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Biomass Waste Valorization: Exploring New Frontiers as Biochemists.

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Abstract

Biomass waste valorization focuses on the conversion of biological waste materials (like agricultural residues, food waste, or forestry by-products) into valuable products such as biofuels, biochemicals, and bio-based materials. It is a sustainable and specific approach to waste valorization that is based on the production of Value-Added Biochemicals. It explores eco-friendly biochemical methods for the valorization of biomass waste into commercially useful compounds. These efforts are essential for environmental sustainability and socio-economic development, as a healthy environment provides resources and ecosystem services while ensuring environmental health. This review highlights advancements in maximizing biomass utilization in waste-to-wealth processes, offering significant waste reduction potential. Innovations in biochemical engineering have enabled the conversion of organic waste into valuable products beyond biofuels, including biogas, bioelectricity, biochar, syngas, bioplastics, bio-based chemicals, animal feed, biofertilizers, green hydrogen, bio composites, pellets, liquid fertilizers, essential oils, and activated carbon etc. Techniques like anaerobic digestion, fermentation, and hydrothermal liquefaction are at the forefront, providing sustainable methods to convert biomass into these diverse resources. A key challenge in waste-to-wealth conversion is optimizing product yield while minimizing waste and environmental impacts. Advances in enzyme engineering and microbial biotechnology have significantly improved process efficiency. For example, engineered microorganisms enhance the conversion of biomass into bioplastics and bio-based chemicals, improving biomass utilization. Furthermore, the production of green hydrogen and biocomposites offers promising alternatives to non-renewable resources, supporting a circular economy. Integrating waste-to-wealth systems with existing waste management infrastructure provides dual benefits: reducing waste volumes and generating renewable resources. This approach addresses waste disposal, reduces greenhouse gas emissions, and supports global sustainability goals, contributing to a cleaner, more resource-efficient future while diversifying sustainable materials and energy options from biomass.

Keywords: Waste valorization, Biotechnology, Bioresources, Biofuels, Sustainability

Introduction

The global surge in industrialization, urbanization and population growth has escalated waste generation, with municipal solid waste (MSW) projected to increase from 2.1 billion metric tons in 2023 to 3.8 billion by 2050, posing existential threat to ecosystems and human health (UNEP, 2024; Waheed *et al*., 2022; Reddy *et al*., 2023). The global direct cost of waste management was an estimated USD 252 billion in 2020. Poor health and climate change from poor waste disposal practices could raise the cost to USD 361 billion (UNEP). (2024). Industrial and agricultural by-products such as plastics and crop residues add to this burden (Olatunji *et al*., 2024). Conventional waste management methods such as landfilling and incineration, contribute to greenhouse gas emissions, soil and water contamination as well as biodiversity loss, while waste complexity and associated costs has made waste management difficult thereby exacerbating environmental degradation (Alao *et al*., 2022; Anyaegbunam, 2016). Transitioning to a circular economy which emphasizes resource efficiency and waste reintegration is critical for sustainability (Ferreira *et al*., 2024). Waste valorization redefines waste as a resource for producing energy, materials, and bio-based products thereby reducing ecological impact and fostering innovation in bioprocess engineering and microbial biotechnology (Rene *et al*., 2023). This approach, including biofuel production from agricultural residues and municipal solid waste supports energy security, economic growth and job creation in green technologies potentially unlocking $4.5 trillion by 2030 (Arancon *et al*., 2013; Ferreira *et al*., 2024). Hence, the present study aims to explore and evaluate innovative bioprocesses that biochemists can employ to convert biomass waste into high-value bioproducts.

Methods

This study evaluates innovative bioprocesses that biochemists can employ to convert biomass waste into high-value bioproducts. Electronic searches of the literature, primarily in databases such as PubMed, Google Scholar, Scopus, and ScienceDirect were used to gather published articles for the development of the manuscript. Keywords such as biomass waste valorization**,** Bioresources, Biofuels, Sustainability, bioenergy and biopolymer were used. A total of 100 scholarly items, including research articles, reviews, books, and other publicly accessible internet sources, were returned by the search procedure. The shortlist included about 20 items that were published from 2015. Due to the scarcity of contemporary studies and their relevance to the chosen topic, articles published before 2015 but not before 2010 were also chosen. The selected articles were thoroughly studied and critically analyzed for this study.

