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Review

High Impact Biomass Valorization for Second Generation Biorefineries in India: Recent Developments and Future Strategies for Sustainable Circular Economy

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Abstract: India's rapidly growing automobile industry has intensified the need for sustainable fuel alternatives to reduce dependency on imported fossil fuels and mitigate greenhouse gas (GHG) emissions. This study examines the potential of second-generation biorefineries as a comprehensive solution for efficient biomass valorization in India. With a projected bioethanol demand of 10,160 million liters by 2025 for India's 20% ethanol blending target, there is an urgent need to develop sustainable production pathways. The biorefinery approach enables simultaneous production of multiple valuable products, including bioethanol, biochemicals, and bioproducts, from the same feedstock, thereby enhancing economic viability through additional revenue streams while minimizing waste. This paper systematically analyzes available biomass resources across India, evaluates integrated conversion technologies (biochemical, thermochemical, and synergistic approaches), and examines current policy frameworks supporting biorefinery implementation. Our findings reveal that second-generation biorefineries can significantly contribute to reducing GHG emissions by up to 2.7% of gross domestic product (GDP) by 2030 while creating rural employment opportunities and strengthening energy security. However, challenges in supply chain logistics, technological optimization, and policy harmonization continue to hinder large-scale commercialization. The paper concludes by proposing strategic interventions to overcome these barriers and accelerate the transition toward a sustainable circular bioeconomy in India.

Keywords: bioethanol blending; biorefinery approach; biomass valorization; sustainable fuel production; circular economy; ethanol policy in India

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1. Introduction

The global energy landscape is undergoing a profound transformation driven by environmental concerns, resource depletion, and the need for sustainable development. Fossil fuels, which have powered economic growth for decades, are now recognized as major contributors to climate change through greenhouse gas (GHG) emissions. This environmental impact, coupled with the finite nature of fossil fuel resources, has intensified the search for renewable alternatives that can meet growing energy demands while minimizing ecological footprints. In this context, biomass has emerged as a promising renewable resource with significant potential to address multiple challenges simultaneously. Unlike fossil fuels, which take millions of years to form, biomass is produced through photosynthesis in a relatively short timeframe, converting atmospheric CO_2 into energy-rich organic compounds [1]. When these compounds are combusted, they release the stored energy and return CO_2 to the atmosphere, creating a carbon-neutral cycle that significantly reduces net GHG emissions compared to fossil fuels. Biomass currently accounts for approximately 14% of global energy consumption, with developing nations utilizing 38% of this energy, particularly in rural areas where access to conventional energy sources remains limited [2]. India, with its favorable climate and extensive agricultural activities, possesses abundant biomass resources that present significant opportunities for sustainable energy production and utilization.

India's vast agricultural landscape, spanning 1.78 million square kilometers [2], generates over 990 million metric tons of agricultural biomass annually [3]. This includes crop residues such as rice straw, wheat straw, sugarcane bagasse, and corn stover, which often remain unutilized or are burned in open fields, contributing to air pollution. Beyond agricultural residues, India's biomass resources encompass municipal solid waste (approximately 160,000 tons daily) [4], forest residues from 71 million hectares of forested land [5], industrial byproducts [6], and aquatic biomass such as algae [7,8], which are increasingly recognized for their biofuel potential.

Traditional approaches to biomass utilization have focused primarily on single-product systems, such as dedicated bioethanol or biogas production facilities. However, these approaches often fail to maximize the value of biomass feedstocks and struggle with economic viability. The biorefinery concept addresses these limitations by enabling the simultaneous production of multiple products—including biofuels, biochemicals, and biomaterials—from the same raw materials [9]. This integrated approach enhances the economic sustainability of biofuel industries by generating additional revenue streams, minimizing waste, and facilitating more efficient resource utilization.

Valorization represents the critical process of converting biomass into valuable products through various conversion pathways [10]. Recent advancements in hydrothermal and biological treatments have significantly enhanced the efficiency of biomass valorization, enabling higher yields of desired products while minimizing environmental impacts [9,11]. These technologies are particularly relevant for second-generation biorefineries, which utilize non-food feedstocks such as agricultural residues, forestry waste, and dedicated energy crops [12], thereby avoiding the food-versus-fuel debates associated with first-generation biofuels. In the context of biomass feedstocks, various materials exhibit differing levels of productivity, contributing significantly to multiple industries. As detailed in the results section, microalgae (Nannochloropsis), used in biodiesel and renewable energy production, show an average productivity of 10.7 m^3/ha/year, with the potential to reach up to 36.3 m^3/ha/year [13]. Switchgrass, utilized for bioenergy and biofuels, has a productivity range of 5.1 to 8.6 Mg/ha/year [14]. Soybean residues, primarily used for biogas production, offer 384.5 m^3/ha/year for biogas [15]. Woody biomass, including pine and eucalyptus, which serve various industries such as bioenergy, pulp and paper, and aviation fuels, can yield up to 115 Mg/ha over a 10-year period [16]. Corn stover and switchgrass, used for bioenergy in pelletized fuels, have unspecified productivity, but their energy density increases when blended [17]. Forest residues from logging, contributing to bioenergy and district heating, can generate up to 40 TWh/year between 2030 and 2050 [18]. These results highlight the varying productivity of biomass feedstocks, emphasizing their potential for large-scale utilization in renewable energy and bio-based product industries.

The implementation of second-generation biorefineries in India faces several challenges, including logistical issues in biomass collection and transportation, technological barriers in conversion processes, and policy frameworks that may not fully support integrated biorefinery approaches. Addressing these challenges requires a comprehensive understanding of available biomass resources, conversion technologies, and policy mechanisms that can foster sustainable biorefinery development.

This paper systematically analyzes second-generation biorefinery approaches for efficient biomass valorization in India. It assesses the availability and characteristics of various biomass feedstocks across different regions, evaluates biochemical, thermochemical, and synergistic technologies for biomass conversion, and examines policy frameworks and institutional mechanisms supporting biorefinery development. Additionally, it identifies challenges and proposes strategies to overcome barriers to commercial implementation while analyzing the potential environmental, economic, and energy impacts of widespread biorefinery adoption within a circular economy framework.

2. Biorefinery Technologies Involved in Biomass Valorization

Second-generation biorefineries mainly utilize non-food feedstock, namely crop residues, agro-processing waste, algae, aquatic plants, and energy crops with a focus on addressing the food security issues allied with first-generation biorefineries [12]. It produces biofuels, bio-products, and biochemicals in an efficient manner [9]. The technologies involved in second-generation biorefineries are biochemical and thermochemical conversion technology (Figure 1) and synergistic approaches for effectively utilizing the resource in a sustainable way.

