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CHEMICAL UPCYCLING OF WASTE BIOMASS INTO HIGH-VALUE CHEMICALS

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ABSTRACT
The chemical upcycling of waste biomass into high-value chemicals presents a promising pathway toward sustainable resource utilization and circular economy goals. This review highlights recent developments in the catalytic transformation of biomass, with particular emphasis on cellulose and lignin, the two most abundant and structurally distinct components of lignocellulosic feedstocks. Cellulose serves as a valuable precursor for platform chemicals such as glucose, HMF, levulinic acid, and FDCA, which are integral to bioplastics and green solvents. Lignin, owing to its aromatic complexity, is increasingly exploited for the production of phenolic compounds, vanillin, and BTX aromatics through advanced depolymerization and selective catalytic processes. We examine key upcycling strategies—including acid and base catalysis, oxidative and reductive conversions, pyrolysis, and hydrothermal methods—along with recent advances in catalyst design and mechanistic understanding. Additionally, challenges related to feedstock variability, product selectivity, and scalability are addressed. This review outlines emerging opportunities for efficient biomass valorization and underscores the pivotal role of cellulose and lignin in the development of high-value, bio-based chemicals.

Keywords:
Catalytic biomass upcycling, cellulose valorization (HMF, levulinic acid, FDCA), lignocellulosic biorefinery, lignin depolymerization and phenolic compounds, and thermochemical & hydrothermal conversion methods

I. Introduction
Waste biomass refers to renewable organic materials generated as by-products or residues from agricultural, forestry, food processing, and municipal waste streams. These include lignocellulosic residues like corn stover, rice husks, sawdust, sugarcane bagasse, food scraps, and algae biomass all derived from biological sources that would otherwise be discarded[1,2] Valorizing waste biomass supports the principles of a circular economy by transforming nominal "wastes" into valuable bioenergy, biomaterials, chemicals, or soil amendments, thereby minimizing resource depletion, greenhouse gas emissions, and environmental pollution while closing material loops[3]. A circular bio-economy achieves both economic and environmental sustainability through cascading use and reuse of biomass across value chains. In particular, food waste valorization through recycling and repurposing plays a pivotal role in mitigating environmental and economic burdens, while accelerating progress toward a circular economy framework. Rai et al. emphasize that annually about 1.3 billion tons of edible food are wasted, generated around 3.3 billion tons of greenhouse gases, underlining the critical urgency of repurposing food waste into high-value products[4]. Recent research has explored the potential of agro-industrial waste as a rich source for the production of novel biomaterials, such as

collagen, chitosan, pullulan, hydroxyapatite, cellulose, gelatin, and carbon-based nanocomposites. These biowastes, when processed using microbial and biochemical routes, have demonstrated commercial viability in diverse applications, exemplifying the successful transition from waste to value-added products[5]. Such innovations reflect the core goals of a circular bioeconomy, wherein biowaste is not merely disposed of but actively repurposed for material, environmental, and economic gain. Among these, lignocellulosic biomass has emerged as a particularly promising feedstock due to its abundance, renewability, and compatibility with sustainable energy strategies. However, its complex, recalcitrant structure poses challenges in efficient pretreatment and conversion. Recent advancements in integrated thermochemical and biological technologies aim to overcome these barriers and maximize energy yield from lignocellulosic biomass, offering a pathway toward more viable bioenergy systems[6]. This shift supports the broader vision of a lignocellulosic biorefinery that emphasizes both energy generation and value-added product development.
Conventional biomass utilization routes include combustion for heat and energy, composing, and anaerobic digestion. While these methods recover some energy and nutrients, they often yield lowvalue outputs and may emit methane or Co2, By contrast chemical upscaling employing targeted transformations such as catalytic upgrading, pyrolysis, hydrothermal carbonization, or chemical looping to convert biomass into high-value chemicals, fuels, and advanced materials. Chemical upcycling can achieve higher product value, greater carbon efficiency, and better alignment with high-value circular economy objectives[7]

II. Sources and types of waste biomass

2.1 Agricultural Waste

Agricultural residues such as corn stover, rice husk, wheat straw, and sugarcane bagasse and other crop by-products constitute one of the planet’s largest yet underutilized biomass streams. Globally, their dry matter production Is estimated to be around 3.7 - 3.8 billion tons per year, with cereals and sugarcane residues accounting for roughly 80% of that total[8,9]. These lignocellulosic materials are particularly rich in cellulose, hemicellulose, and lignin, making them ideal feedstocks for conversion into biofuels, platform chemicals, and bio composites, while also offering potential routes to enzymes and bioactive compounds[10]. Improper disposal of these residues often through open burning or burning in fields contributes substantially to greenhouse gas emissions, soil degradation, and air pollution[11,12]. Therefore, a growing body of literature emphasizes valorization pathways such as biochemical fermentation of bioethanol, production of single-cell protein, generation of biochar or activated carbon, synthesis of bioplastics and adsorbents, and enzymatic extraction of high-value chemicals[10].

