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# Bioenergy and biofuels potential in India: Current and future prospects

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**Abstract**
India has set an ambitious goal for its energy transition, aiming to achieve fifty percent of its total electric power installed capacity from non-fossil fuel sources by 2030 and reach net-zero emissions by 2070. To meet these significant renewable energy targets and achieve energy self-sufficiency, it is essential to maximize the use of domestically available renewable energy alternatives. One viable alternative is bioenergy, which takes advantage of the country's abundant surplus of biomass and other waste materials. Also, the global transition towards sustainable energy has positioned bio-energy and bio-fuels as pivotal alternatives to conventional fossil fuels. This paper provides a comprehensive overview of the current state and future prospects of bio-energy and bio-fuels, exploring their potential to contribute to energy security, environmental sustainability, and economic development. Bio-fuels, derived from organic materials, offer a cleaner, renewable source of energy with lower carbon emissions compared to traditional fuels. Key challenges such as land-use conflicts, feedstock availability, technological limitations, and economic viability are examined. Additionally, the paper explores emerging trends in bio-energy technologies, such as the development of second- and third-generation bio-fuels, bio-refineries, and innovations in biotechnology that could enhance yield and efficiency. The future of bio-energy is discussed in the context of policy frameworks, research investments, and collaborations aimed at scaling up sustainable bio-energy solutions. The findings suggest that while bio-fuels hold significant promise in mitigating climate change and fostering renewable energy adoption, strategic efforts are required to overcome existing barriers and fully realize their potential.

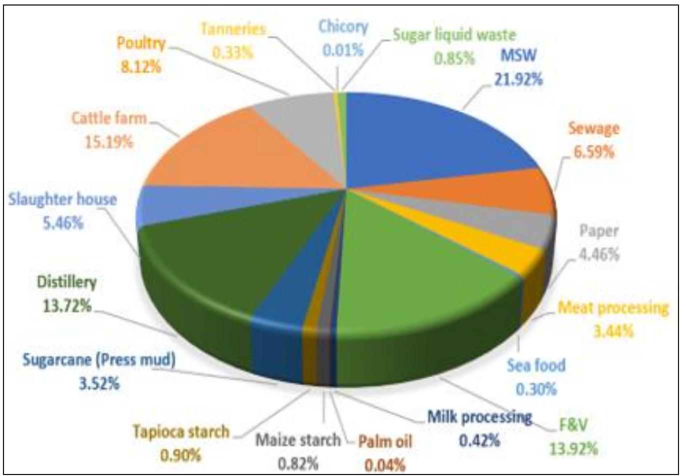
**Keywords:** Bioenergy, biogas, biofuels, food security, sustainability, adoption

## 1. Introduction
As global energy demands continue to rise and concerns about environmental degradation intensify, bioenergy has emerged as a vital component of the renewable energy landscape. Bioenergy refers to energy derived from biological materials, often categorized into primary (e.g., wood and crop residues) and secondary (e.g., biofuels, biogas) sources. Unlike fossil fuels, bioenergy is renewable, widely available, and can contribute to reducing greenhouse gas (GHG) emissions. The increased use of bioenergy could contribute to achieving the goals of the framework convention on climate change (FCCC) to maintain GHG's concentration in the atmosphere below the dangerous level [19]. Since the main constrain in biomass production is land, comparison with food production is an important factor determining the global bioenergy potential. Each year, terrestrial primary production generates roughly $120 \times 10^{15}$ grams of dry vegetative biomass [1], storing $2.2\times10^{21}$ J of energy in plant materials [2]. The world energy demand was $5.5\times10^{20}$ J in 2010. It is expected to increase to $6.6\times10^{20}$ J in 2020 and $8.6\times10^{20}$ J in 2040 [3]. The bioenergy production potential of the world's total land area, excluding infrastructure, cropland, wilderness, and dense forests, is estimated at $190 \times 10^{18}$ J per year, which is 35% of the current global energy demand [4]. This paper aims to review the current state of bioenergy production and utilization, as well as to examine its future prospects in the global energy transition towards a low-carbon economy. Building on the above analysis, the potential estimation and future prospects of biomass and bioenergy are explored to anticipate further advancements in the field.

## 2. Current State of Bioenergy

The current state of bioenergy reflects a dynamic and growing sector within the global energy mix, driven by increasing demand for sustainable and renewable energy sources. Bioenergy is primarily derived from biomass, biofuels, and biogas, and is utilized across various sectors, including power generation, heating, and transportation. According to the definition of Biomass by U.S. Energy Information Administration, Biomass is renewable organic material that comes from plants and animals. Biomass can be burned directly for heat or converted to liquid and gaseous fuels through various processes including combustion, anaerobic digestion, and gasification [5].