Results/Discussion

Bioenergy Production from Waste

The global rise in energy demand, fossil fuel depletion, carbon emission and environmental concerns from waste drive the need for sustainable waste-to-energy (WTE) technologies and circular economy solutions (Mishra *et al*., 2023). Organic waste such as sugarcane bagasse, rice paddy straw and cattle manure has been used to produce biogas, biodiesel and bioethanol aiding waste management (Mishra *et al*., 2023). Plastic and solid biomass waste can be co-pyrolyzed into biofuels and value-added products offering an eco-friendly waste management solution (Wang *et al*., 2021). WTE technologies convert waste into biogas (CO_2, CH_4), liquid biofuels (biodiesel, ethanol), and syngas ($CO+H_2$) for electricity generation. Biodiesel is produced through transesterification, achieving 99.6% pure fatty acid methyl ester from waste cooking oil using supercritical methanol and KOH (Mishra *et al*., 2023). Agricultural waste like rice straw and sugarcane bagasse has been hydrolyzed to produce acetone, butanol and ethanol using Clostridium species. While anaerobic digestion of municipal solid waste yields biogas (Mishra *et al*., 2023).

Production Of Biopolymers, Biochemicals and Enzymes from Waste

The production of biopolymers and biomaterials from organic waste through processes like fermentation, enzymatic hydrolysis and anaerobic digestion supports the circular economy (Jain *et al*., 2022). Biopolymers such as polyhydroxyalkanoates (PHA) and polyhydroxybutyrate (PHB) derived from food waste are biodegradable. When used in the production of bioplastics, degrade into CO_2 and water within months after they are buried, thus reducing plastic and food waste (Capanoglu *et al*., 2022). Biopolymers are used in critical applications in industries like medicine, cosmetics, pharmaceuticals, food industries, water treatment, biosensor development, plastics industries and textiles due to their biodegradability and biocompatibility (Ranganathan *et al*., 2020). Bio-composites from wastes like eggshells, poultry waste, and avocado peel have been used in food preservation and packaging because of their antioxidant and antimicrobial properties (Oluba *et al*., 2024). Aguiló-Aguayo *et al*., (2024), have reported the extraction of Microfibrillated cellulose (MFC) from agroindustrial byproducts. Organic acids such as lactic, succinic, citric have been produced from food waste fermentation and this is influenced by waste composition (Capanoglu *et al*., 2022). Enzymes like α-amylase, glucoamylase, and lipase have been recovered from food waste through fermentation reducing production costs and environmental impact while maintaining high specificity and yield (Capanoglu *et al*., 2022).

Production of Phytochemicals

The demand for plant-derived phytochemicals is growing due to their use in allopathic medicine, either as direct extracts or purified compounds for drug development despite synthetic alternatives (Saravanan *et al*., 2021). Plant wastes are generated in large quantities resulting in pollution. These plant wastes are found to possess therapeutic properties, for example dried mango leaves (Mangifera indica) are rich in antioxidants, antiviral, anti-diabetic, and antitumor compounds like mangiferin (Imran *et al*., 2017). Phenolic compounds, valued for their antioxidant properties interact with lipids, DNA, and proteins to form natural therapeutic agents and have been extracted from agro-industrial waste (e.g., vegetables, fruits, shells, leaves) as tannins, flavonoids, alkaloids, and anthocyanins (Singh *et al*., 2018; Arun *et al*., 2020). Tomato processing waste such as seeds and peels is a source of bioactive compounds like sterols, terpenes, and polyphenols, while coffee production waste contains tannins and phenolic compounds (Navajas-Porras *et al*., 2025).