2.2 Forestry residues

Forestry by-products such as branches, sawdust, bark, off-cuts, tree tops, and stumps constitute a highly abundant and underutilized lignocellulosic biomass stream. These residues are composed primarily of cellulose, hemicellulose, and lignin, offering a versatile feedstock for conversion into bioenergy, prebiotic compounds, and carbon-rich materials. One emerging valorization route is the enzyme-based production of cello-oligosaccharides, which have strong prebiotic properties: COS derived from birch and spruce forest residues stimulated growth in Lactobacilli and Bifidobacteria, highlighting potential nutraceutical applications[13–16]. Another avenue leverages pyrolysis and gasification to transform woody biomass into biochar a stable, carbon-rich material that enhances soil structure, nutrient retention, and carbon sequestration in agro-forestry systems. Its effectiveness varies with feedstock and production conditions, but when optimized, biochar use can substantially benefit soil health and climate mitigation efforts[17]

2.3 Food and kitchen waste

Organic wastes from households, retail outlets, and the food industry are highly heterogeneous mixture, including fruit and vegetable peels, coffee grounds, cooking oils, dairy byproducts, and food processing residues. Although often viewed as low-value, these materials are rich in nutrients, bioactive compounds, carbohydrates, proteins, and lipids making them ideal substrates for valorization into a range of high-value products. Recent reviews emphasize the opportunities in converting food waste into bioplastics, nutraceutical extracts, biochar, and various functional materials through modern biorefinery platforms. For instance, PHAs can be produced from fermented food waste via microbial cultivation, reducing dependence on refined glucose and lowering costs[18,19]. Similarly, food-processing by-products like sow whey and okara have been industrially transformed into amyloid-fibril-reinforced films, showcasing large-scale feasibility[20]. Moreover, integrates processes now enable the recycling of exhausted bioplastics into biochar with yields around 32% which serves effectively as a carbon-rich adsorbent for wastewater treatment or soil amendment enabling a zero waste antioxidant compounds across fruit and vegetable waste streams. Ultrasonic, microwave-assisted, and enzyme extractions have emerged as efficient methods to recover these natural antioxidants for applications in food supplements and cosmetics[21]

2.4 Municipal solid waste

Globally, the degradable fraction of MSW which includes cooked food scraps garden waste, paper, and cardboard accounts for approximately 30-45% of municipal waste by mass. This organic portion is a primary source of methane generation in landfills, where anaerobic decomposition produces a gas mixture typically composed of 60% methane and 40% CO2, significantly contributing to greenhouse gas emissions[22,23]. As methane has roughly 25 times the global warming potential of CO2, diverting this waste from landfills is critical to reducing climate impact. Effective valorization pathways, such as composting, anaerobic digestion, and thermochemical conversions, provide sustainable alternatives. Composting by maintaining aerobic conditions substantially lowers methane emissions compared to landfill disposal and produces nutrient-rich compost that can replace chemical fertilizers. Meanwhile, anaerobic digestion of the organic fraction yields biogas (50-75% methane), which can be used for cooking, heat, power generation, or as a vehicle fuel after purification, while also producing digestate rich in nitrogen, phosphorus, and postassium for agricultural use. Optimizing AD through co-digestion, pretreatment, and process control enhances resource recovery and energy output[22]. Futhermore, integrating AD with pyrolysis has shown promising results in maximizing energy and material recovery. Life-cycle assessment studies reveal that an AD-pyrolysis sequence reduces environmental impact significantly compared to standalone AD or pyrolysis, whereas the reverse order increases impact[24]. Optimized systems can yield biochar (28-40 wt%), bio-oil, and syngas, while improving economic and environmental performance, and enabling carbon capture via soil amendment using biochar[25]

2.5 Algal and aquatic biomass

Aquatic-derived biomass, such as and macroalgae and microalgae, is increasingly recognized as a valuable renewable resource due to its rapid growth, minimal land requirements, and high biochemical content. Its valorization holds promise for multiple applications, including the production of biofuels, biofertilizers, nutraceuticals, and bioplastics. Algae-based systems are also effective in wastewater treatment through nutrient uptake and CO2 sequestration, contributing to environmental remediation. Integrated approaches like high-rate algal ponds and photobioreactors combine biomass cultivation with pollutant removal, creating a circular and sustainable model of biomass utilization[26,27]. Advanced techniques such as hydrothermal liquefaction and anaerobic digestion further enhance the recovery of value-added compounds from aquatic biomass while minimizing waste generation[27]

III. Pretreatment and feedstock preparation

3.1 Physical Pretreatment

Physical pretreatment methods primarily aim to alter the structural properties of lignocellulosic biomass to facilitate better accessibility of lignin for subsequent processing. The most common physical techniques include **size reduction**, such as milling, grinding, or shredding, which increase the surface area and reduce particle size, making the biomass more reactive. Additionally, **drying** is often necessary to reduce the moisture content of biomass, especially when thermal or chemical treatments are involved downstream. While these methods do not alter the chemical structure of lignin, they are essential preparatory steps that improve the efficiency and uniformity of further chemical or biological processing.

3.2 Chemical Pretreatment

Chemical pretreatments are highly effective in breaking down the complex lignocellulosic structure to release and extract lignin. These processes typically use **acidic** (e.g., sulfuric acid) or **alkaline** (e.g., sodium hydroxide) solutions to cleave ether and ester linkages within the lignin– carbohydrate complex, thereby enhancing lignin solubility. Alternatively, **ionic liquids** and **deep eutectic solvents (DESs)** have gained attention for their ability to selectively dissolve lignin while leaving cellulose relatively intact. These solvents offer tunable properties and recyclability, making them promising for sustainable lignin extraction. However, high cost and recovery challenges are limitations that require further optimization.

3.3 Thermochemical Pretreatment

Thermochemical pretreatments utilize heat, pressure, and moisture to alter the lignin structure and disrupt biomass recalcitrance. **Steam explosion** is one of the most widely used methods, where biomass is treated with high-pressure steam and then rapidly depressurized, causing mechanical and chemical disruption of the cell wall. Similarly, **hydrothermal treatment** (also called autohydrolysis) uses hot compressed water to break down hemicellulose and open up the lignocellulosic matrix, enhancing lignin accessibility. These methods partially depolymerize lignin and increase its reactivity for subsequent chemical upgrading. Though energy-intensive, thermochemical methods offer a solvent-free approach and can be integrated with catalytic depolymerization techniques.

