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Short-rotation Tree-based Biofuel Production in India from Agroforestry and Marginal Lands without Compromising Food Security

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Forests are the lungs of the earth as they absorb an enormous amount of carbon dioxide (CO_2) that circulates in the atmosphere. Reducing deforestation, and increasing afforestation, and reforestation are crucial in this boiling climate. The majority of India's current biofuel production methods depend on the agricultural sector, which has a number of challenges and affects the availability of food. These urge for the development of sustainable alternative bioenergy sources. This review primarily focused on three economically significant biofuels, namely biodiesel, bioethanol, and biogas produced from short-rotation trees. Short-rotation tree-based bioenergy is emerging as a significant bioenergy source with maintaining economic, social and environmental sustainability. To sustain one aspect, there should not be any compromise on the other aspects. Therefore, using sustainably grown trees in agroforestry and on marginal lands is encouraged instead of harvesting forest trees for fuel. A well-designed bioenergy system is essential in the contemporary context to achieve a number of goals, including the mitigation of climate change, energy security, carbon sequestration, food security, and agrobiodiversity improvement. Agroforestry and marginal lands can be used to produce tree-based bioenergy without compromising food security. An agroforestry system is a trending farming system, which is sustaino-resilient farming that integrates annual and perennial species. Potential residues and byproducts produced by the woody perennials in agroforestry are often handled through land filling, thermal management, and decomposition, all of which have drawbacks of their own. Hence, they need to be managed effectively in order to produce biofuel products using a circular bioeconomy approach. On the other hand, there is a lack of information on the capability of woody species to produce biofuels and their suitability for agroforestry systems. Hence, this study aims to identify promising, fast growing, economically feasible and co-producing tree species suitable for biofuel production.

Keywords: Agroforestry, Biofuel, Energy security, Marginal lands, Multipurpose trees

INTRODUCTION

Climate change and energy security are the twin problems of India, as it is highly dependent on Russia, USA and gulf countries for import of crude oil. There is an immense demand for energy because India currently has the largest population and the fifth-largest growing economy in the world. According to the India Energy Outlook (2021) report of the International Energy Agency (IEA), India has played a major role in the global market, with the country ranking third in the world for primary energy consumption. Its consumption has reached 6.1 % of global energy consumption, and it can increase up to 9.8 % by 2050. The IEA estimates that India currently spends around $160 billion of foreign exchange annually on energy import. Increased impact of climate change, fiscal burden on oil import, on-going geopolitical tensions and India's aim to become self-reliant have turned to switch towards renewable energy sources for its energy consumption. Hence, the government has announced various initiatives to produce and provide clean and renewable energy to the public such as bioenergy, biofuels,

hydro power, solar energy, and wind power (Rawat *et al*., 2011). Among the renewable energy sources, bioenergy and biofuel play a significant role, as these are economically feasible, eco-friendly, socially healthy (waste to wealth) and production friendly (Rawat *et al*., 2011; Butterbach-Bahl and Kiese, 2013).

The term biofuel is used interchangeably with bioenergy, though biofuels are liquid bioenergy such as bioethanol and biodiesel prepared from microbial fermentation of various agricultural, algal and tree-based feedstock (Mishra *et al*., 2012; Dwivedi and Sharma, 2014). Whereas, bioenergy is a broad term, it is any energy source based on biological matter including both biogas and biofuel. Recently, India amended National Biofuel Policy 2018, making an ambitious target of 20 % ethanol blending by 2025. Ethanol blending is the fermentation of feedstocks, distillation and preparation of alcohol and blending it in petrol which is used as fuel in engines (Malik, 2023). Food crop-based biofuel production can create many challenges like food insecurity, water shortage due to growth of water intensive crops like wheat, rice and sugarcane, food inflation and change in cropping pattern (Gnansounou and Dauriat, 2005). Hence, use of food crops as feedstocks is not feasible for populous countries like India. In fact, some food crops produce more greenhouse gas (GHG) than fossil fuels such as paddy, corn, wheat etc. due to the intensive use of tractors, fertilizers, and processing plants. (Butterbach-Bahl and Kiese, 2013; Edenhofer *et al*., 2014). Selection of sources for energy production should be in accordance with the strategy laid down by the United Nation to achieve Sustainable Development Goals (SDGs). The two main approaches for biofuel production include mitigating GHG emissions, without threatening food production via competition for land and having less negative impact on the environment (Butterbach-Bahl and Kiese, 2013). Hence, it is necessary to look for alternative energy sources without hampering food security and sustainability.

