Review Paper:

Recent advancements in valorisation of *Pongamia pinnata*, a versatile legume tree for bioenergy and biofuel applications

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Abstract
Pongamia pinnata, a multipurpose leguminous tree, has risen to eminence as a sustainable supply of bioenergy and biofuel due to its oil content, tolerance to abiotic stress and marginal land adaptability. The advancements in omics technologies in the recent past have played a considerable role towards the genetic enhancement and holistic exploitation of Pongamia. Genomic and transcriptomic analyses have revealed important genes and regulatory systems in lipid metabolism, growth and responses to various stresses. Profiling of the differential gene expression under stress conditions has helped to understand the tolerance mechanisms that can be used to develop varieties that are resistant to the climatic conditions. Proteomic and metabolomic studies have resolved the functions of proteins and metabolic pathways that are keys in the biosynthesis of oil and accumulation of biomass. New epigenomic research is stressing the importance of heritable variation in the regulation of genes, as a factor leading to improved adaptability and productivity.

A wide range of variability in oil content and fatty acid composition amid different accessions provides a leverage of choice and breeding of high-quality genotypes in production of biodiesel. In addition to oil extraction, deoiled seed biomass can be valorized by thermochemical processes to produce bio-oil, syngas and biochar, or by biochemical processes to produce bioethanol and other bioproducts. Such combined solutions facilitate a circular bioeconomy, where there is zero-waste usage. This review addresses the prevailing situation of omics-based developments, processing technologies and the versatility of uses of Pongamia pinnata, as a guide to future research and commercial implementation in bioenergy area.

Keywords: Biodiesel, Omics technologies, Sustainable bioenergy, Millettia pinnata L., Non edible oils.

Introduction

Pongamia pinnata, (*Millettia pinnata*. L.), commonly known as Karanja in Hindi, is a tree from the Fabaceae family. It has many valuable characteristics, whereby its oil suitability assumes associating with the possibilities in many of the varied bioenergy and biofuel uses[21]. It is an outstanding native leguminous tree of India and has been cultivated in parts of the world that are poorly fertile. The entire seeds of the *P. pinnata* tree contain 35-40% oil in them, where oleic acid is the primary fatty acid, giving it the process of being a capable bio-diesel production feedstock[23]. Pongamia has a long-life cycle, usually sets bloom after 4–5 years of plantation and also requires 9–11 months to develop a mature pod after anthesis. There are numerous positive attributes that were potentially within reach through the understanding of Pongamia genomics and genetics[71].

Limited work has been done on the recent genetic variability, physiological characteristics, biochemical markers and genomic techniques related to *P. pinnata*. Thus, knowledge of the genome and transcriptome of this prospective plant have resulted in the generation of valuable resources for producing better quality. Waste plant tissues and very few seed remnants have applications for chemicals and fuel themselves, up to the level of this versatile tree being put into maximally utilized service. These waste tissues can be processed to extract secondary metabolites and phytochemicals, such as flavonoids, tannins and alkaloids, which have potential applications in pharmaceuticals, natural pesticides and industrial chemicals.

The comprehensive utilization of Pongamia's waste materials aligns with principles of sustainable agriculture and circular bioeconomy, minimizing environmental impact and maximizing resource efficiency. In addition to its biofuel potential, *Pongamia pinnata* possesses a wide array of applications beyond energy production. The oil has been identified as having medicinal properties and can be utilized as a biopesticide and insect repellent [5]. Its seeds and seed cake are rich in protein and can serve as animal feed or organic fertilizer, enhancing the overall sustainability of agricultural systems.

The flowers of the tree are an important source of nectar and pollen, supporting local pollinators and contributing to biodiversity within agroecosystems. These pollinators are drawn to the tree's scented, white or pale pink flowers, which are clustered together and bloom abundantly during flowering. Bees, especially, use Pongamia flowers' nectar and pollen to make a characteristic dark honey, which apart from promoting local apiculture, provide a source of income for rural communities[64].

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Since the Pongamia tree is suitable for weak soils, tolerant to drought and capable of fixing nitrogen from the air, it can be grown without taking away arable land or using big amounts of fertilizers[14]. All these characteristics increase the chances of using *Pongamia pinnata* as a raw material for making both biodiesel and renewable diesel and also support its role in protecting nature and farming.

Research on *Pongamia pinnata* has expanded in recent years, revealing its potential role in mitigating climate change through phytoremediation. The tree has shown promise in removing heavy metals from contaminated soils, thus improving soil health and restoring ecological balance[33]. Studies indicate that Pongamia can effectively rehabilitate degraded lands while providing economic benefits to local communities through the valorization of its multiple products. Despite the growing body of research surrounding *Pongamia pinnata*, significant knowledge gaps remain regarding its genetic variability and physiological traits. Understanding the genetic basis of traits related to oil yield, disease resistance and abiotic stress tolerance is crucial for developing improved cultivars through selective breeding programs.

Recent advancements in genomic techniques offer promising avenues for exploring these traits at a molecular level, paving the way for enhanced productivity and resilience. Moreover, the integration of Pongamia into agroforestry systems presents an opportunity to maximize land use efficiency while promoting biodiversity[24]. By intercropping Pongamia with other crops or planting it alongside fruit trees, farmers can create synergistic relationships that enhance soil health and yield stability. Intercropping systems with legumes such as redgram, horsegram, or annuals such as brinjal and castor have shown that the individual yields of component crops are marginally lower than those under sole cropping.

The combined equivalent yield and overall economic returns are generally higher through better utilization of resources and risk diversification. The wide spacing generally recommended for Pongamia plantations (e.g. 5 m x 4 m, 500 trees per hectare) offers sufficient space for intercrops to develop over several years, especially in the early years of plantation growth before closure of the tree canopy[67]. Economic analyses have shown that total equivalent yield, the sum of the yield of Pongamia and the intercrops, with their respective market prices considered is generally higher in intercropping compared to sole cropping[67]. The explanation is that the risk of total crop failure is reduced: if one crop is not doing well due to pests, disease, or weather, the other components can compensate for it, with more yield stability and financial resilience. This approach not only supports food security but also contributes to the development of sustainable rural economies. As global interest in renewable energy sources continues to rise, *Pongamia pinnata* stands out as a promising candidate for biofuel production and ecological restoration. Its multifaceted applications align with sustainable development goals (SDGs), particularly those focused on climate action, sustainable agriculture and poverty alleviation[72]. Future research should prioritize understanding the mechanisms underlying its resilience to environmental stresses and explore innovative management practices that optimize its cultivation. *Pongamia pinnata* embodies a unique intersection of ecological benefits and economic potential. Its diverse applications from biofuel production to soil restoration underscore its importance as a key player in transitioning towards sustainable energy systems while enhancing ecosystem health.

Continued research efforts aimed at unlocking the full potential of this remarkable tree will be essential for realizing its contributions to both environmental sustainability and socio-economic development. The present review aims to provide a comprehensive overview of the latest developments in the application of *P. pinnata* for bioenergy and biofuel purposes. Studies related to physiological and molecular traits of different Pongamia accessions, where the evidence indicates genetic variation and a possibility to improve them, are listed in the study. Furthermore, the review discusses the latest development using omics technology to explore the genetic tools of this tree species for improving productivity.

Omics approaches for Pongamia improvement

Pongamia pinnata, is a leguminous tree whose oil content is very high, enabling it to produce much bioenergy and biofuel potential because it can grow under different environmental conditions and needs less input in terms of agriculture [71]. The goal of recent developments in valorisation techniques is to optimize the environmental and economic advantages of *P. pinnata* farming. Through insights into *P. pinnata's* genetic diversity, metabolic pathways and stress responses, omics techniques provide opportunities for expediting the improvement of the species. Omics technologies, including transcriptomics, proteomics, metabolomics, epigenomics and genomics, provide strong instruments to clarify the molecular basis of these features and expedite *P. pinnata* improvement initiatives. In order to improve *P. pinnata's* attractiveness as a renewable resource for bioenergy and biofuel applications, this review explores current developments in omics techniques[69].

