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REVIEW ARTICLE

Sustainable bioenergy from agroforestry: A clean pathway to India's green transition

K Ravikarthik[1], K T Parthiban[1*], I Sekar[1], P Kumar[2*], P Subramanian[3], K R Ramesh[1], Ashick Rajah R[1], Sujith P P[4], Kabinesh V[1], R Meenakshi[1], R Moulidharshan[1] & R Nandhakumar[1]

[1]Forest College and Research Institute, Tamil Nadu Agricultural University, Mettupalayam 641 301, Tamil Nadu, India
[2]Horticultural College and Research Institute, Tamil Nadu Agricultural University, Paiyur, Krishnagiri 635 112, Tamil Nadu, India
[3]Agricultural Engineering College and Research Institute, Tamil Nadu Agricultural University, Coimbatore 641 003, Tamil Nadu, India
[4]Dr. Yashwant Singh Parmar University of Horticulture and Forestry, Nauni, Solan 173 230, Himachal Pradesh, India

*Correspondence email - ktparthi2001@gmail.com, kumarforestry@gmail.com

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Abstract

The global transition to sustainable energy systems emphasizes bioenergy as a crucial renewable resource for mitigating climate change and enhancing energy security. India faces the dual challenge of reducing its reliance on fossil fuels while addressing environmental degradation amid rising energy demands due to increasing urbanization and economic growth. Agroforestry emerges as a strategic alternative, integrating biomass production with farming practices to promote bioenergy development while developing ecological and social benefits. India's bioenergy potential can be realized through agroforestry systems that utilize a range of feedstocks, including woody biomass, agricultural residues and organic waste, to generate heat, electricity and biofuels. Notably, global energy-related CO_2 emissions reached 36.3 Gt in 2021, marking a rise of 6 %. Agroforestry systems improve soil fertility, increase carbon sequestration and improve rural livelihoods through multiple sources of income. Conversion technologies such as gasification, pyrolysis and anaerobic digestion, convert these feedstocks into energy. However, limitations remain in terms of cost efficiency, technological adaptability and minimizing land-use conflicts. Scalability on the other hand, requires balancing biomass consumption with food security, particularly on fertile soils, while also promoting bioenergy trees and crops in marginal or degraded regions. It has been estimated that almost 32 % of the total primary energy utilized in the country is generated from biomass. Strategic investments in decentralized bioenergy infrastructure, combined with research on species optimization and biorefinery models, have the potential to accelerate India's transition to renewable energy sources. Biomass-based projects contribute less than 3 % of the power generation in India, while major sources include fossil fuels along with solar, hydro and wind energy. By combining agroforestry and bioenergy objectives, India could achieve its climate obligations, promote rural development and construct a sustainable energy framework that is resilient to global ecological and economic shifts.

Keywords: circular bioeconomy; climate change mitigation; energy policies; energy security; short rotation forestry; waste valorization

Introduction

The urgent need to address climate change, energy security and sustainable development is driving a significant shift in the global energy landscape. Most industrialized and developing nations have recently unveiled strategies to fight climate change and reduce their respective contributions to future anthropogenic global warming (1). As a sustainable and potentially carbon-neutral substitute for fossil fuels, bioenergy derived from biomass is increasingly recognized as an essential part of this transition (2). Renewable energy sources are clean, help stabilize the grid and also aid in economies' transition away from reliance on fossil fuels (3, 4). Biomass can be converted into various forms of energy, including heat, electricity and biofuels. It encompasses a wide range of organic materials, such as forest derivatives, agricultural waste and specific energy plants (5). Due to its flexibility, bioenergy serves as a viable option for reducing dependence on limited fossil fuel reserves and diversifying energy sources. However, the extensive adoption of biomass power generation would require modifications to land, water and energy systems (6), raising concerns about the sustainability of each system.

India faces a significant challenge in addressing its rising energy consumption, which is driven by its rapidly expanding economy and population. Due to urbanisation, industrialisation and increasing living standards, the nation's energy consumption has been steadily rising (7). India's energy demand is expected to rise sharply in line with its anticipated socioeconomic growth, potentially increasing by as much as 400 % over the next 25 years compared to 2003-2004 levels (8). It is also projected to constitute the fastest growth in energy consumption worldwide (9) (Fig. 1) and account for approximately one-quarter of the global energy

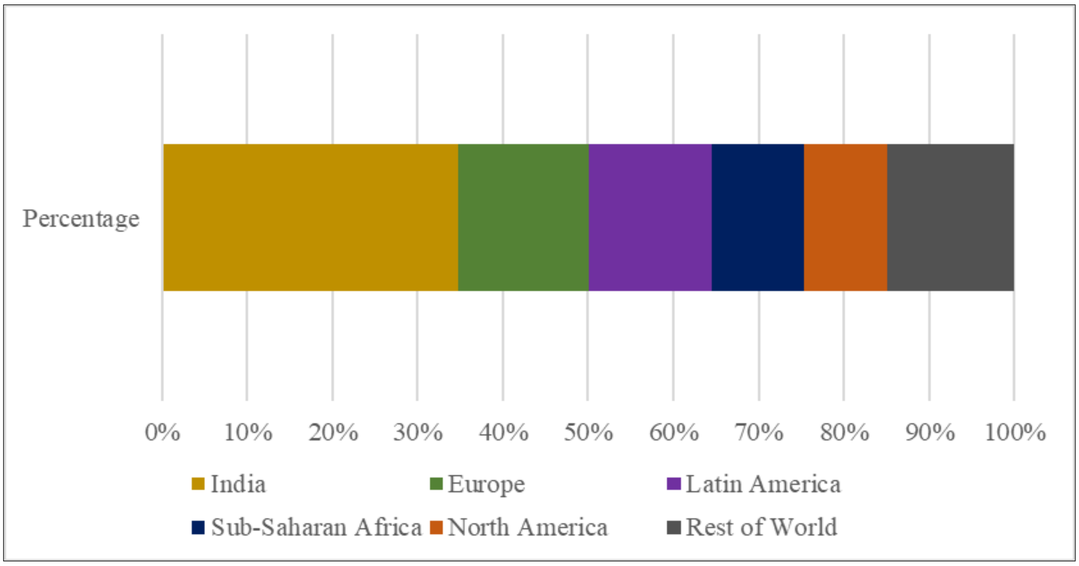

Fig. 1. Predicted shares of growth of bioenergy by country and region (2023 - 2030) (13).

demand growth from 2019-2040 (10, 11). India's energy infrastructure has advanced, but fossil fuels, particularly coal, continue to supply a significant share of its energy needs (12). This dependence raises concerns about energy security and air pollution, in addition to increasing greenhouse gas emissions and exacerbating climate change (13). The Indian government has made bold pledges to become carbon neutral in the upcoming decades and increase the proportion of renewable energy in its overall energy portfolio, acknowledging these challenges.

India has committed to several climate initiatives, including increasing its share of bioenergy and other renewable energy (14). India's Nationally Determined Contribution (NDC), submitted in 2016 outlines commitments to reduce GDP emissions by 33-35 % by 2030 compared to 2005 levels, increase non-fossil power capacity to 40 % by 2030 and create a cumulative 2.5-3 $GtCO_2e$ (gigatonnes of carbon dioxide equivalent) carbon sink through afforestation (15). To significantly enhance clean energy generation, India has set a more ambitious target of 450 gigawatts (GW) of renewable energy capacity by 2030, which includes up to 28-30 GW of biomass power, 140 GW of wind and 280 GW of solar photovoltaic (PV) power (16). India has also recently announced its ambition to enhance its renewable energy output and achieve carbon neutrality by 2070.