India has surplus agricultural residue of 228 million MT and other biogenic waste. The potential for power generation from this surplus agricultural residue is estimated at about 28446 MW [6]. Bioenergy production in India has been growing steadily in recent years as part of the country's efforts to increase the share of renewable energy in its energy mix. The Indian government has set an ambitious target of 50% non-fossil fuel electricity by 2030 to enhance the role of bioenergy, which includes the production of energy from biomass, biogas, biofuels, and waste-to-energy technologies. As of 2023, India has a bioenergy installed capacity of around 10.3 GW, contributing to the total renewable energy capacity. This includes power generated from biomass, bagasse-based cogeneration, and waste-to-energy plants.




Source: Ministry of New and Renewable Energy

**Fig 1:** Sector wise Energy Generation Potential in India

Bioenergy can be derived from various biological materials, with the most common forms being:

- **Biomass:** This includes organic materials like wood, agricultural residues, and other plant matter. Biomass can be combusted directly or processed into biofuels. India generates significant bioenergy from biomass (agricultural residues, wood waste, etc.) and bagasse (a byproduct of sugarcane processing). As on December 2022, Total installed capacity for biomass and bagasse-based cogeneration stands at around 10.2o GW [24]. Biomass power is particularly relevant in states like Maharashtra, Tamil Nadu, and Uttar Pradesh due to the large production of sugarcane.
- **Biofuels:** Liquid fuels such as bioethanol and biodiesel, produced from feedstocks like sugarcane, corn, and oilseeds, are used primarily in transportation. Ethanol blending in petrol has been a key focus. India achieved an 11% ethanol blending rate by 2023, with a target to reach 20% ethanol blending by 2025. Bioethanol is produced mainly from sugarcane molasses and, more recently, from surplus food grains like maize and rice. Biodiesel production, though still in its nascent stages, is growing, with feedstocks including non-edible oils (like jatropha) and used cooking oil.
- **Biogas:** A blend of methane ($CH_4$) and carbon dioxide ($CO_2$) generated through the anaerobic digestion of organic waste materials, biogas is used for electricity generation, heating, and as vehicle fuel. India has over 4.9 million family-type biogas plants operating across rural regions. The National Biogas and Manure Management Programme (NBMMP) promotes the use of biogas, mainly in rural areas, by setting up small-scale biogas plants. These plants use cow dung, agricultural waste, and kitchen waste to produce gas for cooking and electricity. The government's focus is now shifting to larger-scale Compressed Biogas (CBG) plants. Under the SATAT (Sustainable Alternative Towards Affordable Transportation) initiative, there is a push to establish 5,000 CBG plants by the year 2025.
- **Waste to Energy (WTE)**: India's growing urban population has led to an increase in municipal solid waste (MSW). The country has around 200 MW of installed WTE capacity, but this sector faces challenges related to waste segregation and high costs. Efforts are ongoing to improve waste management practices and promote the development of WTE plants.

### 2.1 Types of Bioenergy

**Table 1:** Energy Generation Potential in India from solid waste

| Sectors | Year 2017 (MW) | Year 2022 (MW) | Year 2027 (MW) |
|---|---|---|---|
| Urban solid waste | 1,247 | 1,592 | 2,031 |
| Urban liquid waste | 375 | 479 | 611 |
| Industrial organic waste | 4,068 | 5,192 | 6,626 |
| Total | 5,690* | 7,262 | 9,269 |

***Source***: Ministry of New and Renewable Energy

*The estimated energy potential of 5690 MW from urban solid waste also includes non-biodegradable waste fraction which can be used in other energy generation technologies.

### 2.2 Global Production and Utilization

Biomass production and its potential for generating renewable bioenergy vary between countries based on factors such as geography, resource availability, biodiversity, technology, and economic conditions. Globally, bioenergy contributes approximately 10% of the world's total energy supply, with significant variations across regions [17]. Developing countries, especially in Africa and Asia, rely heavily on local available biomass for cooking and heating, while industrialized nations are exploring advanced bioenergy technologies, particularly

