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Biomass Fuel Usage in Indian Textile Industries: Environmental Impacts, Challenges, and Decarbonization Pathways

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Abstract
This paper presents a systematic technical review of energy consumption patterns, environmental impacts, and the decarbonization potential of biomass fuels in the Indian textile industry. Although the textile sector is frequently described through individual case studies, there is a lack of consolidated analysis integrating energy use, emission intensity, biomass resource availability, and technology readiness at a sectoral level. This review synthesizes published literature, industry reports, policy documents, and secondary statistical data to examine the role of biomass as a low-carbon alternative to fossil fuels for textile process heating. Key aspects reviewed include energy demand across textile subsectors, emission intensity benchmarks, biomass feedstock characteristics, combustion technologies, sustainability constraints, and policy frameworks relevant to India. The analysis highlights that while biomass can contribute to emission reductions when sustainably sourced particularly from agricultural residues its carbon neutrality is highly context-dependent and constrained by feedstock availability, logistics, air pollutant emissions, and land-use impacts. The review also compares biomass with other renewable thermal options and discusses future pathways such as integrated biorefineries and circular bioenergy systems. Overall, this study positions biomass as a transitional decarbonization option rather than a universal solution and emphasizes the need for integrated policy, technology optimization, and sustainability safeguards for the Indian textile sector.
Keywords: Carbon neutrality, Sinking, carbon offset, Decarbonization, Fluidized, Fossil Fuel

1. Introduction

The textile industry touches nearly every part of our lives, from healthcare and everyday clothing to cutting-edge fashion and industrial applications. At its core, textiles are made from fibers, which are generally classified into two categories: natural and man-made. These fibers find use across three broad areas—apparel, home furnishings, and technical or industrial products. Globally, fiber production already exceeds 111 million metric tons each year and is expected to reach about 146 million metric tons by 2030. On average, people around the world consume about 13 kilograms of textiles per person annually. However, this varies widely industrialized countries tend to use more textiles, and as a result, they also generate more waste. Textile manufacturing is highly resource-intensive, requiring vast amounts of water and energy. This not only puts pressure on natural resources but also contributes significantly to water pollution and greenhouse gas emissions. For instance, producing cotton garments consumes around 66,648 kWh of energy, while polyester garments require roughly 91,508 kWh. On top of that, another 30–40% of energy is spent on packaging, transportation, and sales. Most of this energy comes from burning fossil fuels a market worth US $1.85 trillion in 2019. Currently, about 1,000 barrels of fossil fuel are burned every second worldwide. This dependence on fossil fuels is a major driver of global warming, as it releases massive amounts of greenhouse gases. If global temperatures rise more than 2 °C, millions of lives could be lost, and nearly one million species could face extinction. With the world's population growing and industries expanding, energy demand is increasing at an exponential rate. The International Energy Agency (IEA) projects that global energy consumption will rise by almost 50% between 2018 and 2050. If this trend continues, experts believe the world's fossil fuel reserves could be exhausted as early as 2042 [1],

This growing dependence on fossil fuels is leading to an inevitable energy scarcity. Since fossil fuels are limited in supply and contribute heavily to environmental pollution, they are increasingly seen as an unsustainable source of energy. This makes it urgent to search for large-scale, sustainable alternatives to meet the world's future energy needs.

In response to this pressing challenge, researchers worldwide have been exploring bioenergy as a potential solution. Recognizing the risks tied to fossil fuels, many countries began investing in renewable bioenergy production from biomass as early as the 1970s. Bioenergy can take several forms, including biogas, biodiesel, bioethanol, bio-hydrogen, and bioelectricity.

Biomass resources for biofuel production are generally classified into three generations:
First generation: Derived from food crops like sugarcane, corn, wheat, vegetable oils, and animal fats. [2]
Second generation: Made from non-edible lignocellulosic materials such as agricultural residues, forestry waste, sewage sludge, and municipal waste.
Third generation: Based on microalgae and other microbes.
While first-generation biofuels played an important pioneering role, they have been widely criticized. Concerns include their competition with food supply, risks to biodiversity, relatively low competitiveness with fossil fuels, and limited reductions in greenhouse gas emissions. In

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contrast, second- and third-generation biofuels do not compete with food production and require little to no agricultural land or freshwater. They utilize waste materials or microorganisms, making them more sustainable. Notably, third-generation biofuels produce significantly fewer greenhouse gas emissions compared to first-generation alternatives, positioning them as a far more promising path for the future of clean energy [3].

The textile and fashion industries generate an enormous amount of bio-waste in many different forms and conditions. This waste is rich in materials such as cellulose, hemicellulose, protein, and starch—all of which can serve as low-cost raw materials for producing bioenergy through biotechnological processes.