India holds significant potential for bioenergy within the broader context of renewable energy, particularly given the country's abundant biomass resources. Agroforestry, a land management system that combines trees and shrubs with crops and/or livestock, is one potential technique for producing bioenergy in a sustainable manner. Agroforestry has a long history in India and is practiced across a range of agro-ecological zones. Multipurpose trees are typically combined with crops and livestock in traditional agroforestry systems, providing a wide range of goods and services to local communities. Agroforestry systems have several advantages, including enhanced carbon sequestration, greater biodiversity, improved soil fertility and increased biomass production (17).

Agroforestry can help ensure sustainable energy supplies and food security by combining the environmental benefits of forestry with agricultural productivity. One of the most important techniques for mitigating the effects of climate change is carbon sequestration, which is facilitated by agroforestry. Trees absorb carbon dioxide from the atmosphere through photosynthesis and store it in their biomass, making them the main facilitators of carbon sequestration (18). Agroforestry systems, which include crops and trees, can sequester significant amount of carbon than monoculture agricultural systems. Due to its high carbon-absorbing capacity, agroforestry represents an effective strategy for reducing greenhouse gas emissions and combating climate change. However, to optimize biomass production for bioenergy while simultaneously ensuring environmental sustainability and socioeconomic benefits, scientifically grounded and sustainable agroforestry practices must be promoted. As India strives to meet its ambitious climate and energy targets, this necessitates strategic tree species selection, suitable management techniques and effective conversion technologies to address the intricate interactions between energy, water and land systems. This article explores how agroforestry can serve as a sustainable bioenergy source, supporting India's transition to a low-carbon economy. It aims to synthesize conversion technologies, policy frameworks and ecological benefits that position agroforestry as a viable pathway for clean energy production, economic development and climate change mitigation.

What's driving the growth of bioenergy?

Climate change mitigation is the primary force behind bioenergy market development (14). Bioenergy has found success not only in developed nations but also in some developing countries. Interestingly, countries with higher overall renewable energy usage also tend to incorporate more bioenergy in their energy portfolios. Bioenergy has served as a pathway for nations in their gradual transition from carbon-intensive energy systems while reducing their reliance on fossil fuels. While early concerns about bioenergy centered on supply security and the high cost of importing fossil fuels, today's focus has shifted to the benefits of replacing fossil fuels and cutting carbon emissions. The landmark climate agreement at COP21 in Paris and the pivotal COP26 summit considered among the most important international climate action events, have brought renewed attention to renewables and increased investment in bioenergy (14). Much of the current interest in bioenergy stems from concerns about energy security and independence, along with potential economic growth opportunities. Bioenergy also offers countries without significant natural hydrocarbon resources the opportunity to become energy exporters, provided they develop appropriate infrastructure and possess sufficient land and water resources. In the transportation sector particularly, biofuels offer significant benefits (19). While electrification presents another viable option, biofuels remain the most practical and sustainable solution for reducing oil dependency and limiting global warming to within 2 °C this century.

India's renewable energy landscape in 2024

India possesses substantial renewable energy potential from diverse sources including wind, solar, biomass, small hydro and bagasse cogeneration. As of March 31, 2023, the country's total renewable power generation potential was estimated at an impressive 2.10 MMW (Million Megawatts). Breaking this down, wind power leads the way, representing 1.16 MMW of the total potential at 150 m hub height. Solar power follows with 7.48 MMW, while large hydropower contributes 1.33 MMW. The remaining potential comes from smaller sources: small-hydropower at 21134 MW (Megawatts), biomass power at 28447 MW and bagasse cogeneration from sugar mills at 13818 MW (20) (Fig. 2).

Examining the geographical distribution, Rajasthan emerges as the renewable powerhouse of India, accounting for approximately 20.3 % (0.42 MMW) of the nation's total renewable potential. Maharashtra ranks second with 11.79 % (0.24 MMW), followed by Gujarat and Karnataka with 10.45 % (0.22 MMW) and 9.75 % (0.20 MMW) respectively. Together, these four states account for more than half (52 %) of India's total renewable energy potential (20) (Fig. 3).

Overview of agroforestry in India

Agroforestry, a dynamic and integrated land-use system, has deep roots in India's agricultural landscape, representing a convergence of traditional farming practices and modern scientific understanding. It is defined as a system that integrates trees and shrubs with crops and/or livestock, either simultaneously or sequentially, on the same unit of land (21). This integration promotes ecological and economic interactions among the components, resulting in a more diverse, productive and sustainable approach to land management (22). Agroforestry is not merely the planting of trees alongside crops; it is a deliberate and managed interaction that optimizes resource utilization, enhances ecosystem services and improves livelihoods (23). Agroforestry's versatility stems from its ability to adapt to a variety of agro-climatic conditions and provide numerous benefits including food security, timber production, biodiversity conservation, climate change mitigation and increasingly, bioenergy production. In India, agroforestry has evolved from traditional practices in agricultural and cultural systems to more scientifically planned interventions aimed at increasing sustainability and productivity. Historical records suggest that purposeful tree planting paired with crops has been practiced for centuries throughout India, including systems such as Dehesa in semi-arid regions, home gardens in Kerala and poplar-based systems in the Indo-Gangetic plains (23). Formal recognition and scientific advance of agroforestry in India began intensifying in the late 1970s and were further institutionalized with the

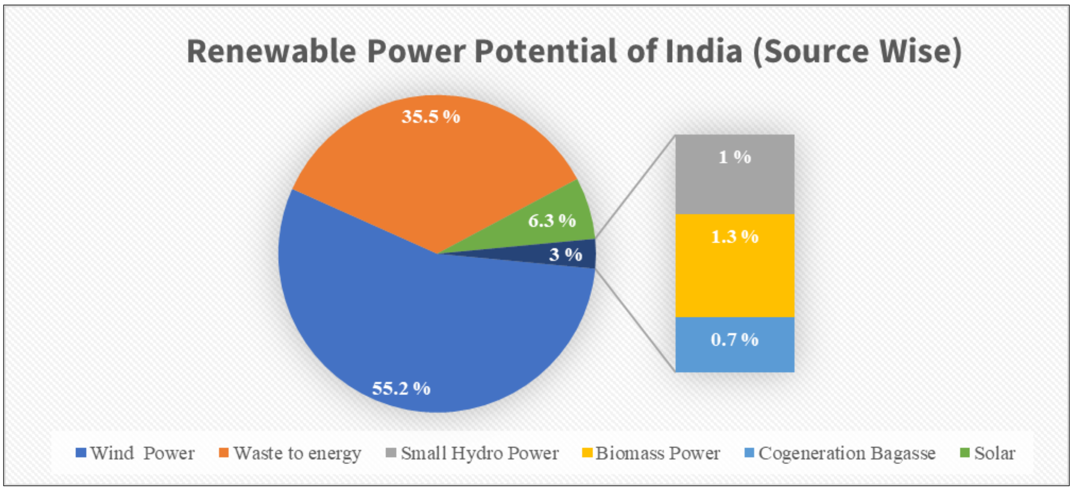

Fig. 2. Estimated renewable power potential in India (20).

