

Valorization of Waste Biomass Sources to Biofuels, Bioenergy and Biomaterials: Integration of Conversion Technologies

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Abstract - In recent times, there has been a surge in the need for energy due to the swift expansion of the population and the advancements made in urbanization and industry. An important aspect of creating sustainable practices while utilizing renewable energy is using agricultural waste as a suitable, eco-friendly replacement for fossil fuels. This paper provides an overview of the level of art at the moment and the bright future of utilizing valuable biomaterials made from agro-industrial wastes and their applications through the circular bioeconomy and waste valorization. Researchers are looking into ways to turn organic materials or recyclable scraps into biomaterials. Collagen can be obtained from various waste materials, including fish, echinoderms, and jellyfish. Chitin and chitosan can be repurposed to create valuable materials. Hydroxyapatite is a valuable material for wound dressings, drug delivery, and cosmetics in nutraceuticals and biomedicine. Researchers are exploring fish waste as an economical and environmentally beneficial substitute to increase collagen production. Liquefaction techniques like thermochemical and hydrothermal liquefaction are used to create bio-oils at high pressures and low temperatures. The paper goes into great detail about the role that energy plays in ensuring world prosperity and emphasizes the possibility of using agricultural waste as a renewable energy source.

Key Words: Renewable energy, Circular bioeconomy, Waste valorization, Biomaterials, Collagen extraction, Microbial fermentation

1. INTRODUCTION

The search for sustainable and renewable energy resources has been intensified by the rapid increase in global energy demand, industrial development, and environmental degradation. Fossil fuels remain as the dominant source of global energy; however, their exhaustion and the

associated greenhouse gas emissions largely contribute to climate change and environmental pollution. Consequently, waste biomass valorisation has emerged as a promising approach for producing biofuels, bioenergy, and value-added biomaterials whilst concurrently addressing waste management and sustainability challenges. Biomass is predominantly known as a carbon-neutral and renewable resource that upholds the transition toward circular bioeconomy and low-carbon energy systems [1]. Current studies highlight that effective biomass conversion techniques can largely mitigate greenhouse gas discharges and enhance energy security, particularly in developing and emerging economies [2]. Extensively, agricultural, forestry, municipal, and industrial activities produce vast quantities of waste generating severe environmental and disposal challenges. Agricultural wastes such as rice straw, corn stover, wheat straw, and sugarcane bagasse represent low-cost and renewable feedstocks for biofuel production. Improper disposition trials such as open burning and landfilling bestow air pollution and greenhouse gas emissions, posing environmental and public health risks. Effective biomass utilization can alleviate these effects and enrich resource reclamation while supporting sustainable development goals [4],[5]. Lignocellulosic biomass has interested major research immersion due to its plenty and minimal competition with food resources, making it qualified for large-scale bioenergy yielding [6].

Thermochemical conversion technologies play a robust role in biomass valorization due to their capability to swiftly convert biomass into energy and fuel products. Technologies such as pyrolysis, gasification, torrefaction, and hydrothermal liquefaction have been highly investigated for producing bio-oil, syngas, and biochar [6],[7],[8]. Quick pyrolysis brings liquid fuels with high energy density, while gasification causes syngas for hydrogen production and electricity generation [6],[7]. Hydrothermal liquefaction is specifically competent for

wet biomass and generates high-quality liquid fuels with advanced energy efficacy [8]. Notwithstanding these odds, thermochemical processes need high energy input, advanced reactor design, and substantial capital investment, which restrict large-scale commercialization. Biological transformation technologies deliver environmentally friendly options by utilizing microorganisms and enzymes to convert organic waste into renewable fuels. Anaerobic digestion and fermentation are broadly used for generating biomethane and bioethanol from agricultural and municipal waste [9],[10]. Anaerobic digestion proffers low energy necessities and lowers environmental impact, while fermentation allows the yield of liquid biofuels from lignocellulosic biomass [9],[10]. However, biological processes often suffer from low yield, long processing time, and sensitivity to environmental conditions, restricting their industrial scalability.

Integrated conversion technologies and biorefinery systems have accumulated major attention as an answer to conquer the boundaries of standalone processes. Hybrid systems such as pyrolysis–anaerobic digestion and gasification–fermentation refine energy efficiency and allow the generation of multiple fuels and chemicals from a single feedstock [2],[11]. The biorefinery theory enables concurrent production of biofuels, bioenergy, and biomaterials, thereby improving economic feasibility and substantiating circular bioeconomy principles [11]. Though, technological sophistication and high operational costs persist to hamper large-scale execution.

Waste biomass valorization also plays a judgmental role in generating high-value biomaterials such as collagen, chitin, hydroxyapatite, silica, and bioplastics. Marine biomass delivers justifiable origins of collagen for biomedical applications, while seafood waste is broadly used for chitin and chitosan production [12],[13],[14]. Biomass-derived bioplastics and silica materials reduce reliance on petrochemical products and reinforce green manufacturing technologies [15].

