IJISEM
INTERNATIONAL JOURNAL OF INNOVATIONS IN SCIENCE ENGINEERING AND MANAGEMENT

International Journal of Innovations In Science Engineering And Management

Check for updates

OPEN ACCESS

Volume: 4

Issue: 1

Month: February

Year: 2025

ISSN: 2583-7117

Published: 01.02.2025

Citation:

Lakshmikantha H M, Preethi Rajesh "Bioenergy In India: Challenges, Potential and Policy Perspectives" International Journal of Innovations In Science Engineering And Management, vol. 4, no. 1, 2025, pp. 148–154.

DOI:

10.69968/ijisem.2025v4i1148-154

Bioenergy In India: Challenges, Potential and Policy Perspectives

Lakshmikantha H M[1], Preethi Rajesh[2*]

[1]*Department of Life Science, School of Sciences, Garden City University, Bangalore, India*
[2]*Department of Life Science, School of Sciences, Garden City University, Bangalore, India*
**Corresponding Author: preethi.rajesh@gcu.edu.in*

Abstract
The increasing global energy demand underscores the need for sustainable alternatives, with bioenergy emerging as a pivotal solution. Bioenergy plays a crucial role in climate mitigation, renewable energy transition, energy security, and rural socio-economic development. In India, bioenergy offers significant potential to meet growing energy needs sustainably through its cleaner, cost-effective approach while aiding carbon sequestration and reducing greenhouse gas emissions. However, challenges such as land and water competition with food crops, unstable markets, limited economic incentives, and socio-economic impacts hinder its adoption. India's vast agricultural biomass resources present immense opportunities, particularly in rural areas, to address these challenges. Advancing second and third-generation biofuels, clear policies, financial incentives, public awareness, and enhanced R&D are critical. A "Solar Energy Alliance"-like initiative for bioenergy, coupled with robust infrastructure and structured guidelines, can attract investments and foster innovation. With targeted reforms, India can unlock bioenergy's potential, achieve climate goals, and ensure a sustainable energy future.

Keywords; Bioenergy, Renewable energy, Biomass, Biofuel, Plants and animal waste

INTRODUCTION

The main force behind global economies is energy. Energy consumption is rising faster due to growing populations and aspirations of higher living standards. GHG emissions and economic growth have been recognised by theorists as having a positive or direct link. Increased energy consumption brought on by economic prosperity is one of the main factors influencing this positive association [1], [2]. Over the past two years, India's GDP has grown by more than 8%, making it one of the fastest-growing nations in the world. This trend is predicted to continue. It is anticipated that in next 25 years, India's energy consumption would more than triple or quadruple from its present level [3]. According to the IEA, fossil fuels now account for 40% of India's main source of energy and 59% of its power output [4]. It is anticipated that India's growing energy needs would cause the country to utilise fossil fuels even more. This would result in a number of social challenges, including disparities between urban and rural residents, health-related illnesses, and other community-level problems, in addition to rising GHG emissions and environmental problems [5], [6].

Bioenergy

Plant and animal waste may be used to create bioenergy, a sustainable energy source. The biomass employed as input materials is made up mostly of plants and other previously live but now deceased species [7]. Fossil fuels are thus not considered biomass in this sense. Biomass types that are often utilised to produce bioenergy include wood, energy crops, food crops like maize, and garbage from farms, yards, and woods. While the necessary biomass production might sometimes raise "greenhouse gas emissions" or result in the loss of local biodiversity, bioenergy can help mitigate the effects of climate change [8]. Based on how the biomass is grown and collected, the environmental effects of biomass production may be troublesome.

