PLANT SCIENCE TODAY
Vol 12(sp3): 01–09
https://doi.org/10.14719/pst.8384

eISSN 2348-1900

REVIEW ARTICLE

A comprehensive review of biomass energy from agroforestry residues

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Received: 19 March 2025; Accepted: 20 May 2025; Available online: Version 1.0: 20 August 2025

Cite this article: Nithes R, Sivakumar B, Balasubramanian A, Senthil NN, Sekar I, Radhakrishnan S, Sivaprakash M, Suganya K, Ashwin NM, Eniya A. A comprehensive review of biomass energy from agroforestry residues. Plant Science Today. 2025;12(sp3):01–09. https:/doi.org/10.14719/pst.8384

Abstract

The rapid growth of the global population, particularly in urban areas of developing countries, has led to an increase in energy consumption and environmental challenges, necessitating the search for sustainable energy solutions. Biomass energy, derived from organic materials such as agroforestry residues, presents a promising avenue for addressing these challenges by offering a renewable and potentially carbon-neutral energy source. This paper explores the potential of agroforestry residues as a sustainable biomass energy source, examining the availability, technological conversion processes, environmental impacts and socio-economic benefits. Agroforestry, a land use system integrating trees and crops, generates significant residues that can be transformed into energy, thereby contributing to rural development, energy security and climate change mitigation. The review highlights the challenges and opportunities associated with biomass energy production, including sustainability concerns, technological and logistical hurdles and the need for supportive policy frameworks. Successful case studies underscore the feasibility and benefits of converting agroforestry residues into bioenergy, emphasizing its role in a circular economy and its contribution towards achieving renewable energy targets and sustainability goals. The paper concludes that, with appropriate management and technological innovation, biomass energy from agroforestry residues can play a pivotal role in the global transition to renewable energy, enhancing environmental sustainability and socio-economic development.

Keywords: agroforestry residues; biomass energy; environmental sustainability; renewable resources; sustainable energy

Introduction

The global population is expanding rapidly, having doubled since 1960 and projected to reach 9 billion by 2050 (1). Developing nations will account for 99 % of this growth, with urban populations increasing by 50 % (2). As a result, cities are consuming an increasing share of global energy. In the early 1990s, urban areas used less than half of the total energy generated, but they now account for two-thirds of global energy consumption (3). This indicates that urban energy demand is rising faster than urban population growth. While fossil fuels remain the primary energy source, there is a growing shift towards sustainable energy strategies to mitigate climate change (4).

Cities contribute to 70 % of human-caused CO_2 emissions (5) and are significant agents of climate change. Moreover, they bear the brunt of its consequences, with around 70 % already experiencing its impact. Given that 90 % of urban areas are coastal, the anticipated rise in sea levels poses heightened risks, particularly for vulnerable cities in developing nations (6). The surge in urban energy consumption has also aggravated urban air pollution, with the World Health Organization (WHO) reporting that 90 % of urban dwellers are exposed to pollution levels surpassing recommended thresholds (7).

Research and advancements geared toward promoting a sustainable future are propelled by the increasing environmental challenges confronting humanity (8). The continuous expansion in economic and energy consumption observed in recent years comes with the cost of environmental deterioration (9). There has been a significant upsurge in greenhouse gas emissions, with CO_2 emissions associated with energy generation climbing from 32.3 billion metric tons in 2012 to 35.6 billion metric tons in 2020 and anticipated to reach 43.2 billion metric tons by 2040 (10). The escalating apprehensions regarding global warming highlight the urgent necessity for solutions across various sectors, with a specific focus on advancing renewable energy sources in the energy sector to reduce CO_2 emissions and improve energy efficiency, thereby facilitating the transition towards a low-carbon society

(11). International institutions are actively involved in facilitating the shift towards more sustainable production and consumption systems (12).

During this transition, innovation that fosters sustainability will be crucial (13). The European Union is dedicated to its bio economy strategy (14). Ongoing research and innovation in the bio economy sector will aid in effectively managing renewable resources, opening new avenues within a circular bio economy framework (15).

