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INDIAN SCENARIO OF BIOMASS AVAILABILITY AND ITS BIOENERGY CONVERSION

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ABSTRACT

Agricultural waste, such as rice husk and wheat straw, are key contributors to India's biomass potential. This work categorizes the types of biomasses available and explores their specific characteristics, such as calorific value and energy conversion efficiency, which are crucial for determining their suitability for bioenergy projects. One of the major challenges in realizing India's biomass potential lies in the supply chain, where efficient collection, storage and transportation are vital to ensure a consistent and sustainable supply to bioenergy plants. India, with its vast agrarian economy, produces around 990 million metric tonnes (MMT) of agriculture-based biomass annually, positioning it as a critical player in the country's energy mix. Despite this, biomass-based energy currently contributes less than 3% of India's total power generation. Historically, biomass energy in India has been used for heating and cooking in rural households, but recent decades have seen a shift towards large-scale energy production. The National Bioenergy Programme, which has set a target of 10 GW of bioenergy by 2030, aims to address these challenges, though gaps in infrastructure and policy implementation remain. India's biomass market offers significant business opportunities, particularly in rural areas where abundant biomass can be converted into energy. The current biomass power generation capacity stands at approximately 10 GW, with projections indicating an increase to 32.9 GW by 2025–26 and 35.9 GW by 2030–31, provided supply chain efficiency and policy frameworks improve. Achieving this target requires strategic planning to maximize biomass availability, as India's estimated surplus biomass is about 230 MMT annually. This work discusses the potential for biomass-based power potential and highlights the need for public-private partnerships, financing mechanisms, and technological advancements to scale bioenergy in India.

Key words : Biomass availability, Biomass power plant, Conversion, National Bioenergy programme.

Introduction

India is currently in a transitional phase from being a developing nation to becoming a developed one. However, its rapidly growing population—currently at 1.4 billion, as reported by World Meter is one of the major challenges hindering its progress. Projections suggest that India's population could surpass 1.7 billion by the 2060s. As the population grows, the demand for essential resources such as food, healthcare, and energy will also increase substantially.

In previous decades, both rural and urban India relied heavily on energy sources like biomass—comprising plant and animal waste, agricultural residues, and wood fuels. Biomass energy refers to renewable resources derived from biological materials and has long been an integral energy source for the country. Today, however, India's energy demand is primarily met by fossil fuels, especially coal and oil. In 2021, the nation's energy consumption was estimated at 9763 terawatt-hours (TWh), with coal and oil dominating the mix. This consumption is projected to grow and within the next two decades, India's energy demand is expected to double, rising from 750 million tonnes (MT) in 2011 to 1469 MT by 2030.

As fossil fuels, such as coal and oil, are finite and increasingly depleting, there is a growing need for alternative energy sources, particularly for a developing country like India. Biomass, a renewable and sustainable resource has been used for centuries and continues to be one of the most significant energy sources for India. Globally, India ranks third in biomass energy production, following China and the United States.

Bioenergy, a form of renewable energy derived from biomass, plays a crucial role in this context. Biomass consists of organic materials that were recently alive and can be transformed into various forms of energy, such as vehicle fuel, heat, and electricity it is analyzed by Chauhan and Singh (2023).

Biomass Availability in India

India, as an agriculture-driven nation, has a gross sown area of about 197 million hectares, supporting a wide variety of crops with varying levels of productivity. This extensive agricultural activity generates substantial crop residues at multiple stages of production, including at the farm, mill, and processing levels. These residues serve critical purposes, being widely used for cattle feed, compost fertilizer, thatching, domestic fuel (for cooking and heating) and other industrial applications. Despite these uses, a significant portion of crop residues, particularly in the form of straw and stubble, remains unutilized. In fact, roughly one-third of the total crop residues generated go unused, representing an untapped economic resource.

According to the Ministry of New and Renewable Energy [MNRE (2021)], a comprehensive study was conducted to quantify surplus biomass from various crops across India during three main agricultural seasons—*Kharif*, *Rabi* and Summer. The study analyzed data from 28 states and 8 Union Territories, with sample districts selected based on 90% of the crop acreage and production within each region.