1) Genomics of *Pongamia pinnata*: Genomic studies on *P. pinnata* have made a rapid progress with the application of next generation sequencing technologies. Availability of reference genomes and comparative genomics has led to the discovery of candidate genes for many agronomically important traits, like oil biosynthesis, seed development and resistance to diseases. Some of the recent studies include genome sequencing and annotation by Shreedevi et al[56]. The development of genomic resources like BAC libraries, physical map etc. have been made and made available through the 'Pongamia Genome Database' (https://Pongamia.jic.ac.in/). Genome-wide patterns of genetic diversity and population structure are revealed by whole genome re-sequencing of 48 *P. pinnata* populations.

Genome-wide association studies (GWAS) and population genomics revealed genomic regions and genes associated with oil yield, seed size, drought tolerance etc. Some of the recent studies include 39 SNP markers linked to 18 genes known for oil biosynthesis[17]. The identification of these SNPs was made possible by recent advances in genome sequencing and assembly. The draft genome of *Pongamia pinnata* assembled using high-throughput Illumina sequencing platforms enabled researchers to annotate over 30,000 gene models and conduct in-depth analyses of key metabolic pathways, including lipid metabolism.

Within the 685 Mb genome, hundreds of genes were mapped to scaffolds associated with fatty acid biosynthesis, elongation, degradation and related processes. SNP discovery was performed by aligning sequencing reads from diverse Pongamia accessions to the reference genome and identifying nucleotide positions showing variation among individuals. These SNPs will be very useful for MAS[71].

De novo repeat prediction revealed that 43.6% of the *Pongamia pinnata* genome consists of repetitive sequences, underscoring the genome's structural complexity and evolutionary dynamics. Among these, long interspersed nuclear elements (LINEs) account for 0.48%, while long terminal repeat (LTR) elements primarily Ty1/Copia and Gypsy/DIRS1 families, make up 6.94%[71]. DNA transposable elements represent 0.64% of the genome, contributing to genomic plasticity and potential gene regulation mechanisms.

Simple sequence repeats (SSRs), or microsatellites, constitute 1.6% and serve as valuable molecular markers for genetic mapping and diversity studies. Low-complexity elements, which are short, repetitive stretches of DNA, comprise 0.02%. Remarkably, a substantial portion 33.9% of the repetitive content remains unclassified, indicating the presence of novel or highly diverged repeat families unique to Pongamia or underrepresented in current repeat databases[62]. This high level of unclassified repeats suggests that the genome has undergone significant species-specific expansion and diversification, which may play important roles in genome evolution, regulation of gene expression and adaptation to environmental stresses.

The abundance and diversity of repetitive elements not only pose challenges for genome assembly and annotation but also provide a rich source of genetic variation that can be harnessed for breeding and improvement programs. Furthermore, the chloroplast and mitochondrial genomes of Pongamia have been sequenced and annotated. The chloroplast genome is 152,968 bp and contains 77 unique protein-coding genes, with a gene density of nearly 60%. It features a 50 kb inversion common to legumes and a novel 6.5 kb inversion. The mitochondrial genome is 425,718 bp and contains 33 unique protein-coding genes, with expanded intergenic and repeat regions similar to other angiosperms[27].

2) Transcriptome Profiling and Differential Gene Expression: Gene expression for *P. pinnata* can help in studying the resulting transcriptional profile patterns under various environmental conditions and at different stages of development with the assistance of the transcriptome. Many genes relevant to high-throughput RNA sequencing technology are associated with oil accumulation, nutrient uptake and transport, considering the response toward stress.

The related study by Farrant et al[14] reports a search for specific genes that may facilitate increasing the oil yields from the seeds of *P. pinnata* by utilizing RNA-Seq. Large-scale transcript profiling facilitated through RNA-Seq has provided details on the gene expression in the tissues concerning the seeds of *P. pinnata*, seedlings of *P. pinnata* and mature plants of *P. pinnata* having different developmental stages and different environmental exposures.

They reported a search for specific genes that might facilitate improving oil yields from the seeds of *P. pinnata* through the use of RNA-seq large-scale RNA. The expression of the genes was comparatively revealed to identify the genes that could participate in the biosynthesis of oil, seed development, stress response and nitrogen and carbon nutrient metabolism. Moreover, multivariate statistical tools, such as PCA, have been used to unravel the effects of environmental factors on gene expression.

The transcriptional profile patterns of gene expression in *P. pinnata* can be well understood under different environments and developmental conditions by determining its transcriptome.

Regarding several studies applying transcriptome analysis, a few critical genes related to the quantification of oil accumulation based on factors such as nutrient uptake transport and stress have been identified. The gene expression analysis of seeds, seedlings and mature plants of *P. pinnata* growing under the most diverse conditions also makes it possible to discuss and compare the tissue-specific gene expression profiling thereof on a more global scale.

Tissue-specific expression of genes involved in all significant oil accumulation pathways, photosynthesis, glycolysis, fatty acid synthesis, glycerolipid metabolism and plastoquinone metabolism had been reported. Genes involved in the transport and storage of nitrogen and carbon were also identified from developing seeds' transcriptomes. Specific transcription factors, protein kinases, LEA proteins and transporters in developing seeds were also identified which were induced under drought and submergence stress treatments. Comparative gene expression analysis was carried out to identify genes involved in oil biosynthesis, seed development, stress responses and nutrient metabolism.

PCA and cluster analysis have been applied as multivariate statistical tools to unravel the effect of different environmental factors on gene expression. The transcriptomic data have assisted in reconstructing gene regulatory networks and metabolic pathways involved in vital physiological processes in *P. pinnata*. In addition, to demystify some molecular mechanisms of oil biosynthesis, carbon partitioning and stress tolerance in *P. pinnata*, co-expression, gene ontology (GO) enrichment analysis and pathway mapping have been used. Kazakoff et al[22] have claimed that their investigation found some main critical regulatory elements in cells and signals that are in control of the plant oil biosynthesis pathways. They used RNA data from *P. pinnata* to identify essential genes and markers correlating to desirable traits. They created lists of genes and reduced the roles of such identified genes and their functions within *P. pinnata* cells using massive databases of other genes. They added RNA information to genetic maps upon which specific characteristics lined up pinpointing the genes associated with qualities central to turning plants into bioenergy and biofuel producers.

Comparative transcriptomic studies of *P. pinnata* have provided insight into the evolutionary dynamics and adaptive strategies toward environmental challenges[18]. These ideals are well captured during the comparative analysis with related legume species, pointing out commonalities and divergent gene expressions coupled with oil metabolism, nitrogen fixation and stress. This makes the difference in the transcriptome of the wild and cultivated populations of *P. pinnata,* the basis of some outstanding studies from Afzal et al[3] in which candidate genes for domestication and improvement were revealed.

3) Proteomics and Metabolomics Applications: These proteomic and metabolomic data, taken together with the genomics and the transcriptomic information, validate the protein and small molecule content of *P. pinnata* fragments. Mass spectrometry identified markers characteristic of oil type, food utility and tolerance to stress. A significant contribution has been made by Sikarwar and Patil[53] in which potential target proteins have been revealed to be the possible way of drought tolerance in the leaves of *P. pinnata* under drought stress through comparative proteomic analysis. In one notable study, drought stress was imposed on three-month-old seedlings of four distinct Pongamia genotypes by withholding water for 15 days.

