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Review

Metal-Based Catalysts in Biomass Transformation: From Plant Feedstocks to Renewable Fuels and Chemicals

Muhammad Saeed Akhtar [1,†], Muhammad Tahir Naseem [2,†], Sajid Ali [3,*] and Wajid Zaman [4,*]

[1] Department of Chemistry, Yeungnam University, Gyeongsan 38541, Republic of Korea; msakhtar@yu.ac.kr
[2] Department of Electronic Engineering, Yeungnam University, Gyeongsan 38541, Republic of Korea; nmtahir@yu.ac.kr
[3] Department of Horticulture and Life Science, Yeungnam University, Gyeongsan 38541, Republic of Korea
[4] Department of Life Sciences, Yeungnam University, Gyeongsan 38541, Republic of Korea
* Correspondence: drsajid@yu.ac.kr (S.A.); wajidzaman@yu.ac.kr (W.Z.)
† These authors contributed equally to this work.

Abstract: The transformation of biomass into renewable fuels and chemicals has gained remarkable attention as a sustainable alternative to fossil-based resources. Metal-based catalysts, encompassing transition and noble metals, are crucial in these transformations as they drive critical reactions, such as hydrodeoxygenation, hydrogenation, and reforming. Transition metals, including nickel, cobalt, and iron, provide cost-effective solutions for large-scale processes, while noble metals, such as platinum and palladium, exhibit superior activity and selectivity for specific reactions. Catalytic advancements, including the development of hybrid and bimetallic systems, have further improved the efficiency, stability, and scalability of biomass transformation processes. This review highlights the catalytic upgrading of lignocellulosic, algal, and waste biomass into high-value platform chemicals, biofuels, and biopolymers, with a focus on processes, such as Fischer–Tropsch synthesis, aqueous-phase reforming, and catalytic cracking. Key challenges, including catalyst deactivation, economic feasibility, and environmental sustainability, are examined alongside emerging solutions, like AI-driven catalyst design and lifecycle analysis. By addressing these challenges and leveraging innovative technologies, metal-based catalysis can accelerate the transition to a circular bioeconomy, supporting global efforts to combat climate change and reduce fossil fuel dependence.

Keywords: biomass conversion; metal-based catalysts; hydrodeoxygenation; platform chemicals; renewable fuels; catalytic upgrading

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1. Introduction

Biomass derived from organic matter has emerged as a crucial resource in the pursuit of renewable and sustainable energy solutions. With the world facing the challenges of climate change and diminishing fossil fuel reserves, the significance of biomass lies in its abundance and potential as a carbon-neutral energy source [1]. Unlike fossil fuels, carbon dioxide released during biomass utilization is counterbalanced by that absorbed during plant growth, rendering it an attractive alternative to fossil fuels [2]. Furthermore, biomass encompasses a broad range of feedstocks, including agricultural residues, forest residues, algae, and organic waste, making it a versatile raw material for energy and chemical production. Its capacity to reduce greenhouse gas (GHG) emissions and address energy security issues underscores its importance in advancing a sustainable future [3].

The growing global demand for sustainable energy and chemicals has intensified interest in converting biomass into value-added products. As population growth and industrial activities escalate, the need for alternative resources that can meet energy demands without exacerbating environmental degradation becomes increasingly urgent [4]. Biomass transformation presents a promising pathway for producing renewable fuels, chemicals, and materials, thereby reducing reliance on petroleum-based resources. Advances in biotechnology and process engineering have considerably improved biomass conversion efficiency, enabling the production of biofuels, such as biodiesel and bioethanol, along with platform chemicals, like 5-HMF, furfural, and levulinic acid [4,5]. These products not only support sustainability goals but also cater to the rising market demand for green and biodegradable products.

Catalysis is pivotal in biomass transformation, enabling the conversion of complex organic structures into simpler, more usable compounds. Metal-based catalysts, in particular, have gained importance due to their ability to efficiently drive various reactions, such as hydrodeoxygenation, hydrogenation, and reforming [6]. Transition metals, including nickel, cobalt, and iron, as well as noble metals, such as platinum, palladium, and ruthenium, exhibit remarkable catalytic activity in biomass upgrading processes. These catalysts help address the inherent challenges of biomass conversion, including the high oxygen content, structural heterogeneity, and thermal instability [7]. By selectively breaking down complex molecules and removing oxygen, metal catalysts enable the production of fuels and chemicals with high energy density and favorable properties.