biofuels for transportation and biogas for electricity generation.
It is estimated that biomass could generate 3,000 terawatt-hours (TWh) of electricity by 2050, potentially reducing $CO_2$ equivalent emissions by 1.3 billion tons per year. Additionally, for every TWh of energy produced, 472.89 kilotons of $CO_2$ are emitted [7]. Globally, renewable energy production increased to 18.6% by 2014. However, in 2018, renewable energy generation increased by 14.5%, slightly lower than average growth (16%) of last decade. The Asia-Pacific region being the leading contributor, accounting for 40% of global renewable energy generation, followed by Europe and North America [18]. Similarly, the rising demand for biofuel as an alternative to conventional fuels has driven a global increase in biofuel production. Among the leading producers, the United States holds the largest share of biofuel production, followed by Brazil and Germany. Key bioenergy producers include Brazil, the United States, and the European Union, where supportive policies and investments in technology have led to the development of robust bioenergy sectors. For instance, Brazil is a global leader in bioethanol production from sugarcane, while the U.S. has made substantial strides in corn-based ethanol and advanced biofuels research.

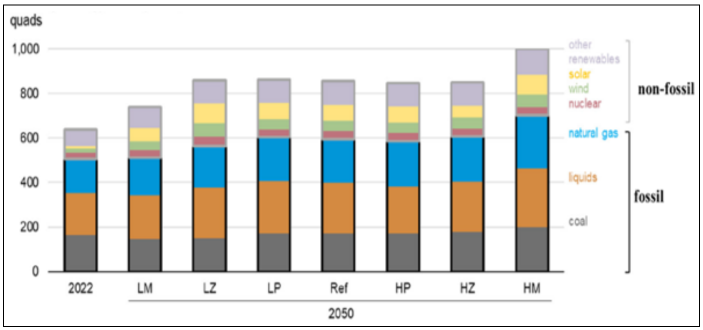



**Fig 2:** Primary Energy use by fuel, world

LZ: Low zero carbon technology cost case; HM: High economic growth case; LM: Low economic growth case; HP: High oil price case; LP: Low oil price case; Ref: Reference case.
Source: U.S. Energy Information Administration, International Energy Outlook 2023

### 2.3 Environmental and Economic Impacts

Bioenergy and biofuels have both environmental and economic impacts, offering a mix of benefits and challenges. Environmentally, biofuels can reduce greenhouse gas emissions compared to fossil fuels, contributing to climate change mitigation by being carbon-neutral when managed well. They also tend to burn cleaner, emitting fewer pollutants, thus improving air quality. Additionally, bioenergy is a renewable source, utilizing biological materials like plants and waste, and it can help in waste reduction by repurposing agricultural and industrial by-products. However, there are notable downsides. Production of biofuel in large scale can lead to deforestation, habitat loss, and biodiversity threats due to extensive land use. Water consumption is another concern, as crops like corn and sugarcane require significant amounts of water, leading to potential water scarcity and pollution from pesticide and fertilizer runoff. Moreover, converting forests to biofuel plantations can create a "carbon debt," releasing more carbon into the atmosphere than is absorbed, while intensive cultivation may degrade soil health.
Economically, biofuels offer potential advantages such as improving energy security by reducing dependence on imported fossil fuels and fostering rural economic development through job creation in farming, refining, and research. They also encourage technological innovation in the agricultural and renewable energy sectors. However, there are challenges, particularly the food vs. fuel debate, as diverting crops like corn and soy for fuel production can drive up food prices and threaten food security, especially in low-income regions. High initial investment costs for biofuel production facilities can also be a barrier, and biofuels are susceptible to volatile commodity markets, which can make them less competitive against fluctuating oil prices. Moreover, in some regions, the shift from food production to biofuel crops may economically displace small farmers. To maximize the positive impacts of biofuels, policies need to focus on sustainable practices, such as promoting second-generation biofuels that use non-food crops and waste materials, to balance economic growth with environmental conservation.

## 3. Future Prospects of Bioenergy

The future prospects of bioenergy are highly promising as the world changes to more sustainable and renewable energy sources. One of its key advantages is its potential for climate change mitigation. Bioenergy is considered carbon-neutral, coupled with carbon capture and storage (CCS) technology, could even result in negative emissions, where more $CO_2$ is sequestered than emitted. Such developments make bioenergy a critical tool in meeting global climate goals like those outlined in the Paris Agreement. Sustainability is another key area where bioenergy can contribute. It can convert agricultural and organic waste into energy, reducing landfill use and methane emissions. By-products such as biochar, produced by pyrolysis process, can also improve soil fertility, contributing to sustainable agriculture.