The research demonstrated that the genotype NRCP25 exhibited superior morpho-physiological and biochemical responses under drought conditions, including higher root length, increased photosynthetic pigments, elevated antioxidant enzyme activities and greater solute accumulation compared to other genotypes. At the molecular level, transcript profiling of drought-responsive candidate genes in NRCP25 showed up-regulation of several important genes: trehalose phosphate synthase 1 (TPS1), abscisic acid responsive elements-binding protein 2 (ABF2-2), heat shock protein 17 (HSP 17 kDa), tonoplast intrinsic protein 1 (TIP 1-2), zinc finger homeodomain protein 2 (ZFP 2) and xyloglucan endotransglucolase 13 (XET 13)[48]. These proteins are associated with osmoprotection, stress signaling, protein stabilization, water transport, transcriptional regulation and cell wall modification, all of which are critical for drought adaptation.

Recent proteomic analyses have mapped the dynamic changes in protein abundance during critical developmental and stress phases in *Pongamia pinnata*. For example, root proteome profiling under salt stress using nanoLC-MS/MS identified 1,062 abundant protein species, with 130 commonly abundant across both control and salt-treated plants[46]. These proteins were associated with diverse biological processes, including flavonoid biosynthesis, seed storage, carbohydrate metabolism and stress defense. Notably, a high abundance of antioxidant enzymes (such as catalase, MDAR and ascorbate peroxidase) and proteins linked to hormone signaling (including ABA-responsive proteins and auxin-induced proteins) was observed under salt stress, illustrating the tree's robust adaptive mechanisms[31].

Gene ontology analysis further classified these proteins into 28 functional groups, encompassing metabolism, signal transduction, photosynthesis, defense and cell wall synthesis. Proteomic studies in *P. pinnata* have determined the structure and function of the proteins in various tissues, developmental stages and environmental conditions. The proteomic tools likely to be resorted to, using a mass spectrometry-based proteome, will target the proteins involved in oil biosynthesis, nutrient production and responses to stress, among others. For example, a few essential enzymes and regulatory proteins involved in lipid synthesis with *P. pinnata* seeds were shown by Yadav et al[65].

A notable example is the proteomic analysis of developing seeds, where more than 300 protein spots were reproducibly detected across four developmental stages using 2D gel electrophoresis and Image Master 2D Platinum software. Out of these, 125 protein spots matched across all stages and several were successfully identified by MALDI-MS/MS. Differentially regulated proteins included essential enzymes and regulatory proteins involved in lipid synthesis, such as those participating in fatty acid biosynthesis and oil body formation. Principal component analysis (PCA) revealed a distinct protein profile at the mature seed stage compared to earlier stages, indicating dynamic changes in the proteome as seeds accumulate oil[76]. These findings highlight the upregulation of key proteins during seed maturation that are directly linked to oil content and quality.

The metabolic characterization of small molecules in the tissues of *P. pinnata*, the two transformational approaches, can be complemented with proteomics. Different techniques for liquid and gas chromatography-mass spectrometry have allowed for the identification and quantification of various metabolites, thereby opening up other parts of primary and secondary metabolic pathways. There is a revelation of the physiological characteristics regarding the quality of oil, the tolerance of stress and the growth patterns in the cells of *P. pinnata*. Factually, critical studies by Ram Mohan et al[41] have identified the metabolites of the leaves of *P. pinnata* related to drought tolerance.

Metabolomics applications in *Pongamia pinnata* have shown that drought-tolerant genotypes like NRCP25 store higher amounts of osmoprotectants like proline and soluble sugars in leaves, which assist in cellular hydration and stability under water scarcity conditions; these genotypes have enhanced antioxidant enzyme activities (like superoxide dismutase and catalase), increased photosynthetic pigments and higher solute accumulation, all of which lead to enhanced drought resistance [48]. Whereas the majority of metabolomic research has concentrated on seed development, data from leaves indicate that the interaction of osmolyte build-up, antioxidant protection and regulation of genes are the biochemical foundations of drought tolerance in *P. pinnata* and represent worthy targets for breeding and biotechnological enhancement of this valuable biofuel crop.

Independently, the proteins and metabolites' grasp in *P. pinnata* thus help in connecting to a large number of activities of the cell. Comparison of levels informs about how they work in concert; this helps focus on the pathways and checkpoints that are vital for maximal results for enhanced oil production, biomass and stress resilience[70]. Markers that enhance such traits will be promising because they can open the way to biotechnological approaches targeting the key metabolic sites. Proteomics and metabolomics findings provide valuable insights for functional validation of candidate genes and metabolic pathways in *P. pinnata.*

Targeted utilization of key protein components through genetic engineering, metabolism and precision breeding offers opportunities for bioenergy and biofuel characteristics of *P. pinnata* in biotechnological applications. Oil biosynthesis includes overexpression of enzymes and utilization of stress-responsive metabolites to improve yield and resilience in *P. pinnata* in various fields[57].

4) Epigenomics for Stress Resilience: Recent studies on *Pongamia pinnata* have revealed the epigenomic foundation supporting its abiotic stress tolerance, most notably drought and salinity. It employs epigenetic modification to regulate gene expression, thereby inducing variability in phenotype. The epigenomic analysis patterns of DNA methylation and small RNA-mediated gene regulation pathways, along with histone modifications, are associated with stress responses within this process[58]. Though extensive studies with specific elaboration of DNA methylation, small RNA-guided gene regulation and histone modifications in *P. pinnata* are still underway, wider plant science and initial transcriptomic examinations indicate that these epigenetic processes play key functions in regulating stress responses.

DNA methylation has been found to control the expression of stress-responsive genes, frequently resulting in the activation or repression of the important pathways allowing plants to acclimate to water deficit or salinity. Small RNAs such as microRNAs and siRNAs are being found more and more to play a role in post-transcriptional gene silencing, acting on mRNAs that code for stress-related proteins and thereby refining the plant's response to unfavorable conditions. Also, histone modifications like acetylation and methylation affect the structure of chromatin and thus the availability of stress-regulated genes to the transcription machinery.

In *P. pinnata*, the upregulation of candidate genes such as trehalose phosphate synthase 1 (TPS1), abscisic acid responsive elements-binding protein 2 (ABF2-2) and heat shock proteins have been reported in transcriptome profiling of drought stress, which are generally epigenetically regulated in other plant species[48]. These revelations coupled with the progress in plant epigenomics suggest that incorporating DNA methylation profiles, small RNA signatures and histone modification maps will be instrumental in deciphering and improving stress resilience in *P. pinnata* and facilitating its cultivation as a sustainable biofuel crop.

Genomics, transcriptomics, proteomics, metabolomics and epigenomics datasets can integrate to identify molecular targets for enhancing symptoms while identifying strains of *Pseudomonas aeruginosa* with potential as sources of bioenergy and biofuels. It may be useful to search for *P. pinnata* for similar purposes which could be beneficial. In the future, research will be centered around conducting laboratory studies by using genetically modified crops so as to investigate the usefulness of those candidate genes and also developing omics-guided breeding strategies which would improve agriculture's sustainability.

In addition to the basic mechanisms described previously, recent plant epigenomics have further elucidated how epigenetic modifications regulate multilayered stress responses, with various implications for *Pongamia pinnata*. Genome-wide methylome studies in closely related leguminous plants indicate that stress-induced DNA methylation alterations tend to occur within promoter regions of genes that are engaged in hormone signaling, ROS detoxification and osmoprotectant biosynthesis, directly influencing their transcriptional activity[4]. In soybean and Medicago, drought and salt stress have been reported to induce locus-specific hypermethylation or hypomethylation that is accompanied by changed expression of genes coding for late embryogenesis abundant (LEA) proteins, dehydrins and ion transporters. Such changes are stable and can last through mitotic and even meiotic division, indicating a stress adaptation component of inheritance[28].