Despite these advancements, several challenges persist in the catalytic transformation of biomass. Catalyst deactivation caused by poisoning, sintering, and fouling remains a notable barrier for sustained catalytic performance [8]. The structural complexity and variability of biomass feedstocks further complicate the development of universal catalytic systems. Moreover, the economic feasibility of large-scale biomass conversion is constrained by the high costs of noble metal catalysts and energy-intensive nature of some processes [9]. Researchers are addressing these issues via the development of robust, cost-effective catalysts, supported materials, and hybrid catalytic systems fabricated to enhance stability and selectivity [10]. Integrating advanced catalytic designs with biorefinery concepts is also being explored to optimize conversion processes and improve resource efficiency.

This review provides a comprehensive overview of metal-based catalysts in biomass transformation, focusing on their critical role in converting plant feedstocks into renewable fuels and chemicals. It explores various metal catalysts, their underlying mechanisms, and applications across different biomass conversion pathways, such as hydrodeoxygenation, gasification, and pyrolysis. The review also highlights recent advancements, challenges, and future directions in this field. By bridging the gap between catalytic research and practical implementations, this work aims to support ongoing efforts to develop sustainable and economically viable biomass transformation technologies.

2. Metal-Based Catalysts for Biomass Transformation

Metal-based catalysts play a pivotal role in converting biomass into renewable fuels and chemicals (Figure 1) [10]. These catalysts enable the selective breakdown of complex organic structures under controlled conditions, facilitating the production of high-value products. Transition and noble metals, in particular, have shown exceptional efficacy in processes such as pyrolysis, gasification, and hydrogenation [11]. Their ability to enhance reaction rates, control product selectivity, and operate under relatively mild conditions establishes them as a cornerstone of biomass conversion technologies. However, a comprehensive understanding of the types, functions, and associated challenges of these catalysts is crucial for optimizing their application in sustainable bioenergy systems [12].