In spite of pivotal advancement, multiple limitations and expertise gaps remain in biomass valorization technologies. Feedstock changeability, high pretreatment costs, process integration complexity, and reduced techno-economic and lifecycle assessments limit commercialization [4],[17]. Furthermore, inadequate policy support and feeble biomass supply chain management limit the adoption of integrated systems [2]. Recent research points out the demand for artificial intelligence-based optimization, enhanced catalysts, and circular bioeconomy plans to enhance efficacy and sustainability [19],[20].

Consequently, this feedback aims to cynically inspect waste biomass valorization for the production of biofuels, bioenergy, and biomaterials, with a focus on integrated thermochemical and biological conversion technologies. The review consolidates present literature, recognizes expertise gaps, and puts forward future research directions to support sustainable waste-to-energy and biomaterial production systems in the Asia-Pacific region and globally.

2. TYPES OF WASTE BIOMASS

Crop residues are leftovers that are extracted straight from the fields of agriculture during the production process. These materials consist of seed pods, leaves, straws, and other materials. These crop residues are thought to be the most readily available and reasonably priced organic waste sources that can be used to make worthwhile products [5]. Agro waste biomass, including crop residues and processing by-products, can be converted into valuable products like bioenergy, biochar, and biodegradable materials through processes such as anaerobic digestion and pyrolysis.

Animal waste biomass from livestock farming activities can also yield valuable products such as biogas for energy generation, compost for soil enrichment, and animal feed additives. These processes not only mitigate environmental pollution but also contribute to renewable energy production, soil fertility enhancement, and sustainable resource utilization. Proper management and utilization of agro and animal waste biomass are crucial for fostering a utilizing a circular economy and lowering dependency on finite fossil fuels. In an effort to improve outputs and formulations, biowastes—more especially, fish waste's organic component has been studied as a low-cost, long-term collagen source [13].

3. THERMOCHEMICAL CONVERSION TECHNOLOGIES

By using thermochemical technology, organic matter can be transformed into synthesis gas, charcoal, and highly oxygenated bio-oil. For the procedure, pyrolysis, gasification, and liquefaction are the three main options. The selection is dependent on the energy, end-use conditions, environmental principles, biomass feedstock, and project specifications [15]. Thermal conversion methods are frequently employed owing to their industrial infrastructure, short processing periods, low water requirements, and capacity to generate energy from waste plastic [18].

3.1. Gasification

A high-temperature oxidation process called biomass gasification produces combustible syngas, biochar, and

bio-oil, all of which can be transformed into different fuel and energy forms [3],[4]. Gasification is a more effective method of extracting hydrogen gas from biomass than burning or pyrolysis [17]. It is thought to be the most effective method for recycling various biomass feedstocks, including waste streams from kitchen, industrial, agricultural, and food wastes. Variables such as reactor type, temperature, catalyst, feedstock, equilibrium ratio, particle size, gasifying agent, and catalyst can all affect the process outcome [18]. Significant amounts of CO₂ and CO are produced during the process, with MSW and agricultural residue having higher CO and CO₂ contents [6].

3.2. Liquefaction

By using liquefaction techniques like thermochemical and hydrothermal liquefaction, bio-oils are created at high pressures and low temperatures. Thermochemical liquefaction is the procedure for creating bio-oil at low temperatures while hydrogen is present and high pressures—whether a catalyst is present or not. Hydrothermal liquefaction (HTL) conversion of biomass to biofuel utilizing subcritical water at pressures between 40 and 220 bar and temperatures between 250 and 374 °. The process includes repolymerization, dewatering, and decomposition. Hydrocarbons become less soluble in water at high pressures and temperatures, but high pressure maintains water in its liquid state [9].

3.3. Pyrolysis

The process of converting biomass into a mixture of solid, liquid, and gas between 350 and 700 °C is known as pyrolysis. While gasification produces fuel gas for the production of heat, Pyrolysis yields pyrolysis oil, a liquid fuel or bio-oil, which is easily transportable and stored [19]. The three types of pyrolysis techniques—slow, fast, and flash—each having a different composition of products. At low temperatures, slow pyrolysis yields char, whereas fast pyrolysis generates bio-oil at high heating rates (>200 °C/s) and regulated temperatures around 500 °C. Flash pyrolysis involves higher heating rates and shorter reaction times. Because fast pyrolysis produces a high yield of petroleum and is an economical, energy-efficient, and ecologically benign process, it is becoming more and more popular for liquid production [7]. In order to replace crude oil, pyrooleum—a dark brown, highly viscous oil with a low calorific value—is being improved by physical, chemical, and catalytic methods.