Small RNA sequencing in legumes under stress has discovered several microRNAs (miRNAs) and phased siRNAs targeting transcription factors (for example, NAC, MYB and DREB families) and ABA biosynthetic and signaling genes [9]. These small RNAs are quickly induced or suppressed in early perception of stress, offering a fine-tuning system for the plant transcriptome and proteome under changing environments. Moreover, drought and salinity stress in model organisms reveal histone modification profiling where higher H3K4 methylation and H3/H4 acetylation at the locus of stress response are related to gene activation. H3K9 and H3K27 methylation are related to repression of genes[37]. These marks on the chromosome are dynamically regulated and reversible upon withdrawal of stress to facilitate plants to achieve growth vs. defense equilibrium.

Integrating these results with current Pongamia research, it is probably the case that such epigenomic reprogramming is taking place in this species and is responsible for its strong stress tolerance. With increasingly affordable high-throughput sequencing and chromatin immunoprecipitation (ChIP) technologies, future *P. pinnata* studies are likely to chart these epigenetic landscapes in detail, allowing for the targeted manipulation of stress memory and resilience traits for sustainable agriculture and biofuels[2].

Omics methodologies now establish a new platform for realizing the full potential of using *Pongamia pinnata* as a fruit tree for bioenergy and biofuel. Modern knowledge now exists on the molecular basis of agricultural traits coming from discoveries in genomics, transcriptomics, proteomics, metabolomics and epigenomics[20]. It has enabled this direction. Hence, to evolve certain modifications, which deal with some issues that the scientists in the *P. pinnata,* should develop tolerant varieties to ill-effects and must provide high-yielding capabilities with the help of the omics technology. These tolerant varieties can also be utilized for enhancing clean, renewable energy and problems of the environment.

Diverse applications of *Pongamia pinnata*: *Pongamia pinnata*, offers a wide range of applications due to its versatile properties as shown in figure 1. Pongamia seeds have high oil quality, so they are suitable for making biodiesel, containing about 30% to 40% of oil. The plant's ability to grow in a variety of agro-climatic conditions makes it a feed stock with a promise of biofuel production contributing to renewable energy initiatives.

It therefore possesses a fatty acid profile that comes close to that of soybean oil making it a viable option for biodiesel production. Global movement toward renewable energy demands the finding of a manifold and renewable energy source. Biomass-based energy, among many, has been repeatedly in the limelight because it could reduce greenhouse gas emissions and provide a secure source of energy. *Pongamia pinnata*, as a versatile and strong tree species, has emerged as a promising candidate in hybrid energy systems[25]. Pongamia oil is a feedstock for biodiesel and has been considered a renewable resource due to its substitution for fossil fuel. With a high cetane number, low sulfur content and fairly good oxidative stability, it is appropriate for blending with conventional diesel[16].

The integration of Pongamia based biodiesel with solar or wind energy resources can ensure increased reliability in hybrid systems because it provides a complementary energy source in periods of low solar or wind resource availability[77]. This also comprises of organic matter rich in such residual seed cake, left in the form of residual seed cake after extraction, to be useful in biogas production.

Biogas so produced will not only energize microgrids but will be used as clean fuel for cooking simultaneously with the hybrids of the remaining renewable energies. The biomass for thermal energy production can be obtained from Pongamia wood and leaves, as a source of biomass without competition with the food crop, as it grows on degraded land[25]. This *Pongamia pinnata* is a perennial tree that gives a carbon sink by absorbing vast quantities of CO_2 during the growth cycle of the tree, therefore supplementing sustainability and environmental dividends of hybrid energy systems. Pongamia grows well on marginal land, hence arable land will be left free from hindrance and forests will be preserved[26].

The multi-purpose tree will generate several streams of income to be produced from biodiesel, biogas and biomass production. It improves soil health due to its nitrogen-fixing properties and will help in reducing greenhouse gas emissions as a source of renewable energy. Diversifying the energy mix reduces dependence on fossil fuels and strengthens energy resilience. *Pongamia pinnata* is high potential for hybrid energy systems producing biodiesel, biogas and biomass besides positive effect on soil health and carbon sequestration, making *Pongamia pinnata* a viable sustainable and diversified energy resource[15].

This research and development into overcoming present day problems and the generation of innovative solutions shall contribute toward clean and resilient energy systems around the world.

Pongamia pinnata parts such as leaves, seeds and stems and roots, are used in Ayurvedic and traditional medicine systems. The plant has antiviral, antiviral, antidiabetic and wound healing properties. Extracts from various parts of the plant have been used to treat skin diseases, eczema, diabetes and gastrointestinal disorders[45]. *Pongamia pinnata* is a precious agroforestry species due to its nitrogen-solving ability and deep root gadget, which enables to enhance soil fertility and structure. It may be intercropped with other agricultural vegetation, offering color and windbreak while improving soil fitness through nitrogen fixation and natural count number accumulation[39].

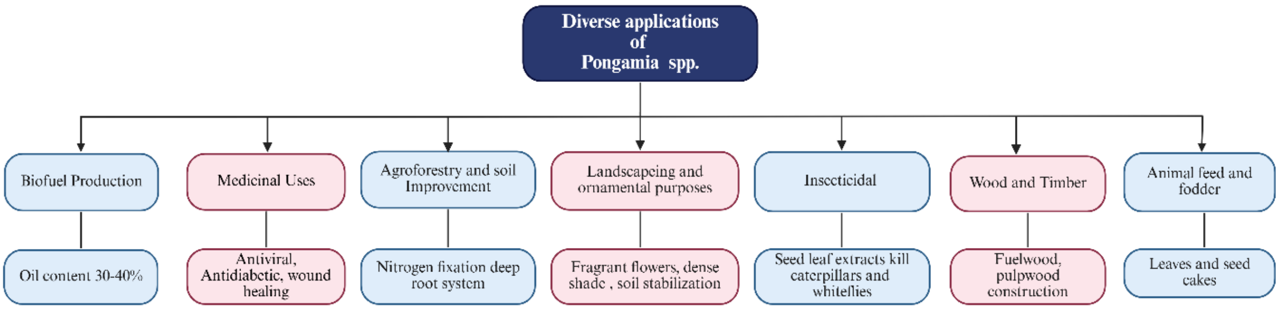

Figure 1: Flowchart summarizing Diverse applications of *Pongamia pinnata*

Pongamia leaves and seed cake (residue after oil extraction) may be used as animal feed and fodder. The seed cake, wealthy in protein (approximately 30-40%), can function as precious protein complement for livestock feed. However, it should be processed to get rid of any toxic compounds[73].

The decorative worth of *Pongamia pinnata* makes it grow well. Its delightful trees, fragrant plants and dense shade are appropriate for beautifying parks, gardens and the waysides, while also assisting in soil stabilization and control of soil erosion through its deep rooting system[60]. Despite it not being the primary reason for growing Pongamia, the tree has a variety of purposes for which its wood can be used, including as fuelwood, pulpwood and in construction. However, its wood is less superior to that of some other timber species and is commonly used when few alternatives exist[25].

Many feel that Pongamia extract is useful because it acts as both poison and protector to unwanted insects that attack plants grown organically before being stored for crop protection.

Oil, fatty acid composition of different accessions of Pongamia: *Pongamia pinnata* is a valuable plant known for its oil and stands out for its unique fatty acid content. As shown in table 2, various fatty acids were obtained from *Pongamia pinnata* along with their functions. This review examines in detail the lipid composition and importance of Pongamia oil[61]. Palmitic acid is a saturated fat which is found in excess amount in Pongamia oil[40]. This characteristic makes the oil stable as well as having a good feel in the mouth due to its solidifying properties. The main function of palmitic acid is to maintain cell membrane structure while at the same time acting as a source of energy for metabolic activities. Pongamia oil requires stearic acid as one of its constituents to perform an essential function by helping to improve its oxidative stability.