Production of Biofertilizers

Plants require nutrients like nitrogen, potassium, and phosphorus for growth, which are depleted from soil after harvest and replenished naturally or through fertilizers (Varjani *et al*., 2019). Chemical fertilizers, commonly used to boost crop yield and pest control have been reported to negatively impact both soil microbes and plants. However, organic fertilizers enhance soil's physical, chemical, and biological properties by microbial breakdown of organic compounds (Varjani *et al*., 2021). Agro-industrial waste rich in nitrogen, phosphorus, and potassium, improves soil fertility and crop yield, offering a sustainable alternative to chemical fertilizers with reduced environmental impact (Mohanty *et al*., 2021; Adesra *et al*., 2021). Biofertilizers formulated from oil palm (Elaeis guineensis) empty fruit bunches and plant growth promoting microbes have been reported (Mahmud & Chong, 2021).

source of bio-waste, treatment approaches and its bio-products and bioenergy

Adapted from Jain *et al*., 2022

Pathways for waste conversion

Biochemical conversion involves the microbial decomposition of biodegradable organic waste by bacteria and fungi occurring in the presence or absence of oxygen to produce products like compost, biogas, biofuels, antibiotics, biofertilizers, and biochemicals. This process is ideal for wastes with high biodegradable organic matter and moisture content which support microbial activity. Key pathways include anaerobic digestion, bio-fermentation, and enzymatic hydrolysis.

Anaerobic Digestion

Anaerobic digestion (AD) is a widely adopted process for managing organic waste, reducing environmental impact and producing energy particularly methane, while supporting sustainable development. In Europe, AD handles 25% of biological treatment with 244 plants and an 8-million-ton capacity (Adekunle & Okolie, 2015). It degrades organic matter under anaerobic conditions using bacteria and archaea, producing methane-rich biogas and nutrient-rich digestate used as fertilizer. AD is prevalent in agriculture for manure management and energy production, primarily through single-stage systems, however two-stage systems which separate hydrolysis/acidogenesis from methanogenesis, show potential for faster, more stable treatment but lack proven industrial benefits (Adekunle & Okolie, 2015).

AD involves a complex reduction process under anoxic conditions comprising four biochemical steps: hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Aslanzadeh, 2014). Hydrolysis is often rate-limiting for complex substrates due to toxic byproducts while methanogenesis limits easily biodegradable substrates (Adekunle & Okolie, 2015). The process relies on two microbial groups (acid-forming and methane-forming) whose balance is critical to avoid reactor instability and low methane yields.

Techniques like membrane separation and pH control enable phase separation based on differing growth kinetics (Adekunle & Okolie, 2015).

- **Hydrolysis**

Hydrolysis transforms insoluble organic compounds (e.g., lipids, polysaccharides) into soluble forms (e.g., monosaccharides, amino acids) using extracellular enzymes secreted by anaerobes like Bacteroides and Clostridia (Merlin Christy *et al*., 2014). The rate depends on substrate type, with cellulose degrading slower than proteins, and microbial specialization (saccharolytic or proteolytic) influences enzyme activity (Adekunle & Okolie, 2015).

- **Acidogenesis**

In acidogenesis, facultative and obligate anaerobes convert hydrolysis products into short-chain organic acids (e.g., acetic, butyric), alcohols, hydrogen, and carbon dioxide. Hydrogen concentration affects product formation with high partial pressure reducing yields of reduced compounds (Adekunle & Okolie, 2015).

- **Acetogenesis**

Acetogenesis involves anaerobic oxidation of acidogenesis products (e.g., volatile fatty acids, alcohols) into methanogenic substrates like acetate, hydrogen, and carbon dioxide. This phase requires collaboration with methanogens, who consume hydrogen to maintain low partial pressure, enabling inter-species hydrogen transfer (Aslanzadeh, 2014; Adekunle & Okolie, 2015).

- **Methanogenesis**

Methanogenesis, which is critical to the overall anaerobic digestion process efficiency is the slowest step and produces methane and carbon dioxide from acetogenesis intermediates using methanogenic bacteria under strict anaerobic conditions (Aslanzadeh, 2014).

BioFermentation

The fermentation bioprocess involves the biotransformation of a substrate rich in carbon and nitrogen to ethanol and other by-products like glycerol, lactic acid, acetic acid, enzymes, biopolymer, biofuels etc. based on which fermentative microorganism is used and the available mineral salts concentration (Bibra *et al*, 2023). Two groups of microbes (saccharolytic and ethanologenic) are important in bio-fermentation and they operate on the principle of co-metabolism, whereby, when saccharolytic microbes break down complex polymeric carbohydrates (starch, cellulose, hemicelluloses, etc.) to simpler utilisable forms, the ethanologenic converts them to ethanol (Gumisiriza *et al*.,2017). Notably, *Saccharomyces cerevisiae* and *Zymomonas mobilis* are the only microbes naturally capable of producing ethanol close to theoretical maximum, with Saccharomyces cerevisiae predominant for current ethanol production based on starch and sugar feedstocks (Gumisiriza *et al*., 2017). Conversely, most organic waste contains cellulose, hemicellulose and lignin, and may require microbial consortia or genetically modified microbes to enhance breakdown and enable efficient cellulosic ethanol production (Gumisiriza *et al*., 2017). Bibra *et al*., (2023) have reported the fermentation of ethanol from organic food waste rich in carbohydrates (35.5-69%) and proteins (3.9-21.9%).