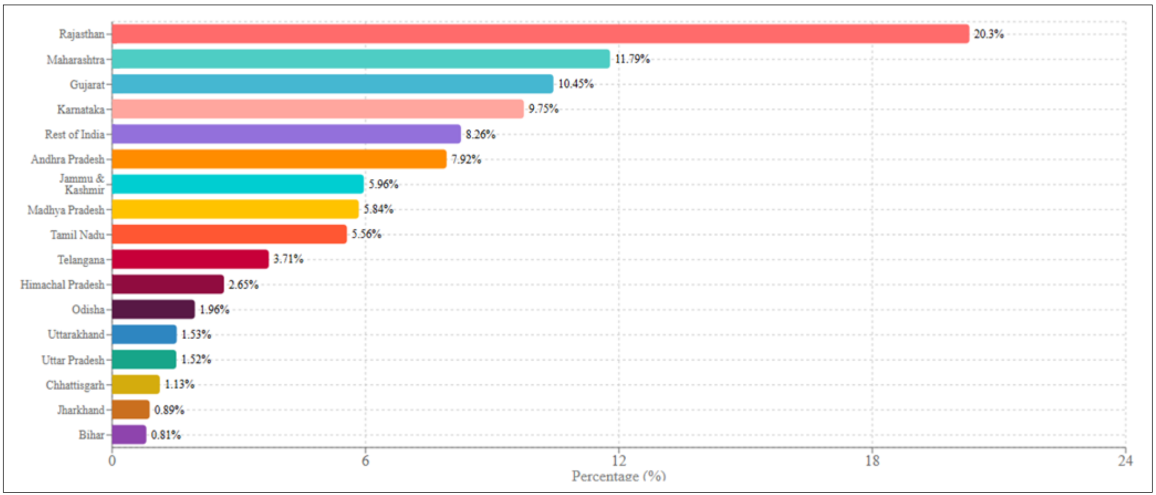

Fig. 3. Estimated renewable power potential in India (Statewise) (20).

establishment of the National Research Centre for Agroforestry (now ICAR-Central Agroforestry Research Institute) in 1988 (24). Agroforestry was significantly mainstreamed into India's development agenda with the National Agroforestry Policy of 2014, the world's first of its kind, a result of decades of research, extension programs and evolving policy support (25). Multiple reasons have influenced this evolution, including increased population strain on land resources, rising wood and energy consumption, environmental concerns, climate change consequences and changed agricultural priorities.

Classification and typology of agroforestry systems

Agroforestry systems can be broadly characterized based on the structure and interaction of their components. Agrisilviculture, a common practice, combines trees with crops, enabling the production of both food and wood. This system can boost soil fertility through nitrogen fixation by leguminous trees, promote water infiltration and offer shade for crops, resulting in higher yields (26). Silvipastoral systems combine trees and livestock, providing food, shade and shelter for the animals while producing timber and other tree products. These systems can improve pasture productivity, reduce soil erosion and increase carbon sequestration. Agrosilvipastoral systems are a more complicated integration that includes trees, crops and livestock on the same unit of land. These systems offer the most diverse range of products and services while maximising land-use efficiency and resilience.

Agroforestry systems in India can be classified into several typologies based on their structure and management. Boundary plantations consist of trees growing along agricultural boundaries and field edges. Block Plantations are compact blocks of trees that are integrated into agricultural cultivation. Scattered trees occur in farmlands and are either spontaneously regenerated or intentionally retained. Alley cropping is a method where agricultural crops are grown between rows of trees or hedges. Home gardens are complex, multi-strata systems with great species diversity. Silvipastoral systems that include trees, pasture and livestock; industrial agroforestry practiced on a commercial scale and increasingly, energy plantations developed specifically for biomass energy production represent key agroforestry systems contributing to India's bioenergy sector (27). The bioenergy potential varies greatly among various classifications, with energy plantations and block plantations typically producing the highest biomass yields per unit area (Fig. 4).

Geographical distribution and regional models

India's diverse agroclimatic zones have led to the development of a wide range of agroforestry models, each tailored to specific environmental conditions and socioeconomic needs. According to the most recent assessment by the Central Agroforestry Research Institute, agroforestry covers approximately 25.32 million hectares, accounting for about 8.2 % of India's total land area (28). Poplar and eucalyptus-based agroforestry systems are widespread in the Indo-Gangetic Plains, particularly in Punjab, Haryana, Uttar Pradesh and Bihar. These systems are typically used in conjunction with vegetable, wheat and rice crops. In addition to providing fuelwood and timber, these fast-growing trees improve soil quality and possess significant potential for bioenergy production (29). Agroforestry systems in the Himalayan region characterized by its cold climate and hilly terrain, commonly include poplar, alder and willow trees in addition to crops (30). These systems are primarily intended to meet local needs rather than to produce commercial biomass.

Drought-tolerant species such as *Prosopis cineraria* (locally known as "Khejri"), *Acacia nilotica* and *Ziziphus mauritiana* are used in traditional systems in semi-arid regions of Rajasthan, Gujarat and Madhya Pradesh. These species not only supply fuelwood but also improve resilience to climate change. Agroforestry systems with species such as Prosopis and bamboo are common in Central India (31). In the southern Indian peninsula, agroforestry techniques are widely adopted, particularly in Tamil Nadu, Andhra Pradesh and Karnataka. These include block plantations with *Melia dubia* and *Casuarina*, traditional agroforestry systems involving *Tamarindus indica* and *Azadirachta indica* and boundary plantations using Eucalyptus and Casuarina. In the early 2000s, biofuel-oriented crops such as Jatropha and Pongamia also expanded significantly in these regions (8). With traditional jhum (shifting farming) fallows giving way to more permanent agroforestry systems and private gardens rich in species diversity, the northeastern states host the largest tree cover outside of forests (32).

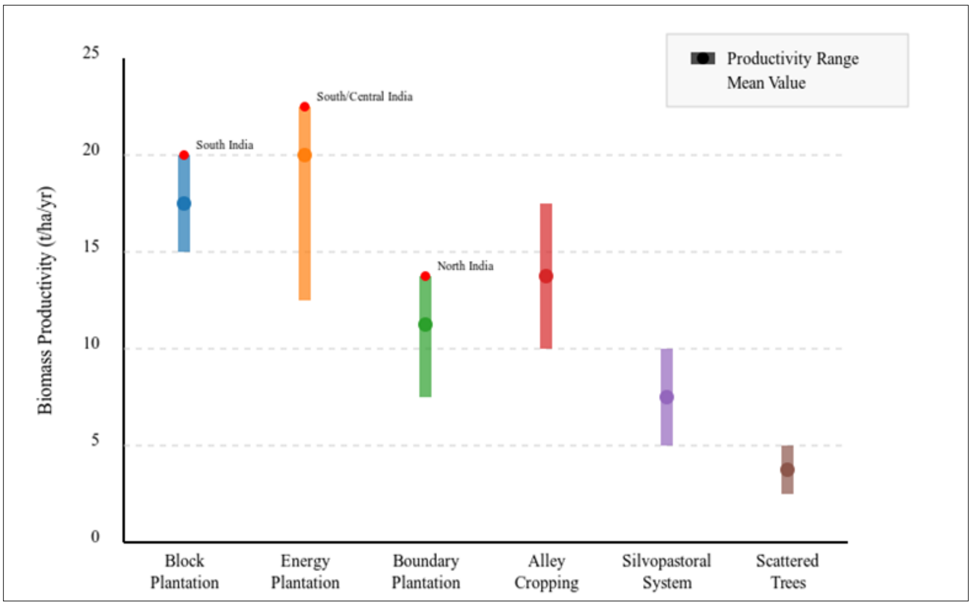

Fig. 4. Biomass productivity variations across major agroforestry systems.