3.4 Biological Pretreatment

Biological pretreatment offers an eco-friendly and energy-efficient alternative for lignin modification by utilizing **lignin-degrading microorganisms** or **enzymes** such as **laccases**, **lignin peroxidases**, and **manganese peroxidases**. These enzymes selectively oxidize and break down complex lignin structures into smaller fragments under mild conditions. This method preserves the integrity of cellulose and hemicellulose, making it highly suitable for integrated biorefineries focused on multiple product streams. However, the main limitations of biological pretreatment are **slow reaction rates**, **low lignin removal efficiency**, and the requirement for precise environmental control (pH, temperature, oxygen availability), which restrict its large-scale industrial application without process intensification.

Kumar et al. review emphasizes the importance of pretreatment in lignocellulosic biomass valorization, focusing on the challenge of removing lignin, which hinders cellulose and hemicellulose hydrolysis. It outlines key physical, chemical, and biological pretreatment methods aimed at improving component accessibility and reducing inhibitory byproducts. Integrated pretreatment strategies are highlighted as more effective than single methods, although further research is needed to develop more efficient and selective processes for industrial applications[40].

Shukla et al. review emphasizes lignocellulosic biomass (LCB) as a sustainable and eco-friendly feedstock for bioethanol production, derived from agricultural residues. Due to its complex structure, effective pretreatment methods—physical, chemical, biological, and physicochemical— are essential to enhance biomass accessibility. The study explores both individual and integrated pretreatment strategies like steam explosion, ionic liquids, and biological degradation, highlighting their role in improving hydrolysis and fermentation efficiency. It also discusses recent advancements and future prospects in pretreatment technologies for large-scale bioethanol production[41].

Saratale et al. study explores the effectiveness of chemical pretreatment methods for saccharifying whole rice waste biomass (RWB) to produce fermentable sugars for ethanol production. Sequential pretreatment using acidified sodium chlorite, sodium bicarbonate, and alkaline treatment achieved high sugar yield (725 mg) and hydrolysis efficiency (90.6%) at low enzyme doses. Structural analysis confirmed effective delignification, and the resulting hydrolysate supported efficient ethanol fermentation by *Saccharomyces cerevisiae* without detoxification. The findings demonstrate a feasible and cost-effective route for bioethanol production from agricultural waste[42].

Daraban et al. study addresses the challenge of feedstock pumpability in hydrothermal liquefaction (HTL) of lignocellulosic biomass by developing pretreatment methods that enable over 20% solid content in wood-based slurries. Two approaches—use of recycled HTL biocrude as a carrier fluid and thermal alkali treatment—are evaluated for their effectiveness. The results show significant viscosity reduction and improved pumpability, even with larger wood particles, making continuous HTL processing more feasible and efficient[43].

Correa et al study evaluates fungal pretreatment using *Ceriporiopsis subvermispora* under nonsterile conditions for various lignocellulosic feedstocks. The sequential inoculation method enhanced enzymatic digestibility in miscanthus, hardwood, and softwood, significantly increasing glucose and xylose yields. Feedstock structure and composition strongly influenced pretreatment success, with effective lignin degradation varying by lignin unit type. Notably, the fungus could also degrade pine terpenes, indicating its potential in selective biomass delignification[44]

Perego et al. review highlights the critical role of acid and base catalysis in improving biofuel production processes, including biodiesel via transesterification and bioethanol through cellulose hydrolysis. It emphasizes the need for cost-effective and high-yield catalytic systems to enhance process efficiency and economic feasibility. The paper provides an overview of commercially applied and pilot-scale technologies that utilize acid-base catalysis for biomass-to-fuel conversion[45].

Vegi et al. study focuses on optimizing the dilute acid pretreatment and enzymatic hydrolysis steps in the lignocellulosic ethanol production process to enhance efficiency and reduce costs. Using kinetic models integrated with mass and energy balances, batch and fed-batch reactor models were developed and optimized via Pontryagin's maximum principle. The optimized conditions significantly improved product concentration, reduced processing time, and boosted profitability, thereby enhancing the techno-economic feasibility of lignocellulosic bioethanol production[46].

IV. Chemical Upcycling Techniques

4.1 Catalytic Processes

Polymers have revolutionized modern life, but their durability has led to severe environmental challenges due to poor degradation and recycling. Chemical upcycling offers a promising solution by converting waste polymers into valuable monomers, fuels, or chemicals. Catalytic processes play a crucial role in enhancing reaction efficiency and product selectivity, making polymer upcycling more viable. While current methods can be cost-prohibitive, recent advances in catalyst development especially for major commercial plastics are paving the way for more efficient and sustainable chemical recycling and upcycling technologies[53,65]. Catalytic upcycling of polyolefin

(PO) plastics using co-reactants like hydrogen, alkanes, or CO_2 offers a sustainable alternative to traditional recycling, enabling conversion into valuable products under mild conditions. Recent advances highlight improved reaction pathways and product diversity, though challenges like catalyst stability and feedstock diffusion remain[66]. This study presents a green approach to convert levulinic acid into alkyl levulinates using a PiNe–SO_3H catalyst derived from waste pine needles. The catalyst enables high yields (46–93%) under mild conditions, shows excellent reusability for up to 10 cycles, and achieves low E-factors (1.2–8.9). The process emphasizes waste minimization, environmental sustainability, and follows a direct esterification mechanism[67,68]. Bifunctional catalysis enables simultaneous activation of reactants, making it a powerful strategy for efficient asymmetric synthesis. These catalysts offer high activity, selectivity, and broad substrate scope under mild conditions, outperforming conventional systems and showing great promise for practical, eco-friendly applications[69].