Table 1 India’s bioenergy production potential

Parameter	Quantity
Power generation potential	Annual power generation potential of 208 billion units (BU) from 28 GW
Additional bagasse-based cogeneration potential	Annual power generation potential of 65 BU from 14 GW
Bioethanol production potential from agri-waste	From sugarcane (1 G): • Sugar/sugar syrup – 9,523.52 KLPD • B molasses – 24,843.98 KLPD • C molasses – 13,309.27 KLPD From rice (2G) – 897.25 KLPD From maize (2G) – 395.67 KLPD
Compressed biogas production potential 7	From cattle dung – 38,981.25 TPD From municipal solid waste – 4,853.98 TPD From paddy straw – 16,377.03 TPD

APPLICATIONS OF BIOENERGY

Biomass heating systems

Heat is produced from biomass via biomass heating systems. For the purpose of producing heat, the systems may use "anaerobic digestion, gasification, combined heat and power (CHP), direct combustion, or aerobic digestion". Biomass heating systems may be pellet-fired, completely or partially automated, or they can be "combined heat and power systems".

Biofuel for transportation

Depending on whether or not food crops are used, biofuels may be roughly divided into two groups according to the source of biomass: Sugarcane, maize, and other food supplies cultivated on fertile land are used to make first-generation (or conventional) biofuels. This biomass's sugars are fermented to create "bioethanol, an alcohol fuel" that may be added to petrol or used in a fuel cell to generate energy. By fermenting carbohydrates found in sugar or starch crops like maize, sugarcane, or sweet sorghum, bioethanol is created. Both Brazil and the United States make extensive use of bioethanol. The most widely used biofuel in Europe is biodiesel, which is made from the oils of plants like sugar beets and rapeseed.

The term "advanced biofuels" refers to second-generation biofuels, which use biomass sources other than food, such agricultural waste and recurring energy crops. Fuels are made from feedstock that is either cultivated on marginal land or on fertile land but is a byproduct of the primary crop. Industrial, agricultural, forestry, and residential waste may also be converted into second-generation biofuels by direct burning, gasification, or anaerobic digestion, which can create syngas and biogas, respectively. Food wastes like vegetable and animal fats may be converted into biodiesel, while cellulosic biomass—which comes from non-food sources like grasses and trees—is being researched as a feedstock for the generation of ethanol.

Climate and sustainability aspects

The source and cultivation of biomass feedstocks have a significant influence on the climatic impact of bioenergy. Carbon dioxide, for instance, is released when wood is burned for electricity. However, if the harvested trees are replaced by young trees in a forest that is properly managed, the new trees will collect carbon dioxide from the atmosphere as they develop, greatly reducing the emissions. Growing bioenergy crops, however, has the potential to destroy soils, uproot natural ecosystems, and use artificial fertilisers and water [9].

Unsustainable wood harvesting accounts for around one-third of all wood used for traditional cooking and heating in tropical regions. Harvesting, drying, and transportation of bioenergy feedstocks usually involve high energy costs, which might result in greenhouse gas emissions. When employing bioenergy instead of fossil fuels, the effects of "land-use change, cultivation, and processing" may sometimes lead to greater total carbon emissions [10].

There may be less area available for food production if cropland is used to generate biomass. Ethanol derived from maize, which uses a large amount of the crop, has replaced around 10% of motor petrol in the US. Because these forests are vital carbon sinks and homes for a variety of species, the removal of forests in Malaysia and Indonesia to produce palm oil for biodiesel has had detrimental social and environmental repercussions. In comparison to other renewable energy sources, a significant area of land is needed to produce a particular quantity of bioenergy since photosynthesis only absorbs a tiny portion of the energy in sunlight.

Future Potential of Biomass Energy in India

The energy industry holds the key to India's future development. Energy from unconventional sources, such as biomass, would be essential to achieving the growth goals for the power industry and the economy as a whole [11]. Through this article, we emphasise the state of biomass energy consumption now and its potential for expansion in the future, taking into account the nation's incentive structure and available technology [12]. In India, biomass is an essential energy source for both residential and commercial energy needs. Aside from powering independent power plants and a few of small-scale enterprises, it is the most widely utilised residential fuel [13].