In India, agroforestry systems yield a diverse array of biomass feedstocks that can be utilized to generate bioenergy. The primary source of bioenergy is woody biomass, which includes wood, branches and root systems as well as crop residues from intercropped annuals. Other significant sources include leaf litter, which also contributes to soil fertility; oil-bearing seeds, which can be used to produce biodiesel and specialized energy crops, such as fast-growing grasses and herbaceous plants cultivated specifically for bioenergy. Among the important woody species are *Dalbergia sissoo* (Shisham), *Populus deltoides* (Poplar), *Prosopis juliflora* (Mesquite), *Gmelina arborea* (White Teak), Eucalyptus (*E. tereticornis*, *E. camaldulensis*), *Melia dubia* (Malabar Neem), *Casuarina equisetifolia* (Australian Pine), *Acacia spp.* (Wattles) and *Leucaena leucocephala* (Subabul). Species notable for biodiesel production include *Jatropha curcas* (Physic Nut), *Madhuca longifolia* (Mahua), *Azadirachta indica* (Neem) and *Pongamia pinnata* (Karanja). The biomass productivity of agroforestry systems varies significantly based on species, site factors, management strategies and system structure. Key factors that influence productivity include genetic material, management practices, site factors, system configuration and rotation cycles. Improved clones or variants can be 30-100 % more productive than unimproved stock; for example, under comparable conditions, clonal Eucalyptus can yield twice the biomass of seed-origin plants (27). According to research from long-term agroforestry experimental locations, properly managed sustainable harvesting can sustain or increase system productivity across multiple generations. For example, with effective management, eucalyptus-based agroforestry in southern India has maintained or increased yields throughout three coppice cycles (33).

Feedstocks for bioenergy production

Wood based feedstocks

Approximately 90 % of the primary energy derived from biomass and more than 10 % of the world's energy supply comes from woody biomass, making it the most significant bioenergy resource worldwide. Woody biomass is widely used for cooking and heating, but it is more often used for direct combustion or pellet manufacturing when it is unsuitable for lumber or pulp production. In India, Trees Outside Forests (TOF), including trees in cities, on farms, along roads and in many other locations supply approximately 91.51 million cubic meters of timber, accounting for 80 % of the country's timber demand. Haryana State is home to TFOs, which roughly occupies 3.38 % of the state's total land area. Trees in the agricultural landscapes of Uttar Pradesh have been shown to sequester 20 million tonnes of carbon, demonstrating the substantial carbon sequestration potential of TOF (34, 35).

About 18 % of India's total energy is derived from wood, primarily used in small-scale and domestic settings (36). Projected increases in the availability of biomass feedstock are expected to support an estimated 35 GW of biomass pellet-based power generation capacity by 2030-31 (37), in addition to the 180-260 GW of biopower generation potential from surplus wood by 2050 (36). Despite the promising potential, several challenges remain: the levelized cost of electricity generated from biomass pellets is higher than that of coal-based power, which could have an impact on economic feasibility. However, the environmental advantages are significant; by 2030-31, biomass power generation could reduce carbon emissions by approximately 205 Mt of CO_2 (37).

Agriculture-based feedstocks

A wide variety of components, such as sugars, starches, lipids and cellulose materials, are included in agricultural biomass. These elements can be obtained from both specific energy crops and agricultural waste. Production of first-generation bioethanol is mostly dependent on food crops, with sugarcane (Brazil) and corn (United States) making up 62 % of global production. Cereals, sugar beets, potatoes, sorghum and cassava are also used as supplements. In terms of biodiesel, soybeans serves as the primary feedstock in the Americas and Europe, palm oil in Southeast Asia and oilseed rape in various other regions. Perennial crops are the primary source of lignocellulosic biomass, used for producing second-generation biofuels. Agricultural biomass is especially important in India, where it can provide roughly 3.96 EJ of energy yearly from 696.38 million tonnes of crop residues, primarily from sugarcane and grains (38, 39).

In India, sorghum stalk, cotton stalk and sugarcane bagasse are the major feedstocks for producing ethanol. Sugarcane-based feedstocks offer a high energy return on investment (40). Furthermore, because of their favorable thermochemical properties, perennial energy grasses grown on marginal land, such as *Cenchnis ciliaris* and *Pennisetum pedicellatum*, exhibit significant promise (41). These agricultural wastes support a variety of bioenergy paths, including biogas production, which decreases waste and emissions while promoting a circular economy (42). The manufacturing of ethanol from surplus agricultural residues, which may generate around 30 billion litres per year, provided appropriate logistics and collection systems are systematically implemented (40) and the production of bio-briquettes, which minimize waste while producing a large amount of energy, represent key pathways in agricultural biomass utilization (39).

Waste-based feedstocks

Waste-based biomass, which is used to generate bioenergy, consists of a variety of organic waste materials from the municipal, industrial and construction sectors (43). This includes biodegradable kitchen waste, food packaging and other discarded items collected by municipalities; wood, plastic and metal debris from construction activities; along with paper waste, textile byproducts and liquid discharges from industrial operations (44). These materials, which are often destined for landfills, hold significant promise for producing renewable energy as they can be gasified to produce syngas or burnt to generate electricity.

India exhibits remarkable potential for the production of energy from municipal waste owing to its enormous waste generation, amounting to roughly 160038.9 tons per day. Approximately 95 % of this material, which is now poorly managed at nearby landfills, is successfully collected by garbage collection systems (45). There is a significant potential for recycling, as 50-80 % of plastic, 30-60 % of paper waste and nearly 100 % of glass materials can be recovered for energy production or reuse (46). In India, biomass availability is largely influenced by the industrial sector, with the food and sugar sectors acting as the primary sources. Other contributors include, leather, food processing and textile industries, although there is still a lack of relevant documentation from reliable sources. Similarly, there are no official databases for waste generated from sawmilling, pulp and paper manufacturing, woodworking, or furniture manufacturing; instead, information is usually limited to small and medium-sized businesses or local sources (47). This points to unrealized potential for producing bioenergy from industrial waste streams, leading to the need for improved management and evaluation.

Bioenergy conversion process for biomass

A variety of technological processes, such as thermal conversion methods (combustion, pyrolysis and biomass gasification) and bioconversion methods (fermentation and anaerobic digestion), are used to transform biomass into energy. Furthermore, an integrated biorefinery (a facility that uses biomass, such as plants or waste, to produce various products, including fuels, energy and chemicals) combines the production of high-value bioproducts with the generation of renewable energy. Numerous bio-based products, including chemicals (such as succinic acid, ethanol, sorbitol, 2,5-furan-dicarboxylic acid, lactic acid, glutamic acid, levulinic acid, aspartic acid and aldehydes) and biopolymers (such as polylactic acid, polyhydroxyalkanoate, bio-ethylene, thermoplastic and starch) are produced in these biorefineries through a variety of conversion pathways using biomass resources (48).

Thermochemical Conversion Technologies

Thermochemical conversion systems use heat to convert biomass into valuable products or energy. These methods show adaptability in a variety of biomass feedstocks, including agricultural wastes, woody biomass and energy crops. Combustion, pyrolysis and gasification are the three main thermochemical conversion processes; each offers unique benefits and applications in the bioenergy sector.

Gasification

Gasification is a thermochemical process that converts biomass into syngas, a flammable gas mixture mostly composed of hydrogen (H_2) and carbon monoxide (CO), at temperatures above 700 °C in a controlled, oxygen-deficient environment (49). Syngas is remarkably adaptable and it can be utilized directly to generate energy in internal combustion engines or gas turbines, providing a cleaner and more efficient alternative to direct combustion. Furthermore, syngas is a fundamental building block for the synthesis of liquid fuels required for transportation, such as methanol and Fischer-Tropsch diesel (50). It is a valuable feedstock for the production of a number of chemicals, including polymers and fertilizers, in addition to fuel. In terms of biomass conversion, gasification offers several advantages. Its high conversion efficiency enables more effective conversion of biomass energy into usable forms. The approach is extremely adaptable when working with a wide range of biomass feedstocks with varying compositions and moisture content (51). Furthermore, gasification is commercially advantageous as it enables the production of high-value products other than energy. Due to the complexity of the technique, parameters such as, temperature, pressure and gasifying agent must be properly managed to maximize syngas purity and minimize undesirable byproducts such as tar. Tar requires additional cleaning operations, which raises the entire cost of the process.