Bio-waste originates at multiple stages of the textile value chain: natural fiber cultivation, fiber processing, yarn spinning, fabric and garment manufacturing, and even post-consumer use. By 2030, global textile waste is projected to reach 148 million tons, with more than 35% consisting of cellulose-based waste. In addition to solid waste, textile manufacturing also produces significant amounts of liquid waste.

The rise of fast fashion has only amplified this problem. With global clothing demand increasing, post-consumer textile waste continues to grow at alarming rates. This makes textile waste a highly promising and sustainable resource for bioenergy production.

In recent years, notable progress has been made in converting different types of waste into bioenergy. Numerous studies and reviews exist in this field, but surprisingly, the specific potential of textile waste as a bioenergy source has not been extensively explored. To our knowledge, no comprehensive review has yet been conducted on this topic.

This review aims to address that gap. We begin by outlining the fundamentals of textile operations and the types of waste they generate, followed by an evaluation of their potential for bioenergy production. We then examine the current methods and challenges of producing bioenergy from textile bio-waste, and finally, we explore future opportunities for renewable and sustainable energy derived from textile and fashion industry waste.

2.0 Indian Textile Sector Overview

The Indian textile industry, deeply rooted in the country's cultural heritage, has undergone a remarkable transformation over the past few decades. Since the economic liberalization of 1991, the sector has evolved from traditional practices into a global powerhouse, integrating modern technologies while still preserving elements of its traditional identity.

This evolution has created a diverse textile value chain, with independent yet interconnected units such as spinning mills, weaving houses, and dyeing facilities. Together, they support an industry that produces across three main categories: textiles and apparel, home textiles, and technical textiles.

A major shift from hand-operated machines to electricity-driven and automated equipment has modernized production, improving efficiency, quality, and output. Today, the Indian textile industry is valued at approximately ₹11.5 lakh crore (US $138 billion). It draws on a wide variety of raw materials, including cotton, jute, silk, wool, and synthetic fibers with cotton standing out as the most dominant. In fact, India is the world's largest producer of cotton.

The industry is highly fragmented, operating across both organized and unorganized segments. On one end, it includes large-scale industrial mills; on the other, it sustains countless small-scale artisans and traditional craft communities. Significantly, Micro, Small, and Medium Enterprises (MSMEs) play a critical role, contributing an estimated 70–75% of India's total textile output. This underscores the importance of MSMEs in shaping the strength and resilience of India's textile sector [4].

Table 1: Indian Textile Sector

Parameters	Description
Total Textile sector market value (FY2024)	Rs. 14.3 Lakh Crores (US$ 172.4 Billion) (Rs. 11.5 Lakh Crores – Domestic Market + Rs. 2.8 Lakh Crores – Exports)
Raw material production (FY2023)	Cotton: 5.83 Million Metric Tonnes (MMT) Jute: 1.64 MMT Wool: 0.03 MMT Silk: 0.03 MMT Man Made Fibre: 1.6 MMT
India's share in global textile production (2023)	5.80%
India's share in global textile trade (2023)	4.60%
Electricity consumption in Textile sector (2024)	16.68 TWh
Indian textile sector emissions	42-67 Million tonnes CO2 (MTCO2)
Contribution to India's GDP	2.30%
Employment (2023)	105 Million (45 Million direct + 60 Million indirect)

Table 1 highlights the scale and energy intensity of the Indian textile sector. Despite contributing only 2.3% to national GDP, the sector emits 42–67 $MtCO_2$ annually, indicating a disproportionately high carbon footprint driven largely by fossil-fuel-based process heating. This reinforces the need for targeted low-carbon thermal energy interventions.

2.1 Study Design

This study adopts a systematic technical review framework to evaluate the environmental impacts, energy performance, and decarbonization potential of biomass fuels in the Indian textile industry. Rather than relying on plant-level primary data, the analysis is based on secondary data sources and published literature to provide a sector-wide perspective on biomass adoption, technology readiness, and sustainability implications.

2.2 Literature and Data Selection

A structured literature search was conducted using major scientific databases and institutional repositories, including Scopus, Web of Science, ScienceDirect, SpringerLink, and Google Scholar, along with reports from IEA, IPCC, MNRE (India), World Bank, and relevant government and industry bodies. The selection criteria were as follows: Inclusion criteria: Peer-reviewed journal articles, review papers, and

conference proceedings, Government policy documents and technical reports, Studies published primarily between 2010 and 2024, Publications addressing energy use, emissions, biomass fuels, industrial heating, and textile manufacturing
Exclusion criteria: Studies unrelated to industrial or textile-sector energy use, Articles lacking quantitative or comparative energy/emission discussion, Opinion-based or non-technical reports without verifiable data

A total of relevant and non-duplicative sources were screened, and those most aligned with biomass energy, textile processes, and decarbonization pathways were synthesized.