3.4. Torrefaction:

A mild thermochemical process (200 °C and 300 °C) called torrefaction increases the carbon content and solid yield of biomass by weakening its fibrous nature in the absence of air [17]. As a result, during combustion, it

releases less hydrogen, oxygen, water vapor, and smoke, increasing the calorific value of biomass. Because biochar does not break down or draw in microbes, it can be kept indefinitely without running the risk of going bad. It is a solid fuel that burns cleanly and is available for purchase on the open market and is used in power plants [19].

4.BIOCHEMICAL CONVERSION TECHNOLOGIES

When waste is treated biologically, it uses less energy and moves through the system more slowly. Conventional processes that can produce biofuels include anaerobic digestion, alcohol fermentation, and photobiological methods. These processes use specialized bacteria and yeast to transform biomass or waste into energy that can be used [20].

4.1. Composting

Composting is the managed aerobic decomposition of organic waste, such as manure, green waste, food waste, and waste from agriculture and humans. Microbes convert organic materials into heat, carbon dioxide, and water. Adjusting the amount of organic material present, the ionic strength, grain size, hydration, warmth, and ventilation is crucial for producing high-quality compost.

4.2. Anaerobic digestion

Enzymatic activity in an anoxic environment is linked to the breakdown of organic matter through the process of bio-methanolation. Anaerobic digestion now includes the organic fractionation of farms' and cities' waste. Examples of feedstocks are algae biomass, sewage sludge, energy crops, and industrial food waste [3],[5]. The processes of fermentation, hydrolysis, and methanogenesis result in the production of volatile fatty acids, ethanol, acetic acid, and gas mixtures. Methanogens are organisms that process a mixture of gases, such as carbon dioxide and methane, which is produced as biogas. Temperature, pH, loading rate, and biomass nutrient profile are among the variables that affect biogas yield. Trace elements (Fe, Zn, Co) and biomass nutrients (C, N and P) affect methanogenesis. Lipid-based biomass has a higher lipid content; hence, it produces more methane. Temperature, pH, loading rate, and nutrient profile are among the variables that affect biogas yield. With increases in pH, carbon dioxide dissolution, and methane concentration, biogas's energy content rises. High operating temperatures and acidic environments promote microbial activity and the production of methane [13].

4.3. Photobiological hydrogen production

When exposed to light, microalgae can produce hydrogen gas, but the hydrogenase enzyme stops it from happening. There are two ways to harvest hydrogen gas: either

produce H₂ and O₂ gas simultaneously or use hydrogenase enzymes to produce hydrogen gas. It is possible to employ methods one and two; method one produces more hydrogen gas, but O₂ throttles it [16]. Using sulfur injections can increase total H₂ yield by threefold [18]. Microalgae can release hydrogen gas when they are exposed to light, but the hydrogenase enzyme prevents this from happening. Producing H₂ and O₂ gas simultaneously or using hydrogenase enzymes to produce hydrogen gas are the two methods available for harvesting hydrogen gas [18].

4.4. Alcoholic fermentation

Alcoholic fermentation results in the production of bioethanol from biomass that contains fermentable sugars like glucose and starch using yeast or bacteria. These polysaccharides are hydrolyzed by acids, bases, or enzymes and are stored in microalgae such as *Scenedesmus*, *Chlorella*, *Spirulina*, and *Dunaliella* [14]. These treatments have disadvantages despite being quick and affordable. While costly and intricate, enzymatic processes are effective. By carrying out primary cell disruption operations, hydrolysis can improve time and efficiency [11]. The remaining solid waste is transformed into useful byproducts through thermochemical processes. To enhance the amount of byproducts produced by microalgal DNA, scientists are looking into gene manipulation. One project is turning CO₂ into biofuels through photosynthesis without the need for extra energy. Scientists are introducing genes for the synthesis of ethanol into cells [15].

4.5. Transesterification

The transesterification process uses bases, acids, and enzymes to create biodiesel. Fatty acid methyl ester is swiftly and gently produced in large yields via base-catalyzed transesterification. Although environmentally benign, enzymatic catalysts need to be refined before being used commercially. Because enzymatic esterification reactions require less energy and less water and salt.

5. CUTTING-EDGE AND HYBRID CONVERSION TECHNOLOGIES

5.1. High-tech HiTAG/HiTSG technology for effectively converting municipal waste and biomass

A novel method for turning solid waste into syngas, electricity, and biofuels like hydrogen is known as high-temperature airflow and air/steam (HiTAG/HiTSG) [11]. It is possible to replace fossil fuels with this novel approach and drastically lessen environmental harm. The processes involved are gasification, which is a cleaner alternative, pyrolysis, drying, and combustion [13]. The

process involves a steam generator, ceramic membrane for H₂ separation, gas cleaning machine, and ceramic regenerator. This innovative technique might replace fossil fuels and cut greenhouse gas emissions for most uses. It seeks to convert waste and biomass at a high thermal level.