Pyrolysis

Pyrolysis, which yields three major products: bio-oil, biochar and syngas, is another important thermochemical process that includes the thermal decomposition of biomass under complete oxygen deprivation. By adjusting the pyrolysis conditions, such as temperature, heating rate and residence time, the relative quantities of various products can be customized (52). Although it typically requires upgrading to improve stability and decrease viscosity prior to engine use, bio-oil, a complex mixture of oxygenated organic molecules, exhibits significant potential as a liquid fuel source. Because of its porous structure, biochar - a solid carbon-rich residue is useful for soil amendment to improve fertility, carbon sequestration to slow down climate change and the in the production of activated carbon for filtration applications. Syngas derived from both gasification and can serve as a source of fuel or electricity (53). The unique benefit of pyrolysis is that it maximises the utilisation of biomass resources by producing a range of valuable products. This multi-product strategy promotes a more circular bioeconomy by enhancing economic viability. Direct fuel use is hampered by the intricacy of the bio-oil composition, which varies based on feedstock and pyrolysis conditions (54). Processing costs are further increased by the need to upgrade bio-oil to meet fuel quality standards.

Combustion

The simplest thermochemical process is combustion, which produces heat by directly burning biomass in the presence of excess oxygen. The heat produced can be utilised for various purposes, including heating buildings and industrial processes, operating combined heat and power (CHP) systems to generate both heat and electricity simultaneously, or producing steam for power plant turbines. Combustion is a commonly used, comparatively well-established and cost-effective process for producing bioenergy, particularly on a smaller scale. However, the direct combustion of biomass can generate air pollutants, such as sulphur oxides (SOx), nitrogen oxides (NOx) and particulate matter; therefore, proper pollution control techniques are required to comply with environmental standards (55). Cofiring biomass with fossil fuels in existing coal-fired power plants provides a rapidly deployable and cost-effective approach to increase the proportion of renewable energy in the electricity mix (56) (Fig. 5).

Biochemical conversion technologies

Biochemical conversion methods use enzymes and microorganisms to convert biomass into valuable chemicals and biofuels. These methods are particularly effective with high-carbohydrate biomass feedstocks, such as the cellulosic fraction of agroforestry biomass, specialised energy crops and agricultural byproducts. The two main biochemical conversion processes are fermentation and anaerobic digestion.

Anaerobic digestion

Anaerobic digestion is a biological process in which microorganisms break down organic matter in the absence of oxygen, generating digestate and biogas, both of which are valuable renewable energy sources. Biogas, mostly composed of methane (CH_4) and carbon dioxide (CO_2), can be burned directly to generate electricity or heat. It can also be converted into biomethane, a purified form with a higher methane concentration that can be injected into natural gas pipelines for distribution. Digestate, the solid and liquid residue remaining after digestion, is rich in nutrients and can be employed as a biofertilizer in agricultural applications, thereby closing the nutrient cycling loop (57). Anaerobic digestion is capable of treating a wide range of biomass feedstocks, including agroforestry residues, livestock manure, municipal solid waste and agricultural byproducts.

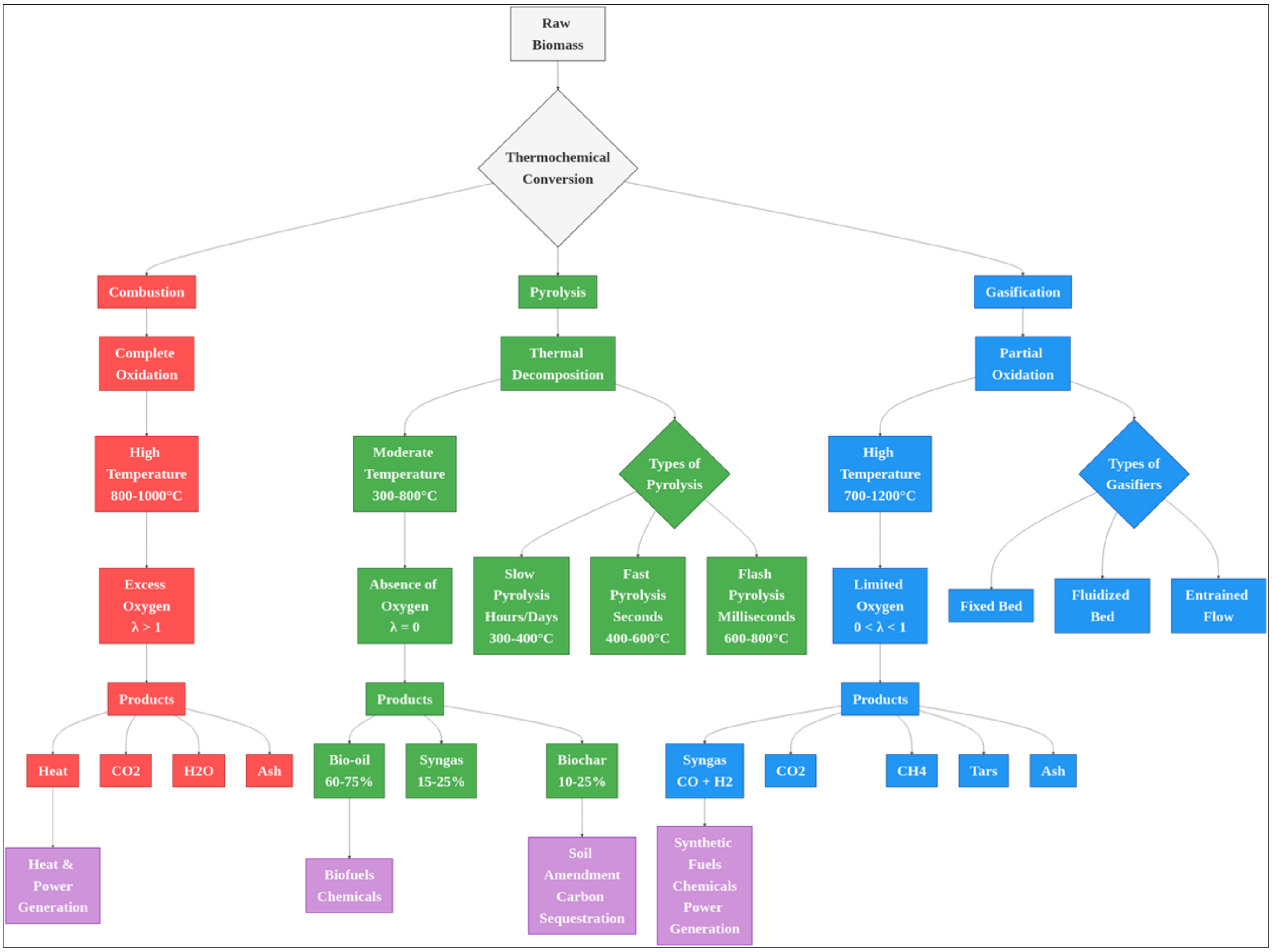

Fig. 5. Thermochemical conversion techniques of biomass.