2.3 Comparative Assessment Framework

To strengthen the engineering rigor of this review, a quantitative benchmarking approach is adopted in this section. Representative emission factors, boiler efficiencies, energy densities, and cost ranges are compiled from IPCC guidelines, IEA databases, and peer-reviewed industrial energy studies. These benchmark values are used to enable a transparent comparison between biomass fuels and conventional fossil fuels in the absence of plant-specific primary data.

All numerical values represent typical industrial benchmarks and are used for comparative engineering assessment rather than precise operational prediction.

Environmental indicators: CO_2 emission intensity, lifecycle greenhouse gas emissions, and local air pollutants (NO_x, PM, VOCs).

- **Resource sustainability**: feedstock availability, residue-to-crop ratios, land-use implications, and carbon payback period
- **Technological readiness**: maturity of biomass boilers, gasification systems, and operational reliability.
- **Economic and logistical factors**: fuel cost variability, transportation requirements, and supply-chain constraints.
- Sector-level emission intensity values and energy consumption trends were used to contextualize biomass performance relative to conventional fuels [5].

2.4 Synthesis and Analysis

Data from multiple sources were cross-compared to identify converging trends, limitations, and trade-offs associated with biomass energy in the textile sector. Emphasis was placed on: Agricultural residue–based biomass as a comparatively sustainable feedstock

Challenges related to carbon neutrality claims Policy, technological, and infrastructural barriers to large-scale adoption. The analysis integrates technical, environmental, and policy dimensions to present a holistic understanding of biomass as a decarbonization option.

2.5 Limitations of the Study

This review has several limitations: The study relies on secondary data and published literature, and therefore does not capture real-time operational variations at individual textile plants.
Emission and energy intensity values are aggregated at sectoral or regional levels, which may mask plant-specific efficiencies or inefficiencies. Lifecycle emission estimates for biomass vary significantly depending on feedstock origin and logistics, introducing uncertainty in comparative assessments.

2.6 Quantitative Comparison of Biomass and Conventional Fuels for Textile Process

To strengthen the engineering basis of the discussion, this section introduces a quantitative comparison between biomass fuels and conventional fossil fuels commonly used in textile process heating, namely coal, furnace oil, and natural gas. Due to the absence of plant-specific primary measurements, benchmark values from peer-reviewed literature, IPCC guidelines, and industrial databases are used. All values represent typical ranges and are intended for comparative assessment rather than precise prediction.

Assumptions Used in the Comparison

Biomass considered: agricultural residues (rice husk, bagasse, cotton stalks), as these represent the most sustainable feedstock option for India.

- **Boiler type:** industrial steam boiler (fluidized bed or fixed bed for biomass; conventional boilers for fossil fuels).
- **Functional unit:** per unit of useful thermal energy delivered (GJth). Lifecycle emissions include fuel production, transport, and combustion, excluding capital equipment manufacturing.

3.0. Energy Density and Efficiency

Biomass fuels exhibit lower energy density than fossil fuels, which directly affects fuel handling, storage, and boiler efficiency. From a boiler design perspective, the lower calorific value of biomass necessitates higher fuel feed rates, larger furnace volumes, and increased auxiliary power consumption, which directly affects system sizing and capital cost.

Table 2: Energy Density and Boiler Efficiency Comparison

Fuel Type	Net Calorific Value (MJ/kg)	Typical Boiler Efficiency (%)
Coal (Indian grade)	18–25	75–85
Furnace Oil	40–42	85–90
Natural Gas	48–50	88–92
Biomass (Agri-residues)	7–15	65–80

Tables 2 provide a comparative engineering assessment of biomass and conventional fuels based on calorific value, boiler efficiency, emission intensity, and fuel cost. These indicators directly influence boiler design, fuel logistics, and

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operational feasibility in textile manufacturing. To deliver the same thermal output, biomass consumption by mass is 2–4 times higher than coal, increasing fuel logistics and storage requirements.[6].

3.1 Emission Intensity (CO_2, SO_x, NO_x)

While biomass combustion emits more CO_2 at the stack than coal on a mass basis, its net lifecycle emissions can be significantly lower when sustainably sourced.

Table 3: Emission Factors for Industrial Fuels (per GJth)

Fuel Type	**CO_2 (kg/GJ)**	**SO_x (g/GJ)**	**NO_x (g/GJ)**
Coal	94–101	800–1,500	300–600
Furnace Oil	77–79	400–900	250–450
Natural Gas	56–58	<10	150–300
Biomass (combustion)	100–110	<50	200–400
Biomass (lifecycle, sustainable sourcing)	5–15	<50	200–400

As per Table 3 review, although biomass combustion shows higher stack CO_2 emissions than coal, lifecycle-adjusted values demonstrate significant climate benefits when agricultural residues are used, highlighting the importance of feedstock selection in emission accounting.