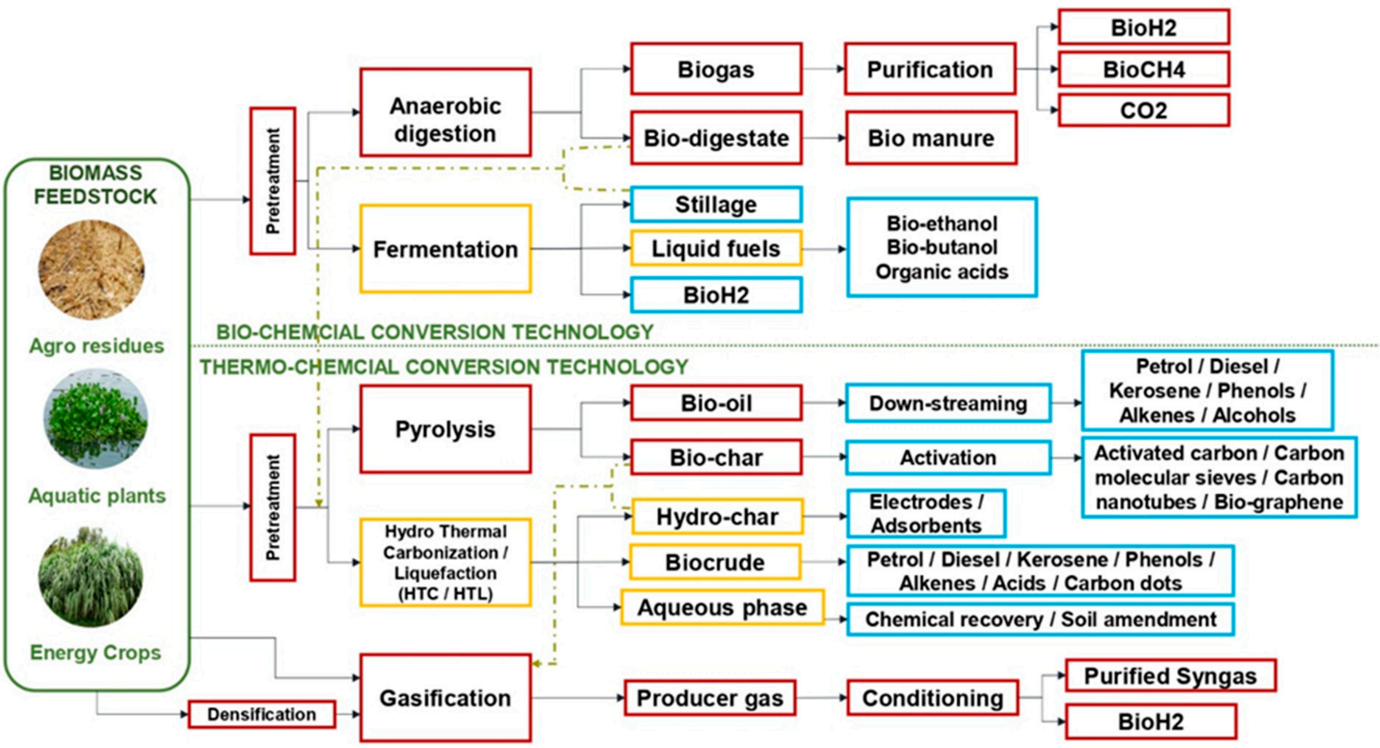

Figure 1. Biorefinery approach to biomass valorization.

2.1. Biochemical Conversion Technology

Biochemical conversion technologies emphasize exploiting biological processes such as fermentation and anaerobic digestion for biomass valorization [19]. The fermentation of pretreated biomass results in the production of biohydrogen, bioethanol, biobutanol, organic acids, biopolymers, and biochemicals upon down-streaming [20]. Anaerobic digestion converts biomass into biogas and bio-digestate. Biogas is a mixture of methane, carbon dioxide, traces of H_2S, and water vapor. This can be purified via steam reforming or the pressure swing method to synthesize biomethane, biohydrogen, and carbon dioxide for commercial applications. The bio-digestate can be used a solid or liquid bio-manure for agriculture as it a good soil amendment material [21]. These technologies are an integral part of second generation biorefineries, allowing them to produce liquid biofuels (bioethanol, biobutanol), organic acids, biochemicals, and biohydrogen, even though they require costly pretreatment operations. The biogas production from biomass is a highly suitable and eco-friendly technology. Pretreatment of wet biomass can be ignored, and high fibrous material requires rigorous pretreatment for the effective digestion of the materials. Bioethanol and biogas production from biological processing is a proven technology in second-generation biorefineries [22].

2.2. Thermochemical Conversion Technology

Thermochemical conversion technology utilizes heat, resulting in chemical reactions of biomass to convert into bioenergy, biofuels, and bioproducts. Combustion, pyrolysis, and gasification are the basic thermo-chemical conversion technologies [23]. Hydrothermal Carbonization (HTC) and hydrothermal Liquefaction (HTL) fall under the label of advanced technologies. Pyrolysis is an anaerobic process that converts biomass into bio-oil, biochar, and pyrogas (Syngas) in the presence of heat. The biochar is used for bioenergy, soil amendment, and as an adsorbent. Bio-oil is used as a biofuel and bio-lubricant in industry [24]. In the gasification process, biomass is partially oxidized to synthesize syngas. Syngas is a mixture of carbon monoxide, carbon dioxide, hydrogen, and hydrocarbons, which can be streamed to produce biohydrogen, liquid fuels, etc. [25]. HTC converts wet biomass into a carbon-dense solid material called hydrochar, along with an aqueous phase and biocrude, under subcritical water conditions. It operates under high pressure and moderate temperature in the range of 2–10 MPa and 180–250 °C, respectively. Subcritical water is liquid water under high temperature and pressure, above normal boiling conditions but below its critical point (T: 100–374.2 °C and P: 0.1–22.1 MPa) [26]. HTL converts wet biomass into a liquid material called biocrude, along with hydrochar and an aqueous phase, under subcritical and supercritical water conditions. This process involves high pressure (10–25 MPa) and high temperature (250–400 °C). Supercritical water is obtained when water exceeds its critical point (Tc: 374.2 °C and Pc: 22.1 MPa). HTC is carried out under subcritical water conditions, while HTL operates under subcritical conditions and can reach supercritical water conditions [27]. The biocrude can be refined to produce petrol, diesel, kerosene, alkenes, phenols, acids, and carbon dots. The hydro-char can be utilized as an electrode, as an adsorbent, and as bio-coal. The aqueous phase can be utilized as a bio-fertilizer, as it contains more nutrients, to grow algae, to recover chemicals, or as a soil amendment material. In general, thermochemical conversion technologies provide litheness in utilizing heterogenous kinds of biomass with higher conversion efficiency [28]. Table 1 details the use of several primary and secondary feedstocks through various biorefinery technologies to yield bioproducts and co-products.

Table 1. Biorefinery Technologies for Biomass Utilization and Value Addition.

Primary Feedstock	Secondary Feedstock	Technology	Products	Co-Products	Reference
Corn Stover	Food waste, crop residues	Fermentation	Bioethanol, Bio-based chemicals	CO_2, Furfural, Lignin	[29–32]
Sugarcane Bagasse	Rice husk, coconut shell	Fermentation	Bioethanol, Biobutanol	Lignin, Xylitol, Acetic acid	[1,33,34]
Paddy Straw	Wheat straw, maize stalks	Fermentation	Bioethanol, Biomethane	Lignin, Animal Feed	[35,36]
Poplar	Willow, Eucalyptus	Fermentation	Bioethanol, Acetic acid	Lignin, Biochar	[37–39]
Cocoa Pods	Coffee husks, banana stems	Fermentation	Biochemical, Organic acids	Liquor	[40,41]
Food Waste	Kitchen waste	Fermentation, Anaerobic Digestion	Bioethanol, organic acids	Biogas, Organic Fertilizer	[42–44]
Coconut Shell	Kernel shells, paddy husk	Pyrolysis	Biochar, Bio-oil, Activated carbon	Pyrogas	[45]
Water Hyacinth	Duckweed, algae	Pyrolysis	Bio-oil, Biochar	Pyrogas, Bio-fertilizer	[46–48]
Willow	Miscanthus, Poplar	Pyrolysis, gasification	Syngas, Biochar, Bio-oil	Heat, Power	[49–52]
Wood	Agricultural residues, sawdust, bark	Pyrolysis, Gasification	Bio-oil, Biochar, Syngas	Biochar, Heat, Power	[53–56]
Switchgrass	Wood chips, wheat straw	Pyrolysis, Gasification	Bio-oil, Syngas	Biochar, Electricity	[57–62]
Microalgae	Seaweed, wastewater	Algae-based Biorefinery	Biodiesel, Bioethanol	Animal Feed, Biochar	[63–66]

2.3. *Synergistic Approach*

Second-generation biorefineries gradually explore synergistic approaches that integrate both biochemical and thermochemical conversion technologies to valorize biomass effectively. For example, bio-digestate from anaerobic digestion can be used as a feedstock to produce biochar or hydrochar through pyrolysis or through the HTC process, respectively. Syngas produced from gasification can further be fermented to produce liquid biofuels. The aqueous phase of the HTL process can be utilized to cultivate algae. Biochar from the pyrolysis process can be used as a feedstock in gasification to produce carbon rich syngas. These synergistic approaches result in higher carbon utilization efficiency, minimize wastage, and produce highly valuable bio-products. It also reduces the capital cost and operational cost alongside higher energy and mass closure and paves the way for the circular economy [67–70].