Biomass encompasses all organic matter present in the biosphere, whether from plants or animals, as well as materials derived from their natural or artificial processing (16). Biofuels derived from biomass include firewood, wood shavings, pellets and certain fruit pits like olives and avocados, as well as nutshells. Among these, firewood in cut and chopped forms is the least processed and is typically burned directly in household appliances like stoves and boilers (17). Wood chips result from the crushing of various agricultural and forest biomass, varying in size depending on the manufacturing or processing method (18). Pellets, on the other hand, are the most refined biofuel, consisting of small cylinders 6 to 12 mm in diameter and 10 to 30 mm in length, produced by compressing biofuels with binders (19). Pellets are particularly used in applications with low energy-to-volume ratios (20).

Fruit pits, seeds and husks, though less commonly utilized compared to standardized fuels like fuel wood, wood chips and pellets, are increasingly recognized as solid biofuels. Notably, mango pits, peanut shells and sunflower seed husks exhibit high energy potential, with a Higher Heating Value (HHV) comparable to other commercially available biofuels (21). Given the rising global production of these by-products, they are becoming particularly attractive for thermal energy generation and CO_2 emission reduction (22).

Biomass is found in a diverse array of materials, including wood, sawdust, straw, seed waste, manure, paper waste, household waste, wastewater and more (23). Biofuels, derived from biomass, are fuels produced directly or indirectly from organic material, including plant materials and animal waste. They serve as an alternative to fossil fuels and are categorized into first-generation (produced from food crops), second-generation (derived from non-food crops and agricultural residues) and third-generation biofuels (obtained from algae and microorganisms) (24). Biodiesel is a renewable fuel produced through the transesterification of vegetable oils or animal fats, yielding a biodegradable, non-toxic and low-emission fuel that can be used in diesel engines with minimal modifications (25). It significantly reduces greenhouse gas emissions compared to petroleum-based diesel, making it a vital component of sustainable energy strategies (26).

Agroforestry represents a traditional land-use approach that holds promise in addressing various contemporary and future environmental challenges. It involves the intentional integration of trees or woody plants within agricultural systems, promoting sustainable land management (27). This encompasses a wide array of systems, including silvopastoral, silvoarable, forest farming, home gardens, as well as hedge, windbreak and riparian buffer strip systems. However, many practitioners of agroforestry fail to recognize it as a distinct and specific land-use practice (27). Within society, agroforestry is perceived as a novel term for an ancient and extensive practice (28). Nonetheless, framing it within the contemporary term "agroforestry" offers a fresh and comprehensive perspective on this approach, considering not only productivity but also other ecosystem services and environmental advantages (29). However, the concept of agroforestry remains unclear to many traditional farmers and even among agroforestry practitioners, there is a lack of awareness. Education is deemed essential in addressing this gap and promoting the wider adoption of agroforestry practices.

One of the concerns raised by farmers from nine countries who participated in the HORIZON 2020 (H2020) project Agroforestry Innovation Network (AFINET) was the potential of agroforestry residues to serve as a significant source of biomass energy. The extensive global coverage of agroforestry systems suggests that they could yield substantial amounts of lingo cellulosic biomass, which is crucial for bioenergy production (27, 28). This is especially pertinent in regions facing challenges related to energy security and access to clean, renewable energy sources. For example, in sub-Saharan Africa, leveraging agroforestry residues could be instrumental in fulfilling the energy requirements of rural households, thereby diminishing dependence on traditional fuels and fostering environmental sustainability.

Pyrolysis is a thermochemical conversion process that decomposes biomass in an oxygen-limited environment to produce biochar, bio-oil and syngas (29). The process is categorized into slow pyrolysis and fast pyrolysis, depending on the temperature and heating rate. Slow pyrolysis operates at lower temperatures (300-500 °C) with longer residence times, typically maximizing biochar production. Biochar is a stable carbon-rich material that, when applied to soil, enhances soil fertility, improves moisture retention and increases microbial activity, ultimately contributing to long-term carbon sequestration and improved soil health (30). Fast pyrolysis, on the other hand, occurs at higher temperatures (450-700 °C) with rapid heating rates and short residence times, producing higher yields of bio-oil, which can be refined into liquid biofuels (31). Syngas, a byproduct of both processes, is a combustible gas mixture that can be used for heat and power generation. The application of pyrolysis to agroforestry residues not only enhances energy recovery but also aligns with sustainable waste management practices by minimizing agricultural waste (32).