### 3.1 Technological Advancements

Technological advancements are also playing a crucial role in bioenergy's future. Improved conversion technologies for biogas, bioethanol, and biodiesel are expected to increase efficiency and lowering costs, making bioenergy more competitive with fossil fuels. Research into genetic engineering of energy crops, aiming to enhance yields and reduce resource use, promises even greater sustainability, economic viability and environmental performance. Key areas of innovation include:

- Second and Third-Generation Biofuels: The second-generation biofuels are produced from non-food biomass sources such as lignocellulosic materials, reducing competition with food production. Third-generation biofuels, produced from algae, promise even higher energy yields and lower environmental impacts. These advancements are crucial for meeting future transportation fuel needs [15].
- Biorefineries: The development of integrated biorefineries, where biomass is transformed into a range of bio-based products (fuels, chemicals, and electricity), represents a promising approach to improving bioenergy efficiency and economic viability.
- Waste-to-Energy Technologies: Utilizing agricultural, municipal, and industrial waste for biogas production through anaerobic digestion or pyrolysis is gaining traction as a means of generating bioenergy while addressing waste management issues.

### 3.2 Policy and Market Development

The future of bioenergy will largely depend on supportive policy frameworks that incentivize investment, research, and innovation. Carbon pricing mechanisms, subsidies for renewable energy, and regulations promoting sustainable land use are essential for inspiring bioenergy adoption. Countries leading in bioenergy development have implemented policies such as renewable energy mandates, tax incentives, and biofuel blending requirements. For example, the European Union's Renewable Energy Directive sets binding targets for the use of bioenergy in electricity, heating, and transport [16]. Additionally, international agreements like the Paris Accord emphasize the role of renewable energy, including biofuels & bioenergy, in reducing global GHG emissions.

Since its establishment, the Ministry of New and Renewable Energy (MNRE) in India has concentrated on advancing the bioenergy sector. This includes addressing issues related to biomass management-both agricultural waste and municipal solid waste and maximizing its energy potential. The ministry's dedicated initiatives have led to the implementation of over 800 biomass power projects, including bagasse and non-bagasse cogeneration projects, with a combined capacity of 10,632 MW for power generation and 140 tons per day (TPD) for compressed biogas (CBG) production [21]. India is also working towards establishing a viable market for bioproducts like biomass pellets and briquettes. Currently, there are nearly 230 manufacturers of biomass pellets and approximately 1,030 briquette manufacturers located across various states, providing these products to power plants and industries [20]. This expansion in the bioenergy sector has been supported by several central-level schemes and initiatives, including:

- A policy for co-firing biomass in thermal power plants mandates a minimum of 5% co-firing of biomass with coal [8]. Currently, India's biomass pellet manufacturing capacity is 2.38 MMT [20], and 83,066 metric tons of biomass have been co-fired in 39 thermal power plants throughout the country [14].
- The Sustainable Alternative Towards Affordable Transportation (SATAT) scheme promotes the use of CBG in the transportation sector. Under the scheme, 9,019 MT of CBG has been sold until August 2022 [9].
- A scheme to promote biomass-based cogeneration in sugar mills and other industries [10].
- New National Biogas and Organic Manure Programme (NNBOMP).
- The Central Pollution Control Board (CPCB) has allocated a fund of INR 50 crore as a subsidy to manufacturers in Haryana, Rajasthan, Punjab, Uttar Pradesh, and Delhi to encourage pellet production and reduce stubble burning.
- Amendments to the National Policy on Biofuels, 2018, permit the use of additional feedstocks for biofuel production and advance the target for 20% ethanol blending in petrol to the ethanol supply year 2025–26, instead of 2030 [11].
- The Government of India has directed the relevant commissions to consider (a) exempting all applicable charges (excluding wheeling and transmission charges) for interstate open access sales of power generated from municipal solid waste to power plants, and (b) relaxing the Deviation Settlement Mechanism (DSM) for municipal solid waste power plants in a manner similar to the relaxations provided for solar and wind power plants.
- A scheme to promote the manufacturing of briquettes and pellets, as well as biomass (non-bagasse) based cogeneration in industries until March 2026, offers INR 9 lakh per metric tonne/hour (MTPH) of pellet or briquette manufacturing capacity (with a maximum Central Financial Assistance or CFA of INR 45 lakh per plant) and INR 40 lakh per megawatt (MW) on installed capacity (with a maximum CFA of INR 5 crore per project) for biomass (non-bagasse) cogeneration initiatives [12].

### 3.3 Bioenergy in the Renewable Energy Mix

Bioenergy is expected to play a complementary role alongside other renewable energy sources such as wind, solar, and hydropower. Its ability to provide baseload and dispatchable power, as well as renewable transportation fuels, makes it a valuable component of the renewable energy mix. Moreover, bioenergy can help balance intermittent renewables by providing flexible energy storage options through biogas and biofuel production.