The capacity to resist rancidity is ensured by the existence of stearic acid in it and it also extends the period during which this product remains safe for consumption. This makes it suitable in edible oils due to some other roles such as maintaining normal cholesterol levels[42]. A considerable portion of Pongamia oil is oleic acid which is a monounsaturated omega-9 fatty acid. Oleic acid is famous for its cardiovascular gains as it aids in mitigating inflammation plus maintaining good heart conditions. This is the reason behind the oil's flexibility making it usable in different ways that may involve cooking or remedies[35].

Healthy human lives depend on linoleic acid, a type of omega-6 polyunsaturated fatty acid[1]. This substance contributes significantly towards skin structure maintenance, immune response and signaling processes within cells. This explains why Pongamia oil is also regarded as a precious reservoir of this substance because it contains linoleic acid which is important for the aforementioned reasons within the body. Linolenic acid offers many health benefits as it is an omega - 3 polyunsaturated fatty acid. Inflammation reduction, improved heart functions and memory are among other things. Human nutrition cannot do without it[42].

Pongamia oil provides essential fatty acids into foodstuffs. Even though it is found only in trace amounts, arachidic acid is a type of saturated fatty acid which completes the entire fatty acid spectrum of Pongamia oil. In addition, this chemical improves its texture and at the same time makes it more stable, hence making it fit for various purposes [59]. The texture and stability of Pongamia oil are greatly influenced by Behenic acid, which is yet another saturated fatty acid that can be found in it. It plays a key role in cosmetic and industrial formulations by making the oil more viscous[43].

Even if there are only small levels of Lignoceric acid present, it affects the properties of this oil. This means Pongamia seed oil can be used in various industries since it can perform multiple functions.

Processing of Pongamia Deoiled biomass

Harvesting the mature seeds of Pongamia deoiled biomass, dehulling to get rid of outer husk, then extracting oil using ways such as mechanical pressing or solvent extraction are step-by-step process[19]. The refined oil is used by biodiesel manufacturing or even other industries where it is needed for quality purposes. Utilizing the byproducts which include seed cake, husk and the remaining biomass, support the production of animal feed, energy generation as well as composting.

Table 1
Value added product of *Pongamia pinnata* and their applications

Value-Added Products	Applications
Proteins and Protein Isolates	Food formulations, nutritional supplements, functional ingredients
Dietary Fiber	Fiber supplements, essential element of basic food
Bioactive Compounds (Polyphenols, Antioxidants, Flavonoids)	Pharmacology, osmotrphic lotion making, nutraceuticals
Starch	Food processing, paper making, clothing manufacture
Oligosaccharides	Gut health, fostering healthy gut bacteria
Essential Oils	Aromatherapy, perfumery, food industry
Phytosterols	Lowering blood cholesterol, heart health-focused dietary supplements, functional foods
Lignans	Antioxidant attributes, promotion of good health, lowering chances for long-term ailments

Table 2
Different Fatty Acids obtained from *Pongamia pinnata* with their functions

Fatty Acids	Functions	Composition %
Palmitic Acid (C16:0)	Maintains cell membrane structure; a source of energy	3.7 – 7.9 %
Stearic Acid (C18:0)	Improves oxidative stability; extends shelf life; maintains normal cholesterol levels	2.4 – 8.9 %
Oleic Acid (C18:1)	Cardiovascular benefits; anti-inflammatory; used in cooking and remedies	44.5 – 71.3 %
Linoleic Acid (C18:2)	Maintains skin structure; immune response; cellular signalling	10.8 – 18.3 %
Linolenic Acid (C18:3)	Anti-inflammatory; improves heart function and memory	~2.6 %
Arachidic Acid (C20:0)	Enhances texture and stability; completes fatty acid spectrum	2.2 – 4.7 %
Behenic Acid (C22:0)	Influences texture and stability; used in cosmetic and industrial formulations	4.2 – 5.3 %
Lignoceric Acid (C24:0)	Affects oil properties; versatile in various industries	1.1 – 3.5 %

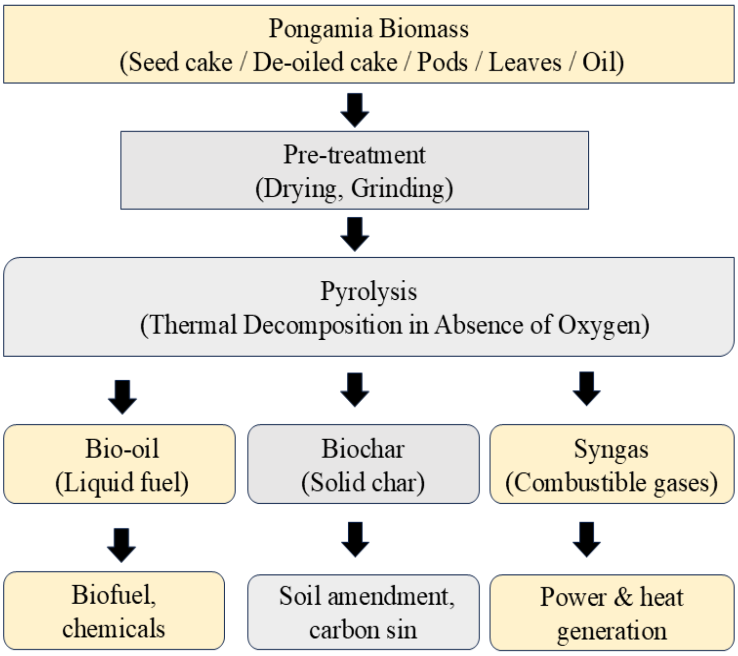

Figure 2: Flowchart summarizing thermochemical methods suitable for biomass processing

Examples of Pongamia oil uses are biofuel production, cosmetics manufacture and pharmaceuticals. This process is divided into three major stages:

1) Thermochemical methods suitable for biomass processing: Thermal methods are some great opportunities for Pongamia deoiled biomass for energy generation and material creation[44]. When you heat it up without using air, this process results in bio-oil and biochar as well as syngas from pyrolysis as shown in figure 2. While gasification means burning part of it slowly under supervision so that it gives off syngas that can be used in making electricity or as a fuel substitute for example, these practices enable the partial combustion of wood without releasing smoke, thereby coming up with syngas used either for heat or for electricity or for biofuel. Torrefaction has found enhancing biomass property.

Pyrolysis is one of the most researched approaches, a thermal decomposition of biomass in an oxygen-free environment, producing bio-oil, biochar and syngas. Studies indicate that slow pyrolysis of Pongamia cake yields high biochar with potential use as a soil conditioner or carbon sequestration material, whereas fast pyrolysis is biased in favor of producing bio-oil as a viable renewable fuel or chemical feedstock. Product composition and quality are functions of processing conditions like temperature, heating rate and residence time and the maximum bio-oil yield is generally achieved in the temperature range 450–550°C[78].

Gasification is another thermochemical pathway where high-temperature partial oxidation of biomass (700–1000°C) produces syngas, a blend of CO, H_2 and minor hydrocarbons. Experiments show that gasification of Pongamia biomass can obtain high conversion efficiency and the produced syngas can be directly utilized to produce heat and power or gets further converted into liquid fuels through Fischer-Tropsch synthesis[30]. Pongamia-based syngas has also been investigated for its applicability to internal combustion engines and fuel cells, providing a green substitute for fossil-based fuels.