Harnessing agroforestry residues for energy production is in line with the principles of the circular economy and sustainable resource management, aiming to minimize waste and optimize resource efficiency (33). However, the effective execution of biomass energy projects centered on agroforestry residues necessitates careful examination of factors such as residue generation rates, seasonal availability and the potential impact of residue removal on soil health and ecosystem services (34). Transitioning from conventional industrial practices to sustainable models is imperative considering limited resources and adverse environmental impacts. In this regard, the establishment of a bio-based economy assumes significant importance, aiming to substitute emission-intensive and non-renewable resources with renewable alternatives (35).

Large-scale biomass extraction for energy raises concerns regarding carbon payback periods, land-use change and deforestation (Table 1). Unsustainable harvesting may lead to soil degradation, biodiversity loss and habitat destruction (36). Additionally, land-use changes for biomass production could compete with food crops, potentially affecting food security (27, 28). The carbon payback period-the time required for reabsorbed carbon to offset emissions from biomass combustion-varies depending on factors such as feedstock type and management practices (29). A poorly managed system with prolonged carbon payback periods may reduce the overall climate benefits of bioenergy (29).

Agroforestry systems and residue generation

Furthermore, harnessing agroforestry residues for energy production is in line with the principles of circular economy and sustainable resource management, aiming to minimize waste and optimize resource efficiency (37). In this regard, the establishment of a biobased economy assumes significant importance, aiming to substitute emission-intensive and non-renewable resources with renewable alternatives (38).

Biomass energy: Concepts and technologies

Owing to its widespread availability across the globe, primarily as a by-product of numerous industrial and agricultural operations, biomass is emerging as a promising renewable energy reservoir with substantial growth prospects (39). A key attribute that makes biomass conducive for energy utilization is its potential for direct combustion, enabling its utilization in waste conversion facilities for electricity generation (40), or in boilers for heat production at industrial and residential scales (41). Nevertheless, it's essential to acknowledge that the direct combustion of biomass may not always be feasible in existing infrastructures, often necessitating physical-chemical or biological treatments to meet the standards of conventional fuels (42). Biomass District Heating (BDH) emerges as a highly efficient system for incorporating natural energy reservoirs into urban settings, resulting in a twofold benefit: a complete reduction (100 %) in CO_2 emissions compared to fossil fuels and enhanced energy efficiency due to the cost-effectiveness of biofuels. Biomass encompasses a diverse array of materials, including wood, sawdust, straw, seed waste, manure, paper waste, household waste and wastewater (43). While certain materials possess intrinsic qualities enabling direct use as fuels, others necessitate pretreatment procedures employing various technologies before their utilization.

Biomass possesses both drawbacks and advantages. One notable advantage is its utilization of forested areas, which can aid in forest maintenance and fire prevention, while also providing employment opportunities (44). Biomass operations contribute to sustained employment generation through activities like raw material extraction from rural and bush areas (45). Currently, the utilization of biomass as a biofuel is an area of significant interest within the scientific community (46).

The supply chains associated with the energy recovery of residual biomass

The supply chains linked to biomass utilization, whether for raw material supply or energy extraction, are intricate due to the specific characteristics and properties inherent to various types of biomasses (47). A significant portion of the costs related to biomass energy production pertains to logistics activities (48). Biomass exhibits notable heterogeneity, high moisture levels, low density, substantial contamination by inert matter and considerable spatial distribution variability, all of which influence the optimization of logistical processes involved in its gathering, transportation and storage (49). These operations often hinder project viability concerning biomass energy recovery, prompting operators to opt for materials with fewer logistical challenges (50). For instance, it is common for operators of biomass power plants to frequently utilize logs from common forest species like *Pinus pinaster* or *Eucalyptus globulus*, despite their higher unit cost in terms of mass or volume(€·m^{-3} or €·t^{-1}), as they entail lower logistics costs compared to residual biomass from forest management activities, owing to their higher density and homogeneity, among other benefits (51).