5.2. Innovative thermo-biochemical hybrid process for efficient conversion of lignocellulosic biomass

Lignocellulosic biomass has been traditionally processed through biochemical or thermochemical methods. Sequential thermochemical biochemical approaches are examples of hybrid treatments that minimize disadvantages while combining the best aspects of both techniques [15]. These methods can overcome biomass resistance, convert biomass into fermentable intermediates, and produce fuels and chemicals. In addition, these systems help simplify fuel processing by removing oxygenates, speeding up fermentation, and turning low-quality biofuels into drop-in hydrocarbon fuels [11]. Hybrid approaches can ultimately produce biofuels that perform like conventional transport fuels.

5.3. Comprehensive method of handling solid organic waste

Urban areas produce massive amounts of MSW, including food scraps and sewage sludge, causing global challenges like rising energy demand and landfill space scarcity. Incineration and anaerobic digestion can reduce MSW output but only treat microorganism-based waste, requiring management [10]. The high levels of cellulose, hemicellulose, and lignin in refractory materials make natural breakdown by AD economically impracticable. By converting carbonaceous solid wastes into thermal energy and commodities and marketable gases, the process known as gasification can treat wastes of this kind [17]. A hybrid system is needed to efficiently recover energy. Utilizing a distributed AD reactor and a gasifier, researchers have created a system that transforms waste into thermal and biological energy. Multiple solid waste types can be effectively and affordably managed by the system. Using a 10kW gasifier and wood chips as producer gas, a 1000 L AD reactor was utilized in a pilot study to turn biodegradable food waste into biogas. However, unified waste-to-energy schemes require further research [6].

6. VALORIZATION OF WASTE BIOMASS TO BIOMATERIALS

Biomaterials possess functionalization, cost-effectiveness, compactness, therapeutic acceptability, tensile stability, and optimal volume. Researchers are exploring methods to generate these chemicals from recyclable waste or organic materials.

6.1. Collagen

Collagen, a valuable protein, can be obtained from meat processing waste such as swine and cattle bones, bovine hides, and pig flesh. It contains a significant amount of glycine, proline, and hydroxyproline. It has been possible to separate types I, II, and IV of collagen from animal sources using an eco-friendly method aligned with the EU's zero-waste goal. Mechanical and enzymatic processes enable successful recovery from various waste materials, including fish, echinoderms, and jellyfish. Collagen type I is produced by a variety of marine species, including fish, dinoflagellates, cephalopods, starfish, and jellyfish. It has the advantages of being cytocompatible, environmentally friendly, low allergenic, and having the capacity to support cell growth. Marine collagen is useful for wound dressings, drug delivery, and cosmetics in nutraceuticals and biomedicine. Its strong water absorption capacity makes it the preferable material for texturizing, coarsening, and gel formation as well. Animal muscle tissue is commonly used to extract collagens for commercial purposes, but it is expensive and may degrade the collagen. Therefore, researchers are exploring fish waste as a cost-effective and eco-friendly alternative to increase collagen production [11].

6.2. Chitin and chitosan-derived biomaterials

Aquaculture waste can be repurposed to create valuable materials like chitin and chitosan through enzymatic deproteinization with bacterial proteases, yielding nutrient-rich protein hydrolysate. Chitosan, derived from seafood waste like leftover crab shells, shrimp, and fish scales, is a promising polymer due to increasing fisheries and seafood consumption. Chitin and chitosan are two naturally occurring amino polysaccharide polymers that show promise as biomaterials. Chitin, which is abundant in nitrogen and derived from the waste products of crustaceans, finds extensive application in the textile, CO₂ capture, and pharmaceutical sectors. Additionally, it is promoted as a blood pressure balancing, weight loss, and inflammation-reducing supplement. It is possible to create biodegradable polymers with chitosan. Shrimp shell waste contains 13.5% to 43.8% chitin, compared to 4% to 37% in squid shell waste [9]. It is possible to salvage 16% to 20% of the chitin found in crabs and lobsters [5]. Fishing industry byproducts such as krill, lobster, prawns, crabs, and shrimp carapaces are the source of commercial chitin. Of these biomass residues, 20–30% are chitin, 30–40% are protein, 30–50% are mineral salts (phosphate and calcium carbonate), and 0–12% are lipids. Protein, inorganic materials, and coloring agents must be eliminated in order to isolate the chitin present in crab shells. Solvent extraction at room temperature is used to accomplish

deproteinization. Crystalline chitin has a number of beneficial qualities, such as eco-safety, antimicrobial activity, biodegradability, biocompatibility, and antigenicity. Variants like N- and O-sulfonated chitin and carboxymethyl- chitin have been synthesized for various biological applications [7],[10].