Short rotation tree species (SRTS) including Ailanthus, Casuarina, Eucalyptus, Poplar, Salix, etc. are potential feedstock, or tree species cultivated specifically for use in biofuel production (Aylott *et al*., 2008; Rawat *et al*., 2011; Sylva *et al*., 2014). The short-rotation tree-based biofuel and bioenergy production is a viable option as trees are less water and fertilizer intensive, fast growing, multipurpose, contain far more carbohydrates than food crops, and produce year-round biomass (Aylott *et al*., 2008). Apart from these benefits, trees are also known for soil fertility restoration, carbon sequestration, timber and non-timber forest produce (NTFP), and also thrive well in marginal lands. Agroforestry and marginal areas can be used to produce tree-based bioenergy without compromising food security (Butterbach-Bahl and Kiese, 2013). Agroforestry system is a trending cultivation practice, which is sustaino-resilient farming that integrates annual and perennial species (Dinesha *et al*., 2023_a). The overall objective is building healthy soil and ecosystem while increasing resilience of farm enterprises on various shocks. Potential residues and byproducts produced by the woody perennials in agroforestry are often handled through landfilling, thermal management, and decomposition, all of which have drawbacks of their own. Hence, they need to be managed effectively in order to produce biofuel products like biodiesel, bioethanol and biogas using a circular bioeconomy approach. On the other hand, there is a lack of information on the capability of woody species to produce biofuels and their suitability for agroforestry systems. Hence, this study aims to identify promising, fast growing, socioeconomically feasible and co-producing tree species suitable for biofuel production.

TREE-BASED BIOENERGY

Tree based bioenergy also known as ‘Dendro energy’ is defined as a renewable energy that is made from trees-based materials (Sylva *et al*., 2014). This review primarily focused on three economically significant biofuels namely biodiesel, bioethanol, and biogas produced from short rotation trees. Fig. 1 depicts various conversion techniques for producing tree-based biofuels.

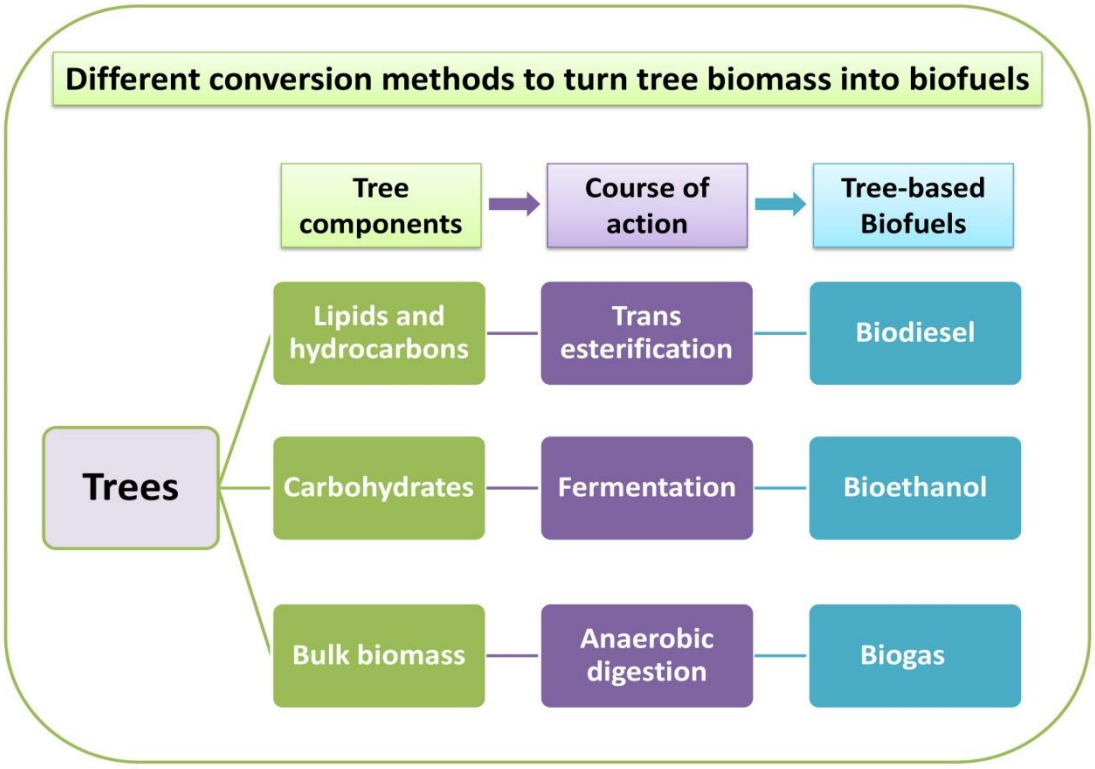

Figure 1. Different conversion methods to produce tree-based biofuels

Apart from biofuels these tree species are also used for energy or electricity generation by conversion into briquette, charcoal and firewood (Fig. 2).