In this context, as delineated in various studies, the primary obstacle hindering the widespread utilization of agroforestry residual biomass is the complexity of the associated supply chain (52), which can be broadly outlined as depicted in Fig. 1.

Environmental Impact Assessment (EIA) for biomass energy production

Environmental Impact Assessment (EIA) is a crucial process in the planning and decision-making for projects that are likely to have significant environmental effects (53-58). Originating from the United States' National Environmental Policy Act (NEPA) of 1969, EIA has become an integral part of environmental governance globally, ensuring that environmental considerations are integrated into the development process (59). The main objective of EIA is to predict environmental impacts at an early stage in project planning and design, find ways to reduce adverse impacts, shape projects to suit the local environment and present predictions and options to decision-makers (60).

Table 1. Presents a synthesis of the approaches from the literature, depending on the type of biomass

Year	Biomass type	Biomass origin	Analysis type	Reference
2018	Walnut shell	Agriculture residue	Ultimate analysis	(17)
2013	Wood bark	Forests	Ultimate analysis	(15)
2017	Wheat straw	Agriculture residue	Ultimate analysis	(49)
2018	Peanut shell	Industrial residue	Ultimate analysis	(45)
2018	Mango stone	Industrial residue	Ultimate analysis	(50)
2016	Avocado Stone	Industrial residue	Ultimate analysis	(51)
2017	Wood	Forests	Ultimate analysis	(49)
2013	Olive stone	Industrial residue	Ultimate analysis	(53)
2005	Almond shell	Industrial residue	Ultimate analysis	(54)
2015	Pine pellets	Forests	Ultimate analysis	(55)
2019	Palm oil Kernel Shell	Industrial residue	Proximate and elemental analysis	(56)
2018	Corn cob waste	Industrial residue	Ultimate analysis	(57)

