenoids, which contribute to its demonstrated antimicrobial, anti-inflammatory, antidiabetic, hepatoprotective, and anticancer properties. These bioactive compounds have been validated through traditional use and supported by modern pharmacological research, underscoring the species' potential for novel drug discovery and herbal medicine development. Economically, *P. pinnata* serves as an efficient non-edible oil source for biodiesel production. Its ability to thrive on marginal lands and yield oil-rich seeds positions it as a sustainable biofuel crop that does not compete with food production. Additionally, its role in agroforestry systems, phytoremediation of heavy metals, and potential applications in the cosmetic and pharmaceutical industries add further economic and ecological value. To fully harness the potential of *P. pinnata*, integrative and multidisciplinary research is essential, particularly in genomics, biofuel optimization, stress physiology, and pharmacology. Promoting its cultivation and utilization could significantly contribute to environmental restoration, renewable energy goals, rural livelihoods, and public health initiatives. Thus, *P. pinnata* stands as a promising candidate for advancing sustainable development across multiple sectors.

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