Torrefaction refers to a mild thermal pre-treatment (200–300°C) in an inert atmosphere that increases the physicochemical quality of biomass[11]. Torrefied Pongamia biomass, as per research, has enhanced grindability, increased energy density and hydrophobicity, better suited for co-firing in coal-fired power stations or advanced bioenergy feedstock. Torrefaction decreases the oxygen-to-carbon ratio, enhancing combustion performance and storage stability.

2) Biochemical methods: There are biochemical ways of dealing appropriately with Pongamia Deoiled biomass as show in figure 3, including the use of enzymes or microorganisms that convert the residual biomass into valuable substances[33]. It is possible that once extraction of oil from these seeds has taken place; the leftovers which could take the forms of seed cake or husks might further undergo enzymatic saccharification or microbial fermentation. Through this process complex carbohydrates are broken into simpler forms, mainly sugars through enzymatic hydrolysis which also serves as the precursor for synthesis of industrial chemicals or biofuel involving ethanol.

Microbial fermentation makes use of bacteria or fungi as microorganisms to metabolize biomass components into desired products like enzymes, organic acids, or other useful compounds. Owing to this, Pongamia biomass can be utilized to manufacture renewable fuel and products, taking care of the environment as shown through the following biochemical pathways[6]. Ongoing studies are targeting increased productivity and easy upscaling for these processes to be used in industries.

a) Pretreatment: The method starts with pretreatment of Pongamia deoiled seed cake or husks to improve the availability of cellulose and hemicellulose. Pretreatment techniques involve dilute acid hydrolysis, alkali treatment, steam explosion, or any combined physical and chemical method. Research indicates that alkali or steam pretreatment methods are most effective in degrading lignin hindrances, raising the surface area for enzymatic activity.

b) Enzymatic Hydrolysis (Saccharification): Following pretreatment, the biomass is subjected to enzymatic hydrolysis with commercial or specially designed enzyme mixtures of cellulases, hemicellulases and β-glucosidases. These enzymes hydrolyze the polysaccharide complexes (cellulose and hemicellulose) to fermentable monosaccharides like glucose and xylose. Research indicates that optimized enzyme loading and reaction conditions can produce high sugar concentrations, making the process acceptable for industrial fermentation.

c) Fermentation: The resulting sugar-containing hydrolysate is then exposed to microbial fermentation. Depending on the end product intended, various microorganisms are utilized: Production of Bioethanol, Yeasts such as *Saccharomyces cerevisiae* or genetically modified bacteria (*Zymomonas mobilis, E. coli*) ferment glucose. Studies prove ethanol yields between 0.4–0.5 g/g sugar from Pongamia cake hydrolysate. *Aspergillus niger* or *Lactobacillus species* of fungi can be used to transform sugars into citric acid, lactic acid, or other industrially important organic acids. A few studies also investigate the application of *Bacillus* and *Streptomyces* in enzyme production.

d) Product Recovery and Purification: The fermentation broth is treated to recover the desired products. In the case of bioethanol, distillation, precipitation and crystallization techniques are employed. The remaining biomass of fermentation may be further treated for biogas generation through anaerobic digestion or may be utilized as fertilizer.

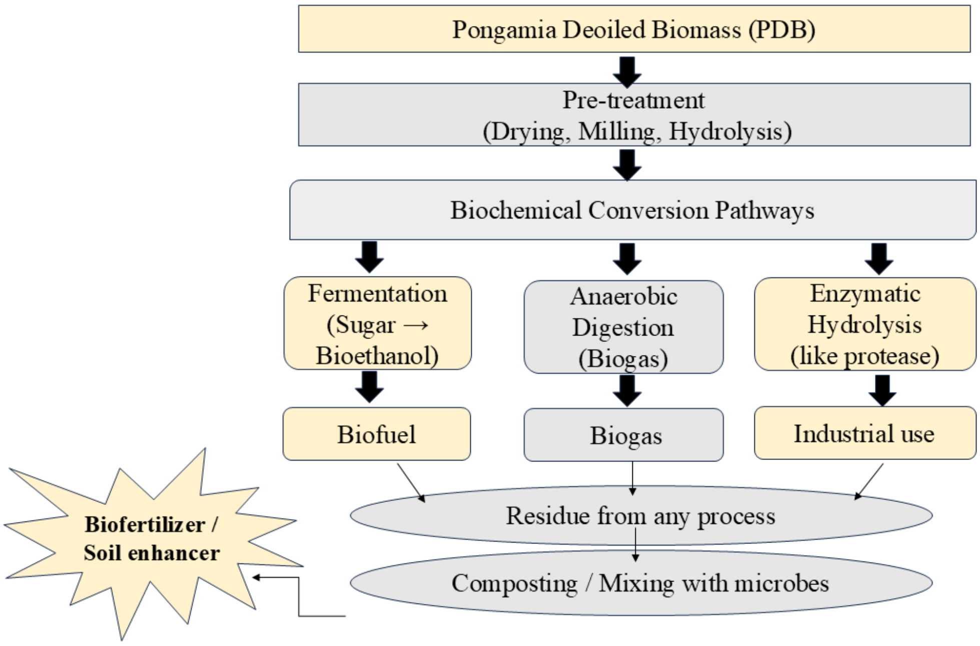

Figure 3: Flowchart illustrating the biochemical conversion of Pongamia deoiled cake to fermentable sugars, bioethanol, biogas and biofuel

e) Valorization of Byproducts: The protein-rich fraction of Pongamia seed cake, following oil and carbohydrate extraction, can be employed for single-cell protein production (for animal feed), enzyme manufacture (as a microbial growth substrate), soil conditioning (as organic fertilizer because of its nutritional value).

f) Economic and Environmental Advantages: This bio integrated pathway not only manufactures renewable fuels and chemicals but also reduces waste, lessens environmental pressure and gives value to agricultural residues. It promotes a circular bioeconomy.

3) Hydrothermal liquefaction: Pongamia deoiled biomass undergoes hydrothermal liquefaction at high temperatures and pressure in water, transforming it into bio-oil. Generally, the process involves finely milling the biomass, mixing it with water and then heating it in a reactor at a temperature range of between 250°C and 400°C as shown in figure 4 under a pressure that may go up to 200 bars[70]. The decay of biomass through heat brings about liquid bio-oil, gases and some solid pieces. It becomes possible to incorporate these hydro liquefication products inside bile acids that are required by digestion of food substances mainly because they contain some hydrocarbons whose origin is particular while being part of the nonrenewable fuel sources as well. Consequently, when compared with customary separation techniques, this approach has more merits including higher bio-oil yields and the ability to process a wide variety of biomasses resulting in improved sustainability.

a) Hydrothermal liquefaction (HTL): HTL is a strong candidate process for the conversion of Pongamia deoiled biomass to liquid bio-oil, utilizing the extraordinary characteristics of water at high pressure and temperature to enable effective biomass degradation [32]. The procedure starts with feedstock preparation, with Pongamia seed cake or husk being finely ground to enhance surface area and blended with water to create a slurry. This is charged into a high-pressure reactor.

b) Conditions of Reaction: The slurry is then heated under conditions usually between 250°C and 400°C with pressures between 100 and 200 bars to ensure that water remains in a subcritical or near-critical condition[8]. Under these conditions, water is not only a solvent but also a reactant and a catalyst, enhancing the hydrolysis, depolymerization and recombination of complex organic molecules in the biomass.

c) Biomass Conversion: During the HTL process, the primary constituents of biomass cellulose, hemicellulose, lignin, proteins and lipids are decomposed to smaller molecules. Cellulose and hemicellulose are hydrolyzed to sugars and then further decomposed to organic acids, alcohols and furans. Lignin is broken down to phenolic compounds, whereas proteins and lipids are processed to nitrogen- and oxygen-containing organics[47]. These intermediates further react by dehydration, decarboxylation and hydrogenation, leading to the production of a complex mixture of hydrocarbons and other organics.

d) Product Separation: The system is cooled and depressurized after the reaction. The products are split into four primary phases. Bio-oil (liquid phase) is the main product, which is composed of energy-dense hydrocarbons, phenolics and other desirable organics. Aqueous phase is of water-soluble organics like low-molecular-weight acids, alcohols and nitrogenous species. Gas phase is of mostly CO_2, CO, H_2 and light hydrocarbons and solid residue (biochar) is of unreacted carbon, minerals and ash.