3. Pros and Cons of Biorefinery Approaches

The execution of second-generation biorefineries comes with various advantages and challenges. Table 2 gives the pros and cons of different second-generation biorefineries. The main advantage of second-generation biorefineries is their dependence on non-food biomass; this promotes food security by utilizing underutilized and plentiful biomass. It also addresses the problem of waste management and environmental issues in the disposal of waste products [71]. The other main advantage is that it addresses the reduction of GHG emissions compared to conventional fossil fuels. It also produces bio-based products, namely bio-char, bioethanol, bio-diesel, biochemicals, and biopolymers, and also produces heat and power, enabling the circular economy [72]. This also paves the way for rural employment, produces additional income for farmers, and reduces dependency on fossil fuels [73].

Second-generation biorefineries also faces challenges like the construction of the plant, as this involves high investment and operational costs. The heterogenous nature of biomass complicates the conversion of biomass into bioenergy and biofuels [74]. The logistics, seasonal availability, and varied composition of biomass also affects the conversion efficiency and quality of the products. The pretreatment of biomass for biorefinery processes, as well as downstream and upstream process, needed to obtain high quality material are an additional hindrance for biorefineries. Non-utilization or non-recovery of by-products can cause environmental problems [75]. For example, pyrogas from the biochar production process and tar from the syngas production process are very harmful if not recovered and utilized properly. The main hinderance is the marketability and wide adoption of these products instead of conventional products.

Table 2. Pros and cons of different second generation biorefineries.

Technology	Pros	Cons	Technology Ready Level	Reference
Anaerobic Digestion	• Yields biogas and bio-digestate (fertilizer) • Quick adoption to manage waste effectively	• Low suitability for heterogenous waste • Purification of biogas is required to meet the energy density of fossil fuel	7–9	[76,77]
Fermentation	• Yields high-value bio-chemicals and bioethanol • High adaptability of biomass feedstock	• Costlier pretreatment operation • Sensitive technology as it involves microbes	5–7	[78,79]
Pyrolysis	• Feedstock flexibility • Easier to integrate with existing facility • Energy efficient technology	• Higher investment • Feedstock preparation tedious • Problematic condensation and down-streaming operation	5	[80]

Table 2. *Cont.*

Technology	Pros	Cons	Technology Ready Level	Reference
Gasification	• Flexibility in feedstock • Energy efficient to produce syngas • Combined heat and power (CHP) production is possible	• High investment • Requirement of uniform size and dried biomass • Tar, slag issues	6–7	[80]
Hydrothermal Carbonization (HTC)	• No requirement of drying wet biomass • Biocrude, biochar, syngas can be produced • Low temperature operation	• Energy intensive operation • High pressure required • Higher investment	5–7	[81,82]
Hydrothermal Liquefaction (HTL)	• No requirement of drying wet biomass • Biocrude equivalent to crude oil	• Energy intensive operation • High pressure required • Higher investment	4–6	[80,83]
Algae-Based Biorefinery	• Algae can be cultivated in wastewater • Higher biomass yield per unit area • Biodiesel from lipids and animal feed from protein • High carbon sequestration	• High water required if it is cultivated in fresh water • Energy intensive harvesting and drying process	6–7	[84–86]
Integrated Biorefineries	• Multiple bioproducts • Circular economy	• Complex design • Higher investment and operating cost	5–6	[81,87]

4. Assessment of Energy and Bioproducts from Biomass

Second-generation biorefineries deliver a substitute to first-generation feedstocks to produce energy and high value bioproducts in a sustainable way and without affecting food security. The bio-products include platform chemicals, bioplastics, bio-based composites, bio-polymers, and biochar. The moisture, bulk density, energy value, and biochemical composition, namely cellulose, hemicellulose, and lignin content, determine the conversion efficiency and bio-energy potential of biomass [88,89]. Bioenergy products have extensive applications, including as thermal energy, transportation fuels, and for power production [90]. The process also yields high-value bioproducts, namely bio-digestate, biochar, bio-active compounds, organic acids, bioplastics, biopolymers, aromatic chemicals, adhesives, and carbon fibers [91]. Table 3 exemplifies biomass properties with estimated energy generation potential and possible bioproducts using the tool developed by Tamil Nadu Agricultural University [92].

Table 3. Energy generation potential and bioproducts from various biomass [92].

	Biomass	Properties	Technology	Estimated Energy Generation Potential	Bioproducts
Crop residues	Crop straws (Paddy straw, wheat straw, barley straw)	Cellulose, %: 30–45 Hemicellulose, %: 20–25 Lignin, %: 10–20 Ash content, %: 4–20 Moisture, %: 8–12 Energy value, MJ/kg: 10–16 Bulk density, kg/m^3: 50–120	Anaerobic digestion	Biogas: 0.3–0.6 m^3 per kg volatile solids	Bio-digestate slurry
			Fermentation	Bioethanol: 0.3–0.5 L per kg dry biomass	Biocompost, animal feed, biochemicals
			Pyrolysis	Biooil: 0.2–0.3 L per kg dry biomass Biochar: 0.2–0.25 kg per kg dry biomass	Pyrogas
			Gasification	Syngas: 1–1.5 m^3 per kg dry biomass	Biochar
			HTC/HTL	Biocrude: 0.3–0.5 L per kg dry biomass Hydrochar: 0.3–0.4 kg per kg dry biomass	Aqueous phase
	Crop stalks (cotton stalk, millet stalk, corn stalk, pea stalk)	Cellulose, %: 30–45 Hemicellulose, %: 15–30 Lignin, %: 10–25 Ash content, %: 3–8 Moisture, %: 8–14 Energy value, MJ/kg: 14–18 Bulk density, kg/m^3: 50–150	Anaerobic digestion	Biogas: 0.3–0.7 m^3 per kg volatile solids	Bio-digestate slurry
			Fermentation	Bioethanol: 0.25–0.45 L per kg dry biomass	Animal feed, organic acids, biochemicals
			Pyrolysis	Biooil: 0.2–0.35 L per kg dry biomass Biochar: 0.25–0.3 kg per kg dry biomass	Pyrogas
			Gasification	Syngas: 1–1.5 m^3 per kg dry biomass	Biochar
			HTC/HTL	Biocrude: 0.3–0.5 L per kg dry biomass Hydrochar: 0.3–0.5 kg per kg dry biomass	Aqueous phase
	Husks and Shells (Coconut, sunflower, coffee, paddy husks and nut shell)	Cellulose, %: 25–45 Hemicellulose, %: 15–25 Lignin, %: 15–45 Ash content, %: 0.5–5 Moisture, %: 5–15 Energy value, MJ/kg: 13–20 Bulk density, kg/m^3: 80–400	Anaerobic digestion	Biogas: 0.2–0.4 m^3 per kg volatile solids	Bio-digestate slurry
			Fermentation	Bioethanol: 0.1–0.25 L per kg dry biomass	Stillage, animal feed
			Pyrolysis	Biooil: 0.3–0.5 L per kg dry biomass Biochar: 0.25–0.35 kg per kg dry biomass	Pyrogas
			Gasification	Syngas: 1–1.5 m^3 per kg dry biomass	Biochar
			HTC/HTL	Biocrude: 0.4–0.6 L per kg dry biomass Hydrochar: 0.3–0.5 kg per kg dry biomass	Aqueous phase