Biomass has higher stack CO_2 emissions than coal but much lower lifecycle CO_2 emissions when carbon uptake during growth is accounted for SO_x emissions from biomass are significantly lower due to minimal sulfur content, benefiting local air quality [7].

3.2 Cost Implications for Textile Boilers

Fuel cost is a decisive factor for MSME-dominated textile clusters in India.

For MSME-scale textile units, fuel cost savings from biomass can be offset by seasonal availability and transport distances, emphasizing the need for localized supply-chain planning.

Table 4: Indicative Fuel Cost Comparison (India, 2023–24)

Fuel Type	**Typical Cost (₹/GJ)**	**Cost Stability**
Coal	350–500	Medium
Furnace Oil	900–1,200	Low (volatile)
Natural Gas	800–1,100	Low (import-linked)
Biomass (Agri-residues)	200–400	Medium–Low (seasonal)

Economic implication:

Biomass offers 20–50% lower fuel cost than coal and oil but suffers from seasonal availability, transport costs, and storage losses, which can offset savings if supply chains are weak.

The results indicate that while biomass offers lower lifecycle emissions and fuel cost advantages, its lower energy density and higher ash content impose operational and maintenance penalties, particularly for MSME-scale textile units.

3.3 Lifecycle Climate Impact

Lifecycle greenhouse gas (GHG) reduction potential varies widely depending on biomass source and logistics.

- **Agricultural residues:** 70–90% GHG reduction compared to coal.
- **Forestry biomass:** 0–50% reduction (depending on carbon payback period)
- **Energy crops:** Highly variable; may offer no short-term climate benefit

Carbon payback periods for woody biomass range from 44 to 104 years**,** making it unsuitable for near-term decarbonization targets in textiles.

3.4 Overall Engineering Trade-off

From an engineering standpoint:

Biomass is technically feasible for textile boilers and compatible with existing steam systems. It provides lower lifecycle emissions and fuel cost advantages, especially when agricultural residues are used. However, lower efficiency, higher fuel volumes, ash handling, and emission control requirements introduce operational complexity. Thus, biomass is best positioned as a transitional or partial decarbonization solution, ideally combined with energy efficiency improvements and other low-carbon heat sources such as solar thermal systems. Biomass is primarily derived from three major feedstock categories, listed here in order of increasing usage:

- Energy Crops – Plants grown specifically for their high biomass yield. Examples include woody crops like willow, poplar, and eucalyptus, cultivated mainly for their wood.
- Waste Biomass – Byproducts from agricultural production, food processing, and wood processing, as well as certain types of solid waste.
- Forestry Products – Biomass obtained through harvesting trees from forests.

Research suggests that energy crops may offer the largest theoretical supply potential among these categories. However, in practical terms, wastes and residues are the most viable feedstock for sustainable biomass. Unlike forestry products or large-scale energy crop cultivation, waste-based biomass avoids deforestation risks, reduces competition with food production, and offers the strongest potential to be genuinely carbon neutral, which shown below figure [8].

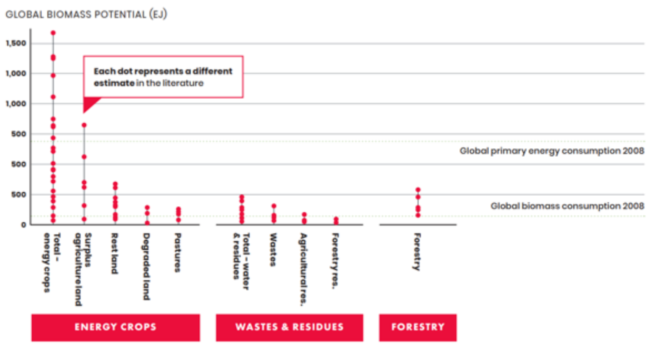

Figure 1: Estimates of biomass potential from three major feedstock sources.

Figure 1 illustrates that waste and residue-based biomass provide the most sustainable and immediately deployable feedstock, whereas energy crops and forestry biomass pose higher risks related to land use, carbon payback period, and ecological impact.

Biofuels are liquid fuels derived from biomass. Because they are in liquid form, they are primarily used in the transport sector. However, converting biomass into biofuels requires additional energy, and biofuels have limited or no applications for process heating in the textile industry, as we will discuss later.

By contrast, the direct use of biomass for industrial heating is a well-established technology. It is already widely used in industries such as food and beverages and pulp and paper, making biomass the largest renewable source of industrial heating today. In these industries, biomass is used to generate electricity or as fuel for air heaters, boilers, and ovens.
In the textile industry, biomass use would primarily focus on steam boilers and thermal oil boilers, which are essential for process heating.