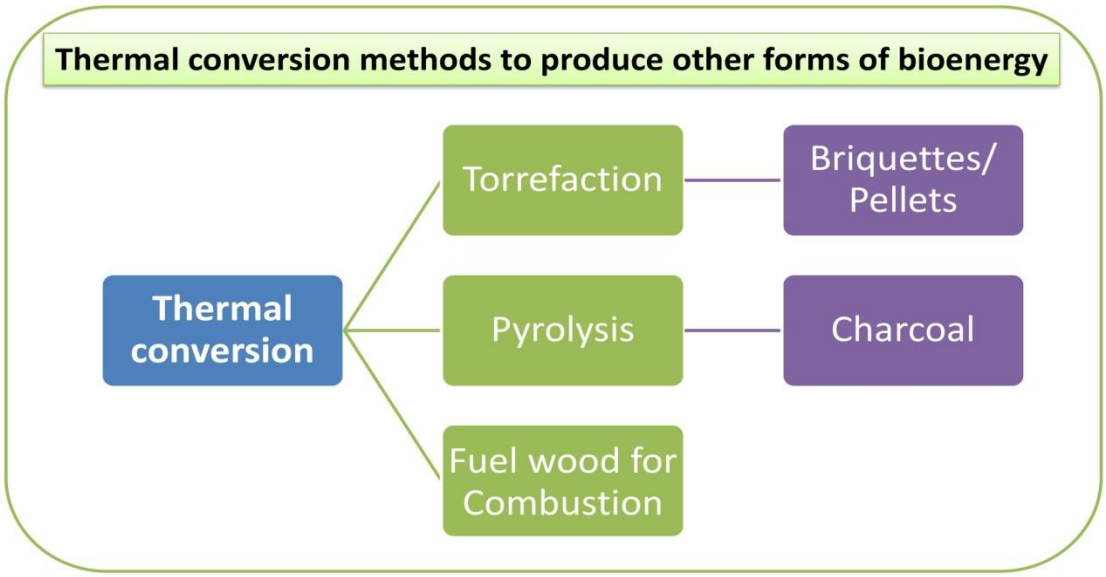

Figure 2. Different thermal conversion methods to produce other forms of bioenergy

In many areas of the country, people utilize firewood in addition to LPG connections to meet their energy needs for their household, industries, brick-making operations, and a number of other activities (Singh *et al*., 2021). Another significant bioenergy source is charcoal, which is the solid byproduct produced when wood is "carbonized" or "pyrolyzed" under controlled conditions (Paul *et al*., 2019). In addition, woody biomass can be used to produce electricity at scales suitable for community use. In India, Tata Energy and Resources Institute (TERI) and many other institutes are developing advanced electricity generation systems by using tree biomass. According to the Food and Agricultural Organization (FAO), wood is one of the most efficient sources of bioenergy in terms of the amount of energy released per unit of carbon emitted when compared to other energy crops (Aylott *et al*., 2008). Trees don't have to be harvested every year; instead, the harvest can be postponed until market prices are high and the products can be used for a variety of purposes. Tree crops have been found to have many benefits for the soil and water quality compared to conventional agricultural crops. Some genotypes have yearly yields of up to 11 oven dry tonnes per hectare (Aylott *et al*., 2008). Prioritizing the usage of short rotation tree species over timber trees will not have any adverse influence on the availability of raw materials for other construction and manufacturing industries. Utilizing appropriate and sustainable technology to convert surplus biomass into useful forms of energy presents potential to address many challenges. The short-rotation multipurpose trees suitable for tree-based bioenergy production from agroforestry and marginal lands are discussed below.

Biodiesel

Biodiesel is the mono alkyl ester of long chain fatty acids obtained either from plant-based oil or animal fat (Dwivedi and Sharma, 2014). Blending of biodiesel with diesel up to 20 % requires no modification in the existing internal combustion engine. Biodiesel can bring reduction in unburned hydrocarbon emission by 30 %, carbon monoxide (CO) by 20 % and particulate matter by 25 % (Dwivedi and Sharma, 2014). Plant based biodiesel can be produced either from edible oil or non-edible oil. There is a huge gap in demand and supply of edible oil in the country that is met by importing from other countries. Hence, non-edible oil sources seem to be a viable option for cultivation, extraction of oil and production of biodiesel.

Jatropha curcas

Jatropha is an oil rich biofuel shrub or small tree, native to Central America and spread across all over the world. It is a high yielding drought tolerant tree commonly known as “miracle tree” for biofuel production that can be grown under marginal, degraded and infertile soil so as not to displace food crops (Kumar and Sharma, 2011; Ong *et al*., 2011). It also has medicinal properties against microbes, inflammation, hypertension and cancer. Jatropha is also a raw material for soap industry, paint and lubricant manufacturing and a potential source of fertilizers and bioplastics. Oil content of seeds ranges from 27-40 % and grows well in marginal lands (Daniel and Hegde 2007). The oil can be directly used in diesel generators and engines without processing it. Seed cake obtained as a by-product after oil extraction acts as a good source of animal feed and fertilizer, organic waste materials can be digested to produce biogas (Lokesh *et al*., 2015). Economic feasibility of Jatropha biodiesel is considered, there is a 90 % recovery rate and cost of production of biodiesel mainly depends on the cost of oil followed by operating cost (Nevase *et al*, 2012).