6.3. Hydroxyapatite

Ca₁₀(PO₄)₆(OH)₂, or hydroxyapatite, is a valuable material that is used in implants because of its non-inflammatory and bioactive qualities. Unusual materials that may be used to extract hydroxyapatite include algae, fish scales, seashells, eggshells, and animal carcasses. Fish, swine, and cow bones are typically prepared by calcining them at high temperatures and removing proteins from them by washing them in an alkaline solution. Bovine bones are processed to extract natural hydroxyapatite using alkaline, subcritical water, and thermal techniques [11].

6.4. Bioplastics

Bioplastics are environmentally friendly polymers that can be broken down by naturally occurring microbes. But not every organic polymer can be composted. Bio-PET, despite containing renewable carbon, is not biodegradable. The main drivers of bioplastics growth are biopolymers like PHAs and PLA. Over 56% of the world's production of bioplastics is made up of nonbiodegradable polymers like Bio-PE and Bio-PET that are derived from biomass. The development of novel substitutes like bio-PEF, which has enhanced qualities for packaging drinks and other goods, is anticipated to increase the production of bio-PE [4].

6.5. Silicates and Silica

Production of silicates and silica salts from biowaste, such as rice husks, is gaining popularity. Plants absorb silicic acid from the soil, resulting in the formation of hydrated amorphous silica that accumulates in various parts of the plant. Rice husks are particularly rich in silica, making them a valuable source. The high silica concentration in bio-silica and its byproducts, along with the presence of calcium carbonate, adds to their attractiveness for various applications [3].

Typical methods of extracting biogenic silica from rice husks (RHs) involve removing trace metals through acid treatment, followed by pyrolysis at temperatures of 500–700°C for 8–24 hours. Microwave-assisted solid-state ashing with rice husks, sugarcane bagasse, and bamboo culm is a viable and economical method of removing SiO₂. By removing Ca from RHs or using inorganic biowastes as a source of Ca, like egg or oyster shells, biowaste can also be utilized to create biogenic silicates [2].

TABLE-1: VALORIZATION OF WASTE BIOMASS TO BIOMATERIALS

S . N o .	Type of biomaterial	Source of waste	Major findings	Applications	References
1	Collagen	Skin of marine puffer fish <i>Lagodon rhomboides</i>	43.1% acid solubilized collagen, 56.6% Pepsin soluble collagen. highest solubility at acidic pH. 100% biocompatible on NIH3T3 cell lines.	Wound dressing applications	[2]
2	Collagen	Skin of sole fish	Type I Collagen Yield - 19.27 ± 0.05 mg/g of sole fish skin Optimized conditions: 0.54 M acetic acid concentration, 1.90 M	Mimicked commercially available Type I Calfskin collagen with fibril structures	[5]

			NaCl concentration, 32.32 h, 8.97 ml/g solvent /fish skin ratio 32.32 h.		
3	Polyhydroxyalkanoates	Sewage and food waste	Eight times lower societal costs and four times lower environmental impacts than polyurethane	Adhesives and sealants	[4]
4	Polyhydroxyalkanoates (PHAs)	Municipal solid waste organic fraction	Yield of PHA – 40 g/kg of MSW	Bioplastics	[7]
5	Pure silica Silica	Rice husk	Purity - 98.67 %, Surface area – 625 m ² /g	An environmentally friendly process for managing solid waste that uses rice	[9]

				husk to create pure silica	
6	Magnesium substituted silica	waste from bambo o leaves , sugarc ane bagass e, and rice husk	Purity: 98%; Yield: 78%, 71%, and 52% from sugarc ane bagass e, bambo o leaves, and rice husk	-	[10]
7	Hydroxyapa tite	Waste egg shells	Hydro xyapati te prepare d in piper betel leaves extract	Anti- bacteria l and biofilm inhibito ry activity for dental biomat erials	[17]
8	Hydroxyapa tite	Egg shells	Hydro xyapati te particle s synthes ized by micro wave irradiat ion resulte d in needle like structu res	Biomed ical applicat ions	[11]

			with dimens ion – 60-80 nm length, 10-15 nm width at pH 10		
9	Nano hydroxyapat ite	Egg shells	Micro wave assiste d conver sion with an yield of 45 %	Biomed ical applicat ions	[21]
10	Chitosan	Body carapa ce of sand crabs	Flake like orthorh ombic crystal s of particle size 110 – 220 µm	Biomed ical applicat ions	[22]
11	Chitosan	Crab shells	Anti- virulen t and anti- biofilm propert y	Cathete r fabricat ions	[19]
12	Chitin & chitosan	Penae us mergu iensis shrim p waste	Chitin convert ed to chitosa n by autocla ve method Yield – 87%	-	[16]