The most common way to use biomass for heating is through direct combustion in boilers to produce steam. Two main types of biomass boilers are used in industry:

- **Fluidized Bed Boilers:** The most widely adopted type. In this system, biomass is burned within a hot bed of sand or other inert particles. An upward airflow of combustion air suspends the fuel-particle mix, creating fluid-like movement that ensures efficient combustion.
- **Fixed Bed Boilers:** In this design, combustion air enters from below a grate. Solid biomass fuel burns on the grate, with partial gasification occurring. The gases then undergo secondary combustion in a higher chamber, completing the process.

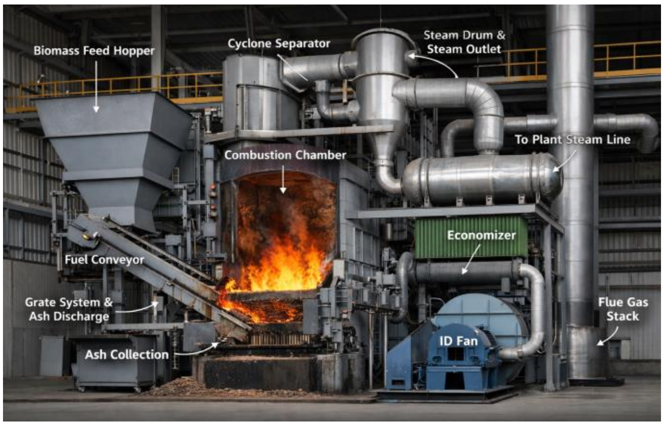

Figure 2: Industrial Biomass Boiler

Figure 2 demonstrates the complexity of industrial biomass boiler systems compared to fossil-fuel boilers, highlighting additional subsystems for fuel handling and ash removal that contribute to higher operational and maintenance demands.

As discussed earlier, biomass exists in many different forms, each with its own energy density, combustion behavior, and logistical requirements. This diversity makes it more complex to compare biomass directly with other fuel sources. Among the different options, agricultural residues are often considered the most sustainable source of biomass. To assess their potential, one key measure is the residue-to-crop ratio (RCR)—the amount of residue generated relative to the primary crop.

A World Bank report (2018), based on a survey in Vietnam, highlights this variation by presenting data on the RCR, moisture content, and lower heating value of different agricultural residues. Even within the same category of crop residue, these values can differ significantly, showing how variable agricultural biomass can be as an energy source [9].
In many cases, these residues require additional processing before they can be effectively used as biomass fuel for energy generation.

Table 5: characteristics of key agricultural residues

Agricultural Biomass Residue	Residue to Crop Ratio	Content	Net Calorific Value (MJ/kg residue)
Rice straw	0.33-2.15	12%	12.6
Rice husks	0.15-0.36	10.50%	13
Sugarcane trash	0.05-0.30	25%	12.5
Sugarcane bagasse	0.14-0.40	50%	7.5
Maize waste	1.0-3.8	16%	12.5
Maize cobs	0.2-0.5	17.60%	14.1
Maize husks	0.2-0.4	16%	12.5
Cotton stalks	2.76-4.25	12.50%	15

In principle, sustainable biomass refers to biomass that is carbon neutral and does not cause environmental harm when harvested. This is often seen as the best-case scenario. However, in reality, many if not most sources of biomass fail to meet this standard. Wood and wood-derived fuels, which dominate biomass use in many regions, are a good example [10]. According to IPCC guidelines, they are actually less efficient energy carriers than coal and often produce more CO_2 emissions per unit of energy. Scientific studies also show that while tree plantations and agroforestry can provide biomass, their long-term carbon sequestration potential is lower than that of natural forests left intact. Moreover, tree monocultures lack the broader ecosystem benefits of natural forests, such as supporting biodiversity and providing habitats for a wide range of species. This debate has sparked controversy in Europe. The inclusion of forest biomass under the EU's Renewable Energy Directive, which categorizes it as a renewable energy source with carbon benefits, has faced strong opposition. Critics argue that such categorization overlooks the real environmental costs. Despite this, woody biomass from forests remains the largest source of bioenergy in the EU, with over one-third of it coming directly from primary sources rather than recycled or waste wood [11].

One of the main criticisms of using woody biomass as a renewable energy source is the assumption that new tree growth can compensate for the carbon released when biomass is burned. In reality, the carbon payback period—the time it takes for newly planted trees to reabsorb the carbon emitted—can range from 44 to 104 years. This long timeframe casts doubt on whether woody biomass can serve as a meaningful short- or medium-term climate solution [12]. Research underscores this concern. A group of scientists has estimated that replacing fossil fuels with wood could actually lead to 2–3 times more carbon emissions per unit of energy by 2050. Similarly, a European Commission study found that only certain residues, such as slash (small branches and twigs), could deliver short-term climate benefits while supporting biodiversity. Other sources of woody biomass like stumps, whole trees, or forest-to-plantation conversions often harm ecosystems and fail to provide carbon benefits [13].