Table 3. *Cont.*

Biomass		Properties	Technology	Estimated Energy Generation Potential	Bioproducts
Agro Processing Residues	Fruit and Vegetable Waste (Peels, pomace, seeds)	Carbohydrates, %: 20–40 Lipids, %: 2–40 Ash content, %: 2–8 Moisture, %: 10–90 Energy value, MJ/kg: 10–25 Bulk density, kg/m^3: 250–800	Anaerobic digestion	Biogas: 0.2–0.4 m^3 per kg volatile solids	Bio-digestate
			Fermentation	Bioethanol: 0.1–0.25 L per kg dry biomass	Bio-composites, biopolymers
			Pyrolysis	Biooil: 0.3–0.5 L per kg dry biomass Biochar: 0.25–0.35 kg per kg dry biomass	Pyrogas
			Gasification	Syngas: 1–1.5 m^3 per kg dry biomass	Biochar
			HTC/HTL	Biocrude: 0.3–0.5 L per kg dry biomass Hydrochar: 0.4–0.6 kg per kg dry biomass	Bioactive compounds
	Oil industry (Fruit bunches, fronds, oil cake)	Lignin, %: 5–25 Ash content, %: 4–20 Moisture, %: 12–60 Energy value, MJ/kg: 14–20 Bulk density, kg/m^3: 100–600	Anaerobic digestion	Biogas: 0.3–0.5 m^3 per kg volatile solids	bio-compost, bio-digestate
			Fermentation	Bioethanol: 0.1–0.25 L per kg dry biomass	Bioplastic, animal feed
			Pyrolysis	Biooil: 0.3–0.6 L per kg dry biomass Biochar: 0.2–0.35 kg per kg dry biomass	Pyrogas
			Gasification	Syngas: 1–1.5 m^3 per kg dry biomass	Biochar
			HTC/HTL	Biocrude: 0.3–0.5 L per kg dry biomass Hydrochar: 0.3–0.6 kg per kg dry biomass	Phenols, biochemicals
	Brewery and Distillery Waste (Spent grain, distiller's dried grains)	Cellulose, %: 17–30 Hemicellulose, %: 15–35 Lignin, %: 10–18 Lipids, %: 5–12 Moisture, %db: 8–12 Moisture, %wb: 70–80 Energy value, MJ/kg: 10–12 Bulk density, kg/m^3: 200–300	Anaerobic digestion	Biogas: 0.3–0.5 m^3 per kg volatile solids	Bio-digestate
			Fermentation	Bioethanol: 0.1–0.25 L per kg dry biomass	Biocompost
			Pyrolysis	Biooil: 0.3–0.5 L per kg dry biomass Biochar: 0.2–0.4 kg per kg dry biomass	Animal feed
			Gasification	Syngas: 1–1.5 m^3 per kg dry biomass	Biochar
			HTC/HTL	Biocrude: 0.3–0.5 L per kg dry biomass Hydrochar: 0.3–0.5 kg per kg dry biomass	Biochemicals, phenols

Table 3. *Cont.*

Biomass		Properties	Technology	Estimated Energy Generation Potential	Bioproducts
Energy Crops	Perennial Grasses (Switchgrass, miscanthus, Napier grass)	Cellulose, %: 30–50 Hemicellulose, %: 20–30 Lignin, %: 10–25 Ash content, %: 1–8 Moisture, %: 10–20 Energy value, MJ/kg: 15–19 Bulk density, kg/m^3: 50–150	Anaerobic digestion	Biogas: 0.3–0.5 m^3 per kg volatile solids	Organic acids, Bio-digestate
			Fermentation	Bioethanol: 0.2–0.35 L per kg dry biomass	Biocompost
			Pyrolysis	Biooil: 0.2–0.4 L per kg dry biomass Biochar: 0.2–0.3 kg per kg dry biomass	Pyrogas
			Gasification	Syngas: 1–1.5 m^3 per kg dry biomass	Biochar
			HTC/HTL	Biocrude: 0.2–0.4 L per kg dry biomass Hydrochar: 0.4–0.6 kg per kg dry biomass	Biochemicals, nutrients
	Woody Crops (Willow, Casuarina, eucalyptus)	Cellulose, %: 40–50 Hemicellulose, %: 25–30 Lignin, %: 20–30 Ash content, %: 0.5–3 Moisture, %: 10–15 Energy value, MJ/kg: 17–20 Bulk density, kg/m^3: 180–350	Anaerobic digestion	Biogas: 0.2–0.4 m^3 per kg volatile solids	Bio-digestate
			Fermentation	Bioethanol: 0.15–0.25 L per kg dry biomass	Pharmaceuticals
			Pyrolysis	Biooil: 0.2–0.4 L per kg dry biomass Biochar: 0.3–0.4 kg per kg dry biomass	Aromatic oils, pyrogas
			Gasification	Syngas: 1–1.5 m^3 per kg dry biomass	Biochar
			HTC/HTL	Biocrude: 0.2–0.4 L per kg dry biomass Hydrochar: 0.4–0.6 kg per kg dry biomass	Liquid fertilizer
	Non-edible plant (jatropha)	Cellulose, %: 35–45 Hemicellulose, %: 20–30 Lignin, %: 25–35 Ash content, %: 4–10 Moisture, %: 8–14 Energy value, MJ/kg: 18–22 Bulk density, kg/m^3: 200–300	Anaerobic digestion	Biogas: 0.3–0.5 m^3 per kg volatile solids	Bio-digestate
			Fermentation	Bioethanol: 0.12–0.20 L per kg dry biomass	Bioplastics
			Pyrolysis	Biooil: 0.2–0.4 L per kg dry biomass Biochar: 0.3–0.4 kg per kg dry biomass	Pyrogas
			Gasification	Syngas: 1–1.5 m^3 per kg dry biomass	Biochar
			HTC/HTL	Biocrude: 0.2–0.4 L per kg dry biomass Hydrochar: 0.4–0.5 kg per kg dry biomass	Nutraceuticals, biochemicals

Table 3. *Cont.*

	Biomass	Properties	Technology	Estimated Energy Generation Potential	Bioproducts
Aquatic biomass	Algae (microalgae and macroalgae)	Cellulose, %: 10–20 Hemicellulose, %: 5–15 Lignin, %: <1 Ash content, %: 10–40 Moisture, %wb: 80–90 Moisture, %db: 10–20 Energy value, MJ/kg: 10–25 Bulk density, kg/m^3: 100–300	Anaerobic digestion	Biogas: 0.2–0.4 m^3 per kg of biomass	Bio-digestate
			Fermentation	Bioethanol: 0.1–0.2 L per kg biomass	bioplastics
			Pyrolysis	Biooil: 0.1–0.3 L per kg biomass Biochar: 0.2–0.3 kg per kg biomass	Nutraceuticals
			Gasification	Syngas: 1–1.5 m^3 per kg biomass	Biochar
			HTC/HTL	Biocrude: 0.3–0.5 L per kg biomass Hydrochar: 0.3–0.5 kg per kg biomass	Nutrient recover, chemicals
	Water hyacinth and duckweed (aquatic plants)	Cellulose, %: 15–40 Hemicellulose, %: 10–30 Lignin, %: 1–20 Ash content, %: 10–25 Moisture, %wb: 80–95 Moisture, %db: 5–20 Energy value, MJ/kg: 10–18 Bulk density, kg/m^3: 80–250	Anaerobic digestion	Biogas: 0.2–0.4 m^3 per kg of biomass	Bio-digestate
			Fermentation	Bioethanol: 0.1–0.2 L per kg biomass	Organic acids
			Pyrolysis	Biooil: 0.1–0.3 L per kg biomass Biochar: 0.2–0.3 kg per kg biomass	Pyrogas, biochemicals
			Gasification	Syngas: 1–1.5 m^3 per kg biomass	Biochar
			HTC/HTL	Biocrude: 0.3–0.6 L per kg biomass Hydrochar: 0.3–0.5 kg per kg biomass	Biochemicals, nutrients