At the national level, India's total gross cropped area was approximately 198.11 million hectares, and the overall crop production stood at 774.38 million tonnes. The total biomass potential from this crop production was estimated to be 754.50 million tonnes. Out of this, nearly two-thirds around 525.98 million tonnes is already utilized for various purposes such as domestic consumption, cattle feeding, compost fertilizer, and other agricultural needs. The remaining one-third, approximately 228.52 million tonnes, represents surplus biomass that is currently unutilized and holds significant potential for alternative uses, particularly in the bioenergy sector. This surplus biomass, which includes agricultural residues, presents a critical opportunity for India to tap into renewable energy sources. The country's growing population not only increases the pressure on energy demand but also contributes to the rising levels of biowaste, including agricultural residues, municipal solid waste, kitchen waste, and industrial waste. This growing volume of waste underscores the vast potential for converting these resources into bioenergy, providing a sustainable solution to meet India's expanding energy needs.

By effectively utilizing surplus biomass for bioenergy production, India can address its dual challenges of waste management and energy scarcity, while also contributing to global efforts in combating climate change through the promotion of renewable energy sources.

Several mathematical models have been proposed by scientific groups to promote the sustainable use of agricultural biomass for energy production, soil fertilization, livestock nutrition and industrial applications. Bijarchiyan *et al.* (2020) developed a multi-echelon, multi-objective model for designing a sustainable supply chain for bioenergy generation using the anaerobic digestion process. Skrbic *et al.* (2020) analyzed the utilization potential of agricultural biomass for energy purposes, identifying key barriers that limit its widespread use. Meanwhile, Milicevic *et al.* (2018) created a mathematical model for co-firing pulverized coal and biomass in experimental furnaces. This model provides a solid foundation for further research on co-combustion processes, offering insights into optimizing energy generation from various pulverized fuels, including biomass and coal.

Agricultural-based Biomass

India stands as an agricultural powerhouse, with agriculture playing a central role in its economy and biomass production. According to the Department of Agriculture and Farmers Welfare DA and FW, (2022), the country has a net sown area of approximately 139.3 million hectares (Mha), which accounts for 42.4% of India's total geographical area of 328.7 Mha. This vast agricultural landscape is a testament to India's capacity for large-scale crop production, contributing significantly to its economic stability and the generation of biomass.

The report further reveals that the total cropping area dedicated to major food grains, including rice, wheat, nutri/coarse cereals, and pulses, spans around 129.34 Mha. The net production from these food grains amounts to an impressive 308.65 million tons (Mt). Additionally, the cultivation of other essential crops is also noteworthy: oilseeds cover 28.79 Mha with a production of 36.10 Mt; sugarcane occupies 4.86 Mha, yielding 399.25 Mt; cotton is grown on 13.01 Mha with a production of 35.38 Mt; and jute/mesta covers 0.67 Mha, producing 9.56 Mt.

Table 1 shows that rice occupies the largest share of cultivated land in India, accounting for 34% of the total cropping area. Wheat, pulses, and maize follow, covering 23%, 22% and 7% of the country's total cropping area, respectively. In addition to these staple crops, oil crops

Table 1 : The cropping details of major crops grown in India.

Crops	Area	Production	Yield
Rice	4.51	122.27	27.13
Wheat	31.62	109.52	3464
Nutri/Coarse cereals	23.83	51.15	2146
Pulses	28.83	25.72	892
Foodgrains	129.34	308.65	2386
Oilseeds	28.79	36.10	1254
Sugarcane	4.86	399.25	82,205
Cotton	13.01	35.38	462
Jute and mesta	0.67	9.56	2595

Area-Million ha, Production-Million Tons, Yield-kg/ha

are cultivated on approximately 15% of the total agricultural land, as highlighted by Pant *et al.* (2019).

Currently, India produces around 990 million metric tons (MMT) of agricultural biomass annually, making it the second-largest producer globally, behind only China. Despite this substantial production, the country's surplus biomass availability is estimated to be around 230 MMT. This surplus biomass represents a significant resource that remains underutilized and holds tremendous potential for renewable energy generation and other economic uses.

Municipal Waste-Based Biomass

India generates approximately 160,038.9 tons of municipal solid waste (MSW) per day. Of this waste, 50–80% of plastic materials, 30–60% of paper waste, and nearly 100% of glass materials are recyclable, highlighting the significant potential for resource recovery and waste reduction through effective recycling practices by CPCB (2022).

Forest-based Biomass

In forest ecosystems, soil holds the largest portion of carbon stock, followed by above ground biomass. However, in certain cases, above ground biomass can surpass soil in carbon storage. As of 2021, the estimated carbon stock in India's forests was 7204.0 million tons (Mt), reflecting an increase of 79.4 Mt from the previous assessment. Among Indian states, Arunachal Pradesh holds the highest forest carbon stock, followed by Madhya Pradesh, Chhattisgarh and Maharashtra. The report further highlights that soil organic carbon is the primary reservoir of forest carbon. Moreover, a combination of effective forest management practices and afforestation initiatives can work together to enhance forest biomass, potentially increasing bioenergy production in the future.