4.2 Thermochemical Conversion

Thermochemical conversion Plastic waste is one of the most critical issues in recent years. Upcycle plastic waste as valuable feedstock has attracted huge attention. This Review summarizes thermochemical conversion methods that can convert plastic waste into energy, chemicals, and value-added materials. It also highlights the recent development of catalytic thermochemical conversions and the current challenges of catalytic thermochemical conversion of plastic waste. very short summery[70]. Pyrolysis offers a promising method to upcycle complex textile waste into valuable materials and energy. Despite challenges due to waste inhomogeneity, ongoing research may establish it as an effective end-of-life solution[71]. The surge in plastic use, especially during COVID-19, has intensified environmental concerns due to increased waste from PPE. Traditional disposal methods like incineration and landfilling worsen pollution and waste valuable resources, prompting the need for sustainable plastic waste solutions[72].This study compares pyrolysis and hydrothermal liquefaction of polyurethane, finding that 400 °C hydrothermal liquefaction yields oil rich in carbon, aniline, and p-aminotoluene. These valuable chemicals could support sustainable polyurethane production and enhance plastic circularity[73]. Solvolysis is a chemical recycling method that breaks down plastics like PET into valuable monomers using reagents and heat. It includes processes like alcoholysis, hydrolysis, and ammonolysis, offering lower environmental impact and energy needs than pyrolysis[74].

4.3 Oxidative and reductive conversion

Lignin valorization to value-added platform chemicals may play a pivotal role in the sustainable production of biofuel from renewable biomass. This paper reviews oxidative lignin depolymerization chemistries employed in the papermaking process and oxidative catalysts that can be applied to biorefinery lignin to produce platform chemicals. The potential synergies of integrating new catalysts with commercial delignification chemistries are discussed[65]. Lignocellulosic biomass (LCB) is a sustainable alternative for biofuel production, but its complex structure and inhibitory byproducts from pretreatment make fermentation challenging. Advances focus on engineering microbes to co-utilize sugars and tolerate toxins[75].

4.4 Platform chemical and intermediates

Biomass is a promising alternative to fossil sources for chemical production, with hydrothermal processes enabling efficient, solvent-free conversion of raw biomass into valuable chemicals like furfural and levulinic acid. Process intensification is key to bridging lab-scale and industrial applications[76]. Biomass-derived C5–C6 sugars can be catalytically converted into valuable platform chemicals. Recent advances focus on catalyst design and process optimization, though challenges remain in aqueous-phase reactions and reactor selection[68].

Recent advancements have showcased efficient catalytic processes both heterogeneous and enzymatic for converting waste biomass into high-value chemicals like succinic acid, muconic acid, and other bio-based monomers[67,68]. Techniques such as selective oxidation, hydrodeoxygenation, and fermentation have been optimized for improved yields and sustainability.Steam gasification of pine sawdust showed the best performance, yielding high hydrogen (46.96%), low CO_2 (4.99%), and excellent energy (80.91%) and exergy (86.03%) efficiencies, offering a strong pathway for efficient biomass upcycling[72]. To scale up solvothermal biomass conversion, process intensification is essential through improved work-up technologies, optimized feedstock use, and integrated reaction-purification steps while aligning upstream chemistry with downstream engineering and economic considerations[76].

V. Chemical Upcycling of Waste Biomass Into High-Value Chemicals from Lignin

Lignin, a highly complex and abundant aromatic polymer found in the cell walls of plants, presents a promising yet challenging feedstock for the production of high-value chemicals. Unlike cellulose and hemicellulose, lignin is rich in aromatic structures, making it a unique renewable source for producing aromatic compounds traditionally derived from petroleum. Through various chemical upcycling strategies—such as catalytic hydrogenolysis, oxidative depolymerization, and reductive catalytic fractionation (RCF)—lignin can be depolymerized into a range of valuable monomers and intermediates. These include vanillin, a widely used flavoring agent and precursor in pharmaceuticals; phenol and its derivatives, which are important in the manufacture of resins and adhesives; catechol and guaiacol, used in agrochemicals and dye production; and platform aromatics like benzene, toluene, and xylene (BTX), applicable in fuel and polymer industries. Emerging techniques like biochar-supported catalysis, deep eutectic solvents, and electrocatalytic systems have shown promise in improving selectivity and yield in lignin valorization. Despite its potential, the inherent heterogeneity and recalcitrance of lignin pose significant barriers to efficient conversion, making the development of robust, selective catalysts and integrated biorefinery approaches crucial for future progress in lignin-based chemical production.

Schutyser et al. addresses that lignin valorisation is crucial for sustainable biorefineries, focusing on three key steps: lignocellulose fractionation, lignin depolymerisation, and upgrading into valuable chemicals. Effective fractionation and depolymerisation aim to prevent lignin condensation and preserve or stabilize reactive intermediates. Advanced strategies like catalytic or biological funneling simplify complex product mixtures into target chemicals. Integrated, selective, and scalable processes are essential for future development[28].

Azadi et al. The literature highlights the urgent need to reduce fossil fuel dependency by exploring biomass as a low-carbon alternative for fuel and chemical production. While carbohydrate conversion technologies are mature, lignin valorization remains underdeveloped, with most lignin still used for combustion. Recent research focuses on thermochemical methods like depolymerization, gasification, and upgrading to convert lignin into valuable products such as biofuels, hydrogen, and aromatics. Advancements in these technologies could enhance biorefinery economics and sustainability, with policy support playing a crucial role in future development[29].