5. Policy Framework for Supporting Biorefinery Development

India’s biorefinery development began in response to the 1970s oil crisis, which spurred the search for alternative renewable energy sources. In the 1980s, the government established the Commission on Additional Sources of Energy under the Department of Science and Technology, which later became the Department of Conventional Energy in 1982. A significant development came in 1987 with the creation of the Indian Renewable Energy Development Agency, which played a key role in advancing renewable energy projects [93]. The National Policy on Biofuels, introduced in 2018, serves as the cornerstone for India’s biorefinery strategy. It categorizes biofuels into basic, advanced, and third-generation types and sets ambitious targets, such as a 20% ethanol blend in petrol and a 5% biodiesel blend by 2030. The policy also expands the range of feedstocks for biofuel production, including damaged food grains and lignocellulosic biomass [94].

To promote lignocellulosic biorefineries, the JI-VAN Initiative was launched, providing financial aid and fostering technological advancements [95]. Measures such as Viability Gap Funding (50,000 million INR over six years), 100% foreign direct investment allowances, and central tax exemptions support these efforts. Additionally, the Minimum Purchase Price mechanism ensures the commercial feasibility of bioethanol and biodiesel [96].

India's institutional framework for biofuels operates on multiple levels, with the National Biofuel Coordination Committee, led by the Prime Minister, at the helm. The Biofuel Steering Committee, reporting to the Cabinet Secretary, provides further support. At the regional level, biofuel boards are responsible for overseeing the implementation of biofuel initiatives, though coordination between states continues to present significant challenges [97,98].

Several ministries contribute to the policy's execution [96]:

- Ministry of New and Renewable Energy (MNRE): Formulates overarching policies and provides research support.
- Ministry of Petroleum and Natural Gas (MoPNG): Oversees marketing, pricing, and procurement.
- Ministry of Agriculture (MoA): Conducts feedstock research.
- Ministry of Rural Development (MoRD) and Ministry of Panchayati Raj (MoPR): Promote Jatropha and other plantation initiatives on wastelands.
- Ministry of Science and Technology (MoS&T): Focuses on non-edible oil feedstocks.
- Ministry of Environment and Forests (MoEF): Monitors environmental impacts.
- Ministry of Finance (MoF): Provides financial incentives.

This integrated framework ensures a comprehensive approach to biofuel development, though better coordination between central and state policies is essential.

India's agricultural sector generates substantial crop residues, often managed through open burning, contributing to air pollution. The National Policy for Management of Crop Residue (NPMCR) 2014 promotes in situ residue management technologies, satellite monitoring, and financial support for farmers. However, implementation has been limited to states such as Punjab, Haryana, and Rajasthan.

The National Green Tribunal's ban on crop residue burning in four states and the promotion of mechanized solutions, such as turbo happy seeders and Super-Straw Management Systems, have mitigated residue burning to some extent. Despite this, challenges persist, with significant residues still burned; 50% of Punjab's and 16.9% of Haryana's rice straw residues were burned in situ during 2018–2019 [99].

Central and state governments have initiated several policies to promote bioenergy from crop residues:

- Punjab's 2012 Energy Policy targeted 600 MW of biomass power by 2022 but achieved only 62.5 MW by 2020.
- Haryana's 2018 Bioenergy Policy aimed for 150 MW but showed limited progress.

Central initiatives include biomass co-firing in coal plants and lignocellulosic ethanol plants developed by Indian Oil Corporation and Hindustan Petroleum. These plants are projected to utilize 57.7 Mt of crop residues annually, leaving a surplus of 120 Mt unaddressed [99].

6. State-Level Bioenergy Development Initiatives

State-level efforts in bioenergy development remain uneven. States like Gujarat and Uttar Pradesh are pioneering innovative policies. Gujarat's Waste-to-Energy Policy and Uttar Pradesh's Bioenergy Development Board exemplify progressive approaches to bioenergy. Conversely, states such as Jharkhand and Chhattisgarh have limited diversification in bioenergy projects. Table 4 summarizes key state-level bioenergy initiatives.

Table 4. State-wise Summary of Bioenergy Development in India [96,100].

State/Union Territory	Key Activities and Initiatives	Remarks	Source
Punjab	Biogas from agro-waste, gasification, co-generation in sugar mills.	Proactive state with remarkable agro-waste energy production.	[101]
Haryana	Biofuels, bioenergy, and biogas programs, along with both grid-connected and off-grid initiatives.	Programs are well-directed and regularly upgraded.	[102]
Uttar Pradesh	Bioenergy Development Board; biogas, biodiesel, and bioethanol missions.	Effective grassroots-level programs.	[103]
Rajasthan	Biomass power, biogas, forest department involvement.	Policies need updating but cumulative efforts are reliable.	[104]
Gujarat	Waste-to-Energy Policy, biomass power, co-generation projects.	Proactive state; innovative waste-to-energy policy.	[105]
Madhya Pradesh	Grid-connected and off-grid biomass projects.	Significant private-sector involvement.	[106]
Jharkhand	Biogas and biomass power programs.	Limited diversification in bioenergy projects.	[107]
Chhattisgarh	Policy-based incentives for bioenergy.	Information on bioenergy options is limited.	[108]
Telangana	Biomass and biogas programs, spanning from cooking applications to megawatt-scale power generation.	Appreciable efforts for rural and urban regions.	[109]
Andhra Pradesh	Biomass-based captive power in sugar mills.	Active in bioenergy development.	[110]
Karnataka	Biogas, combustion, and co-generation schemes.	Well-planned bioenergy development direction.	[111]
Tamil Nadu	Waste-to-energy, biogas, and gasification projects.	Effective grid-connected urban initiatives.	[112]
Maharashtra	Incentives for biomass briquettes and waste-to-energy projects.	Comprehensive decentralized bioenergy policy.	[113]
Odisha	Improved cook stoves, biomass gasification.	Cumulative incentive-based schemes.	[114]
West Bengal	Biogas production, village energy security programs.	Significant urban MSW-to-energy efforts.	[115]
Tripura	Biogas plants and improved cook stoves (Unnat Chulha).	Ground-level initiatives are commendable.	[116]
Sikkim	Renewable energy nodal agency.	Limited information on bioenergy activities.	[117]
Nagaland	Financial support for Unnat Chulha and NBMMP.	Focused on grassroots-level clean energy.	[118]

Table 4. *Cont.*

State/Union Territory	Key Activities and Initiatives	Remarks	Source
Meghalaya	Subsidies for Unnat Chulha and NBMMP.	Basic bioenergy initiatives.	[119]
Kerala	Biogas plant setups under NBMMP.	Well-organized renewable energy programs.	[120]
Assam	Biogas and biomass gasification programs.	High potential for bioenergy.	[121]
Chandigarh	MSW-to-energy projects.	Efficient urban waste management for energy.	[122]

The framework for biorefinery development in India emphasizes technological advancements to support the biofuel sector. Key initiatives include the promotion of pilot projects aimed at testing and optimizing biorefinery processes. These pilot projects act as a testing ground for refining technologies and scaling up production, laying the groundwork for broader industrial applications. Moreover, the framework fosters industry-academia partnerships, which play a pivotal role in advancing research and development. Collaboration between academic institutions and industrial players ensures the seamless transfer of knowledge and the integration of cutting-edge innovations into practical applications. Additionally, international collaborations have been prioritized to facilitate the transfer of global expertise and advanced technologies, further bolstering the sector's growth. Specific focus has been placed on enzyme development and the creation of indigenous technologies, which are critical for enhancing the efficiency and sustainability of biofuel production processes [123,124].