While some governments and organizations have introduced biomass sustainability certifications some voluntary, others mandatory these systems face significant implementation challenges. They are therefore far from a perfect solution for ensuring sustainable biomass sourcing.

4.0 Biofuels and the Textile Industry

Biofuels, which are liquid fuels derived from biomass, are mostly used in the transport sector. Key types include:

- Biogas/Renewable Natural Gas (RNG)
- Bioethanol
- Biodiesel

Among these, only biogas/RNG has potential relevance to the textile industry, but even then, its role is limited. Biogas can be produced from diverse sources such as agricultural biomass, animal waste, food-processing residues, or landfill methane. However, it is often produced onsite by industries like food processors because of the high costs of infrastructure and logistics [14]. This makes it less accessible for external users such as textile factories, thereby limiting its potential for decarbonization in the sector [14].

4.1 Strengths and Opportunities of Biomass

Despite its challenges, sustainably sourced biomass offers several opportunities:

Carbon Neutrality

Plants absorb CO_2 during growth, offsetting emissions released when burned. Under the right conditions, biomass combustion can reduce lifecycle greenhouse gas emissions by up to 90% compared to fossil fuels [15]. With the addition of carbon capture and storage (CCS) known as BECCS (bioenergy with CCS), biomass could even deliver carbon-negative energy. However, CCS remains expensive and underdeveloped, and in textiles, the CO_2 stream from boilers is too small to justify it today.

Waste Reduction & Circular Economy

Biomass derived from industrial byproducts (e.g., in pulp, paper, or food industries) can be a low-cost and sustainable heating fuel. In textiles, solid cotton waste (such as cottonseed or gin trash) could be converted into bioenergy, supporting onsite circularity [16]

Reliable Supply: Unlike wind and solar, biomass can provide a continuous energy source, making it attractive for industries that need steady heating.

Mature Technology: Biomass boilers are already a commercially proven technology, capable of achieving the high temperatures required for process heating in industries including textiles in multiple countries [17].

4.2 Technology-specific barriers

Bioenergy technologies (BETs) come in many forms and vary widely depending on several factors—like the type of raw materials they use (for example, wood, rice husks, cow dung), how long they last (short-, medium-, or long-term), what they're used for (cooking, heating, etc.), and how often they need maintenance (daily, weekly, monthly). Because of this diversity, and the uncertainty in how well these technologies actually perform, policymakers often find it challenging to develop effective strategies. The Ministry of New and Renewable Energy (MNRE) has tried to account for these differences in its policies and programs [18]. A breakdown of the specific challenges for each type of technology is below that.

Biomass-based energy systems face significant technical and operational challenges across gasification, combustion, and biogas pathways. In biomass gasification, limited commercial availability of 100% producer gas engines, inadequate gas cleaning systems, persistent tar formation, and strong dependence on biomass quality constrain reliable power generation—particularly at lower capacities. These issues are compounded by insufficient life-cycle operational experience and difficulties in grid integration, especially in rural areas where active grids and dedicated evacuation infrastructure are lacking. Biomass supply-chain limitations, including the absence of standardized practices for energy plantations, inadequate sizing and drying technologies, and poor moisture management, further affect system performance. Biomass combustion systems exhibit limited flexibility to fuel variability, challenges in flue gas cleaning, operational risks, and restricted availability at capacities below 2 MW. Similarly, energy plantation development is hindered by the lack of high-yield planting material and mechanized biomass handling methods. Biogas systems, while technically viable, show limited success in village interiors due to land and water constraints, performing better in peripheral or agricultural settings.

4.3 Challenges

The biggest challenge with biomass lies in whether its source is truly sustainable. While some forms of biomass are promoted as "carbon neutral," this claim is widely debated. For example, large-scale plantations for biomass have caused massive deforestation, releasing huge amounts of CO_2. In Southeast Asia, palm oil plantations are one of the leading drivers of rainforest and peatland destruction. Even though byproducts like palm kernel husks can be used as biomass fuel, the overall environmental damage often outweighs the benefits [19].

Growing energy crops also requires fertilizers, which themselves release large amounts of CO_2 during production, along with nitrous oxide (N_2O)—a greenhouse gas far more potent than CO_2. Poor land management can make things worse, as land used for energy crops often competes with land needed for food production. This creates risks for local food security, especially in resource-constrained regions. On top of that, competition from other industries drives up costs, reducing the economic attractiveness of biomass for textiles.
Transporting biomass adds another layer of emissions. Unlike natural gas, which moves efficiently through pipelines, biomass has to be hauled by trucks, trains, or ships—vehicles that run on fossil fuels. Harvesting with heavy diesel equipment also produces emissions that are often overlooked. When all of this is considered, biomass may not actually deliver on the promise of being a carbon-neutral energy source. In fact, according to the IPCC, burning biomass produces more CO_2 per unit of energy than coal.