Enzymatic Hydrolysis

Enzymatic hydrolysis is a key method for treating food waste and producing bioethanol. This has advantages over chemical hydrolysis by eliminating the production of toxic byproducts and corrosion (Sakar *et al*., 2024). It breaks down polysaccharides in food waste into simple sugars (e.g., glucose, fructose, xylose) for fermentation, with glucoamylase being the dominant enzyme due to its ability to convert starches into glucose (Anwar Saeed *et al*., 2018). The efficiency of bioethanol production depends on the enzyme formulation tailored to the food waste composition (Salimi *et al.*, 2019). Studies demonstrate high ethanol yields from various food wastes using enzymes like α-amylase, cellulase, and pectinase, with efficiencies ranging from 83–99.6% of theoretical yields (Ntaikou *et al.*, 2021).

Thermochemical Conversion Process

Thermochemical process involves decomposition of carbonaceous organic matter under high temperature to produce heat energy, fuel oil or gas and other value-added product such as charcoal. The main technological options under this category include incineration, pyrolysis, gasification and hydrothermal carbonization. Thermochemical process is useful for less dense wastes and low moisture content (Rajaeifar *et al.*, 2017). The most commonly available thermal technologies are discussed

Incineration

Incineration involves burning municipal solid waste (MSW) in oxygen at 800–1200°C for at least 2 seconds, producing heat, ash (bottom and fly), and flue gas (Alao *et al.*, 2022). This method requires minimal pre-treatment and converts heat into electricity or steam for district heating/industrial use through the steam Rankine cycle, with applications in power-only or combined heat and power (CHP) systems (Alao *et al.*, 2024; Patil *et al.*, 2024). Electricity is integrated into the grid, and heat enhances energy efficiency, though byproducts include ash and emissions (Patil *et al.*, 2024).

Pyrolysis

Pyrolysis thermally decomposes organic waste, biomass, and synthetic materials (e.g., plastics, rubber) in the absence of oxygen at 400–800°C, yielding biochar, bio-oil, and syngas (Patil *et al.*, 2024). Product quantity and quality depends on heating rate, temperature, residence time, feedstock, reactor type and catalysts (Alao *et al.*, 2024). Syngas supports electricity generation, bio-oil is used in biofuels/chemicals, and biochar serves as a fossil char substitute or soil enhancer (Al-Rumaihi *et al.*, 2022). Pyrolysis types (slow, fast, and flash) vary by retention time and temperature, with slow pyrolysis favoring biochar and fast/flash maximizing bio-oil (Alao *et al.*, 2024).

Gasification

Gasification converts biomass, municipal solid waste and solid fuels into syngas (containing methane, carbon monoxide, nitrogen, etc.) using gasifiers (20–500 kW) with gasifying media like heat, oxygen, and steam (Patil *et al.*, 2024). The process requires drying feedstock at 100°C and shredding for uniformity before gasification which occurs at 700–1000°C with limited oxygen to maximize fuel gas production, while minimizing condensable hydrocarbons and unreacted chars (Shahzad *et al.*, 2024). The choice of gasification technique depends on steam application and gasifying agents (Fang *et al.*, 2021). Syngas is used for electricity, biofuel production, or chemical synthesis, with tar and ash as byproducts (Patil *et al.*, 2024).

Hydrothermal Carbonization

Hydrothermal carbonization is an emerging technology for treating wet biomass, organic waste, and agricultural residues. Minimal pre-drying may be necessary. The temperature treatment (ranging from 180 ◦C to 250 ◦C) under high pressure yields hydrochar, which is a carbon rich material. Liquid by-products may also be produced, with the potential for soil amendment. The energy embedded in the hydrochar can be utilized for electricity generation or other applications contributing to the energy market. Moreover, the hydrochar can be applied as a soil conditioner, addressing the agricultural market's demand for sustainable soil improvement (Patil *et al.*, 2024).