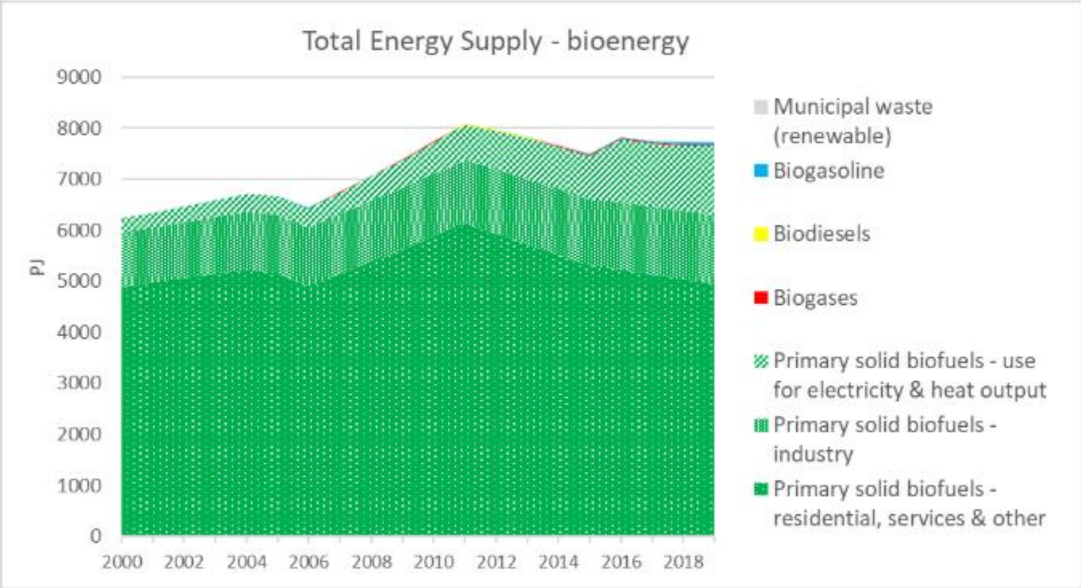

Figure 1 Development of total energy supply from bioenergy in India 2000 – 2019 [4]

Globally, biomass provides over 1% of the power demand, or around 257 TWh annually. The industrial and residential areas get around 4.5 EJ (105 Mtoe) of direct heat from biomass and waste, while "combined heat and power (CHP) plants" provide 2 to 3 EJ (47 to 70 Mtoe) of heat, according to modern combustion technologies. These figures exclude the conventional burning of biomass, which is mostly used in underdeveloped nations [14].

It is believed that India now has 500 million metric tonnes of biomass available annually. Biomass availability, including forestry and agricultural wastes, is projected by MNRE to be between 120 and 150 million metric tonnes annually, with a capacity of around 18,000 MW. Additionally, bagasse-based cogeneration at the nation's 550 sugar mills may provide an extra 5,000 MW of electricity.

Environmental impact

Emissions of greenhouse gases may be either increased or mitigated by bioenergy. It's also well acknowledged that local environmental effects might pose issues. For instance, the areas where biomass is produced may experience considerable social and environmental strain as a result of rising biomass consumption [15]. The main factor causing the effect is biomass's poor surface power density. Comparing the low surface power density to, say, fossil fuels, the result is that far bigger land areas are required to generate the same quantity of energy [16].

Bioenergy Technologies

Bioenergy is made up of organic matter that comes from crops, trees, plants, or waste products from industry, cities, and people.