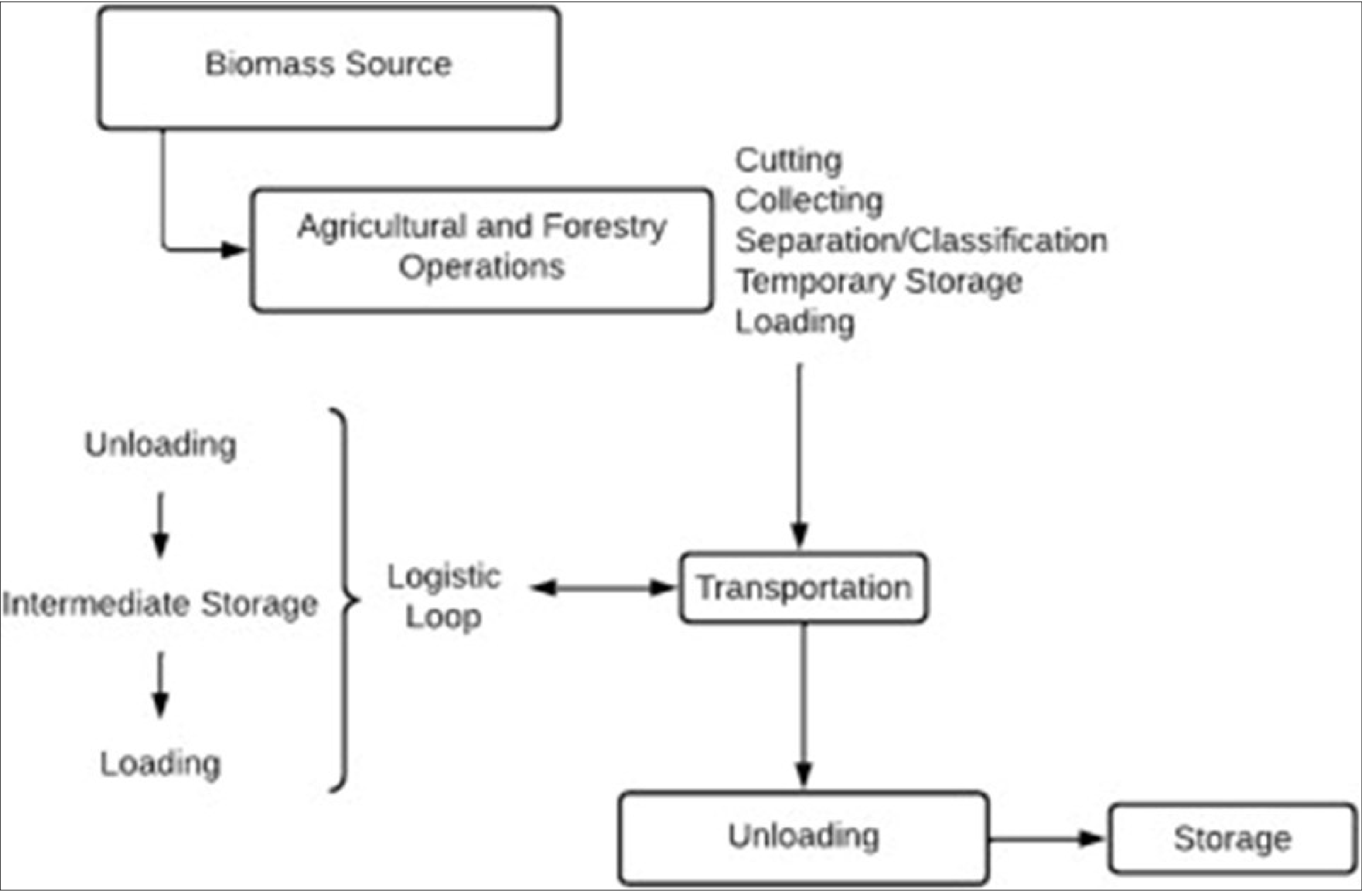

Fig. 1. Supply chain for agroforestry residual biomass.

The EIA process involves several key stages: screening to determine which projects require full or partial assessment, scoping to identify which potential impacts are relevant to assess, conducting the impact assessment and developing mitigation measures, reporting the findings in an Environmental Impact Statement (EIS) or report, public participation to ensure that stakeholders are consulted and informed and finally, reviewing of the EIS followed by decision-making prior to project approval (61).

Critically, the effectiveness of EIA processes depends on their regulatory context, the scope and depth of the environmental analysis and the degree of public and stakeholder participation (Table 2). The Convention on Environmental Impact Assessment in a Transboundary Context (the Espoo Convention, 1991) and the European Union's Directive on EIA (Directive 2011/92/EU) are examples of regulatory frameworks that aim to standardize and strengthen the EIA process across borders and jurisdictions (62, 63).

The utilization of biomass for energy production is often touted for its potential to reduce GHG emissions compared to fossil fuels (64). The carbon neutrality of biomass is highly debated. Studies show that biomass burning still emits CO_2 and actual carbon sequestration depends on sustainable management. The carbon neutrality of biomass is a contested concept (65). Yet, the lifecycle emissions of biomass energy are generally lower than those of coal and natural gas when sustainably sourced and utilized (66). This is particularly relevant for agroforestry residues, which, if left to decompose naturally, would emit carbon dioxide (CO_2) and methane (CH_4), potent GHGs. Therefore, converting these residues into energy can be a mechanism for carbon mitigation, capturing the CO_2 that would otherwise be released into the atmosphere. However, the reduction in GHG emissions depends on various factors, including the efficiency of the energy conversion technology used and the management practices employed (67).

Biodiversity impacts are another critical aspect of the EIA for biomass energy projects. Agroforestry systems, by their nature, support a higher level of biodiversity than conventional agricultural or forestry systems (68). The sustainable harvesting of biomass from these systems can maintain or even enhance biodiversity levels by promoting a mosaic of habitats and preventing the conversion of land to monoculture crops or intensive agriculture (69). Nonetheless, the scale of biomass extraction must be carefully managed to avoid negative impacts, such as habitat destruction or the overharvesting of woody biomass, which can lead to a decrease in soil fertility and an increase in erosion (70).