Despite these advancements, several challenges persist, particularly in infrastructure development and technology optimization. Many biorefineries face hurdles in establishing the necessary infrastructure to support large-scale operations. Technological refinement is another pressing issue, as efforts to improve efficiency and scalability remain ongoing. Nonetheless, the framework has made notable achievements, including the establishment of multiple 100 Kiloliters per Day commercial-scale biorefinery plants. These facilities demonstrate the feasibility of large-scale biofuel production, marking a significant step forward for the sector. Furthermore, the initiatives have yielded substantial environmental benefits, such as a reduction in crop burning incidents, which helps mitigate air pollution and aligns with broader environmental sustainability goals. Another critical outcome is the creation of employment opportunities in rural areas, contributing to the socio-economic development of these regions [94,98].

Looking ahead, India's biorefinery policy framework continues to evolve with an emphasis on sustainability and long-term impact. Enhanced technological support remains a priority, with efforts focused on advancing biorefinery technologies and improving their integration into existing systems. The framework also highlights the importance of supply chain management, aiming to optimize the collection, storage, and distribution of feedstock materials. In parallel, the development of robust markets for biofuels is being pursued to ensure the economic viability of the sector. A critical aspect of the future outlook involves the integration of state-level initiatives with central government policies. This harmonization aims to create a cohesive policy environment that leverages regional strengths while aligning with national objectives. Such measures are essential for achieving India's renewable energy goals and establishing a sustainable bioeconomy [94]. Figure 2 depicts renewable flow management, emphasizing efficient bio-resource use for sustainable fuels.

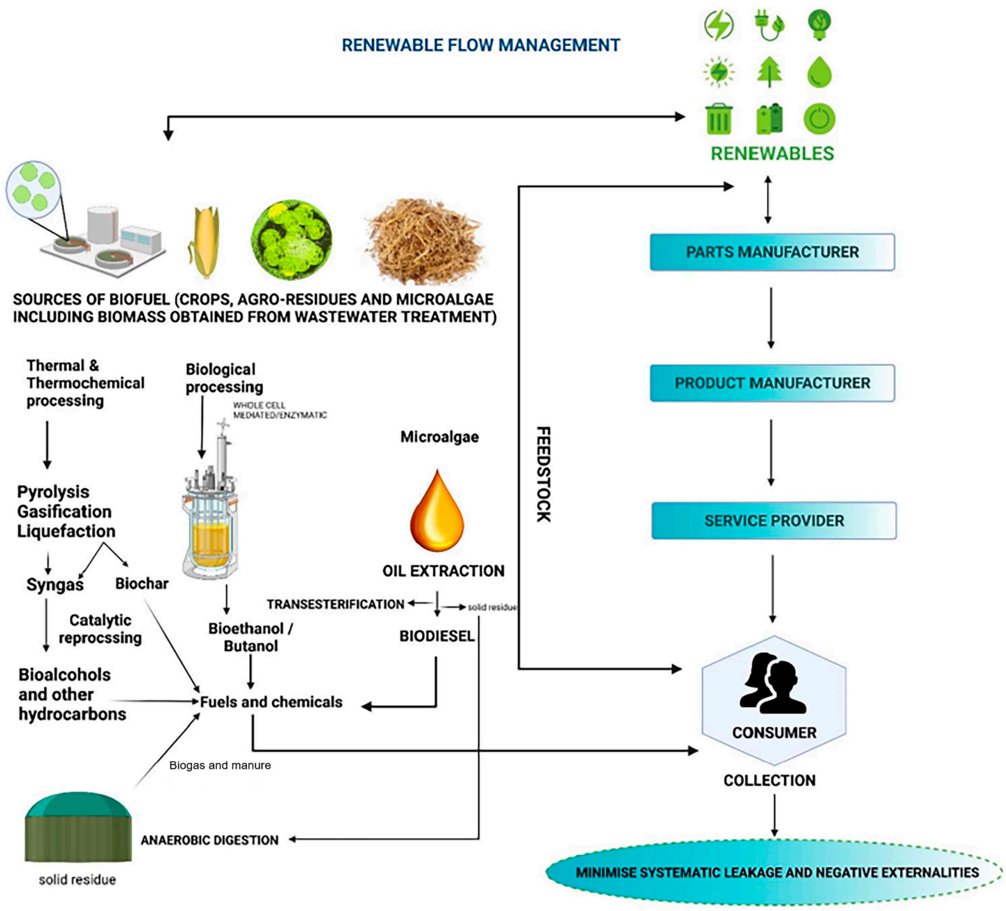

Figure 2. Management of renewable energy flows within a circular economy [125].

7. Impact on the Environment, Economy, and Energy Sectors

7.1. Environment

Second-generation biorefineries in India present substantial environmental advantages over traditional fossil fuel systems. By prioritizing the use of lignocellulosic biomass rather than food-based crops, these biorefineries contribute to sustainability while reducing competition for agricultural resources. The shift towards second-generation biofuels aligns with India's broader environmental objectives, significantly lowering GHG emissions and minimizing reliance on fossil fuels. Biofuels derived from lignocellulosic feedstocks are considered near carbon-neutral, as the carbon dioxide released during combustion is counterbalanced by carbon sequestration during plant growth [126].

When these compounds are combusted, they release the stored energy and return CO_2 to the atmosphere, creating a carbon-neutral cycle that significantly reduces net GHG emissions compared to fossil fuels. Biomass currently accounts for approximately 14% of global energy consumption, with developing nations utilizing 38% of this energy, particularly in rural areas where access to conventional energy sources remains limited [2]. India, with its favorable climate and extensive agricultural activities, possesses abundant biomass resources that present significant opportunities for sustainable energy production and utilization.

Traditional approaches to biomass utilization have focused primarily on single-product systems, such as dedicated bioethanol or biogas production facilities. However, these approaches often fail to maximize the value of biomass factors. Table 5 summarizes the key environmental advantages of second-generation biorefineries, highlighting their role in reducing GHG emissions, enhancing resource efficiency, and promoting sustainability through innovative waste management and conservation strategies.

Table 5. Environmental Benefits of Second-Generation Biorefineries.

Environmental Impact	Description
Reduction in GHG Emissions	Lignocellulosic biofuels approach carbon neutrality, offsetting CO_2 emissions through plant sequestration.
Waste Valorization	Utilization of agricultural residues prevents open field burning, mitigating air pollution.
Biodiversity Conservation	Sustainable biomass sourcing reduces the need for agricultural land expansion, limiting deforestation.
Water Conservation	Advanced biorefineries consume 30–70% less water compared to first-generation biofuels; water recycling systems improve efficiency.
Soil Health Improvement	By-products such as biochar and bio-digestate enhance soil carbon content and microbial activity, improving agricultural sustainability.

7.2. Economy

Second-generation biorefineries play a crucial role in reducing India's dependence on fossil fuel imports, thereby enhancing national energy security. With an annual agricultural waste production of approximately 1043 million metric tons, India possesses a substantial feedstock base for biofuel generation. This biomass has the potential to yield around 64 billion litres of bioethanol annually, aligning with government initiatives aimed at promoting renewable energy and attracting industrial investments [127].