Table 2 features and benefits of key Bioenergy technology (BETs)

Bioenergy Technologies	Features	Benefits
Biomass Gasification	biomass that has been transformed into combustible gas for use in electrical or mechanical internal combustion engines. capacities ranging from 10 kg/h to around 500 kg/h. It is feasible to provide the grid with power and fulfil the demands of rural areas. needs a steady supply of biomass	Rural areas might be fully supplied with power by small-scale gasifiers (between 20 and 500 kW), with any excess being sent into the national grid. In dual fuel systems, diesel savings may reach up to 80%, and in 100% producer gas, they can reach 100%. creating jobs in rural areas. Degraded reclamation of land. fossil fuel replacement. Sequestration of carbon by forests on damaged areas

Biomass Combustion	In a boiler, biomass is burned to produce steam, which is then utilised to create electricity. It is feasible to provide the grid with power and fulfil the demands of rural areas. needs a steady supply of biomass	reclamation of degraded land. replacement of fossil fuels. Forestry on degraded terrain sequesters carbon. comparatively more cost-effective. creation of jobs
Biogas	The perfect fuel for cooking. basic, domestic technology. initially expensive yet cost-effective. extensive distribution experience	planting forests and conserving trees. decreased contamination of indoor air. significant increases in living standards. Saving fuel wood increases the possibilities for conserving forest carbon sinks.
Efficient cook stoves	powered by tiny wood fragments or unique pellets created from compressed and dried agricultural waste. Compared to dried wood or cow dung cakes, they produce less smoke and provide more energy. able to cut wood use by at least 50%	Low device cost protection of village trees and forest plantations. significant gains in life quality, particularly for women. moderate potential for conserving forest carbon sinks. may be among the most economical local and global contaminants.
Bio-fuels	obtaining oil from the seeds of inedible plants, such as Mahua, Neem, and Jatropha curcas, and combining it with fuel or diesel. India's technology is still in its infancy. Water and land limitations	Independence. Transport fuel requirements may be satisfied. Replacement of fossil fuels and so reducing GHG emissions

LITERATURE REVIEW

(Singh & Clough, 2024) [17] the existing bioenergy production and consumption system, negative socio-economic and ecological effects restrict its climate mitigation potential. Since "biomass cultivation, feedstock refining, and processing" have a strong connection to natural resource use (water, energy, chemicals, and fertilisers) and other nutrient cycles, bioenergy is neither carbon neutral nor renewable. In certain locations, large-scale bioenergy projects harm "food security, land use change, ecosystem services, and biodiversity". Third, bioenergy production's negative social and ecological repercussions are shifted from consumers to producers, making the globalised bioenergy economy unsustainable. We address key system interventions to be deployed across the system to manage the unanticipated negative effects of the current "bioenergy production and consumption regimes".

(Deka et al., 2023) [1] research objectively evaluates agricultural crop residues, bioenergy, and syngas production in all 28 states and 8 UTs of India. This analysis included 43 main agricultural wastes from 28 crops grown in various Indian areas, based on 2017-18 crop production figures and normal estimating methodologies. A Python gasification model assessed syngas production potential using literature parameters. Annually, 869.11 MT of gross residue and 288.14 MT (33.15%) of excess residue are produced. Uttar Pradesh generates the largest excess crop residue (57.72 MT) and sugarcane has the highest national potential (62.68 MT). Bioenergy output from excess crop waste was predicted at 4.88 EJ for 2017-18. Syngas production represents 37.64% of India's total residual potential. Methanol (MeOH) synthesis from this syngas should yield 81.7905 MT of MeOH with 1.85 EJ of equivalent energy.

(Garg et al., 2023) [8] emphasises biofuel crops, which might be the energy heroes of the future. The energy provided by bioenergy crops will be greener, cheaper, and help sequester carbon. First, second, third, devoted, and halophyte bioenergy crops are categorised by their functions. Growing bioenergy crops may be difficult, but they can help mitigate climate change, capture of carbon, nitrous oxide emissions, nitrate leaching, and ecological balance. Competition for water and land with our primary food crops, market volatility, reduced economic incentives to develop and transport bioenergy crops, and societal repercussions are some of the obstacles we may face in cultivating bioenergy crops. Growth of bioenergy crops may help meet future energy needs despite the hurdles.