Fermentation

Fermentation is a biochemical process in which microbes, usually bacteria or yeast, convert sugars and carbohydrates into biofuels like bioethanol and other valuable products. Bioethanol, a fermented liquid alcohol fuel, can be used as a vehicle fuel either alone or in combination with gasoline. Lignocellulosic biomass, which accounts for a substantial amount of agroforestry residues, can be converted into bioethanol through a multistep process that includes pretreatment, enzymatic hydrolysis and fermentation. Pretreatment severely disrupts the complex structure of lignin and hemicellulose that surrounds cellulose, making it more susceptible to enzymatic degradation. Enzymatic hydrolysis converts cellulose into fermentable sugars, which microorganisms subsequently ferment to produce bioethanol (58). Although fermentation presents a promising route for producing sustainable transportation fuel from renewable biomass resources, particularly from the abundant lignocellulosic biomass in agroforestry systems, the high cost of pretreatment and cellulase enzymes, as well as the requirement for effective fermentation processes, remains a challenge (Fig. 6). Research is being conducted to enhance the economic viability of this significant technology by developing more effective pretreatment techniques, reducing the cost of enzymes and increasing fermentation yields (Table 1).

Woody biomass from tree pruning and thinning can be efficiently converted through thermochemical processes like gasification and pyrolysis. Agricultural residues, such as crop residues and livestock manure, can be effectively utilized through anaerobic digestion. Integrating various conversion technologies to utilize the diverse biomass resources generated in agroforestry systems can maximize the overall energy output and economic benefits. Furthermore, the development of integrated biorefineries, which combine multiple conversion technologies to produce a range of bioenergy products and other valuable byproducts, holds significant potential for enhancing the sustainability and economic viability of bioenergy from agroforestry.

Impacts of bioenergy

Environmental impacts

Bioenergy obtained from tree-based systems in India has shown considerable environmental benefits when compared to traditional energy sources. Depending on the tree species and management approaches, agroforestry-based bioenergy systems can sequester 5- 25 tonnes of carbon per hectare annually (59). This carbon sequestration potential represents an important climate change mitigation method for India, where emissions grew at a rate slightly over 7 % faster than GDP during 2023 (60). Tree-based bioenergy systems also promote biodiversity by providing habitat for a variety of species and contribute to improved water resource management. It has been found that strategically integrating trees into bioenergy production landscapes reduces water runoff by 25-30 % while improving groundwater recharge rates in semi-arid regions. The utilisation of local tree species for bioenergy, such as *Pongamia pinnata* and *Azadirachta indica* has been demonstrated to be more compatible with long-term water management in India's diverse agroclimatic zones.

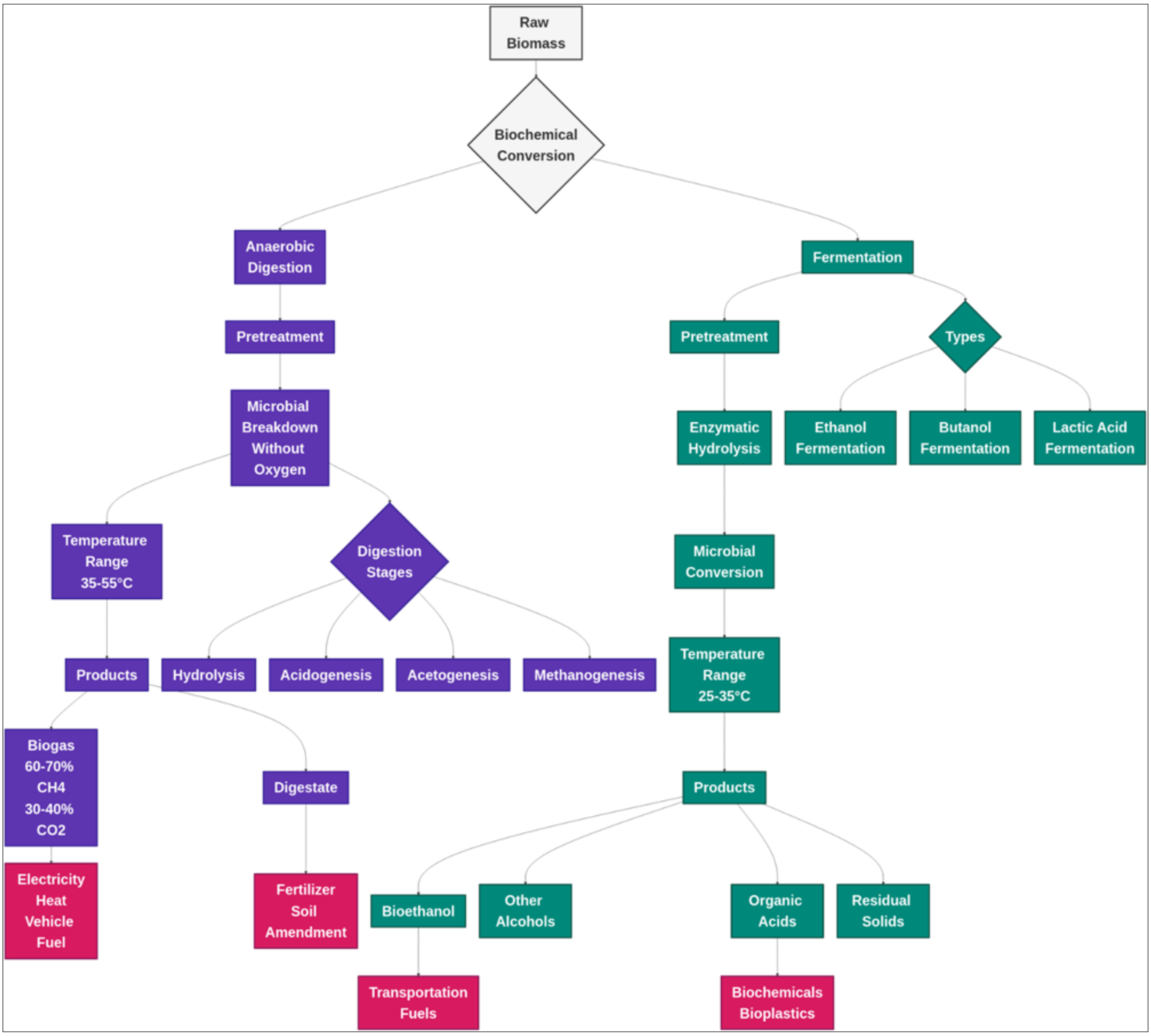

Fig. 6. Biochemical conversion techniques of biomass.