Pongamia pinnata

Pongamia also known as ‘*Karanja’* is the most common multipurpose, fast-growing tree found near roadside, canal side, waste, marginal and community lands (Chakravarty *et al*., 2010). The seeds contain 30-40 % oil, which is used as lamp oil and lubricant in various industries (Devi *et al*., 2008). Apart from this, flowers, roots, bark, leaves and sap have medicinal properties, used in traditional medicine. It is a most preferred tree species due to its ability to fix nitrogen, reduce soil erosion and grow well in waterlogged soils, waste land, and withstand

harsh climatic conditions (Chakravarty *et al*., 2010). As per economic viability is concerned, 1000 kg of pongamia seeds can yield 270-300 kg of crude pongamia oil. After transesterification of crude pongamia oil, it produces 85-90 L of biodiesel and 15-16 L glycerin as a by-product (Dwivedi and Sharma, 2014). Pongamia feed stock accounts for 60 % of cost of production so, increasing production and productivity can lower the cost of production. Study from Fiji reported that the cost of production of biodiesel to be $ 1.44 per L and the benefit cost (BC) ratio was 1:0.6 (Prasad and Singh, 2020).

Calophyllum inophyllum

This fast-growing evergreen tree, also referred to as "Indian laurel," is prevalent in southern India and Andaman Islands. Both India's east and west coasts are conducive for its growth along with Casuarina and Pongamia. It is claimed to be highly salt tolerant, grows well in saline, rocky, waste, marginal and waterlogged soils where food crops can't grow (Dagar *et al*., 2020). Trees are also grown as windbreaker and soil erosion controller along with food crops. Growing various commercial crops with this tree as agroforestry can generate extra income to farmers (Dagar *et al*., 2020). It is a most prominent tree used in shipbuilding and timber industries. The seeds are a source of tamanu oil, used as massage oil, tropical medicine, lamp oil and water proofing. Tree flowers twice a year, starts bearing fruits at the age of five and produces seeds of 12-100 kg per annum. Non edible oil produced from the seeds is an ideal source for biodiesel production (Namita *et al*., 2017). The by-products obtained during biodiesel production are used as raw materials in pharmaceutical and cosmetics; oil cake also enriches soil fertility. According to the study, one hectare of plantation may generate an ideal output of 7.5 tons, from which 3.1 tons of biodiesel might be produced (Namita *et al*., 2017). Another study observed that 10 % blending with conventional diesel produced the best performance and emission characteristics such as high brake thermal efficiency and lower smoke emissions as compared to diesel (Ong *et al*., 2011).

Simarouba glauca

Simarouba glauca also known as Lakshmi taru, Paradise tree and bitterwood is an excellent multipurpose fast-growing tree introduced from America in 1960 to Maharashtra. It can grow well in wide climatic conditions and marginal lands (Mishra *et al*., 2012). Due to its dense canopy and strong root system, the tree is a good soil binder, which reduces soil erosion, improves carbon sequestration and supports microflora by reducing soil temperature. It is highly resistant to pest attack, hence an excellent tree for furniture manufacturing, toy making and paper making. Seeds are an excellent source for biofuel production, especially biodiesel production. Flowering starts at an age of 4-6 years and seeds contain 60 % of oil and act as low-cost feedstock for biodiesel with high oil yield and an added benefit of an ability to grow on marginal lands (Mishra *et al*., 2012). Hence, it generates huge employment to thousands of farmers, artisans, carpenters and pharmacists. Some studies reported that 1 ha of Simarouba plantation would accommodate 200 plants and produced 6000 kg of yield that would provide more than 1 tons of oil (Mishra *et al*., 2012). Oil cake produced during processing can be used as fertilizer, manure and pesticide.

Azadirachta indica

Azadirachta indica commonly known as 'Neem' is a common multipurpose tree spread across many parts of the country. It grows well even in eroded soil and is known as a living plant requiring only hot weather and less water for survival. Neem is the most preferred tree in the world due to its medicinal and insecticidal properties. It is an evergreen tropical forest tree that starts bearing fruits at an age of four years and becomes fully productive in 10 years. A single neem tree can produce 50 kg of fruits annually (Girish and Shankara, 2008). Seeds contain 30-40 % of crude oil, hence it is a potential tree for production of biodiesel as it has higher molecular weight, viscosity, density and flash point than diesel (Girish and Shankara, 2008; Chakravarty *et al*., 2010). A study from rural Karnataka reported that the net energy ratio of neem biodiesel has been found to be 26 times higher than

diesel and 12 times higher than Jatropha biodiesel (Lokesh *et al*., 2015). A hectare of neem plantation has the ability to sequester an additional 8.65 tons CO_2 ha^{-1} of CO_2 in addition to the 1.35 tons of biogenic CO_2 that is released during the neem biodiesel life cycle. As far as the economic aspect is concerned, neem is a feasible source of biodiesel. One of the studies reported that neem biodiesel showed higher benefit to cost ratios (2.84) and gross production values (Kumar *et al*., 2021).