Jing et al. emphasizes the roles and interactions of metal hydrogenation sites (Ru, Pt, Pd, Rh) with acidic supports (Nb, Ti, Mo) in achieving selective conversions. The review also explores strategies for producing other value-added compounds and offers future research perspectives in this promising area[30].

Karagoz et al. explores the underutilized potential of lignin from lignocellulosic biomass for pharmaceutical applications, beyond its conventional use in materials and fine chemicals. It reviews lignin extraction methods like organosolv and ionic liquids, and highlights the therapeutic potential of lignin-derived compounds in antimicrobial, antiviral, antitumor treatments, and drug delivery. The study emphasizes the need for advancements in biomass processing, compound purification, yield improvement, and clinical validation to enable commercial viability in healthcare[31].

Costa et al. review highlights the oxidative depolymerization of lignin as a promising route to produce high-value chemicals such as phenolic monomers (e.g., vanillin, syringaldehyde) and dicarboxylic acids. It discusses key challenges like improving reactivity and selectivity while preventing lignin condensation. The study focuses on advances made by the LSRE group in lignin oxidation using oxygen or hydrogen peroxide in alkaline media, with an emphasis on products from various lignin sources and delignification processes[32]

Liu et al. literature emphasizes the biomanufacturing challenges in lignin valorization due to the heterogeneity and toxicity of lignin-derived aromatic compounds. It highlights recent advances like plant cell wall engineering and ‘lignin-first’ pretreatment to improve feedstock quality. The review also explores various microbial systems for converting aromatics into valuable chemicals, with special focus on non-model microbes naturally suited for aromatic metabolism as promising candidates for efficient lignin valorization[33].

Ma et al. investigates the catalytic fast pyrolysis of alkaline lignin using zeolite catalysts with varying acidity and pore sizes to enhance chemical yields. The catalysts facilitate the conversion of lignin intermediates into stable products while minimizing coke formation. Results show that catalyst properties significantly influence liquid yield and product selectivity—H-ZSM5 favored phenol alkoxy species, while H-USY achieved the highest liquid and aromatic hydrocarbon yields. The findings underscore the importance of catalyst design in optimizing lignin pyrolysis outcomes[34].

Wendisch et al. review highlights lignin’s potential as a renewable feedstock for producing chemicals, biofuels, and materials, focusing on the challenges of its depolymerization and upgrading. It summarizes recent techniques like alkaline oxidation, fast pyrolysis, hydrogenolysis, and hydrolysis for generating phenolic monomers. The study also explores biological and chemocatalytic pathways for converting these monomers into valuable bulk and fine chemicals, such as muconic acid and adipic acid, while outlining future prospects for industrial application[35].

Chung et al. review emphasizes lignin's potential as a renewable raw material for commodity polymers, highlighting its abundance, strength, and non-competition with food sources. Despite its historical study, lignin's application is limited by low reactivity and processing challenges. Current strategies focus on improving its usability by blending or copolymerizing with natural or synthetic polymers. The article explores various lignin-based materials and their broad technological applications[36].

Stewart et al. review explores the evolving perception of lignin from a low-value waste to a promising raw material for high-value applications. A survey under the EUROLIGNIN network reveals significant growth in research and commercialization of lignin-based products, especially in polymer and binder industries. Lignin's phenolic structure enables its use in replacing phenolics in resins and as a binding/dispersing agent, with about 1 million tonnes used annually. The review also discusses market economics and future needs for lignin to become a mainstream industrial resource[37].

Natte et al. review highlights the growing importance of valorizing lignin-derived feedstocks— such as phenols, alcohols, and ketones—for producing high-value chemicals and fuels. Beyond lignin depolymerization, it emphasizes various transformation methods including amination, hydrogenation, oxidation, and carbonylation. These processes enable the synthesis of diverse compounds like amines, esters, heterocycles, and pharmaceutical intermediates, showcasing lignin's broad potential in sustainable chemical production[38].

Jing et.al [12] review addresses the urgent need to develop efficient and scalable lignin depolymerization strategies for sustainable fuel and chemical production. It focuses on the role of lignin radicals and bond cleavage (C–C/C–O) in determining product outcomes through methods like photocatalysis, electrocatalysis, and pre-oxidation under mild conditions. The paper emphasizes oxidative depolymerization as the most promising route and advocates for systematic strategies to overcome current industrial limitations in lignin valorization.

Laurichesse et al. review presents lignin as a promising aromatic renewable resource for producing chemicals and polymers, despite limitations due to its complex and variable structure. It outlines key lignin extraction methods and focuses on three major chemical modification strategies: fragmentation into aromatic compounds, introduction of new reactive sites, and functionalization of hydroxyl groups. The study highlights lignin's potential in creating novel macromolecular architectures and biobased materials, while also addressing current challenges and future prospects for its industrial application in polymer synthesis[39].