Soil health is intricately linked to the sustainability of biomass energy production from agroforestry residues. The removal of agricultural and forestry residues for bioenergy purposes can lead to soil nutrient depletion, affecting soil quality and productivity (71). However, sustainable residue management practices, such as leaving a proportion of residues in the field to decompose and returning ash from biomass combustion to the land, can mitigate these effects and contribute to the maintenance of soil organic matter levels.

Water resource management is another essential consideration in the EIA process. The cultivation of biomass crops and the processing of residues can have significant water demands, potentially leading to water scarcity in vulnerable regions (72). Moreover, the use of agrochemicals in some biomass production systems can lead to water pollution if not

Table 2. Successful examples of biomass energy production from agroforestry residues

Study title	Authors	Year	Key findings	Reference
Environmental and energy assessment of biomass residues to biochar as fuel: A brief review	Mengshan Lee et al.	2020	Explores environmental and energy benefits of biomass residues for biochar production, emphasizing carbon abatement and highlighting challenges like environmental burdens and low energy efficiency.	(15)
Sustainable bio-ethanol production from agro-residues: A review	Anubhuti Gupta, J. Verma	2015	Reviews the potential of agro-residues as feedstock for bio-ethanol production, discussing challenges and limitations of current technologies.	(16)
A comprehensive review on feasibility of different agro residues for production of bio-oil, biochar and pyro-gas	Jinesh B. Shah, Janak B. Valaki	2023	Reviews the conversion of agro residues into energy products like bio-oil, bio-char and pyro-gas, emphasizing the potential for sustainable energy solutions.	(17)
The potential of agricultural residues for energy production in Calabria (Southern Italy)	A. Algieri et al.	2019	Estimates biomass from agricultural residues in Southern Italy for energy conversion, suggesting the feasibility of small-scale CHP units.	(18)
Multifaceted application of crop residue biochar as a tool for sustainable agriculture: an ecological perspective	Rishikesh Singh et al.	2015	Discusses the benefits and challenges of using crop residue biochar in agriculture, focusing on soil amelioration and C sequestration.	(19)
Energy crops and their implications on soil and environment	H. Blanco-Canqui	2010	Reviews the impacts of growing energy crops on soil properties, SOC sequestration, and water quality, advocating for sustainable systems in marginal lands.	(20)

properly managed. Implementing best practices for water use efficiency and pollution control is vital to minimize the impacts of biomass energy production on water resources.

The socio-economic dimensions of biomass energy production, though not strictly environmental, are often included in EIAs due to their interdependence with environmental sustainability. The development of biomass energy projects can provide significant economic benefits, including job creation and the diversification of rural economies (73). However, these projects must be developed in a manner that respects the rights and livelihoods of local communities, ensuring equitable access to the benefits of biomass energy and avoiding negative impacts such as land grabbing or the displacement of traditional land uses (74).

Socio-economic aspects

The socio-economic aspects of biomass energy from agroforestry residues encompass a broad range of impacts on society and economies, touching on issues of rural development, employment, energy security and sustainable development (Fig. 2).

Rural development and livelihoods

Biomass energy projects utilizing agroforestry residues can significantly contribute to rural development by providing alternative income streams for farmers and landowners. Through the valorization of residues that are otherwise considered waste, these projects can transform agricultural practices, offering additional revenue sources. Agroforestry systems not only enhance the productivity of land but also diversify income sources, thereby reducing vulnerability to market and environmental shocks. The integration of biomass energy projects within these systems can further amplify these benefits, promoting rural development and sustainable land management practices (75).