Aside from CO_2, biomass combustion generates other pollutants such as volatile organic compounds, nitrogen oxides (NO_x), and particulate matter (PM). Burning biomass also leaves behind ash that contains toxic substances like PAHs, PCBs, and heavy metals. Disposal of this ash raises serious environmental concerns, especially in densely populated regions or countries with weaker environmental regulations. Another drawback is the variability in biomass moisture levels wet biomass produces less heat and burns less efficiently [19].

4.4 Engineering Performance and Operational Implications of Biomass Systems in Textile Industries

Boiler Performance in Textile Applications

Biomass-fired boilers used in textile industries are primarily designed to meet medium-pressure steam and thermal oil requirements for processes such as dyeing, bleaching, drying, and finishing. Typical operating pressures range from 8–25 bar, with steam generation capacities varying from 1 to 25 TPH, depending on plant scale.

Compared to fossil-fuel-fired boilers, biomass boilers generally exhibit lower combustion efficiency, typically in the range of 65–80%**,** largely due to higher fuel moisture content, heterogeneous fuel composition, and incomplete combustion. Fluidized bed boilers demonstrate superior performance relative to fixed bed systems, particularly in handling variable fuel sizes and moisture levels. Their uniform temperature distribution (750–900 °C) reduces clinker formation and improves combustion stability.

However, biomass boilers require larger furnace volumes and higher excess air ratios than coal or gas boilers, increasing capital cost and footprint an important constraint for space-limited textile mills, especially MSMEs.

4.5 Combustion Characteristics of Biomass Fuels

Biomass fuels differ significantly from fossil fuels in terms of volatile matter content, ash composition, bulk density, and moisture variability. Agricultural residues commonly used in India (rice husk, cotton stalks, bagasse) have volatile matter contents exceeding 60–70%**,** enabling rapid ignition but also leading to unstable flame characteristics.

High alkali and silica content in residues such as rice husk causes slagging, fouling, and ash agglomeration**,** particularly at higher operating temperatures. These phenomena reduce heat transfer efficiency and increase shutdown frequency. In contrast, woody biomass offers more stable combustion but raises sustainability and carbon payback concerns.

Fuel preprocessing such as drying, size reduction, and briquetting can significantly improve combustion efficiency but adds energy penalties and operational costs, reducing overall system attractiveness.

4.6 Operational Challenges in Textile Mills

Biomass systems introduce several complexities that are absent in conventional fossil-fuel boilers:

- **Fuel handling and storage:** Biomass fuels require large storage areas, controlled moisture conditions, and stringent fire safety measures.
- **Feed rate variability:** Fluctuations in fuel quality and feed rates lead to unstable steam output, adversely affecting process consistency, which is critical for textile quality control.
- **Start-up and load-following limitations:** Biomass boilers exhibit slower start-up times and limited load-following capability, making them less responsive than gas-fired systems.
- **Emissions control:** Emissions management is more demanding due to higher levels of particulate matter and unburned hydrocarbons.

4.7 Scalability and Industrial Integration

Scalability remains one of the key limitations of biomass systems in the textile sector. While large integrated textile parks can justify centralized biomass boilers**,** standalone small and medium textile units struggle due to:

- Irregular biomass supply
- Lack of economies of scale
- Higher per-unit energy costs
- Logistics and storage constraints

Biomass systems are therefore more suitable as partial or hybrid solutions, integrated with fossil fuels or solar thermal systems, rather than as complete replacements.
Engineering Perspective on Biomass Decarbonization Potential

From an engineering standpoint, biomass should be viewed as a transitional decarbonization option. Its effectiveness depends heavily on fuel quality control, boiler design optimization, and hybrid integration strategies. Without addressing combustion instability, maintenance intensity, and scalability constraints, large-scale adoption in the Indian textile sector will remain limited.

4.8 Strengths and Opportunities

On the other hand, solar thermal systems offer a very different set of advantages. Their adaptability whether using simple non-concentrating collectors or advanced concentrating technologies means they can be customized to meet many of the textile industry's heating needs.

The biggest benefit is that solar thermal delivers zero-emissions heating, helping companies meet stricter environmental regulations while cutting their carbon footprint. Since sunlight is free, fuel costs are eliminated. With supportive climate policies and growing financial incentives, solar thermal is becoming more economically viable. It also strengthens energy security by reducing dependence on imported fossil fuels and shielding industries from volatile fuel prices.

Another key strength is the maturity of solar thermal technology. It is already proven and can be integrated with existing manufacturing systems. Emerging solar thermal storage systems add even more potential, allowing excess solar heat to be stored and used at night or during cloudy periods. Ongoing R&D is focused on reducing costs and improving storage durability, making solar thermal an increasingly practical choice for industrial applications, including textiles [20].