1 3	Chitin & chitosan	Penaeus merguensis shrimp waste	Chitin converted to chitosan by deacetylation using 50% NaOH	Anti-oxidant activity	[19]
1 4	Hydroxyapatite microspheres	Shells of Abalone and oyster	Hydrothermal method, Adsorption is exothermic and spontaneous	Adsorption of Congo red dye	[13]
1 5	Hydroxyapatite powder	Fish bones	Mean size of particles is 3.259 μm	Dental fillings	[15]
1 6	Hydroxyapatite/chitosan composites	Tilapia fish scales	In batch adsorption, the maximum adsorption amount is 75–570 mg/g, and in fixed bed adsorption, it is 94 mg/g.	Elimination of heavy metal ions from wastewater	[14]

7. VALORIZATION OF WASTE BIOMASS TO BIOENERGY

7.1. Bioethanol

Global consumption of bioethanol, a renewable liquid biofuel made from plants or agricultural waste, is widespread. Production has surged in response to demand, with 134.5 billion liters expected to be consumed globally by 2024 [6]. Although its main application is as fuel, bioethanol is also utilized as a feedstock for the production of personal hygiene items, disinfectants, and chemicals and pharmaceutical industries.

Bioethanol is a popular fuel for internal combustion engines, especially when mixed with gasoline. This blend offers advantages like improved performance, cost savings, and a significant reduction in harmful emissions. It cuts down on CO₂ (90%), SO₂ (60-80%), and particulate matter (40%), leading to less air pollution, environmental security, and reduced release of greenhouse gases and cancer-causing compounds [4]. Bioethanol production from waste biomass is cost-effective and aids in waste management. The use of food crops as feedstocks has generated discussion, though, because of ethical and practical issues surrounding the use of food as fuel. Non-food substitutes like wood, agricultural residue, and industrial and municipal waste are the subject of current research in an effort to address this [7]. These alternatives are economically viable, readily available, sanitary, and have positive environmental impacts. Crop residues and waste wood are examples of agricultural wastes that are favored as feedstocks for the production of bioethanol. Improved production methods and locally available feedstocks have led to a 65% share of bioethanol in biofuel production. Innovations include cost-effective pretreatment methods and optimization to reduce energy consumption, residence time, and increase product yield [15].

7.2. Biohydrogen

A clean, carbon-free biofuel made from biomass is called biohydrogen. It is a highly energy-dense renewable fuel that finds extensive application in a number of industries, including transportation, power generation, and medicine. Biohydrogen promotes the circular economy and has positive social and economic effects [16]. Because biohydrogen combustion produces no gaseous pollutants or CO₂ when compared to conventional combustion engine fuels, it is an environmentally beneficial option that helps slow down global warming. While the technology is still relatively expensive, comparing biohydrogen to other renewable fuels, there are benefits

because it is made from sustainable and renewable biomass.

There are numerous methods for producing biohydrogen, including solar gasification, pyrolysis, thermochemical gasification, microbial electrolysis, fermentation, biophotolysis, and supercritical conversion [13]. When compared to traditional procedures, these methods provide benefits including lower energy usage, more eco-friendliness, higher yield, and sustainability. A number of criteria need to be taken into account when choosing feedstocks for the generation of biohydrogen, including availability, productivity, biodegradability, Chemical Oxygen Demand (COD), Volatile Solids (VS) Concentration, C/N ratio, and inhibitory chemicals. Because agricultural wastes are plentiful, easily converted, and generate high-quality products, they have demonstrated potential as a renewable feedstock [9].

7.3. Biomethane

Biomethane is an eco-friendly biofuel produced by purifying biogas to eliminate carbon dioxide and other impurities. Moreover, it can be created through the gasification of other organic materials. Whereas biomethane is mostly constituted of 1-3% CO₂ and 95-97% CH₄, Typically, 50–70% CH₄ and 30–40% CO₂ are present in crude biogas, and other constituents. Power plants, heating systems, and energy generating all use biomethane. In order to lower CO₂ emissions from engines and cars, it is being used more and more as a sustainable fuel alternative to natural gas and biogas. Reduced carbon emissions, cheaper production costs, and the sustainability of the energy and environmental systems are some advantages of biomethane. But it also has disadvantages, such as a strong smell, the possibility of explosions, and the fact that its primary component, CH₄, is a powerful greenhouse gas. However, the Because of its high energy content and net-zero emissions, biomethane production is low-cost and environmentally friendly, attracting resources and efforts. Making feedstock out of agricultural wastes is one kind of intervention. Anaerobic digestibility is based on the C/N ratio and factors such as VS, COD, BOD, nutritional value, and the existence of inhibitory compounds. 3) Anaerobic digestion and conversion can be improved a lot by pre-treating feedstocks using physical, biological, chemical, thermochemical, or combined methods. This also helps produce biomethane from agricultural waste more cheaply.