Hydrothermal Liquefaction

Hydrothermal Liquefaction is a waste-to-energy process that converts feedstocks into high-energy bio-oil and other products (e.g., adhesives, resins, bio-polyols, polyurethane foams) under 4–25 MPa and 200–374°C (Sakar *et al*., 2024). The process involves hydrolysis of biomass into monomers, decarboxylation into smaller compounds and recombination into new compounds through condensation or polymerization (Gollakota *et al*., 2018). Catalysts enhance reaction kinetics and product quality; alkali catalysts (NaOH, KOH) reduce char formation and increase bio-oil yields, while acidic catalysts (H_2SO_4, H_3PO_4) lower temperature and reaction time (Sakar *et al*., 2024). Hydrothermal liquefaction (HTL), using water as a medium at 250–374°C and 4–25 MPa, is ideal for high-moisture feedstocks like algae, moisturized municipal solid waste, cattle manure, and sewage sludge, leveraging water's abundance and cost-effectiveness (Sakar *et al*., 2024).

Integrated Waste to Energy System

Pyrolysis–anaerobic digestion.

Anaerobic digestion generates digestate that can be dried and used in pyrolysis processes to generate biochar thereby improving energy sustainability and cost-efficiency (Begum *et al*., 2024). Integrating these processes enhances resource recovery from agricultural waste, boosting electricity yield by 42% compared to anaerobic digestion alone (Monlau *et al*., 2015). Biomass pretreatment improves bio-oil quality while biochar from digestate pyrolysis excels as a soil conditioner due to higher potassium, phosphorus, surface area, and water retention (Begum *et al*., 2024). Digestate derived bio-oils with fewer hydrocarbons, phenols and esters than raw food waste, resemble biodiesel and suit vehicle fuel needs. Improved biofuel recovery results from syngas biomethanation, which uses anaerobic microorganisms to convert CO_2, H_2, and CO into CH_4 (Yang *et al*., 2020; Begum *et al*., 2024). Combining liquid digestate and biochar improves soil quality making this approach sustainable for waste reduction and resources recovery in energy and agriculture (Begum *et al*., 2024).s

Hydrothermal liquefaction–anaerobic digestion

Anaerobic digestate management faces challenges like odor, environmental pollution, presence of pathogens and high costs or overuse when applied as liquid fertilizer (Kassem *et al*., 2020). Integrating hydrothermal liquefaction (HTL) with anaerobic digestion (AD) enhances energy recovery from organic waste by converting high-moisture anaerobic digestate into biocrude, a precursor to green transportation fuels (Kassem *et al*., 2020; Begum *et al*., 2024). HTL is well-suited for wet feedstocks like digestate, and post-HTL wastewater, retaining 40% organic matter and 80% nutrients serves as a sustainable resource for algae cultivation and further AD (Begum *et al*., 2024). This integrated HTL-AD approach maximizes resource recovery and material efficiency (Begum *et al*., 2024).