5.0 The Integrated Bio refinery Concept for the Future

A bio refinery works much like a traditional oil refinery, but instead of fossil fuels, it uses biomass as its raw material. Through biological conversion processes, it produces a mix of outputs biofuels, value-added products, and platform chemicals making it a sustainable and versatile solution for the future. What makes the integrated bio refinery approach particularly powerful is its efficiency: it can simultaneously generate bio-based products as well as secondary energy carriers such as fuel, heat, and power [21].

In India, pilot projects have explored both conventional biofuels (like biodiesel and ethanol) and advanced biofuels (such as those from lignocellulosic biomass). However, producing them profitably remains a challenge without strong government policies and subsidies to support a sustainable market.

Europe offers a working example of this concept. There, integrated bio refineries have been successfully combined with existing industrial infrastructure to co-produce both value-added bio-based products and biofuels, maximizing the use of available biomass resources. This demonstrates how an integrated approach can turn waste into high-value streams while addressing four critical dimensions: availability, affordability, sustainability, and productivity [22]. India is now pushing forward with this vision through the launch of its "Mission Integrated Biorefineries." The mission aims to accelerate the development and demonstration of innovative solutions, with the ambitious goal of replacing at least 10% of fossil-based fuels, chemicals, and materials with bio-based alternatives within the next decade. A major milestone on this path is the commissioning of a 10 TPD capacity pilot plant in Panipat, Haryana, featuring the first indigenous technology for on-site integrated enzyme production a key step toward scaling up the country's bio economy.

6.0 Key Contributions of This Study

This study provides an engineering-oriented synthesis of biomass fuel utilization in the Indian textile industry, moving beyond predominantly descriptive and policy-driven discussions in existing literature. The key contributions of this work are summarized below:

- **Engineering-centric performance evaluation of biomass systems**
  The study systematically assesses biomass-based boiler systems from an engineering perspective, focusing on combustion behavior, thermal efficiency, operational stability, maintenance intensity, and scalability constraints relevant to textile process heating applications.
- **Integrated technical comparison with conventional fossil fuels**
  A structured comparative framework is developed to evaluate biomass fuels against conventional energy sources (coal, furnace oil, and natural gas) using technical, environmental, and operational indicators that directly influence textile manufacturing performance.
- **Identification of practical deployment constraints in industrial settings**
  The study highlights critical real-world limitations, including fuel heterogeneity, ash-related fouling, load-following constraints, and increased maintenance requirements—that are often underrepresented in existing studies but strongly affect industrial adoption decisions.

Together, these contributions provide a clearer basis for technology selection, system design, and informed policy alignment aimed at decarbonizing thermal energy use in the Indian textile sector.

7.0 Conclusions

India's bioenergy sector is showing steady growth, but progress remains relatively slow. As of 2022, biomass-based projects account for less than 3% of the nation's total power generation. In comparison, fossil fuels dominate with 58.2%, followed by solar (14.6%), hydro (12.7%), and wind (10.2%). Still, the potential is immense. Based on time-series analysis, India's biomass power potential is projected to reach 32,937.83 MWe by 2025–26 and 35,994.52 MWe by 2030–31. This can only be achieved through strategic planning to maximize the use of agricultural residues—the country produces about 990 MMT of agricultural biomass annually, of which 230 MMT is surplus and available for energy production. To unlock this potential, India must focus on:

- Formulating forward-looking policies and regulatory frameworks.
- Improving harvesting efficiency.
- Encouraging production of high-value, low-volume compounds.
- Strengthening supply chains, financing, and technology deployment.

Currently, India has 12 commercial compressed biogas (CBG) plants with a combined output of 18,461.7 tons per year—a figure far below the potential from surplus crop residues, animal waste, forest residues, press mud, spent wash, and municipal solid waste (MSW).

Among these, MSW offers a particularly promising pathway. Converting the organic fraction of MSW through anaerobic digestion and composting provides a low-cost renewable energy option while also reducing waste volumes. Rejects from composting can be diverted to waste-to-energy (WTE) plants for combustion, with the resulting ash safely landfilled. Such a system could divert up to 94% of MSW from landfills, out of the 29,427.2 tons generated daily across India.

In summary, India has tremendous potential to convert biomass into reliable, cost-effective, and environmentally sustainable energy. To realize this potential, however, immediate action is needed in:

- Efficient waste segregation, transport, and treatment
- Public awareness and education
- Financing mechanisms and R&D–industry collaboration
- Strong policy enforcement and system integration

By adopting these corrective measures, India can truly move from waste to wealth, advancing the vision of Atmanirbhar Bharat (self-reliant India) while addressing energy security and environmental sustainability.

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