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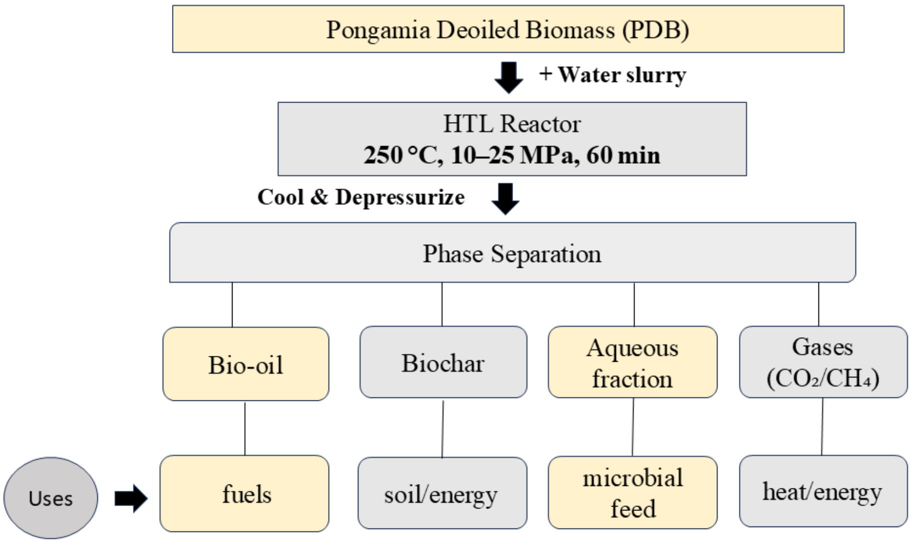

Figure 4: Flowchart illustrating the hydrothermal liquefaction (HTL) of Pongamia deoiled biomass

e) Bio-oil Upgrading and Utilization: The HTL crude bio-oil usually has higher energy density and less oxygen content compared to pyrolysis bio-oil and is thus more favorable for direct application as a fuel or upgrading further into transport fuels and chemicals[51]. Improved quality of the HTL bio-oil, by further hydrodeoxygenation, catalytic cracking, or blending with petroleum cuts, can be achieved according to research, allowing it to be employed in existing fuel infrastructure.

f) Valorization of Co-products: The water phase can be treated to recycle precious chemicals or can serve as a nutrient feed for microbial processes. The gas phase, which is CO_2 and H_2 rich, can be recovered and utilized for chemical synthesis or energy generation. The solid biochar can be utilized as a soil conditioner, for carbon sequestration, or as activated carbon precursor[36].

g) Advantage and Sustainability: HTL is unique in terms of processing wet biomass directly without any energy-intensive drying procedures needed in other thermochemical processes. It produces greater yields of bio-oil and can accommodate a broad scope of feedstocks, ranging from crop residues, algae to food waste[13]. These attributes render HTL a very flexible and sustainable avenue for producing renewable fuels and chemicals from Pongamia deoiled biomass towards a circular bioeconomy.

Deoiled seed biomass-derived value-added products

Deoiled seed biomass is the residue from the extraction process of the oil, although containing value-adding compounds beneficial for many other such industrial applications. As shown in table 1, various value-added products derived from *Pongamia pinnata* and their respective applications have been highlighted. The major categories are: Seeds usually equate to a good source of protein from which isolate or protein concentrate can be derived. They have important role in food formulations as nutritional supplement and functional ingredient [7]. The nutritional aspect of food is essential in digestion. If food contains fiber, then most probably the nutritive element of food is higher. Fiber extracted from de-oiled seed biomass may be used as a fiber supplement or an essential element of basic food [75].

Seeds are packed with numerous nutrients which are beneficial for health [49]. So, polyphenols, antioxidants as well as flavonoids belong to such type of bioactive element that can be found in plenty of product. In pharmacology, osmotrophic lotion making, ingredient production for nutraceuticals, this ingredient is used. There are numerous uses of starch obtained from seeds [66]. It has been widely used in food processing, paper making and clothing manufacture because of its properties that enable it to become thick, gel or bind substances together. According to recent studies on gut health [75], there are antidotal properties found in some seeds which are oligosaccharides. These are carbohydrates made up of a few simple sugars attached to each other. Some foods as well as supplements that are designed to foster healthy gut bacteria, contain these substances.

Some of the seeds yield essential oil that is very valuable for their sweet-smelling nature as well their medical importance. Aromatherapy, perfumery and food industry are some of the areas where essential oils are applied[54]. Deoiled seed biomass, which has been observed to contain cholesterol analogs called phytosterols, has been suggested to aid in lowering blood cholesterol; as such it is incorporated in heart health-focused dietary supplements as well as functional foods [63].

There are certain seeds that contain high amounts of lignans which are polyphenolic substances having antioxidant attributes. They have been widely researched due to their possible promotion of good health through lowering chances for long-term ailments like cancer and heart diseases[55].

Economic Impacts of *Pongamia pinnata*: The main economically valuable product obtained from *Pongamia pinnata* is biodiesel derived from its oil rich seeds. Due to this reason, the species is considered one of the best options to reduce the present demand for fossil fuels. Its fast growth and ability to thrive in marginal lands turn it into an attractive option for agroforestry, which contributes much to rural income, especially under poor soil conditions. The wood from the tree is of superior quality, usable in construction, furniture and any other wood products, further increasing the tree's economic value. Leaves and pods find application in traditional medicine, thus expanding the products available for market access.

Utilization of *Pongamia pinnata* for the production of biodiesel presents a large avenue for the mitigation of dependence on fossil fuels, as studies indicate that maximum transesterification of the Pongamia oil can result in 78.25% biodiesel content by weight in laboratory settings and even higher percentages above 90% have been achieved with optimization of the processes[16]. The Pongamia biodiesel conforms to ASTM fuel properties such as viscosity, density, cetane number and heating value and can be used as a direct replacement or blend with fossil diesel in transport, power generation and industrial use. The use of Pongamia trees is especially beneficial since they grow on marginal soils, can withstand drought and salinity and are not a competitor to food crops, thereby providing a sustainable and non-food feedstock supply.

Pongamia plantations also give oil yields of around 1000 liters/hectare per year, with seed yields typically below 2500 kg/hectare, allowing for large-scale biofuel production without compromising food security. The environmental advantages are also enormous with Pongamia biodiesel combustion releasing far less greenhouse gases than petroleum diesel, helping in the mitigation of climate change and enhancing air quality[38]. These characteristics, along with the economic viability of biodiesel production and the capacity to harvest non-edible locally available feedstocks, make *Pongamia pinnata* a strategic crop for national energy portfolio diversification and promoting sustainable energy options, particularly in areas with high energy needs and restricted access to conventional energy sources.

Reducing Reliance on Fossil Fuels

One of the most important uses of *Pongamia pinnata* is its potential to reduce dependence on fossil fuels. The oil rich seeds of this tree can be processed into biodiesel, a renewable and sustainable alternative to conventional petroleum-based fuels. This biofuel may be applied in various sectors such as transport, generation of power and industrial purposes, hence decreasing greenhouse gas emissions and reliance on fossil fuels. The use of Pongamia for biofuel production, therefore, is particularly inviting in countries burdened with energy demand and not adequately served with conventional energy resources[50]. Besides this, with the growing global demand for biofuels linked to climate protection, *Pongamia pinnata* would give an opportunity to add diversity to your energy portfolio and to reduce the ecological footprint of producing energy.