VI. Chemical Upcycling of Waste Biomass Into High-Value Chemicals from Cellulose

The global reliance on petroleum-derived products and the increasing volume of biomass waste have intensified the need for sustainable resource utilization. Among the various components of lignocellulosic biomass, **cellulose**—the most abundant biopolymer on Earth—holds immense potential for chemical upcycling into high-value products. Traditionally underutilized agricultural residues, food waste, textile waste, and industrial by-products rich in cellulose are now being reimagined as renewable feedstocks for value-added applications. Through advanced chemical and enzymatic treatments, cellulose can be transformed into nanocellulose, platform chemicals, biodegradable films, and regenerated fibers, contributing significantly to the development of a circular bioeconomy. This section explores recent advancements in the valorization of wastederived cellulose, highlighting its conversion into high-performance materials and its implications across sectors such as packaging, textiles, and biomedicine. Gunaseelan et al. in his review explores the sustainable production of carboxymethylcellulose (CMC) from agricultural and industrial waste, promoting circular economy practices. CMC's biodegradability and functional versatility support its applications in food, packaging, biomedicine, and environmental remediation. Upcycling cellulose-rich waste into CMC offers a cost-effective, eco-friendly solution to waste management while enabling high-value material generation[47]. Ma et al. in his study addresses the environmental impact of textile waste by regenerating colored waste cotton fabrics into new fibers via wet spinning, effectively recycling both fiber and color. It examines how pretreatment affects color retention and polymerization, with acid pretreatment enabling color preservation. The regenerated fibers demonstrated mechanical strength comparable to commercial viscose[48]. Kim et al. focuses on the thermo-chemical valorization of paper packaging waste (PPW) via pyrolysis, using $FeSO_4$ pretreatment to enhance syngas and furfural production. The pretreatment improved product selectivity and catalytic efficiency, with biochar aiding biodiesel synthesis. The results demonstrate a sustainable, carbon-neutral pathway for converting lignocellulosic waste into valuable chemicals and fuels[49]. Melo et al. presents all-cellulose composites made from hydroxypropyl methylcellulose (HPMC) and bacterial cellulose nanocrystals (BCNCs) as a sustainable alternative to fossil-derived plastics. The optimized dispersion of BCNCs improved the mechanical strength and barrier properties of transparent HPMC films. The composites were produced using green methods and industrial waste, aligning with circular bioeconomy goals[50]. Haslinger et al. proposes an upcycling method for cottonpolyester blended textile waste using the ionic liquid [DBNH][OAc] to selectively dissolve cellulose. After separating PET, high-quality cellulose fibers were regenerated via dry-jet wet spinning, with mechanical properties comparable to commercial Lyocell. The process supports circular economy goals by recycling blended textile waste into valuable fibers[51]. Ma et al. demonstrates the use of the ionic liquid 1,5-diazabicyclo[4.3.0]non-5-ene-1-ium acetate as an effective solvent for upcycling paper and cardboard waste by dissolving cellulose, hemicellulose, and lignin for fiber spinning. The resulting fibers exhibited high tensile strength and were successfully used to create prototype textiles. Residual lignin in cardboard also served as a natural dye, enhancing sustainability[52]. Sophia et al. addresses the environmental crisis caused by the persistence of commercial polymers and explores chemical recycling and upcycling as promising solutions. These processes convert plastics into monomers, fuels, or valuable chemicals, with catalysts playing a key role in improving efficiency and selectivity. The review highlights advancements in catalytic methods and emerging strategies for recycling common polymers[53]. Qiu et al. presents a sustainable strategy to upcycle cotton and cotton-polyester textile waste into highvalue photonic materials using acid hydrolysis and hydrothermal treatment. Cellulose nanocrystals (CNCs) and carbon quantum dots (CQDs) are coassembled into biodegradable, recyclable films with tunable optical properties for applications like anticounterfeiting. A life cycle assessment confirms the process's low environmental impact[54]. Ximena et al. explores two chemical methods—cationization and TEMPO-mediated oxidation—for extracting high-performance cellulose nanofibrils (CNFs) from post-consumer cotton textiles. The resulting Cat-CNFs and TOCNFs differ in morphology, surface charge, and colloidal stability, impacting the properties of nanopapers and foams made from them. These materials exhibit strong optical and mechanical performance, showcasing the potential of textile waste for nanomaterial production[55]. Pandey et al. presents a green method for producing nanofibrillated cellulose (NFC) from sugarcane bagasse using natural deep eutectic solvents (NADES) combined with acetosolv pretreatment, followed by high-intensity ultrasonication. The approach achieved high cellulose yield and efficient nanofibrillation, producing stable NFCs with minimal structural alteration. The work supports sustainable biomass valorization and eco-friendly alternatives to petroleum-based resources[56]. Négrier et al. upcycles cotton and regenerated cellulose textile waste into highly porous, lightweight cellulose materials using ionic liquids ([EMIM][OAc] and [DBNH][OAc]) and nonsolvent induced phase separation. Various drying techniques produced materials with tunable porosity, surface area, and morphology. The research highlights how solvent choice, cellulose molecular weight, and coagulation pathways influence final material properties[57]. Oshikata et al. presents a biorefinery approach to upcycle cotton textile residues into bioethanol, carboxymethylcellulose (CMC), and cellulose acetate (CA) using enzymatic hydrolysis followed by chemical transformation of the non-hydrolyzed residue. Fed-batch hydrolysis with enzyme and substrate feeding achieved up to 60.2% cellulose-to-glucose conversion. The process demonstrates the potential for high-yield, value-added product generation from cotton waste[58]. Kanai et al. upcycles hop stems (HS), an agro-industrial waste with high cellulose content, into cellulose nanofibers (CNFs) using TEMPO-mediated oxidation. Pretreatment improved CNF purity and crystallinity, with both pretreated and non-pretreated samples showing similar nanoscale dimensions and thermal behavior. The work highlights the potential of HS as a sustainable feedstock for high-performance nanomaterials[59]. SIlva et al. explores the use of bacterial cellulose (BC) as a sustainable raw material for producing Lyocell-type man-made cellulosic fibers (MMCF) via the Ioncell® spinning process. BC solutions showed excellent spinnability, and the resulting fibers and garments demonstrated strong mechanical performance. Additionally, BC enhanced the quality of recycled viscose fiber blends, improving spinnability and strength[60]. Kim et al. highlights the potential of upcycling food by-products into nanocellulose to reduce food waste and improve resource efficiency. Nanocellulose, valued for its renewability, biocompatibility, and multifunctional properties, is suitable for applications in food, biomedicine, packaging, and more. The review discusses top-down and bottom-up production methods and the commercial relevance of different nanocellulose types[61]. Weiland et al. proposes an integrated manure management system that upcycles herbivore manure, particularly elephant manure, into biogas, fertilizer precursors, and high-value cellulose nanofibers. The approach enables efficient nanocellulose extraction from the residual substrate after biogas production, offering a sustainable alternative to wood-derived cellulose with reduced environmental impact[62]. Lee et al. demonstrates the fabrication of edible packaging films using cellulose extracted from kimchi waste, with sorbitol and citric acid as plasticizer and crosslinker. The films exhibited good chemical purity, uniform surface dispersion, hydrophilicity, and thermal stability comparable to commercial cellulose-based films. The approach highlights the potential of food waste upcycling for sustainable packaging applications[63]. Haslinger et al. explores the chemical upcycling of dyed pre- and post-consumer cotton waste into new colored man-made cellulose fibers using dry-jet wet spinning and a superbase-based ionic liquid. Most dyes and waste types could be successfully dissolved and spun into colored fibers, which showed improved mechanical properties and color fastness. While color changes occurred during processing, the regenerated fabrics maintained bright, reusable colors[64]. Process involving conversion of low-value agricultural or industrial biomass waste into valuable chemicals and materials using chemical reactions[67,70]. Unlike traditional recycling, upcycling improves the quality and functionality of the product. Key methods include catalytic conversion, pyrolysis, and hydrothermal processing. Products obtained include biofuels, bioplastics, solvents, and platform chemicals like levulinic acid and furfural. This approach supports sustainability, reduces environmental waste, and adds economic value to biomass.