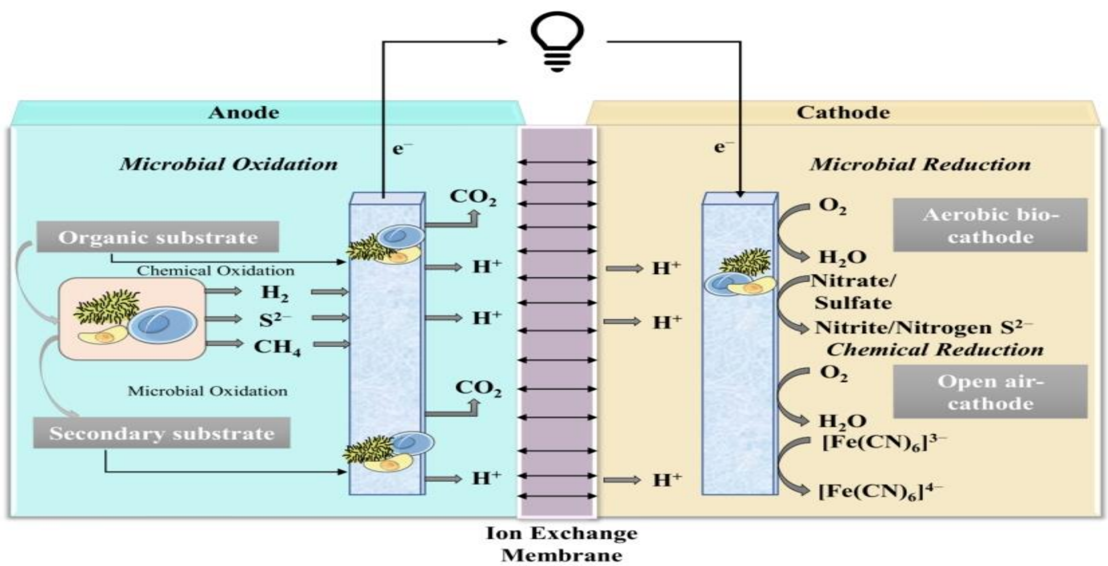
Hydrothermal Liquefaction–Fermentation

Hydrothermal liquefaction (HTL) converts high-moisture biomass into biocrude oils, producing a significant aqueous phase (HTL-AP) containing carbon, nitrogen, organics, inorganic components and heavy metal ions (Watson *et al*., 2020). Although typically considered waste, HTL-AP's rich chemical composition makes it a potential energy source. Anaerobic fermentation can transform HTL-AP into eco-friendly chemicals and fuels, but inhibitors may require pretreatment (e.g., extraction, partial oxidation, adsorption) to enhance biodegradability (Watson *et al*., 2020; Quispe-Arpasi *et al*., 2018). Alternatively, aerobic fermentation being faster and oxygen-dependent, is a viable method for producing value-added products from HTL-AP (Gu *et al*., 2019).

Innovatives Waste Conversion Techniquies

Bioenergy generation from microbial fuel cells

Microbial Fuel Cells (MFCs) utilize microbial metabolism to convert organic matter into bioenergy such as electricity, biohydrogen, and biogas (Slate *et al.*, 2019). In MFCs, microorganisms oxidize organic matter at the anode releasing electrons and protons which generate electric current as electrons flow to the cathode, reacting with an electron acceptor like oxygen to form water (Nawaz *et al.*, 2020). Biohydrogen production in MFCs involves microbes like Clostridium spp. and Rhodobacter spp. using pathways such as dark fermentation and photofermentation, with strategies like metabolic pathway modification and optimal substrate selection to enhance yield (Ferreira *et al.*, 2022; Pandya *et al.*, 2024). Methane production is facilitated by electroactive methanogens, with electrochemical stimulation and optimized conditions improving output (Alves *et al.*, 2022; Liu *et al.*, 2023). Advances in electrode materials, such as carbon-based and novel options with increased surface area and biocompatibility, enhance electron transfer and power generation (Lorant *et al.*, 2022). Synthetic biology improves electron transfer efficiency by engineering microbes with enhanced pathways or synthetic shuttles (Zhang *et al.*, 2020). MFCs also treat wastewater by using organic pollutants as fuel, simultaneously generating electricity and reducing pollution, with ongoing pilot-scale applications (Malik *et al.*, 2023).



Schematic representation of the working principle of MFCs. Adapted from Malik *et al.*, 2023

Microbial Metabolism and Waste Valorization

Microorganisms degrade lignocellulosic biomass by secreting hydrolytic and lignin-degrading enzymes, breaking down the rigid cell wall structure and hydrolyzing biopolymers like hemicellulose and cellulose into monomeric sugars (Joshi *et al.*, 2024). This process, involving cellulolytic and hemicellulolytic microbes, supports simultaneous fermentation to produce biofuels such as ethanol, furfural, and methane, alongside byproducts like acetate and organic acids (Reguera *et al.*, 2015; Joshi *et al.*, 2024). Notable microbes include bacteria (e.g., Bacillus sp., Cellulomonas sp.) and fungi (e.g., Aspergillus niger, Trichoderma reesei) known for biopolymer hydrolysis (Joshi *et al.*, 2024). Advances in bioconversion involve synthetic control of microbial metabolic pathways to enhance product yields, demonstrated in bioengineered *Escherichia coli* producing higher alcohols (e.g., isobutanol, 1-butanol) from glucose. This was achieved by amplifying 2-ketoacid decarboxylases and alcohol dehydrogenases, overexpressing genes like ilvIHCD and alsS from Bacillus subtilis and silencing genes for byproducts and pyruvate competition, yielding ~300 mmol/L (22 g/L) isobutanol under microaerobic conditions (Arancon *et al*., 2013).