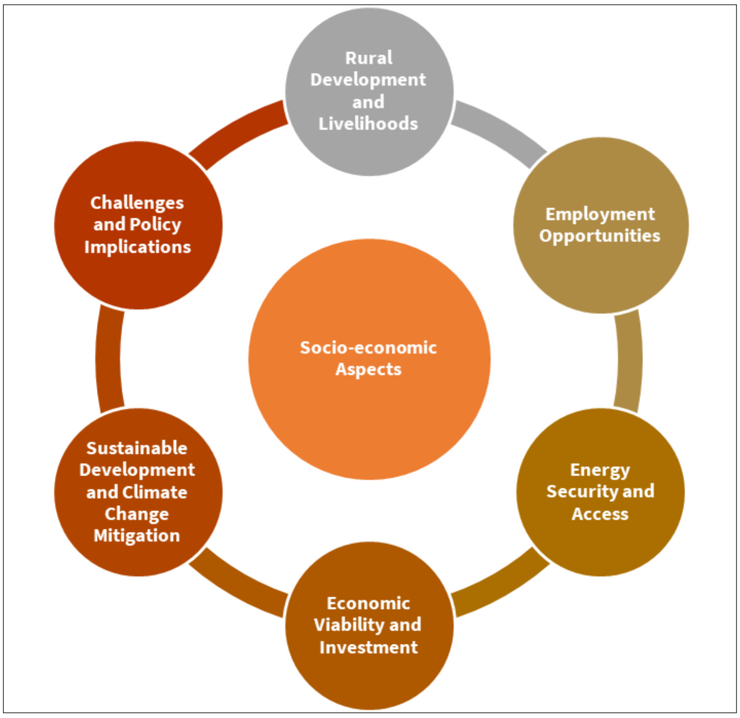

Fig. 2. The socio-economic aspects of biomass energy from agroforestry.

Employment opportunities

The production, processing and utilization of biomass for energy generation are labour-intensive processes compared to fossil fuel extraction and power generation, thus potentially creating substantial employment opportunities. As per a report by the International Renewable Energy Agency (76), the bioenergy sector, including biomass from agroforestry residues, is poised to become a significant employment generator, offering jobs in collection, transportation, processing and maintenance of biomass energy facilities. These jobs are often localized, contributing to the retention of the workforce in rural areas.

Energy security and access

Biomass energy from agroforestry residues can play a critical role in enhancing energy security, particularly in regions heavily reliant on imported fossil fuels. By diversifying the energy mix and utilizing locally available biomass resources, countries can reduce their dependency on external energy sources and mitigate the impacts of volatile fossil fuel prices (77). Additionally, biomass energy can improve access to energy in remote and rural areas, where extending the conventional power grid may be economically unfeasible. This decentralization of energy production promotes energy democracy and resilience (78).

Sustainable development and climate change mitigation

The transition to biomass energy is aligned with the global agenda for sustainable development, particularly in the context of climate change mitigation. Biomass energy, when sourced and utilized sustainably, offers a carbon-neutral alternative to fossil fuels, as the CO_2 emitted during combustion is offset by the carbon sequestered during the growth of biomass (70). However, careful consideration is required to ensure that biomass energy projects do not lead to adverse effects such as deforestation, loss of biodiversity, or competition with food production (79).

Economic viability and investment

The economic viability of biomass energy projects is contingent upon various factors, including the availability and cost of biomass, technological efficiency and market conditions for biomass energy. Government policies, including subsidies, tax incentives and support for research and development, play a pivotal role in enhancing the economic attractiveness of biomass energy (80). Investment in biomass energy technologies not only fosters innovation but also drives down costs, making biomass energy more competitive with conventional energy sources.

Challenges and policy implications

While biomass energy presents numerous socio-economic benefits, it also faces challenges such as competition for land, potential impacts on food security and the need for significant upfront investment. Policies aimed at promoting biomass energy must carefully balance these considerations, ensuring that biomass energy contributes positively to socio-economic development without compromising environmental sustainability or food security.

The socio-economic aspects of biomass energy from agroforestry residues are integral to understanding its potential role in a sustainable energy future. By fostering rural development, creating employment opportunities, enhancing energy security and contributing to sustainable development and climate change mitigation, biomass energy can play a pivotal role in the global transition to renewable energy. However, achieving these benefits requires careful planning, supportive policies and ongoing monitoring to mitigate potential negative impacts.