7.4. Biobutanol

Microbial fermentation employing renewable feedstocks such as sugar, starch, or cellulosic biomass yields biobutanol, a four-carbon butanol. Greater than that of gasoline in terms of vaporization heat, this cutting-edge biofuel is appropriate for internal combustion engines. It also has a higher octane number, less volatility, and a greater energy content. Biobutanol is less corrosive, releases less harmful emissions, and can be moved using current infrastructure. Apart from its usage as a fuel for transportation, biobutanol finds its use in a multitude of industries, including paints, cosmetics, detergents, chemicals, herbicides, resins, plasticizers, food, and pharmaceuticals. However, obstacles like biofouling, limited fermentation yield, scaling problems, and economic viability prevent its widespread manufacturing [13].

7.5. Biomethanol

Biomethanol is generated from natural and renewable resources including biomass, sugars, and starch waste. It can also be mixed with ethanol or gasoline to create a more affordable fuel for internal combustion engines (ICEs). By ensuring thorough and effective combustion, biomethanol lowers greenhouse gas emissions and the production of soot. It has minimal flammability, lower NO_x emissions, and excellent performance. Its poor quality of ignition, low energy content, corrosivity, and viscosity are some of its disadvantages. Additionally, incomplete combustion may cause the release of additional pollutants such formaldehyde and formic acid [11]. The chosen alcohol for transesterification is methanol, which is also frequently used as a fuel in transportation. It is more reactive and has a higher propensity for azeotrope production. It is also inexpensive and simple to recover. Formaldehyde, acetic acid, chloromethane, methyl tertiary-butyl ether, and other organic compounds are all synthesized using methanol. It is utilized in the manufacturing of inks, resins, adhesives, coatings, and medicines in addition to being a solvent and automobile antifreeze [6]. Although biogas or synthetic gas can be used to create methanol, technological developments have made it possible to employ biomass such as wood, crop leftovers, sewage, and agricultural waste as an inexpensive feedstock for long-term, sustainable production. It is anticipated that the automotive, manufacturing, chemical, electronics, maritime, and pharmaceutical industries will use more methanol. Although gasification is seen to be the most feasible approach to produce biomethanol, biomass can also be converted to biomethanol through anaerobic

digestion liquefaction, pyrolysis, and additional biological pathways [2].

7.6. Biodiesel

Biodiesel is a greener fuel derived from renewable materials such as vegetable oils, animal fats, and recycled cooking oil [2]. It produces fewer pollutants and greenhouse gasses than fossil fuels, making it a sustainable fuel replacement. In comparison to diesel derived from fossil fuels, biodiesel burns more efficiently, has a higher flash point, and is non-toxic. With non-edible feedstock, the problems of cost and food chain conflicts have been addressed [2],[5]. Different feedstocks and production techniques result in quality variances of biodiesel. Different types of vehicles, including trains, aeroplanes, generators, and cars, use biodiesel as a fuel. The production of biodiesel has increased dramatically as a result of growing public awareness of environmental pollution and greenhouse gas emissions from transportation vehicles. Biodiesel may now be produced from agricultural wastes, and new methods for growing microalgae have been developed for this purpose.

TABL-2: VALORIZATION OF WASTE BIOMASS TO BIOMATERIALS

S · N o ·	Biofuel	Biomass	Pretreatment method	Conversion method	Optimum conditions	Yield	References
1	Bioethanol	Wheat straw	Hydrolysis	Fermentation	Temp: 50-60° C, pH: 4.5-5.5	64.02 %	[2]
2	Bioethanol	Sugarcane bagasse	Delignification	Hydrolysis, and fermentation	Temp: 60-70° C, pH: 4.0-5.0	63.874 ppm	[18]
3		Rice	Enzymatic	Hydrolysis	Temp:	44 %	[2]

S · N o ·	Biofuel	Biomass	Pretreatment method	Conversion method	Optimum conditions	Yield	References
	Bioethanol	husk	hydrolysis	and fermentation	50-60° C, pH: 4.5-5.5		
4	Bioethanol	Apple wood	Enzymatic hydrolysis	Fermentation	Temp: 50-60° C, pH: 4.5-5.5	70 %	[23]
5	Bioethanol	Pal m wood	Chemical pre-treatment	Fermentation and Saccharide Conversion	Temp: 60-70° C, pH: 4.0-5.0	22.90 g/L	[14]
6	Bioethanol	Corn cobs	Pre-hydrolysis	Solid State Fermentation	Temp: 50-60° C, pH: 4.5-5.5	42.24 g/L	[24]
7	Biohydrogen	Sorghum stover	Enzymatic delignification	Anaerobic fermentation	Temp: 35-40° C, pH: 6.5-7.5	40.201 mL/g	[18]
8	Biohydrogen	Corn stalk	Ca(OH) ₂ -enzymolysis	Phototrophic fermentation	Temp: 35-40° C, pH:	35.76 mL/g	[23]