Underutilized Trees for Biodiesel Production

Sapindus mukorossi

It is commonly referred to as the "Soap nut tree." It is a large deciduous tree that may reach a height of 20 m and is a member of the Sapindeacea family. The species is native to western coastal Karnataka, Maharashtra, and Goa and grows in the lower foothills and mid hills of the Himalayas at elevations of up to 1,200 m. It also grows well in moist and deep loam soil. Durable, light-yellow wood is used in both construction of homes and agricultural implements. The fruit pulp is used in traditional soap making, and the seed is high in saponin, a natural detergent frequently used for cleaning, a textile industry, and an emulsifier. Fruits are reported to contain six different fatty esters of tetracyclic triterpenoids and sesquiterpenoids glycosides. Leaf is reported to contain a variety of flavonoids, including quercetin, apigenin, kaempferol, and rutin (Chakraborty and Baruah, 2013). The entire fruit may be widely used for commercial purposes because the pulp can be used as a raw material in the chemical industry and the kernel can be used as a byproduct for biodiesel. According to a study by Chakraborty and Baruah (2013), a single tree may produce roughly 123 kg of fruits annually; consequently, sustainable utilization of seeds in biodiesel production will improve the economic viability of planting in agroforestry and other waste lands.

Madhuca indica

Madhuca indica commonly known as “Mahua” is a fast growing, multipurpose and tropical Indian tree. It is considered as a holy tree for the tribe due to its usefulness. Several parts of three, including the bark, are used in traditional medicine. The fat is used in the manufacturing of soap, skin care and also as a vegetable butter. Flowers are used in liquor production, which is a source of income for tribes. Single tree can produce 20-200 kg of seeds per annum and each seed contains 35-40 % of oil (Ghadge and Raheman, 2005). The oil can’t be used directly as fuel due to its higher kinematic viscosity, poor cold flow properties and poor spray characteristics. Hence, oil needs to be processed by pyrolysis, micro-emulsification, dilution, blending and transesterification (Ghadge and Raheman, 2005).

Aphanamixis polystachya

Locally known as "Royna " or "Pithraj," it is an Indian native and grows abundantly in Assam, Bengal and south Indian coastal states. Seed has a relatively high oil content (40-45 %) compared to some other non-edible oil resources, which is recognized as a promising and affordable feedstock for the manufacturing of clean biodiesel. For the synthesis of biodiesel from Royna, three essential processes, such as saponification, acidification, and esterification, were used (Rahman *et al*., 2022). The obtained biodiesel's calorific value and viscosity, which were 42.1 MJ/kg and 2.1 mm^2/s at 25°C, are very similar to that of commercial diesel.

Amoora wallichii

This "Amari" tree is a member of the Meliaceae family, commonly found in Assam, Arunachal Pradesh, West Bengal, and the Andaman Islands. The tree is threatened by expanding agriculture, timber use, and habitat degradation (Kakati *et al*., 2017). In addition to having biodiesel potential, it's also used for the production of wood, food, and medicine. The seeds are large in comparison to other plants and its oil content is 42.85 %

(Kakati *et al*., 2017). With 84.61% unsaturation, the main fatty acid components of seeds are linoleic (33%) and oleic acids (23%).

Bioethanol and Biogas

The Indian government recognized the advantages of using ethanol as energy and has made ethanol blending mandatory in order to reap all such benefits (Malik, 2023). The average ethanol production is significantly below the average consumption, and the demand for ethanol is even growing exponentially. India has enormous plans to ramp up bioethanol use across the economy, and the International Energy Agency anticipates that in a few years it will overtake the United States and Brazil as the third-largest ethanol market in the world. In order to achieve the intended goals, the Indian ethanol sector must be improved. Biogas has traditionally been used to provide heating gas for home and industrial uses as well as to provide hydrogen for the heavy chemical industry. However, recently, gasification has drawn a lot of attention for its potential to produce electricity. The production of biogas is the sustainable method because it can use every part of the tree and generates less pollution than other bioenergy production methods. In this context, short-rotation trees namely Casuarina, Eucalyptus, Poplar and Willow are becoming more popular in the production of Tree-ethanol and biogas (Rawat *et al*., 2011). This is because they can grow quickly on degraded, fallow, and arable fields and provide cleaner fuel than conventional diesel. The following section discusses some of the significant trees that can be used to produce tree-based bioethanol and biogas from agroforestry and marginal areas (Plate 1).