Challenges and opportunities

The transition to biomass energy from agroforestry residues presents a unique set of challenges and opportunities. These facets are crucial for policymakers, stakeholders and researchers aiming to harness the potential of biomass energy sustainably and efficiently.

Challenges

Sustainability and resource competition: One of the primary challenges is ensuring the sustainability of biomass production. There is a potential for competition between biomass for energy and other land uses, such as food production and conservation. Sustainable land management practices are essential to mitigate these risks and ensure that biomass production does not compromise food security or ecosystem health (69).

Technological and logistical hurdles: The conversion technologies for biomass to energy are diverse but often face efficiency and economic viability issues. There is a pressing need for advancements in technology to improve conversion efficiency and reduce the costs associated with biomass energy production. Additionally, logistical challenges in collecting, transporting and processing agroforestry residues can hinder biomass energy projects' feasibility and efficiency (78).

Economic and financial barriers: The initial investment required for biomass energy projects is significant and financial mechanisms are needed to support these investments. Overcoming economic and financial barriers is crucial for the development and scaling up of biomass energy solutions (70). This includes the need for policies that provide financial incentives, support research and development and encourage the adoption of biomass energy technologies.

Policy and regulatory frameworks: The lack of clear and supportive policy and regulatory frameworks can impede the growth of the biomass energy sector. Researchers have emphasized the importance of coherent policies that support the sustainable development of biomass energy, including regulations that adequately address the environmental and social impacts of biomass production (71).

Opportunities

Carbon neutral energy source: Biomass energy offers the opportunity to produce carbon-neutral energy, contributing to climate change mitigation efforts. The role of biomass energy in reducing greenhouse gas emissions is well established, as the carbon dioxide released during energy production is offset by the carbon sequestered during plant growth.

Rural development and job creation: The development of biomass energy projects can stimulate rural economies by creating new jobs and providing additional income streams for farmers and landowners. The potential of biomass energy to contribute to rural development, lies in its' ability to create employment opportunities in the collection, processing and management of biomass (76).

Energy security and diversification: By utilizing locally sourced biomass, countries can enhance their energy security and reduce dependence on imported fossil fuels. Biomass energy can play a key role in diversifying energy sources and improving energy security, particularly in regions with abundant biomass resources (80).

Innovation and technological advancement: The biomass energy sector presents opportunities for innovation and technological advancements. However, continued research and development are essential for improving biomass conversion technologies, increasing efficiency, reducing costs and expanding the range of biomass materials that can be used for energy production.

Conclusion

The exploration of biomass energy from agroforestry residues within this paper underscores its significant potential as a sustainable energy source, capable of addressing global challenges related to energy consumption, environmental pollution and climate change. By leveraging the vast, yet underutilized resources of agroforestry residues, societies can transition towards more sustainable and renewable energy systems that not only mitigate greenhouse gas emissions but also foster rural development, enhance energy security and contribute to a circular economy. However, realizing this potential necessitates overcoming technological, logistical and policy-related hurdles to ensure the sustainable production and utilization of biomass energy. With concerted efforts in research, innovation and supportive policy frameworks, biomass energy from agroforestry residues can become a cornerstone of global renewable energy strategies, aligning economic development with environmental sustainability.

Acknowledgements

I would like to thank my Chairman Dr. B. Sivakumarfor guiding me throughout the process and I am grateful to the Forest College and Research Institute for providing me with all the facilities. I extend my thanks to the project entitled ‘Development of genetics stocks, genomic resources for *Neolamarckia cadamba* (Kadam) for timber value and medicinal properties’ and for providing me financial support.

Authors' contributions

BS helped in choosing the review topic and formulated the outline. AB, NSN, IS, MS, RN, SR and KS participated in development of ideas related to the topic and drafted the manuscript. AE and MAN of ideated in sequence alignment and helped in overall correction of the manuscript. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interests to declare.

Ethical issues: None

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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