S · N o .	Biofuel	Biomass	Pre-treatment method	Conversion method	Optimum conditions	Yield	References
					7.0-7.5		
9	Biohydrogen	Potato peel	Mechanical and thermochemical	Dark anaerobic fermentation	Temp: 35-40°C, pH: 6.5-7.5	2.63 m L/g	[17]
10	Biohydrogen	Corn cob	Thermochemical	Photofermentation	Temp: 50-60°C, pH: 6.5-7.5	132 L/kg	[25]
11	Biohydrogen	Rice straw	Alkaline	Fermentation	Temp: 35-40°C, pH: 6.5-7.5	22.08 m mol/L	[16]
12	Biohydrogen	Sugarcane bagasse	Thermal	Phototrophic fermentation	Temp: 35-40°C, pH: 6.5-7.5	513 m L/g	[11]
13	Biobutanol	Wheat straw	Biological	Acetone-Butanol-Ethanol fermentation	Temp: 30-35°C, pH: 5.5-6.5	14.2 g/L	[26]

S · N o .	Biofuel	Biomass	Pre-treatment method	Conversion method	Optimum conditions	Yield	References
14	Biobutanol	Fruit bunch with an empty oil palm	Mechanical	Concurrent fermentation and saccharification	Temp: 30-35°C, pH: 5.5-6.5	3.97 g/L	[23]
15	Biobutanol	Corn cob bagasse	Alkaline	Acetone-Butanol-Ethanol fermentation	Temp: 30-35°C, pH: 5.5-6.5	175.7 g/kg CCB	[18]
16	Biobutanol	Sugarcane bagasse	Alkaline	Simultaneous saccharification and fermentation	Temp: 35-40°C, pH: 5.5-6.5	1.95 g/L	[12]
17	Biobutanol	Corn cob	Non-alkaline	Fermentation	Temp: 30-35°C, pH: 5.5-6.5	1.09 g/L	[11]
18	Biobutanol	Rice straw	Alkaline	Simultaneous saccharification and	Temp: 30-35°C, pH:	2.93 g/L	[10]

S · N o .	Biofuel	Biomass	Pre-treatment method	Conversion method	Optimum conditions	Yield	References
				fermentation.	5.5-6.5		
19	Biomethane	Cassava peel and Water hyacinth	Not stated	Anaerobic combined digestion	Temp: 35-40°C, pH: 7.0-7.5	21 L/g VS	[17]
20	Biomethane	Sugarcane trash	Alkaline	Anaerobic Digestion	Temp: 35-40°C, pH: 7.0-7.5	18 L/g VS	[27]
21	Biomethane	Sugar Beet Leaves	Enzymatic	Anaerobic Digestion	Temp: 35-40°C, pH: 7.0-7.5	51 L/g VS	[28]
22	Biomethane	Rice straw	Thermal processes and ozonolysis	Hydrolysis and Anaerobic Digestion	Temp: 50-60°C, pH: 6.8-7.2	37 L/g VS	[24]
23	Biomethane	Sugarcane bagasse	Hydrothermal	Anaerobic Digestion	Temp: 55-60°C, pH: 6.8-7.2	24 L/g VS	[21]

S · N o .	Biofuel	Biomass	Pre-treatment method	Conversion method	Optimum conditions	Yield	References
24	Biomethane	Bagasse from sugarcane and water hyacinth	Alkaline	Anaerobic Digestion	Temp: 35-40°C, pH: 7.0-7.5	30 L/g VS	[20]

8. CONCLUSIONS

This paper outlined the significance of energy for world prosperity in detail and emphasizes the possibility of using agricultural waste as a renewable energy source. Various thermochemical conversion methods, such as gasification, liquefaction, pyrolysis, and torrefaction offer efficient ways to produce biofuels and bio-oils from biomass. Biological conversion technologies like anaerobic digestion and photobiological hydrogen production also play a significant role in generating usable energy from waste. Advanced and hybrid conversion technologies, such as HiTAG/HiTSG and integrative treatment processes, provide innovative solutions for converting solid waste into valuable products, contributing to a sustainable circular bioeconomy. Agro waste biomass and animal waste biomass are converted into valuable products like bioenergy, biochar, and biogas through processes such as anaerobic digestion and pyrolysis. These practices mitigate pollution, promote renewable energy, and enhance soil fertility, contributing to a circular economy and reducing reliance on finite fossil resources. Strategic waste management is essential for sustainable resource utilization and environmental stewardship.

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