Plate 1. Short-rotation trees for bioenergy production from diverse land use systems

Acacia hybrid

Acacia hybrid is an offspring that resulted from interspecific crossing between *A. mangium* and *A. auriculiformis*, naturally or artificially. As compared to both the parents, it is now being developed in many countries due to its quicker growth, straighter stem, lighter branching, superior wood qualities, higher resistance to pests and diseases, and greater adaptability to various site conditions (Sharma *et al*., 2018). Some Acacia hybrids have been successfully incorporated within agroforestry systems in Bangladesh, Indonesia and Vietnam (Sunarti and Nirsatmanto, 2020). However, in certain states namely Karnataka, Kerala, and Orissa, energy plantations and black plantations were established for social and industrial interests (Vijaykumar *et al*., 2011; Sharma *et al*., 2018; Sunarti and Nirsatmanto, 2020).

Ailanthus excelsa

Earlier studies highlighted the potential of *A. excelsa* wood as a feedstock for ethanol production and offered useful information for developing sustainable biofuels (Sahay and Rana, 2017). They reported that the hemicellulose hydrolysate from wood had a high sugar content and exhibited minimal inhibitory effect on yeast growth, pointing to its potential as a feedstock for the generation of ethanol.

Casuarina equiestifolia

The nitrogen fixing Casuarina tree is one of the best choices for bioenergy production since it continuously produces litterfall, is able to thrive in a wide range of soil and climatic conditions, including nutrient- and moisture-limited marginal lands (Divya *et al*., 2011; Rawat *et al*., 2011). It is one of the most promising tree species for the production of biogas and is known as "the best firewood in the world". It is widely dispersed in the coastal regions of Andhra Pradesh, Karnataka, Orissa, Tamil Nadu, and Pondicherry. The high calorific wood (5000 kcal/kg) easily ignites even when it is still green, and the ashes retain heat for a long time (Kanna, 2011; Rawat *et al*., 2011). Farmers in Tamil Nadu and Pondicherry successfully adopted Casuarina clone-based agroforestry system intercropping with cowpea, groundnut or black gram with the optimum spacing of 2 m x 1 m paired row without sacrificing the stand density of trees (Divya *et al*., 2011). The study revealed that intercropping with casuarina had a strong complementary effect on the growth and productivity and improved the income of farmers and was economically viable when compared to monocropping of casuarina plantation (Divya *et al*., 2011). The area under casuarina in Tamil Nadu is increasing over the years due to the assured market, high returns from trees and credit facilities offered by the financial institutions.

Eucalyptus hybrid

Although native to Australia, eucalyptus species are widely cultivated worldwide as short-rotation hardwoods for a wide range of products (Rockwood *et al*., 2008). Itis a fast-growing species with favorable properties such as high cellulose content, limited lignin proportion and hemicellulose made up of acetylated glucuronoxylan. In recent years, eucalypt planting has increased, especially in tropical nations, with reports of yields as high as 70 m^3 ha^{-1} yr^{-1} within 5 years of rotation (Rockwood *et al*., 2008). It is anticipated that the gasification of biomass residues and used pulping liquors into syngas will result in new value streams (Rockwood *et al*., 2008). Syngas could be transformed into high-value commodities like biofuels, electricity, chemicals, and a variety of products.

Gliricidia sepium

It is a fast growing, nitrogen-fixing, high coppicing tree highly suitable for dendro-energy production (Sylva *et al*., 2014). It can be planted as undergrowth in many plantations, to provide shade in cocoa, coffee and tea plantations, as a vine support in pepper and vanilla plantations and used in various afforestation or reforestation works (Latt *et al*., 2000). It is advised for use as biofuel due to its low ash level, moderate nitrogen concentration,

high energy value, and low sulphur content. Apart from dendro power, it is also used as fodder, manure. This tree can withstand adverse weather conditions and climate change impacts.

Leucaena leucocephala

The *L. leucocephala* tree has been used in earlier studies to produce bioethanol and biogas (Latt *et al*., 2000; Alemán-Ramirez *et al*., 2022). It offers a variety of advantages as a high-energy density tree, and its nutrient content makes it valuable for the generation of biogas, bio-oil, biodiesel, ethanol, charcoal, activated carbon, and other substances. This is quite aggressive and produces a lot of biomasses, which is estimated to be 50 tons/ha/yr with the high coppicing ability (Alemán-Ramirez *et al*., 2022). It also contains high cellulose and low lignin. According to earlier studies, *L. leucocephala* performed best in the dry zone, while *G. sepium* performed best in the wet zone (Latt *et al*., 2000).