India's bioethanol market, valued at USD 2.35 billion in 2023, is anticipated to double by 2030, growing at a compound annual growth rate (CAGR) of 8.7%. Additionally, the biomethane and biohydrogen markets, valued at USD 4.2 billion and USD 1.47 billion, respectively, demonstrate significant growth potential [128]. The influx of private investments has been a key driver of this expansion, with major industrial players such as Reliance Industries and the Adani Group investing heavily in the sector. Notably, the Adani Group has pledged an estimated USD 50 billion toward biohydrogen production and the development of sustainable energy infrastructure [129].

Beyond energy security, biorefineries contribute to rural economic development by generating employment and producing high-value biochemical by-products such as furfurals, xylitol, and organic acids. The integration of a circular economy model further enhances profitability by repurposing agricultural residues, mitigating both environmental and economic losses linked to conventional waste disposal practices [97]. Table 6 highlights the key economic advantages of second-generation biorefineries, including market growth and investment.

The expansion of second-generation biorefineries in India is poised to drive long-term economic sustainability. Continued advancements in biofuel technology, integration of renewable energy sources, and supportive government policies will further strengthen this sector's contribution to energy security and economic development. Additionally, increased focus on research and innovation in enzyme-based conversion processes and biomass valorization will optimize the economic benefits of biorefineries while ensuring environmental sustainability [127,130].

Table 6. Economic Benefits of Second-Generation Biorefineries.

Economy Impact	Description
Reduced Fossil Fuel Dependency	Domestic biofuel production reduces crude oil imports, strengthening trade balance and energy security.
Market Growth	India's bioethanol market is projected to grow at a CAGR of 8.7%, potentially doubling by 2030.
Investment Attraction	Major corporations like Reliance and Adani Group have committed substantial investments in bioenergy.
Value-Added Products	Biorefineries produce high-value chemicals such as xylitol, furfural, and organic acids, enhancing profitability.
Rural Development	Increased demand for agricultural residues boosts rural incomes and stimulates local supply chains.

7.3. Energy

India's shift toward biomass-based energy solutions is a key response to its growing energy demands, which increased from 6101 Mtoe in 1973 to 13,699 Mtoe in 2016 [96,131]. The development of second-generation biorefineries is poised to contribute significantly to reducing GHG emissions, with potential reductions of up to 2.7% of GDP by 2030, supporting India's commitments under the Paris Agreement [132].

Solar energy integration into biorefinery operations has proven highly effective, harnessing India's vast annual solar potential, which exceeds 5000 trillion kWh [133]. Additionally, Combined Heat and Power (CHP) systems have been integrated into biorefineries, optimizing resource utilization and resulting in lower environmental impacts compared to conventional energy systems [134]. The strategic placement of biorefineries helps minimize transportation costs, which can account for up to 20% of operational expenses. Geographical variations in biomass availability require region-specific solutions to ensure cost-effectiveness and operational efficiency [135,136]. The integration of CHP systems in biorefineries further enhances energy efficiency. These systems can achieve 80–90% overall efficiency, compared to the 30–40% efficiency seen in conventional power generation systems [134]. Table 7 summarizes the critical factors influencing India's transition to biomass-based energy solutions

Table 7. Energy Benefits of Second-Generation Biorefineries.

Economy Impact	Description
Energy Demand Growth	Energy demand rose from 6101 Mtoe (1973) to 13,699 Mtoe (2016).
GHG Emissions Reduction	Potential 2.7% reduction in GDP by 2030 from second-generation biorefineries.
Solar Energy Potential	India's annual solar potential exceeds 5000 trillion kWh.
CHP Efficiency	CHP systems in biorefineries achieve 80–90% efficiency, compared to 30–40% for conventional systems.
Renewable Energy Contribution	Increased demand for agricultural residues boosts rural incomes and stimulates local supply chains.
Energy Diversification	Biomass diversifies India's energy portfolio, reducing reliance on fossil fuels.
Decentralized Energy Production	Biorefineries contribute to rural electrification by reducing transmission losses.
Integration with Other Renewables	Combines solar with biomass to address intermittency and optimize solar potential.
Grid Stability	Biogas and biomethane enhance grid stability, supporting renewable energy integration.
Transportation Costs	Transportation can reduce biorefinery operational expenses.

7.4. Life Cycle Analysis (LCA)

Life Cycle Analysis (LCA) provides a detailed evaluation of the environmental performance of biorefinery systems, analyzing their entire value chain. Studies conducted in India have highlighted several key findings in LCA:

- Carbon Footprint Reduction: Bio-derived products consistently demonstrate lower GHG emissions compared to fossil-based alternatives. For example, bio-derived polyethylene reduces emissions by 0.75 kg CO_2-eq/kg compared to conventional petrochemical processes [137].
- Process Optimization: Advances in production methods have significantly decreased environmental impacts. Optimized charcoal value chains, for instance, reduced emissions from 2.15 CO_2-eq to 0.50 CO_2-eq through improved processes and better resource utilization [138].
- Holistic Impact Assessment: LCA studies assess environmental impacts beyond carbon emissions, including water quality, land use, biodiversity, and human health.
- Technology Comparison: LCA facilitates comparisons between different conversion pathways. Biochemical routes often show advantages in water-related impacts, while thermochemical pathways may excel in energy efficiency.

The integration of circular economy principles within LCA frameworks has led to the development of closed-loop systems that maximize resource recovery and minimize waste. For example, lignin residues from bioethanol production are increasingly being repurposed into high-value applications such as bio-composites, pharmaceuticals, and biosensors [139].

7.5. Circular Economy

The circular economy approach has the potential to significantly transform India's biorefinery sector. This approach systematically designs out waste and pollution, keeps materials in productive use, and regenerates natural systems. Key aspects of circular economy integration include:

- Resource Efficiency: Circular biorefinery models have demonstrated significant improvements in resource use, with some systems achieving near-zero waste through cascading biomass components [140].
- Environmental Performance: Circular approaches have been shown to reduce GHG emissions by 39–86% and decrease non-renewable energy usage by 65% compared to linear production models [137].
- Economic Value Creation: The circular bioeconomy creates new revenue streams by revalorizing materials previously considered waste. For example, lignin valorization has applications in polymers, bio-composites, and nanomaterials, with global markets projected to reach USD 1.2 billion by 2025 [139].
- Rural Development: Circular biorefinery models stimulate rural economies by establishing collection centers, preprocessing facilities, and local value-addition activities.
- Social Inclusion: These models also promote social inclusion by incorporating traditional knowledge and providing marginalized communities with opportunities to participate in biorefinery value chains.

The adoption of circular economy principles ensures that India's biorefinery sector promotes sustainability on environmental, economic, and social fronts. This holistic approach aligns with the United Nations Sustainable Development Goals while addressing challenges in waste management, resource efficiency, and inclusive development [141]. Innovations in India's circular bioeconomy include integrated biorefineries that produce multiple products from a single feedstock, agricultural practices that return nutrients to soil via biochar and digestate, and collaborative models linking urban waste generators with rural biomass processors. Table 8 provides an overview of the key environmental, economic, and social impacts of integrating LCA and circular economy principles in India's biorefinery sector.

Table 8. Key Parameters of LCA and Circular Economy Integration in India's Biorefinery Sector.

Parameter	Details
Carbon Footprint Reduction	Bio-derived polyethylene reduces emissions by 0.75 kg CO_2-eq/kg compared to fossil-based polyethylene.
Process Optimization	Charcoal value chain emissions reduced from 2.15 CO_2-eq to 0.50 CO_2-eq through process improvements.
Circular Economy Resource Efficiency	Circular biorefineries demonstrate near-zero waste and enhanced resource use through cascading biomass.
Environmental Performance of Circular Economy	Circular approaches reduce GHG emissions by 39–86% and non-renewable energy by 65% compared to linear models.
Economic Value Creation	Lignin valorization for polymers, bio-composites, and nanomaterials, with a market projected at USD 1.2 billion by 2025.
Sustainability Alignment	Circular economy principles support environmental, economic, and social sustainability goals, aligned with the UN SDGs.