Policy and Market Challenges

While *Pongamia pinnata* presents promising potentials, its translation into this highly valued product is threatened by several policies and market related challenges[34]. Among others, one crucial factor is a general lack of substantial policy and fiscal incentives to attract large scale cultivation and investment in commercial production, nationally and internationally, for biofuels and related products from Pongamia. That is where supportive frameworks by Government policy can provide the impetus necessary for such cultivation on a large scale through subsidy programs, grants for research, or even access to the marketplace for the farmers. In addition, there are other established biofuels such as soybean and palm oil that make for competitors to Pongamia biodiesel. Most of them are cheaper due to the better infrastructure and more mature supply chains. Overcoming market barriers in improvements of processing technologies, reduction in production costs and creating sustainable supply chains will be critical.

Although *Pongamia pinnata* has strong potential as a biofuel crop, large-scale adoption is hindered by strong policy and market constraints. The biggest hindrance is that there are no significant policy and fiscal incentives directed at Pongamia cultivation and biofuel production that can stimulate investment and check commercial growth [12]. Although some Governments, like that of India, have set subsidies and grants for biodiesel plants based on non-edible oils like Pongamia, these efforts are less intense than incentives supporting more developed biofuel crops like soybean and palm oil. Mature infrastructure and supply chains for these rival feedstocks reduce the cost of their biodiesel and appeal to investors and producers alike, further marginalizing Pongamia in the market.

Also, a lack of specialized procurement mechanisms, restricted access to market for smallholder farmers and inadequate research fund resources hinder the establishment of a sustainable Pongamia supply chain. Conquering these hurdles would take a multi-faceted strategy: enhancing Government policy structures to offer focused subsidies, tax credits and low-interest loans for Pongamia-driven projects; research and development investments to advance processing technologies and lower the cost of production and creating sustainable supply chains that compete with entrenched biofuel industries. Only through such policy and market interventions, *Pongamia pinnata* can realize its potential as a central actor in the global shift towards renewable energy.

Societal Impacts

Pongamia pinnata can deliver value societally, particularly where the plant helps in checking soil erosion through erosion control to improve soil fertility and to act as a carbon sink[10]. This seed tree is recommended for reforestation efforts in formerly forested, desertification-prone districts with degraded areas that have lost their flora. In rural areas, it offers promising potential for sustainable livelihoods at a number of different levels-from planting and nurturing or directly from their local ecosystems to processing valued for their biodiversity benefits. It provides jobs concerning agro-forestry and wood extraction into usable products through the value chains and production for biofuels. This employment opportunity contributes indirectly to improving the standard of living across the communities.

Because it is available to small growers, additional income streams produced from the biodiesel seed and medicinal uses of the foliage could be useful to these people. Broad scale improvement of Pongamia may lead to, or contribute more broadly, directly or indirectly, to socio-economic benefits relevant to food assurance and resilience within given communities by enabling ecological restoration and biodiversity management.

Pongamia pinnata provides significant benefits to society, especially in communities that are experiencing environmental degradation and rural poverty. It has a strong root system that prevents soil erosion and increases soil fertility through fixation of atmospheric nitrogen, hence being useful in ecological restoration and reforestation efforts in areas with desertification risks or where indigenous vegetation has been destroyed[74]. As a carbon sink, Pongamia plantations play a role in mitigating climate change by sequestering huge amounts of atmospheric CO_2 during their life cycle. Socio-economically, Pongamia facilitates sustainable rural livelihoods through employment throughout the value chain, from nursery management and tree planting to seed harvesting, oil extraction and biofuel processing [68]. These activities create local employment opportunities for communities, such as smallholder farmers and generate income from the sale of seeds for biodiesel and foliage for traditional medicine.

Introducing the tree's use into agroforestry systems enhances biodiversity, supports ecosystem functions and can enhance food security and community resilience by restoring degraded lands and rural economy diversification. Large-scale adoption of Pongamia not only promotes environmental rehabilitation and climate change objectives but also provides real socio-economic benefits, in concurrence with objectives of sustainable agriculture and rural development.

Way forward

The potential of value-added compounds from deoiled seed biomass could be leveraged by adopting a strategic approach. In other words, it requires investing in research and development aimed at discovering novel compounds and improving extraction methods as well as engaging in partnerships with research organizations and companies so as to promote faster innovation. To achieve broader application, it is important that we diversify into various fields like pharmaceuticals; cosmetics or nutraceuticals. It is key to continuously improve the need for continually improving processes and strategies through consistent evaluation and process optimization, targeted marketing strategies to broaden market and raise awareness as well as meeting market access regulatory requirements, this is done by implementing sustainable practices in production and extraction processes which help in reducing the impact on the environment at the same time maintaining strict product quality measures, thus ensuring that the product remains consistent and safe.

Developing the value-added possibilities of deoiled Pongamia seed biomass calls for a multi-pronged and strategic strategy, as also emphasized in recent studies. Investment in sophisticated research and development is key to the discovery and identification of new bioactive compounds like phenolics, flavonoids and protein hydrolysates, which have been shown in laboratory tests to possess antioxidant, antimicrobial and nutraceutical activities. Optimization of extraction and purification techniques e.g. the use of green solvents, enzymatic hydrolysis, or supercritical fluid extraction, can maximize yield, purity and sustainability, rendering such processes more feasible for industrial production.

Collaboration among academies, research institutions and private enterprise can promote innovation, expedite technology transfer and aid commercialization in various industries such as pharmaceuticals, cosmetics and functional foods. Diversification in these areas is further assisted by research demonstrating the effectiveness of compounds from Pongamia in skincare products, food supplements and as natural preservatives. Ongoing optimization of processes through life cycle assessment and techno-economic analysis is essential to achieve cost-effectiveness, to reduce the environmental footprint and to produce high-quality products. Segmented marketing plans and public education campaigns can increase market coverage and create awareness of the advantages of Pongamia-derived products.

In addition, conformity to international regulatory requirements and certifications is vital to gain market access, particularly in healthcare-related sectors. The use of eco-friendly manufacturing practices, namely, waste valorization, energy-conscious processing and traceability systems, not only will minimize the ecological impact but will also instill consumer confidence by maintaining the quality and safety standards. Together, these strategies place Pongamia deoiled seed biomass as a sustainable and multi-purpose biomass for the production of high-value products benefitting economic, environmental and social objectives.

Conclusion

Pongamia pinnata is rapidly gaining recognition as a promising multipurpose legume for sustainable bioenergy and ecological restoration. Integrative omics approaches, encompassing genomics, transcriptomics, proteomics, metabolomics and epigenomics, have illuminated complex regulatory networks governing its development, lipid biosynthesis and abiotic stress resilience. Key genetic loci and pathways associated with drought and salinity tolerance, as well as elevated oil accumulation, have been identified, accelerating molecular breeding and precision biotechnological interventions. Advances in proteo-metabolomic profiling reveal the accumulation of stress-inducible proteins and metabolites.

Emerging epigenomic insights point to transgenerational regulatory mechanisms enabling adaptation to marginal environments. As a non-edible oilseed, Pongamia underpins sustainable biodiesel production and valorization of residual biomass into high-value bioproducts. Its deployment in integrated biorefinery systems enhances resource circularity and mitigates environmental footprints. Collectively, these scientific advances position *Pongamia pinnata* at the forefront of climate-resilient agriculture and renewable energy innovation, offering scalable solutions for energy security, rural development and land rehabilitation.

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