Aquatic Biomass

Algae are gaining significant attention as a promising source of biomass for renewable energy production. One of their key advantages is their ability to generate large quantities of biomass—up to 280 tons per hectare annually—while also having a high oil production potential of up to 30 tons per hectare annually. Additionally, algae can be cultivated in wastewater with minimal external inputs, greatly reducing production costs. However, precise estimates for large-scale conversion of this aquatic biomass into bioenergy are still lacking as noted by Ranjan *et al.* (2019).

Technologies for biomass conversion

Biomass conversion technologies are broadly categorized into two types: thermochemical and biochemical. The choice of a specific conversion technology depends on several factors, including the type of biomass feedstock, its moisture content, the quality and quantity of available feedstock, and the desired end products. Additionally, economic factors such as profitability and market accessibility, as well as environmental considerations, play a crucial role in selecting the appropriate technology, as outlined by Garba (2020).

Thermochemical Conversion

Three primary pathways for thermochemical conversion are direct combustion, gasification, and pyrolysis as noted by Mahinpey and Gomez (2016).

Direct combustion, gasification, and pyrolysis are essential biomass conversion processes, each with unique advantages. Direct combustion involves heating biomass at 800-1000°C, undergoing drying, devolatilization, and oxidation of char, and is most effective with moisture content below 50% as noted by Hupa *et al.* (2017) and Lam *et al.* (2019). Gasification converts biomass into syngas, biochar, electricity, and heat using heat, steam, and oxygen, performing best with 10-15% moisture content noted by Gao *et al.* (2023), while also reducing environmental waste. Pyrolysis breaks down biomass in an oxygen-free environment, producing bio char, bio-oil, and syngas noted by Saravanan *et al.* (2021). Advanced gasifiers now improve efficiency, offering a more effective alternative to traditional combustion for energy generation.

Table 2 shows the Operating conditions and main products in different pyrolysis types including conditions like time, heating rate and temperature and based on that the different products are produce.

Biochemical conversion

According to William *et al.* (2020), biochemical conversion is the process of converting biomass using enzymes from bacteria or other microorganisms into gaseous or liquid fuels, such as biogas or bioethanol.

Table 2 : Operating conditions and main products in pyrolysis types.

	Residence Time	Heating Rate	Temperature	Main Products
Slow	Days	Very show	400 ^{0}C	Char
Conventional	5–30 min	20–100 ^{0}C/min	450–650 ^{0}C	Liquid, gas, char
Fast	0.5–5 s	1000 ^{0}C/s	450–650 ^{0}C	Liquid

Time-day, minute and second, Heating Rate-^{0}CC/minute and ^{0}C /second, Temperature-Celsius

Anaerobic digestion and fermentation are key processes for converting organic waste into energy. In anaerobic digestion, microbes break down waste to produce biogas (40–65% methane, 35–55% carbon dioxide, and trace gases) and digestate, a nutrient-rich residue useful as a soil conditioner Ghosh *et al.* (2020), Wang and Lee (2021). The biogas can be used for heat or upgraded into fuels (Ge *et al.*, 2014 and Xu *et al.*, 2018). Fermentation, involving microorganisms like yeast, converts biomolecules like glucose into alcohol or acids under anaerobic conditions noted by Patra *et al.* (2022). Simple sugars ferment easily, while complex components need extra processing noted by Galbe *et al.* (2011).

Policy framework

India has strategically embarked on a well-planned path to harness its bioenergy potential, focusing primarily on biogas, biomass power and co-generation as key contributors. A range of programs and initiatives have been implemented to promote the development and deployment of bioenergy technologies across the nation.

The Ministry of New and Renewable Energy (MNRE) has been at the forefront of efforts to harness bioenergy, launching initiatives like the National Bioenergy Programme to capitalize on surplus biomass, cattle dung, industrial, and urban biowaste available across India. Through this program, MNRE has extended significant support, including Central Financial Assistance (CFA), to incentivize the establishment of bioenergy projects, such as biogas, Bio CNG and power generation from urban, industrial, and agricultural waste/residues.

In the biogas sector, the government has introduced various programs to address both local and national needs. One such initiative is the Gobardhan scheme, which provides financial assistance of up to Rs. 50 lakh per district for setting up model community biogas plants. Furthermore, the Ministry of Power has implemented the SAMARTH Mission (National Mission on Use of Biomass in Thermal Power Plants), which encourages the blending of biomass with coal in existing thermal power plants.