Table 1. Comparison of conversion technologies of different biomass

Conversion Technology	Process Description	Main Products	Advantages	Challenges	References
Gasification	High-temperature (≥700 °C) conversion of biomass in an oxygen-deficient environment to produce syngas (H_2 + CO)	Syngas (used for power generation, liquid fuels and chemicals)	High efficiency, flexible feedstocks, multiple high-value products	Tar formation requires additional cleaning; precise control needed	(49)
Pyrolysis	Thermal decomposition of biomass in total oxygen deprivation	Bio-oil, biochar, syngas	Multi-product process supports circular bioeconomy; biochar aids soil fertility	Bio-oil requires upgrading for fuel applications; cost of processing	(52)
Combustion	Direct burning of biomass in excess oxygen for heat and power	Heat, steam, electricity	Mature, cost-effective, simple process	Emissions (SOx, NOx, particulates) require control; lower efficiency	(55)
Anaerobic Digestion	Microbial breakdown of organic matter in oxygen-free conditions	Biogas (CH_4 + CO_2), digestate (biofertilizer)	Converts waste into energy and fertilizer; reduces landfill waste	Biogas purification needed for grid injection; process stability depends on feedstock	(57)
Fermentation	Microorganisms convert sugars into bioethanol or other biochemicals	Bioethanol, other biofuels	Utilizes lignocellulosic biomass; potential for sustainable fuels	High costs of pretreatment and enzymes; efficiency challenges	(58)

Socioeconomic impacts

Tree-based bioenergy systems have provided significant socioeconomic benefits in rural India. Comprehensive research found that integrated agroforestry-bioenergy systems enhanced annual farm revenue by 30-45 % compared to conventional agriculture in Karnataka (61). This diversification of income streams has been especially beneficial to small and marginal farmers, who account for roughly 86 % of India's farming population. Women's empowerment has also played a significant role in the socioeconomic impact on bioenergy development in India. Women's participation in decision-making increased by 37 % in households involved in bioenergy value chains compared to those relying purely on traditional agriculture (62). Moreover, reduced reliance on fuelwood collection, which is traditionally to the responsibility women, has saved rural women an average of 10-15 hr per week in areas with access to locally produced bioenergy (63). However, the socioeconomic benefits of bioenergy initiatives are not distributed equally. Factors such as access to credits, land ownership patterns and existing social inequalities significantly influence who benefits the most from these efforts. Although landless workers comprise a significant portion of the rural labour force, they often receive minimal benefits from tree-based bioenergy systems unless inclusive measures are intentionally integrated into project planning.

Energy security and rural development

Tree-based bioenergy systems make a substantial contribution to energy security in rural India, where over 25 % of the population still lacks reliable access to electricity. Decentralised bioenergy systems using locally generated woody biomass have successfully powered mini-grids serving homes in many villages across India, providing hours of electricity per day. This reliability stands in stark contrast to the national grid, which experiences hours of daily outages in many rural locations (64). The localized nature of tree-based bioenergy production has played a crucial role in advancing rural development by fostering energy independence. Villages with functional bioenergy systems have experienced a 23 % increase in newly established small-scale enterprises within three years of implementation. Educational outcomes have also improved, with students getting an extra 2.4 hr of evening study time per day with school attendance rising by 18 % as a result of reliable energy supply. Furthermore, healthcare facilities in these communities have improved their vaccine and drug storage capacity, resulting in a 15 % increase in immunization rates and enhanced management of chronic illnesses (65). The emergence of tree-based bioenergy value chains has greatly stimulated rural economies by establishing new economic connections. Each megawatt of bioenergy capacity generated by agroforestry systems creates roughly 30 direct and 70 indirect employments throughout the supply chain. This rise in economic activity has played a crucial role in narrowing the income disparity between rural and urban regions, reducing the gap by around 12 % in areas with well-established bioenergy infrastructure (66).

Land use change and food security

The relationship between tree-based bioenergy systems and food security in India presents both opportunities and challenges. On the positive side, incorporating bioenergy plants into agroforestry systems can enhance overall farm productivity (67). Studies have shown that planting bioenergy trees, such as *Pongamia pinnata* and *Melia dubia* along field boundaries results in only a marginal reduction in food crop yields (3-5 %), while simultaneously generating significant biomass, equivalent to 2.3 tonnes of oil per hectare. Additionally, certain tree-legume combinations in agroforestry systems improve soil fertility by increasing nitrogen levels by 18 -25 % over a three-year period, ultimately benefiting subsequent crop production (68). Conversely, unregulated expansion of bioenergy plantations can pose risks to food security. Studies reported from Tamil Nadu revealed that large-scale conversion of agricultural land into monoculture bioenergy plantations resulted in a 28 % decline in local food production, disrupting food supply and price stability. The extent of these impacts depends largely on existing land use practices. Utilizing degraded lands which is estimated at 75 million hectares across India has been found to support bioenergy production without adversely affecting food supply (69). However, converting fertile croplands to bioenergy cultivation has shown a net negative effect on local food security, despite potential economic advantages. To address this concern, India's bioenergy policies now emphasize the use of marginal lands, wastelands and agricultural residues, aiming to minimize competition with food production.

Technological adaptation and innovation

Tree-based bioenergy development in India has resulted in substantial technology improvements customized to local conditions. Gasification systems for agroforestry biomass are now 15-20 % more efficient than the first-generation models (70). Traditional practices such as coppicing and pollarding have been incorporated into mechanized harvesting, increasing labour efficiency by 40 % while maintaining environmental sustainability. Improved biomass handling has also decreased post-harvest losses from 25 % to less than 10 % in trial programs. However, issues in standardization and quality control persist, with studies indicating that 32 % of bioenergy systems underperform due to mismatches between biomass characteristics and conversion technologies (71). This emphasizes the necessity for region-specific technology modifications to meet India's different agroclimatic conditions (Fig. 7).

Policies and provisions in India

Electricity act

The Electricity Act of 2003 provides the main legal framework for India's electricity sector, including provisions to promote cogeneration and renewable energy sources. Section 86(1)(e) mandates State Electricity Regulatory Commissions (SERCs) to support renewable energy and cogeneration, placing them on an equal footing for development (72). This Act facilitates the development of a National Electricity Policy by mandating rules that emphasize renewable energy integration, as well as authorizing regulatory commissions to establish Renewable Purchase Obligations (RPOs) and Renewable Energy Certificates (73). It lays down provisions that provide crucial legal backing for India's transition to a more sustainable and efficient energy sector.

Biomass co-firing policy

India's biomass co-firing strategy aims to incorporate renewable energy into coal-fired power generation while addressing residual burning. With approximately 750 million metric tonnes of biomass produced each year, including 230 million metric tonnes of surplus agricultural residue (74), the Ministry of Power mandated in 2021 that compatible coal units employ a 5-10 %

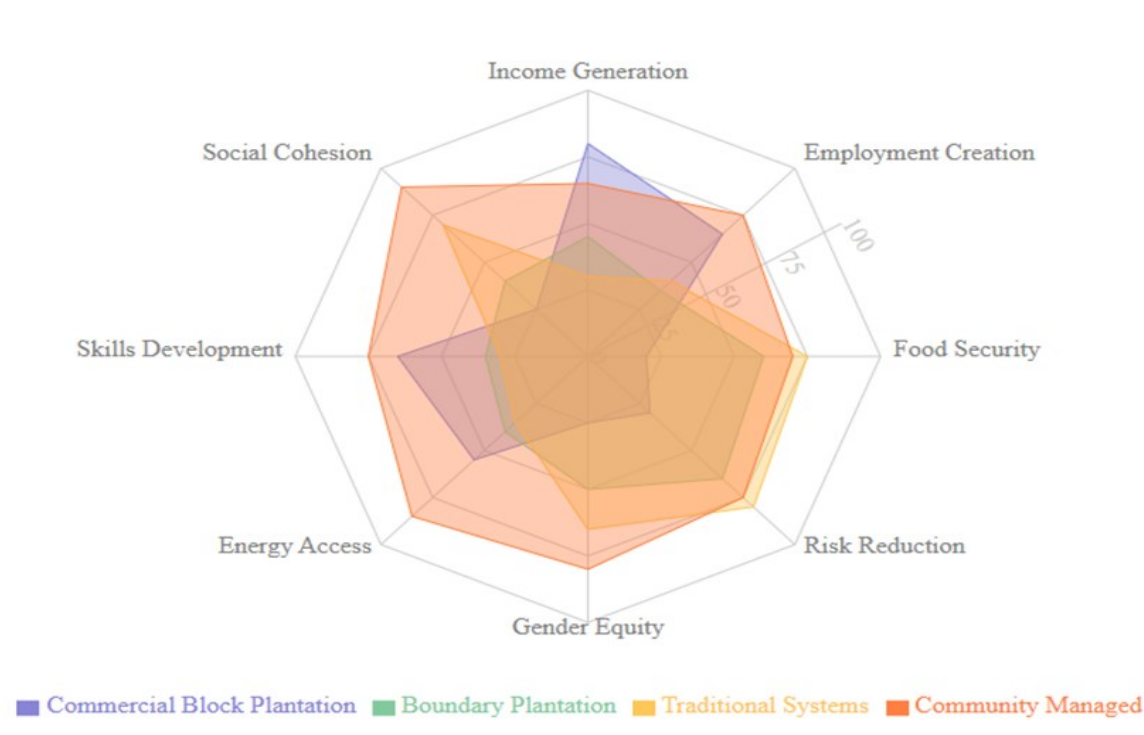

Fig. 7. Socioeconomic impacts of bioenergy-oriented agroforestry systems.