(Srivastava, 2023) [11] India has been a climate protection leader in recent years and one of the few nations to meet NDC reduction goals. The "Ministry of New and Renewable Energy" created a national bio energy strategy in 2009 and amended it in 2018. By 2030, India was planned to reach 500 GW of non-fossil energy capacity, meet 50% of its energy needs with renewable energy, and cut its carbon intensity by more than 45%. The strategy aims to minimise import reliance, clean the environment, manage MSW, create jobs, invest in rural infrastructure, and boost farmer income. This article discusses bioenergy, its forms, conversion technologies, social, economic, ecological, and environmental implications, and sustainable bioenergy production issues. According to the research, India has implemented many bioenergy laws and initiatives to boost bioenergy.

(Negi et al., 2023) [18] Bioenergy production in India relies on agricultural biomass. 230 million metric tonnes of "agriculture-based biomass" from key crops are available annually for home consumption, cattle feeding, compost fertiliser, etc. Trends suggest a pan-Indian total biomass power potential of 30,319.00 MWe from the chosen crops for 2019–2020. Adding biomass from multiple energy sources may boost it to 50,000 MWe. Bioenergy generation is also indicated by the country's rising "municipal solid waste (MSW)" output of 0.16 Mt per day. India's sources of biomass "(agricultural residues, municipal solid waste, forest-based biomass, industry-based biomass, and aquatic biomass)" and their potential for bioenergy (CBG, bioethanol, power, co-generation, etc.) generation through bioconversion technologies are reviewed in this article. It summarises India's bioenergy situation and government efforts to meet future demand via biomass to energy conversion.

(U. Ghosh et al., 2021) [12] investigate biomass potential and power generation issues. When reviewing biomass-based power generating literature, several issues were evaluated since bioenergy is a major renewable energy source. India's biomass energy is examined in this study. Energy from biomass is cheaper and cleaner. Environmental pollution is also regulated. Renewable biomass energy might benefit rural India. Biomass energy generation offers rural areas several opportunities for innovation and application. To completely realise India's potential, need efficient, renewable, sustainable, nonconventional, and equally vital energy supplies. One of the world's most precious renewable energy sources is ethanol that biomass generates.

(Upadhyay, 2021) [13] At the Climate Change Conference (COP27) Summit, India presented its long-term low-emission development plan to the "United Nations Framework Convention on Climate Change (UNFCCC)", which is the most well-received move on a global scale. One of the measures or tactics to accomplish the long-term objective of lowering carbon emissions is the use of biofuels. By 2025, India was proposing to mix 5% biodiesel with diesel and 20% ethanol with petrol. Despite their immense promise, biofuels also face difficulties.

(Kothari et al., 2020) [19] Cooking, transport, and power production are possible using biogas, biodiesel, bio-ethanol, and biomass gasification. India has implemented many bioenergy policies and initiatives to boost bioenergy. The nation cannot exploit bioenergy alternatives to their full potential owing to policy deficiencies. Implementing bioenergy policy involves technological, institutional, financial, environmental, and social obstacles. India implements a new bioenergy strategy to boost bioenergy production. This essay explores and critically analyses current bioenergy policy and previous Indian experiences for bioenergy uptake. Logistic and linear models are used to explain bioenergy technology knowledge and readiness to pay for biogas and upgraded cookstoves from a survey. In rural India, socio-economic elements affect bioenergy policy success.

(J & Majid, 2020) [20] India wants to use renewable energy to boost economic growth, energy security, access, and climate change. By providing inexpensive, dependable, sustainable, and contemporary energy to people, sustainable development is feasible. India leading the world's most desirable renewable energy markets is due to strong government backing and an improving economy. To quickly expand the renewable energy sector, the government has created regulations, initiatives, and a permissive environment to encourage international investment. Over the next several years, renewable energy is expected to produce many homes employment. Renewable energy development in India has led to substantial successes, prospects, predictions, power production, problems, investment, and job possibilities. We highlighted renewable sector challenges in our assessment. Governments, innovators, project developers, investors, industries, stakeholders, departments, researchers, and scientists will benefit from the review's suggestions.