Poplar hybrid

Hybrid poplars are bred from multiple tree species, including eastern cottonwood (*Populus deltoides*), a tree native to the Southeast that also has high biomass productivity. These are potential feedstock cultivated specifically for use in biofuel production. Hybrid poplars can produce a large amount of biomass over relatively short rotations and can resprout from stumps after harvest. Short-rotation poplar can reportedly be used to economically manufacture bioethanol in the United States (Dou *et al*., 2017). Results also indicated that, when compared to biochemical conversion, quick pyrolysis, or thermochemical conversion, was found to be better for producing bioethanol from short-rotation poplar and to have a greater energy recovery rate.

Salix hybrid

Salix, sometimes known as the ‘Willow’, is quickly gaining popularity in the tree ethanol production process with poplar and eucalyptus. This is because they provide a cleaner fuel than conventional diesel and can grow swiftly on damaged, fallow, and cultivable lands (Dou *et al*., 2017). Studies reported short-rotation woody crops' lignocellulosic biomass as a source of energy for the synthesis of second-generation bioethanol (Stolarski *et al*., 2015; Dou *et al*., 2017). Willow biomass harvested over a three-year cycle had higher cellulose and lower lignin content than poplar biomass. Under ideal circumstances, the yield of willow can reach 30 t/ha/yr, while in agricultural practice it is only 5 to 15 t/ha/yr (Stolarski *et al*., 2015).

Other Forms of Tree-based Bioenergy

In addition to the biofuels, other bioenergy sources derived from short-rotation tree species include firewood, charcoal, and wood briquette. A brief summary of each of these three sources of energy are given below.

Fire wood

The amount of fuelwood utilized in India significantly grew as a result of population growth, despite the fact that the amount needed for cooking in India significantly decreased over time (Singh *et al*., 2021). According to the study, during 2011-12, the largest amount of cooking fuelwood was obtained from agroforestry systems (64%), followed by forests, and from common property resources (Singh *et al*., 2021). To meet our industrial and domestic demand, trees like Ailanthus, Acacia hybrid, Casuarina, Gmelina, Melia, Poplar and Salix have better clonal material and standard developed production protocols. Hence, there is an urgent need to promote these tree species in order to reap the benefits of growing them in agroforestry and other marginal lands. A. nepalensis also known as ‘Alder’ is a pioneer species; it grows well in land abandoned after cultivation or rocky sites exposed by landslides. Its wood dries easily, burns well and is an important source of firewood and charcoal (Paul et al., 2019). This nitrogen fixing tree is very helpful in erosion control, soil reclamation, intercropping and

used as a shade tree for greater Cinchona officinalis and Eletaria subulatum in the central Himalayas. A. altissima wood indeed seems appropriate to be used in the production of high-quality firewood as compared to other fast-growing species. This quality, of course, refers to high calorific value, energetically dense and less ash contents (Yang *et al*., 2015). A. nilotica, A. altissima, A. lebbeck, C. equiestifolia, E. camaldulensis, L. leucocephala and Casuarina equiestifolia trees are harvested for firewood application in less than four years of planting.

Charcoal

It is a lightweight black carbon residue that is created by burning wood and other plant materials in an oxygen-poor environment in order to completely eliminate all water and volatile components. Considering India's tropical climate and other favorable factors, short-rotation forestry is a highly viable solution for the fast and profitable production of tree biomass (Singh *et al*., 2022). Tree biomasses are chosen in the iron manufacturing sector because they provide high carbon charcoal with a greater yield and calorific value and contain less ash-forming components, which reduce slag volume and contamination (Singh *et al*., 2022). *A. altissima* is also used in co-firing with coal in power plants and could potentially be used as a renewable energy source in co-firing applications (Yang *et al*., 2015). A. nepalensis wood is an important source of firewood and charcoal in Indian states namely Arunachal Pradesh, Meghalaya and Sikkim (Paul *et al*., 2019). Some of the potential species that are used for charcoal production are *A. nilotica, A. altissima, A. lebbeck, C. equiestifolia, E. camaldulensis, L. leucocephala* and *S. sesban*. *Casuarina equiestifolia* produces high-quality charcoal with calorific value > 7000 kcal/kg. In Asia, leaf litter from plantations is frequently removed and utilized as fuel. It has been used for both domestic and industrial uses. The tree's nitrogen-fixing capacity, good stem form, rapid growth, light crown, and short rotation period of 3–4 years make it an ideal choice for agroforestry systems and the smaller landholdings of the majority of Indian farmers (Rawat *et al*., 2011). Charcoal made from *Prosopis juliflora* wood is highly sought after in the industrial sector due to its high carbon content, but it also raises a variety of ecological concerns. It was introduced in several dry land regions of India to prevent desertification, restore degraded soils, stop deforestation, and address the lack of fuelwood and fodder.