combination of biomass pellets with coal. This requirement will increase to 7 % beginning in fiscal year 2025-26. This strategy has been supported by the National Mission on Biomass Cofiring and the SAMARTH programme, both of which focus on developing strong biomass supply chains and providing financial incentives for pellet manufacturing. Scientific studies show that carbon-neutral nature of biomass co-firing significantly reduces carbon emissions. However, implementation faces challenges including high pelletization costs, logistical barriers in biomass collection and the need for technological upgrades in power plants (75).

National policy on biofuels

National Policy on Biofuels, 2018, introduced by the Ministry of New and Renewable Energy, represents a significant evolution from its 2009 predecessor, aligning with global biofuel advancements and national initiatives like Make in India and Swachh Bharat Abhiyan. Initially hindered by inconsistent feedstock availability, the policy has been amended based on recommendations from the National Biofuel Coordination Committee (NBCC) to expand feedstock options, advance the ethanol blending target in petrol from 2030 to 2025-26 and promote production in Special Economic Zones. India is looking into sustainable aviation fuel (SAF) to minimize aviation emissions, but the high cost 60-70 % more than conventional gasoline remains a key obstacle. The DGCA monitors fuel regulations and India's participation in CORSIA requires carbon offsets beginning in 2026. With some of the highest aviation fuel prices globally, fuel costs account for 30-40 % of airline expenses and a proposed carbon tax could raise costs even further. To encourage SAF adoption, the government is contemplating tax incentives, subsidies and infrastructure development, with the goal of making bio-jet fuels a commercially viable option in the long run (76).

Other provisions

Amended National Tariff Policy, 2016 significantly boosts waste-to-energy initiatives by mandating Distribution Licensees to procure 100 % of power generated from such plants within their states, proportional to their total power procurement. This establishes a guaranteed market for waste-to-energy projects, encouraging investment in the sector (77). Furthermore, the 2015 revision to the Central Motor Vehicles Rules provides provisions for bio-CNG as a vehicle fuel, aligning with India's emission reduction goals (78). The government has strengthened the biofuel sector through various fiscal and financial schemes, such as the Waste to Energy Programme, support for biomass-based cogeneration in industries, the Galvanising Organic Bio-Agro Resources (GOBAR)-DHAN initiative and the Pradhan Mantri JI-VAN Yojana. These integrated policies and initiatives highlight India's commitment to creating a circular economy, reducing reliance on fossil fuels and meeting renewable energy targets (79).

Furthermore, the Ministry has implemented several biogas development programmes, including the transition from the National Biogas and Manure Management Programme (NBMMP) to the New National Biogas and Organic Manure Programme (NNBOMP), which aims to establish 0.25 million biogas plants, producing approximately 0.8 million SCMD of biogas (80). These activities support India's ambitious climate protection targets stated at COP26, which include 500 GW of non-fossil energy capacity by 2030 (81) and net-zero emissions by 2070 (82) (Table 2).

Conclusion

Bioenergy from biomass and agroforestry presents India with an excellent opportunity to enhance energy security, mitigate carbon emissions and stimulate economic growth. India has the ability to increase its renewable energy portfolio while reducing reliability on fossil fuels by integrating massive biomass resources such as agricultural wastes, dedicated energy crops and trees outside forests. Agroforestry, in particular, offers a sustainable method of biomass production by promoting carbon sequestration, biodiversity protection and rural livelihoods. Despite its potential, bioenergy is underutilised, accounting for less

Table 2. Different policies and provisions for promoting bioenergy in India

Policy/Act	Description	Key Provisions	Challenges	References
Electricity Act (2003)	Provides the legal framework for India's electricity sector, promoting renewable energy and cogeneration	Section 86(1)(e) mandates SERCs to promote renewables; enables National Electricity Policy, RPOs and RECs	Implementation varies across states; enforcement challenges	(72)
Biomass Co-firing Policy	Integrates biomass into coal-fired power plants to reduce emissions and manage agricultural waste	5-10 % biomass blending in coal plants (7 % from FY 2025-26); supported by the National Mission on Biomass Cofiring and SAMARTH program	High pelletization costs, logistical issues, power plant technology upgrades	(74)
National Policy on Biofuels (2018, amended)	Encourages biofuel production and use, aligned with global sustainability goals	Expanded feedstock options; ethanol blending target advanced to 2025-26; SAF promotion	High cost of bio-jet fuel (60–70 % higher); potential carbon tax impact on aviation	(76)
Amended National Tariff Policy (2016)	Supports waste-to-energy projects by ensuring power purchase agreements	Requires distribution licensees to buy 100 % of waste-to-energy power within their states	Limited technological advancements; financial viability concerns	(77)
Central Motor Vehicles Rules (2015 Amendment)	Allows bio-CNG as a vehicle fuel to reduce emissions	Supports biofuel adoption in the transport sector	Infrastructure and supply chain challenges	(78)
Waste-to-Energy and Biogas Initiatives	Various programs to promote biomass cogeneration and biogas development	GOBAR-DHAN, Pradhan Mantri JI-VAN Yojana, NNBOMP targeting 0.25 million biogas plants	Capital-intensive projects; scalability concerns	(79)
Renewable Energy and Climate Goals	India's commitments to non-fossil energy expansion and net-zero targets	500 GW non-fossil energy by 2030; net-zero by 2070	Financial and technological hurdles in meeting targets	(81, 82)

than 3 % of India's total power generation, with fossil fuels dominating at 58.2 %. However, with strategic interventions implemented, biomass power capacity is expected to reach 35994.52 MWe by 2030-31. These include strengthening biomass supply chains, optimising conversion technologies such as gasification, pyrolysis and anaerobic digestion, as well as enhancing policy frameworks. India's existing policies, such as the National Policy on Biofuels and biomass co-firing mandates, lay a solid foundation. However, more research and investment are needed to maximise biomass productivity and ensure long-term sustainability. A multidisciplinary approach, encompassing policymakers, researchers, companies and communities, is critical. With targeted interventions and technological developments, bioenergy can play a critical role in India's transition to a net-zero carbon economy by 2070, promoting energy independence, climate resilience and economic empowerment.

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Authors' contributions

KTP conceptualized the review topic and guided the overall outline and structure. IS, KR, PK, PS and KRR provided critical insights, contributed to content development and supported drafting the manuscript. ARR, SPP, RM[1], RM[2], RN and KV participated in literature review, technical input and refinement of specific sections. All authors reviewed and approved the final manuscript. [RM[1] stands for R Meenakshi and RM[2] stands for R Moulidharshan].

Compliance with ethical standards

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