Engineered Enzymes for Waste Degredation

Biorefineries enable sustainable conversion of organic waste into energy and high-value products, enhanced by metabolic engineering of microorganisms through gene deletion, overexpression, or pathway integration (Alibardi *et al*., 2020; Ben Tahar and Fickers, 2021). Saccharomyces cerevisiae, a key bioethanol producer, was engineered to metabolize xylose by overexpressing genes like Piromyces xylose isomerase and Pichia stipitis xylulose kinase, achieving high xylose consumption and ethanol titers (Ben Tahar and Fickers, 2021). Consolidated bioprocessing, that is combining hydrolysis and fermentation was achieved by expressing trifunctional cellulases from Clostridium cellulolyticum in S. cerevisiae EBY100, yielding 1.42 mg/L ethanol from cellulose. Biohydrogen production through dark fermentation was improved in E. coli by inactivating hycA and deleting genes for hydrogenases, lactate dehydrogenase and fumarate reductase achieving 2.11 mol/mol glucose, that is 90% of the theoretical maximum (Ben Tahar and Fickers, 2021). Succinic acid production was enhanced in Yarrowia lipolytica strain PGC202 by disrupting the succinate dehydrogenase gene (YALI0F11957g) and CoA-transferase gene (Ylach) enabling efficient production from fruit and vegetable waste at low pH with a 13-fold increase over the parental strain (Ben Tahar and Fickers, 2021).

Circular Economy and Waste Upcycling

Global waste generation reaching 2.12 billion tons annually poses significant environmental challenges with most waste sent to landfills emitting pollutants (Kish, 2016). A circular economy aims to mitigate climate change and promote sustainability by converting waste into high-value products through mechanical, thermochemical, and biochemical processes, prioritizing chemical recycling over simple reuse (Kish, 2016; Sung, 2023). Traditional methods like incineration are inefficient producing pollutants such as mercury, dioxins and carbon dioxide, while anaerobic digestion is limited to biodegradable waste leaving digestate with odor, pathogens, and heavy metals that risk environmental contamination (Kassem *et al*., 2020; Kish, 2016). Emerging (integrated) waste-to-energy technologies like hydrothermal liquefaction–anaerobic digestion and pyrolysis–anaerobic digestion enables the conversion of both biodegradable and non-biodegradable waste into clean energy products like hydrogen, synthetic fuels, and “green” chemicals, reducing landfill use and fossil fuel dependency (Kish, 2016; Begum *et al*., 2024). These technologies require efficient processes and reliable cleaning systems to prevent pollution, with product outcomes varying by feedstock and processing conditions (Kish, 2016).

Challenges and Future Directions

Despite its promise, waste valorization faces significant hurdles such as;

Technological Limitation: Many processes remain energy-intensive or economically unviable at scale. For example, enzymatic recycling of plastics is still slower and costlier than mechanical method.

Waste Heterogeneity: Mixed or contaminated waste streams complicate processing; necessitating advanced sorting and pretreatment technologies.

Policy and Behavioral Gaps: Inconsistent regulations and consumer resistance to recycled products hinder market adoption.

Conclusion

Waste valorization represents a transformative opportunity for biochemists to address the global waste crisis while advancing sustainable innovation. By leveraging cutting-edge biochemical techniques, such as anaerobic digestion, microbial fermentation, enzymatic catalysis, and synthetic biology, this field unlocks the potential of waste materials to produce high-value products like biofuels, biodiesel, bioplastics, biopolymers and bioactive compounds. The investigation of new frontlines in waste valorization not only mitigates environmental degradation and resource scarcity but also fosters a circular bioeconomy, aligning with global sustainability goals. This study underscores the critical role of biochemists in driving technological breakthroughs, overcoming scalability challenges, and creating economic opportunities through waste-to-resource conversion. Ultimately, waste valorization paves the way for a resilient, resource-efficient future, where waste is no longer a burden but a valuable asset for scientific, environmental, and societal progress.

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