The diverse strategies for upcycling cellulose-rich waste illustrate a transformative shift toward resource-efficient and environmentally responsible material production. From nanocellulose to regenerated fibers and biodegradable composites, these innovations not only address waste management challenges but also support the growing demand for sustainable alternatives to petrochemical-derived products. As technologies mature and scale up, cellulose valorization stands as a key pillar in advancing circular economy models across multiple industries.

VII. Catalyst Development and Mechanistic Insights

Shuhao Li et al. provide a compelling case for using density functional theory (DFT) to advance catalyst development by directly linking quantum-level understanding to real-world catalytic performance. The article discusses how DFT enables researchers to visualize electronic structure, reaction pathways, energy barriers, and transition states, which are crucial for rational catalyst design. The review highlights several landmark accomplishments, including predicting new catalytic materials, explaining the effects of catalyst composition and surface structure, and guiding the synthesis of site-specific catalysts. By integrating theoretical calculations with experimental validation, DFT not only accelerates the discovery of improved catalysts but also deepens our ability to manipulate catalytic functions at the molecular level, promoting the more efficient use of energy and resources in chemical industries[77].

The review by Sheng Yao et al. focuses on the mechanistic understanding of CO2 reduction to higher alcohols. This paper evaluates both experimental and computational studies to unravel how different

catalyst structures, active sites, and promoters steer reaction selectivity and yield. The authors emphasize the interplay between metal choice, alloying, and surface modifications, as these factors drastically affect the formation and stabilization of key intermediates. Mechanistic insights reveal that certain copper-based or multi-component catalysts are particularly effective, and the review outlines how further advancements could emerge from combining operando spectroscopies with advanced simulations. The work concludes by highlighting challenges such as catalyst deactivation and the need for improved product separation, but it is optimistic about the development of highly active and robust electrocatalysts for sustainable fuel and chemical manufacturing[78].
A significant step in rational catalyst design is presented by Seihwan Ahn et al. This work bridges computational predictions with experimental realities, illustrating how quantum chemical modeling can transform catalyst optimization. The paper showcases successes where prediction of mechanistic pathways directly led to novel catalysts with enhanced reactivity or selectivity in organic and organometallic transformations. A recurring theme is the importance of integrating empirical knowledge with theory, as small changes in catalyst structure may result in significant changes in reactivity. The review encourages the wider adoption of computational approaches, which, paired with high-throughput experimentation, could lead to breakthroughs in selective catalysis and sustainable synthesis routes[79].
Another substantial advance is described by the research of Zhou et al., who explore dual ligand metal–ligand cooperative (MLC) catalysis. Their analysis, based on advanced DFT studies, details how the synergistic effects of having two ancillary ligand sites allow for dynamic site-switching during the catalytic cycle. This mechanistic flexibility facilitates lowered energy barriers and improved orbital interactions during critical reaction steps, ultimately enhancing catalytic efficiency. Their work not only elucidates the roles of specific ligand groups but also provides theoretical design strategies for novel catalysts that can outperform traditional single-site analogs. This kind of mechanistic clarity, building on both theory and experimentation, is driving the frontier of catalyst engineering[80].