(Purohit & Dhar, 2018) [7] The ANSWER MARKAL model was used in this research to evaluate the economic viability of biofuels made from lignocellulosic agricultural waste. The findings show that India's first-generation biofuel pipeline does not currently provide enough ethanol and biodiesel to achieve the nation's biofuel objective. The NPB's 20 percent blending requirement by 2030, however, might be met by lignocellulosic agricultural residues, which can yield 38 and 51 billion litres of lignocellulosic ethanol/BTL in 2020 and 2030, respectively. Evaluate the need for investment in the second-generation biofuel sector, the effect on rural employment in various scenarios, and the reduction of carbon dioxide emissions in addition to the supply of biofuel.

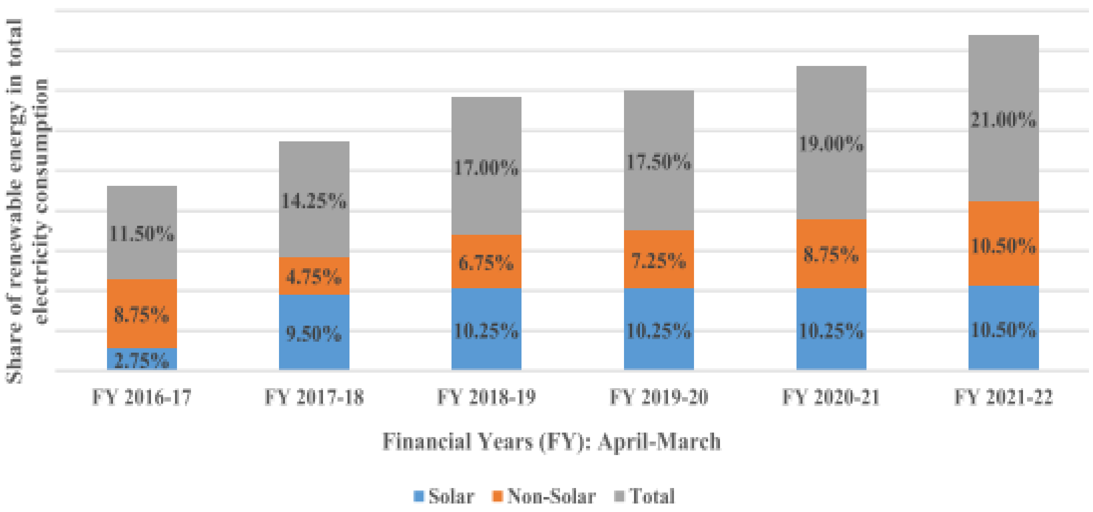

Figure 2 Target share of renewable energy in India's power consumption [20]

CONCLUSION

Bioenergy holds significant potential to meet India's growing energy demand sustainably. It offers cleaner, cost-effective energy while contributing to carbon sequestration and reducing greenhouse gas emissions. However, the adoption of bioenergy faces challenges such as competition for land and water with food crops, unstable markets, inadequate economic incentives, and socio-economic concerns. Despite these obstacles, India's vast agricultural biomass resources provide immense opportunities for bioenergy generation, particularly in rural areas. The government's focus must shift towards the development of advanced second and third-generation biofuels supported by clear policies, financial incentives, and robust infrastructure. Efficient waste segregation, transportation, treatment, public awareness, and enhanced R&D collaboration are critical to establishing a smooth and effective bioenergy system. Additionally, integrating bioenergy into rural and remote regions can promote innovation, employment, and additional income for farmers. Policy reforms are essential to address lacunae such as ambiguous execution timelines, inadequate investor frameworks, and limited support for private sector involvement. A "Solar Energy Alliance"-like initiative for bioenergy could catalyze investments and drive innovation. With structured guidelines, technology development, and infrastructure enhancements, India can unlock the potential of bioenergy to meet its climate goals, reduce fossil fuel dependency, and pave the way for a sustainable energy future.

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