These hybrid renewable energy systems are gaining popularity as independent power solutions for remote areas due to advancements in renewable technology and rising petroleum prices [22]. These systems combine multiple renewable energy sources to enhance efficiency and ensure a balanced supply. Their adoption is driven by benefits such as improved supply security, reduced carbon emissions, enhanced power quality, reliability, and increased job opportunities for local communities. Given the intermittent nature of renewable sources, hybrid systems effectively mitigate these challenges by integrating different energy sources.

A recent study modeled a hybrid power generation system incorporating solar, wind, and biomass using MATLAB. This simulation included all realistic components of such a system. The findings revealed that the electricity generated by the PV/WIND/BIOMASS hybrid model is significantly higher and more cost-effective compared to traditional systems, while also being environmentally friendly [13].

### 3.4 Challenges and Solutions

India has the potential to generate reliable, cost-effective, and environmentally sustainable bioenergy to meet its energy needs, including for power generation, transportation, and modern heating applications. However, progress in this area has been slow. As of August 2022, biomass power, cogeneration, and waste-to-energy projects accounted for less than 3% of the country's total installed generation capacity [23]. Additionally, the bioenergy sector faces several risks and challenges that hinder its growth and wider adoption. Following are the risks and challenges:

- **State policies focus on biomass in power generation:** Current state policies primarily emphasize the use of biomass for power generation, despite its potential for other applications such as biofuel production and industrial heating through biomass processing.
- **Inadequate feedstock supply (fuel reliability and quality):** A key challenge is ensuring a reliable, long-term fuel supply for bioenergy projects. Uncertainty in fuel availability or quality can undermine project success, as economics depend on consistent energy output. Developers seek secure contracts with feedstock suppliers to avoid competing offers, which also reassures lenders by lowering project risk.
- **Lack of public data on biomass availability across geographies:** Biomass availability data, especially at the district or block level, is limited and often requires individual research, complicating project planning. As a result, stakeholders must conduct their own assessments, which may lead to inaccurate, time-consuming, and costly

estimates of surplus biomass for bioenergy production.

- **Limited storage options:** Biomass storage has long been a challenge in India, particularly for agricultural residues. Limited storage capacity is a key reason for stubble burning, especially in northern states, where excess biomass is burned in open fields due to lack of offtake and storage options.
- **Supply chain bottlenecks:** Transporting biomass, especially agricultural waste, requires specialized vehicles due to its varying size and density. However, commercial solutions are limited, and transportation is mostly handled through temporary, improvised methods.
- **Limited offtake of biofertilizers:** There is an urgent need to encourage farmers to adopt biofertilizers, as many are still unaware of their benefits, including improved nutrient uptake, crop growth, yield, nutrient efficiency, and quality. Biofertilizers can also boost local allied industries. The slow adoption of biofertilizers remains a significant barrier to private sector investment in the country's biogas sector.
- **Limited platforms for biomass trading:** Few platforms exist for trading and exchanging raw and processed biomass, where sourcing agencies, aggregators, and producers can list and sell their resources to buyers. Currently, biomass trading in India is fragmented and limited to a few states, despite the growing demand for biomass and waste for bioenergy projects.
- **Lack of adequate financing mechanisms:** Lenders are generally hesitant to offer both short- and long-term loans, and when they do, the interest rates are higher than those for other clean energy projects, driving up the overall project costs.
- **Environmental Concerns:** The environmental impacts of bioenergy, particularly related to land use, deforestation, and biodiversity loss, must be carefully managed through stringent sustainability criteria and certification schemes.

## 4. Conclusion

The current energy demand was met by fossil fuels at 80%, biofuels at 11.3%, uranium at 5.5%, and other renewable source energy at 2.2%. Of all the renewable energy sectors in 2010, bioenergy accounted more than 80% [25]. Bioenergy represents a promising solution for addressing the global energy and environmental challenges of the 21st century. Its diverse applications, from transportation fuels to electricity generation and waste management, position it as a key player in the transition to a low-carbon economy. However, realizing its full potential requires addressing challenges related to sustainability, feedstock supply, and economic viability. Looking ahead, advancements in bioenergy technologies, supportive policy frameworks, and the integration of bioenergy with other renewable sources will shape the future of bioenergy. With appropriate measures, bioenergy can contribute significantly to achieving global energy security and climate goals, providing a cleaner, more sustainable energy future.

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