VIII. Process Integration and Techno-Economic Aspects

The integrated techno-economic and life cycle assessment conducted by Wunderlich et al. provides a holistic view of how combining these methodologies supports early-stage technology decisionmaking. Using microemulsion systems for rhodium-catalyzed hydroformylation as a case study, the authors perform detailed simulations and cost modeling to compare a new rhodium-based system with established cobalt-based benchmarks. Their work reveals that the choice of catalyst, process design, and leaching rates significantly influence both economic viability and environmental impact. Results show that microemulsion techniques, when coupled with efficient recycling and separation, offer major advantages in sustainability and profitability for fine chemical production. This approach exemplifies the growing importance of combining technoeconomic and environmental perspectives for designing competitive and green catalytic processes[81].
A meticulous process analysis by Moinee et al. delves into the integration of CO2 capture with subsequent catalytic utilization to produce valuable chemicals. Their work demonstrates that integrating these steps into a single system enhances carbon and energy efficiency compared to running the operations separately. The study quantifies this by showing a remarkable reduction in both energy use and greenhouse gas emissions for the integrated configuration. Economically, integration allows for drastic savings on capital equipment due to fewer compressors, heat exchangers, and reactors. However, raw material costs increase slightly because of the need for multiple feed streams. Despite these nuances, the findings underscore the environmental and financial benefits of process integration, encouraging the adoption of such strategies in industrial settings[82].
A recent study led by Yang et al. investigates process integration for bioplastic monomer production, focusing on converting biomass-derived glucose to FDCA (furandicarboxylic acid). Detailed heat integration using pinch analysis reduces external energy input, thereby lowering costs and environmental impacts. The techno-economic analysis reveals that process design modifications—

especially those that improve reaction yields and minimize waste, combined with intelligent heat and mass integration—can make bioplastics a viable and scalable alternative to petrochemical-derived materials. This research reinforces the principle that process integration is central to the economic feasibility of next-generation catalytic biorefineries[83].
A 2024 study by Ahmad et al. exemplifies the use of detailed process simulation and cost analysis to evaluate new paths for furfural production from sugarcane bagasse. The authors employ rigorous economic modeling to assess the feasibility and scaling potential of catalytic fast pyrolysis in comparison to traditional methods. By considering both direct production costs (reactor design, operational parameters) and wider market factors (feedstock price, market demand for furfural), they show how shifts in process configuration impact the overall techno-economic picture. Their work underscores that a holistic approach—one that considers both integration and detailed cost drivers—is required to make catalytic bio-conversions industrially competitive[84].

IX. Challenges and Future Perspectives

Beil et al. summarize the outcomes of an interdisciplinary workshop on photocatalysis and highlight the multifaceted challenges facing the field. The review details how advances in artificial photosynthesis, photobiocatalysis, and sustainable photoredox catalysis could revolutionize fuel and materials synthesis by harnessing sunlight. However, the authors recognize critical barriers, such as understanding complex reaction mechanisms, tuning quantum yields, and scaling up photoreactors with uniform efficiency. They stress that greater collaboration across chemistry, materials science, and biology is required to surmount these challenges. Integrating spectroscopic and computational methodologies, alongside practical reactor engineering, could enable photocatalysis to deliver on its promise of enabling a true circular economy and sustainable chemical industry[85].
Kalz et al. discuss the future challenges in heterogeneous catalysis, especially under dynamic operating conditions representative of real industrial reactions. The review recognizes the importance of capturing catalyst transformations under true working environments, which often involve fluctuations in reactant supply, temperature, and pressure. Key challenges include understanding catalyst deactivation, improving selectivity while maximizing atom efficiency, and adapting catalyst design to renewable energy inputs. The authors call for new experimental techniques, in situ analytics, and digital tools (such as machine learning and data-driven models) that can unravel the behavior of catalysts in dynamic systems and ultimately steer research toward more robust, adaptable catalytic materials[86].
A 2024 perspective by Chen et al. addresses environmental catalysis technology for NOx removal, outlining the urgent need for efficient, selective, and economically viable catalysts. The article reviews innovative NOx reduction catalysts, identifying bottlenecks such as catalyst poisoning, limited low-temperature activity, and cost issues associated with precious metals. The authors emphasize that future progress depends on developing multifunctional catalysts, improved elucidation of reaction pathways, and integration with renewable energy sources. Environmental catalysis must evolve with more sustainable feedstocks and resource-efficient processes, requiring breakthroughs both in materials science and systems integration[87].
Finally, Mukhtar et al. review the status and remaining hurdles in heterogeneous catalysis for biofuel production, particularly for biodiesel from non-edible oils. The authors identify issues such as feedstock variability, catalyst lifespan, tolerance to impurities, and deactivation. Their survey of recent innovations highlights the potential of new structured catalysts, improved reactor designs, and procedures for catalyst regeneration. Despite the promise of bio-based processes, widespread adoption is limited by technical and economic barriers, necessitating further research to improve efficiency and reduce costs while maintaining environmental benefits[88].

X. Conclusion

Recent advancements have showcased efficient catalytic processes both heterogeneous and enzymatic for converting waste biomass into high-value chemicals like succinic acid, muconic acid, and other bio-based monomers[67,68]. Techniques such as selective oxidation, hydrodeoxygenation, and fermentation have been optimized for improved yields and sustainability. Steam gasification of pine sawdust showed the best performance, yielding high hydrogen (46.96%), low CO_2 (4.99%), and excellent energy (80.91%) and exergy (86.03%) efficiencies, offering a strong pathway for efficient biomass upcycling[72]. To scale up solvothermal biomass conversion, process intensification is essential through improved work-up technologies, optimized feedstock use, and integrated reaction-purification steps while aligning upstream chemistry with downstream engineering and economic considerations[76]

Abbreviations
AD – Anaerobic digestion
COS – Cello-oligosaccharides
PHA – Polyhydroxyalkanoates

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