Bioenergy production potential

India's bioenergy potential is immense, as highlighted by PwC, with the ability to generate 208 billion units (BU) of power annually from 28 GW of capacity, alongside an additional 65 BU from bagasse-based cogeneration. Biogas production is also promising, with key feedstocks including cattle dung (38,981 TPD), municipal waste (4,853 TPD) and paddy straw (16,377 TPD). In the bioethanol sector, first-generation sources such as sugar/syrup, B molasses, and C molasses offer production capacities of 9,523, 24,844, and 13,309 KLPD, respectively. Second-generation sources like rice and maize contribute 897 and 395 KLPD. These bioenergy resources are crucial for advancing India's clean energy transition and meeting its sustainability goals, reducing reliance on fossil fuels, and lowering greenhouse gas emissions. Additionally, leveraging agricultural residues and waste for energy supports rural development by

Table 3 : 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
Compressed biogas production potential	From cattle dung – 38,981 TPD From municipal solid waste – 4,853 TPD From paddy straw – 16,377 TPD
Bioethanol production potential	From sugarcane (1G):Sugar/sugar syrup – 9,523 KLPD B molasses – 24,844 KLPD C molasses – 13,309 KLPD From rice (2G) – 897 KLPD From maize (2G) – 395 KLPD

creating jobs, improving waste management and providing decentralized energy solutions in off-grid regions, further contributing to energy security and environmental sustainability. Expanding investments and infrastructure, along with policy support, can unlock the full potential of India's bioenergy sector.

Risk and challenges

These are some following key risk and challenges in bioenergy sector:

- State policies prioritize biomass for power generation, limiting its broader use in biofuel production and industrial heating.
- Unpredictable feedstock supply and inconsistent quality hinder bioenergy projects, with long-term viability relying on stable fuel contracts, adding risk for developers and lenders.
- The absence of granular biomass data complicates project planning, forcing stakeholders into costly, time-consuming assessments, hindering accurate evaluation of surplus for energy production.
- Limited storage for agricultural biomass residues, especially in northern India, leads to harmful practices like stubble burning, missing opportunities for biomass energy production.
- Transporting agricultural biomass is challenging due to varied sizes and densities, and the lack of specialized vehicles worsens supply chain inefficiencies, restricting biomass utilization.
- The lack of organized platforms for biomass trading creates market fragmentation, hindering connections between producers, aggregators, and buyers, and limiting a cohesive national biomass market.
- The bioenergy sector struggles with financing, as lenders are hesitant and offer higher interest rates than other clean energy projects, driving up costs and reducing competitiveness.

Strategy for overcoming challenges in bioenergy sector

- Sustained R&D investment is vital to overcome technological challenges in bioenergy, particularly in advancing second-generation ethanol, biomass palletization, and biogas upgrading, enhancing efficiency and viability.
- Strengthening policy interventions, such as targeted subsidies and streamlined regulations, is essential for incentivizing bioenergy adoption and building investor confidence in the sector.
- Robust biomass supply chains require stakeholder collaboration, infrastructure investment and digital platforms for efficient trading and aggregation, ensuring a reliable and sustainable biomass supply.
- Capacity-building initiatives and knowledge sharing can enhance skills and awareness in the bioenergy value chain, with public-private partnerships and international collaborations accelerating innovation and technology transfer.
- Exploring new bioenergy markets, like sustainable aviation fuels and clean cooking solutions, can enhance India's energy mix. Innovative financing, market incentives, and public procurement policies can stimulate demand and create new revenue streams for stakeholders.

By harnessing India's agricultural abundance, fostering innovation, and creating an enabling policy environment, the bioenergy sector can become a key driver of sustainable development, energy security and economic growth.

Conclusion

This review paper provides a comprehensive examination of India's biomass availability and its potential for bioenergy conversion. It highlights the significant untapped resource of surplus agricultural biomass, estimated at 230 million metric tonnes annually, which could be leveraged to meet growing energy demands. The paper discusses various types of biomass, including agricultural residues, municipal waste, forest biomass, and aquatic sources like algae, and explores their conversion through thermochemical and biochemical technologies. Additionally, it identifies key challenges in the biomass energy sector, such as inefficient supply chains, policy gaps, feedstock inconsistency and financing hurdles, while emphasizing the role of public-private partnerships, technological advancements, and strategic policy interventions in overcoming these obstacles. Overall, the paper underscores the critical need for effective utilization of biomass in India's energy mix and offers insights into improving bioenergy production through better infrastructure, policies, and market integration.

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