Wood briquette

Potential sources for briquetting include residues from the agricultural lands, biomass from agroforestry and other LUS, and sawdust from sawmills. The key factors that determine whether a raw material is suitable for making briquettes are moisture content, ash content, flow properties, and particle size. There are many different raw materials available in India, including sawdust, groundnut shells, cotton and maize stalks, rice husk, and tamarind shell. It may be used alone or in combination with coir pith, coffee husk, mustard stalk, sunflower stalk, bagasse, wood chips, etc. The availability, collection, and drying issues with the agricultural residue are drawbacks. Numerous studies reported that the technological advantages of tree-based briquetting, along with the accompanying economic and environmental benefits, made it extremely appealing (Kanna, 2011; Kamperidou *et al*., 2018). The briquette manufactured from casuarina needles has received a lot of attention in Tamil Nadu and may find widespread use in commercial and industrial applications in addition to meeting residential energy needs and encouraging clean development mechanisms (Kanna, 2011). Another study that assessed the calorific value and ash content of wood and bark for the production of wood pellets suggested *Ailanthus altissima* (Kamperidou *et al*., 2018). *A. altissima* wood and bark both displayed good heating values and a low ash level when compared to *Robinia pseudoacacia* and other species, placing it in the highest quality category for pellets. This short-rotation tree may thrive in a variety of conditions, making it a potentially viable feedstock for the production of briquettes due to its high energy density and low ash contents (Kamperidou *et al*., 2018).

CHALLENGES AND SOLUTIONS

Some of the key issues with promoting biofuels include lack of cultivation practices, precision techniques, quality planting materials, compatible machines, Infrastructure, marketing and transportation. Growing trees in agricultural land is relatively light demanding, nutrient and water intensive, and has faced criticism for prioritizing fuel above food. Compared to growing corn or sugarcane for ethanol, the process of growing the tree biomass uses less energy. Every ton of biomass production requires roughly 10,000 gallons of water hence resource use efficient AF tree crop combinations should be encouraged. It is conceivable that the production currently dependent mostly on food crops could be replaced by tree-based biodiesel. Some problems including low productivity on marginal and degraded lands for biomass energy production drive up costs as compared to other energy sources. Future energy and transportation requirements in India will be met by bioenergy and biofuels. This promotes India's self-reliance while simultaneously reducing climate change and promoting a cleaner environment. India must boost its production for the intended ethanol blending scheme to be accomplished. The integration of tree species in agroforestry and other tree-based LUS contributes greatly to the improvement of soil fertility and health, which is essential for socioeconomic and ecological sustainability (Dinesha *et al*., 2023$_b$; Dey *et al*., 2023). However, further multidisciplinary research is necessary to produce sustainable bioenergy and biofuels.

INSTITUTIONAL AND POLICY SUPPORT

The Global Biofuel Alliance, which was established at the G20 Summit, further demonstrates India's dedication to Net Zero. By promoting clean energy, the alliance will increase energy security and circular economies. The national biofuel policy provides tax redemption, subsidies to close the viability gap, and a biofuel input depository. Recently, the Indian government increased the export duty on broken rice, wheat, and sugar by 20 % and banned their export. The Gobar Dhan scheme was launched by the Jal Shakti ministry with the aim of clean rural India and to produce waste to wealth. In addition, various government policies and projects have sparked research into microbes and more advanced technologies. Special attention and policy support should be given to tree-based energies. Fortunately, recent policy developments and results of programs using wood-based bioenergy in many countries suggest that wood fuels may become more and more appealing as sources of industrial energy. The Indian government is promoting carbon-neutral energy plantations by developing an initiative to plant jatropha and other short-rotation species for biodiesel production (Hooda and Rawat, 2006). In addition, government initiative in emphasizing production and purchasing of sustainably produced trees from farmers' fields at fair prices can aid in improving the socioeconomic situation of farmers.

CONCLUSION

Tree-based bioenergy production can be encouraged through agroforestry system and other tree planting programs. However, large scale production through plantation should be avoided as the space taken would interfere with local food production and natural forests like as seen in palm, and rubber unsustainable plantations. The best option is growing trees in marginal, unproductive and agricultural smallholdings along with food crops. This allows locals to improve their livelihoods and economic activity by selling their produce locally, which adds to decentralized bioenergy generation and it also reduces transmission losses while encouraging private-sector investment in small power plants. The choice of tree species for bioenergy production is crucial, and it is recommended if it is based on regional conveniences, profitability, industrial viability, and technological feasibility. These trees thus can be cultivated on barren lands in order to enhance the feedstock and can be used as an alternative renewable, cost-effective, and eco-friendly energy source for bioenergy production, either standalone or blended with petro-diesel. Promising short-rotation trees were discussed in this chapter, however some of the underutilized trees require proper validation from actual field data. In order to promote and adopt these species extensively, further research, policy support and public awareness are needed.

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