8. Roadmap to Implement Biorefinery Approach

Implementing biorefineries to maximize biomass valorization requires a multidisciplinary approach that integrates bio-engineering, chemistry, and agricultural sciences. In India, where agricultural residues and other biomass types are abundant, the potential for second-generation biorefineries is substantial. This roadmap highlights the strategic integration of technologies and policies needed to realize this potential, focusing on thermochemical and biochemical conversion pathways [132].

Biorefineries represent a transformative approach to achieving sustainability and economic viability in bio-based industries. This guide outlines six critical steps for developing and optimizing biorefineries, ensuring they meet environmental, economic, and policy objectives.

1. Process Development and Optimization: This stage focuses on improving biorefinery efficiency and sustainability by optimizing feedstock cultivation, processing, and product recovery to reduce GHG emissions and non-renewable energy use [142]. Optimization of the entire value chain is essential to achieving cost-effectiveness and economic viability.
2. Supply Chain Development: Effective supply chain management ensures the smooth delivery of biomass to the biorefinery. Selecting strategic locations minimizes transportation costs, while optimizing biomass production and developing efficient logistics systems improve the overall operational efficiency of the supply chain [135].
3. Integration with Existing Infrastructure: Biorefineries can enhance their capabilities by integrating with existing petrochemical plants, creating hybrid systems. Utilizing advanced biotechnology enables the seamless adaptation of current infrastructure, bridging gaps and maximizing resource utilization [143].
4. Economic Viability and Revenue Diversification: To achieve financial sustainability, biorefineries must diversify their revenue streams. Producing high-value biochemicals alongside biofuels, generating energy for self-sustaining operations, and exploring additional revenue opportunities are critical to their long-term success [144].
5. Policy and Regulatory Support: A robust and stable policy framework is essential for fostering growth in biorefinery projects. Clear subsidies, legal guidelines, and

mandates are needed to inspire confidence among investors and ensure compliance with environmental and economic objectives [96].

6. Environmental Monitoring and Circular Economy: Monitoring and reducing the environmental impact of biorefineries is a cornerstone of their development. Implementing life cycle assessments and adopting circular economy principles, such as resource recovery and closed-loop systems, ensures sustainability and minimizes waste [145].

Step-by-Step Roadmap for Biorefinery Development and Optimization

1. Identify Objectives and Goals: Define the primary objectives, such as reducing GHG emissions, improving sustainability, and achieving economic viability. Align goals with global and regional sustainability [96].
2. Conduct Feasibility Studies: Evaluate the availability of biomass feedstocks and their environmental impact. Assess market demand for bio-based products and energy [135].
3. Develop Process Design and Optimization: Design efficient processes for feedstock cultivation, processing, and product recovery. Incorporate advanced technologies to maximize energy efficiency and minimize waste [141].
4. Build an Efficient Supply Chain: Choose strategic locations to reduce transportation costs. Optimize biomass production and logistics for collection, transport, and preprocessing [135].
5. Integrate with Existing Infrastructure: Develop hybrid systems that combine biorefineries with petrochemical plants. Utilize biotechnology to bridge gaps and enhance operational efficiency [143].
6. Establish Economic Models: Create a financial plan that includes high-value biochemicals, biofuels, and self-sustaining energy generation. Diversify revenue streams to ensure long-term viability [144].
7. Engage Policy and Regulatory Stakeholders: Work with policymakers to establish subsidies, mandates, and guidelines. Foster investor confidence by ensuring regulatory compliance [96].
8. Implement Environmental Monitoring and Sustainability Practices: Conduct life cycle assessments to track environmental impact. Apply circular economy principles like resource recovery and closed-loop systems [145].
9. Pilot and Scale-Up: Launch pilot projects to validate designs and processes. Scale up operations based on pilot results, ensuring efficiency and sustainability.
10. Continuous Improvement and Innovation: Regularly review and refine processes to incorporate technological advancements. Monitor market trends to adapt products and services accordingly.

9. Challenges

India faces unique challenges and opportunities in adopting second-generation biofuels. Current production is dominated by first-generation biofuels, including sugarcane and Jatropha, which are insufficient to meet the National Policy on Biofuels (NPB) target of 20% blending by 2030. Achieving these targets will require transitioning to lignocellulosic ethanol and biomass-to-liquid (BTL) biodiesel technologies, supported by robust research and development and industrial-scale deployment.

Second-Generation Biofuels: A single demonstration plant in Pune, Maharashtra, processes 100 dry tons of biomass per day, including residues like corn stover and bagasse. However, scaling these technologies remains a challenge due to cost and infrastructure limitations. By 2030, it is estimated that India can produce 50 billion litres of biofuels from agricultural residues, meeting the 20% blending target [132].

Feedstock Challenges: Limited availability of dedicated energy crops and the unsustainable use of sugarcane molasses highlight the need for diversified feedstock collection mechanisms [146].

Investment Needs: Transitioning to second-generation biofuels under a Business-As-Usual (BAU) scenario requires USD 2 billion by 2030, while achieving NPB goals necessitates USD 32 billion in cumulative investments [132].

10. Conclusions

This study highlights the significant contributions of second-generation biorefineries in the sustainable energy transition, with a particular focus on India. The research shows that second-generation biorefineries can effectively utilize non-food biomass feedstocks, such as crop residues and agro-processing waste, for the production of biofuels, biochemicals, and bio-based products. Through the integration of biochemical and thermochemical conversion technologies, these biorefineries not only help in reducing greenhouse gas emissions but also contribute to energy security and waste minimization. Notably, bioethanol, biogas, and biohydrogen production from these sources can significantly support India's renewable energy goals, including the target of a 20% ethanol blend by 2025.

The study demonstrates the importance of government policies such as India's National Biofuels Policy, which provides a robust framework for promoting biorefinery development and advancing bioethanol production. The research also shows the potential for rural economic growth, as biorefineries can generate jobs and produce high-value by-products like furfurals, xylitol, and organic acids, which help to promote a circular economy.

However, several challenges remain, such as the high variability in biomass feedstock properties, difficulties in process integration, and supply chain inefficiencies. Despite these limitations, the findings indicate that second-generation biorefineries, when optimized, have a strong potential to be economically viable. For instance, the bamboo-based bioethanol refinery in Assam and the lignocellulosic biorefinery in Karnataka provide promising models of large-scale implementation, demonstrating that with proper investment and technological advancements, biorefineries can become sustainable economic drivers.

Future research should focus on overcoming these barriers by improving biomass feedstock pretreatment processes and fermentation efficiencies. Furthermore, the integration of advanced technologies, such as IoT-enabled monitoring systems and machine learning, could be explored to enhance operational efficiencies and sustainability. Additionally, international comparisons of biorefinery technologies, policies, and market dynamics could offer valuable insights for accelerating the global adoption of second-generation biorefineries.

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Abbreviations

The following abbreviations are used in this manuscript:

LCA	Life Cycle Analysis
GDP	Gross domestic product
GHG	Greenhouse Gas
HTC	Hydrothermal Carbonization
HTL	Hydrothermal Liquefaction
CHP	Combined Heat and Power
MNRE	Ministry of New and Renewable Energy
MoPNG	Ministry of Petroleum and Natural Gas
MoA	Ministry of Agriculture
MoRD	Ministry of Rural Development
MoPR	Ministry of Panchayati Raj
MoS&T	Ministry of Science and Technology
MoEF	Ministry of Environment and Forests
MoF	Ministry of Finance
NPMCR	The National Policy for Management of Crop Residue
CAGR	Compound Annual Growth Rate
BAU	Business-As-Usual
NPB	National Policy on Biofuels
BTL	Biomass-To-Liquid

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