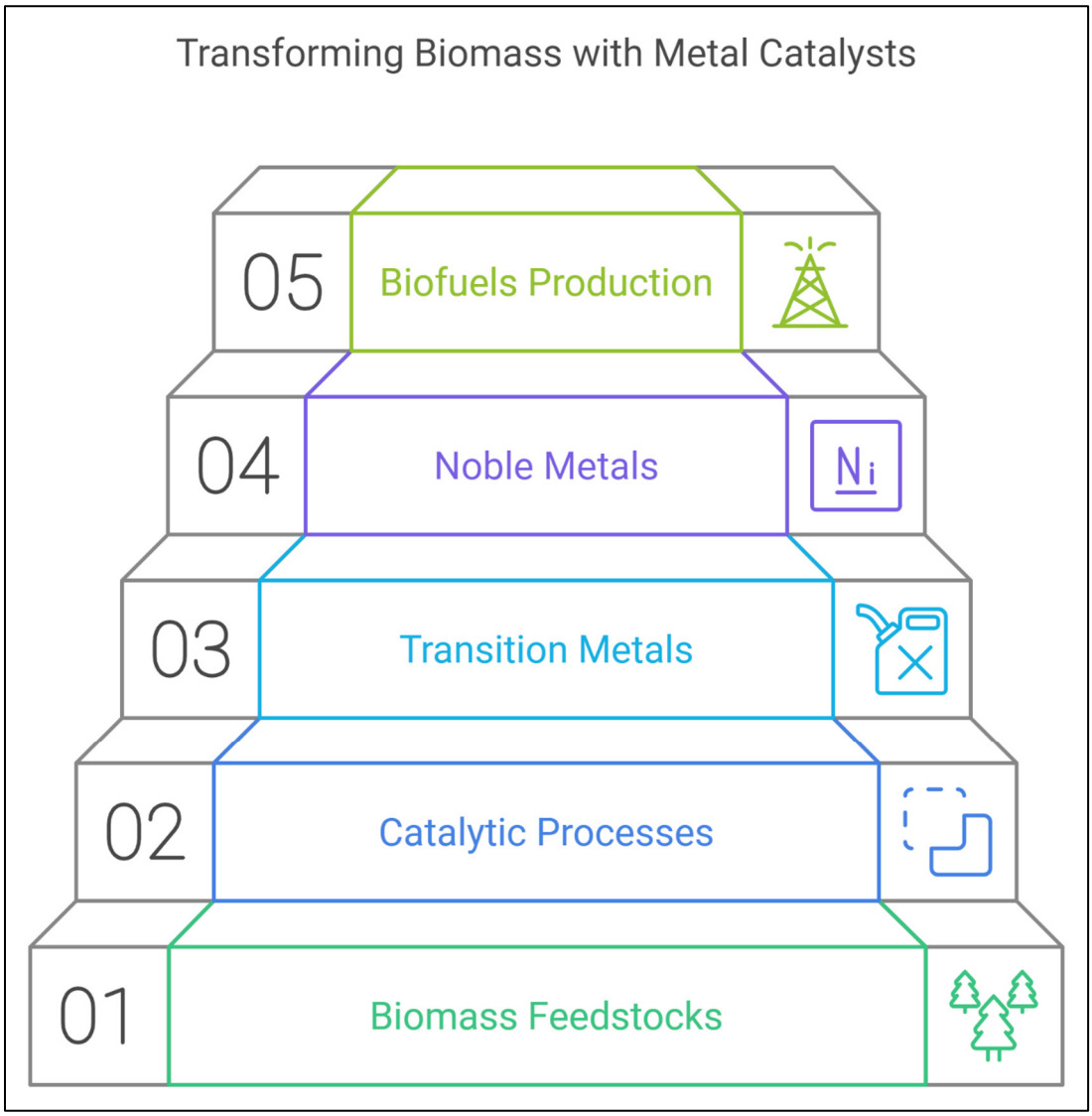

Figure 1. Mechanisms of Metal Catalysts in Biomass Transformation.

2.1. Transition Metals

Transition metals such as nickel (Ni), cobalt (Co), and iron (Fe) are integral to biomass conversion processes due to their abundance, cost-effectiveness, and high catalytic activity [13]. These metals are extensively employed in industrial applications such as pyrolysis, gasification, and hydrogenation, where they facilitate the transformation of biomass into biofuels and platform chemicals. Their versatility across various operating conditions enables efficient biomass decomposition and reliable product recovery, making them invaluable for diverse reaction pathways [14].

2.1.1. Applications in Pyrolysis, Gasification, and Hydrogenation

Transition metals possess remarkable efficiency in various biomass upgrading applications. In pyrolysis, nickel catalysts are highly effective in breaking down lignocellulosic biomass into bio-oil, syngas, and char [15], providing crucial intermediates that can be further refined into transportation fuels. Gasification relies on cobalt and iron catalysts to convert biomass into hydrogen-rich syngas, a versatile feedstock for the Fischer–Tropsch process [16]. Furthermore, hydrogenation reactions catalyzed by these metal catalysts enhance bio-oil quality by stabilizing reactive intermediates, enhancing energy density, and

reducing oxygen content. These applications highlight the transformative capabilities of transition metals in addressing energy and sustainability challenges [17].

2.1.2. Mechanisms of Deoxygenation and Hydrogenation

Biomass feedstocks are characterized by a high oxygen content, which limits their use as fuel-grade products. Transition metals facilitate deoxygenation, removing oxygen as water or carbon dioxide, and thus convert oxygen-rich intermediates into hydrocarbons [18]. Nickel catalysts, for instance, exhibit strong activity for hydrodeoxygenation (HDO) reactions, selectively cleaving C–O bonds to produce hydrocarbon-rich fuels [19]. Similarly, cobalt catalysts are pivotal in hydrogenation processes, saturating unsaturated bonds and improving product chemical stability. These mechanisms highlight the ability of transition metals to efficiently transform biomass into high-energy fuels [20].

2.2. Noble Metals

Noble metals, such as platinum (Pt), palladium (Pd), and ruthenium (Ru), are widely recognized for their exceptional catalytic activity and selectivity. These metals excel in processes requiring precise control over reaction pathways, including hydrodeoxygenation, hydrogenolysis, and reforming [21]. Their outstanding performance ensures high yields and minimal byproduct formation. However, their high cost and limited availability present significant challenges, highlighting the importance of exploring their applications in conjunction with strategies to reduce economic constraints [22].

2.2.1. Role of Pt, Pd, and Ru in Enhancing Catalytic Efficiency

The efficiency of noble metal steams from their ability to adsorb and activate reactant molecules, facilitating crucial bond-breaking and rearrangement processes [23]. Platinum and palladium are extensively used in hydrogenation and hydrodeoxygenation reactions, converting biomass-derived intermediates into stable, high-value products [24]. For instance, palladium catalysts are particularly effective in upgrading furfural into biofuels and solvents. Ruthenium catalysts, in contrast, excel in aqueous-phase reforming, generating hydrogen and alkanes from biomass [25]. These metals offer unparalleled catalytic precision, making them essential for high-performance biomass conversion applications.

2.2.2. Limitations: Cost and Availability

The primary drawback of noble metals is their high cost and limited availability, which constrain their scalability in industrial biomass conversion [26]. To mitigate this, researchers are developing bimetallic catalysts that combine noble metals with transition metals, thereby reducing reliance on expensive elements while preserving catalytic performance [27]. Additionally, innovations in catalyst supports and recycling techniques aim to extend the lifetime and reusability of noble metal catalysts, improving their sustainability for long-term applications.

2.3. Heterogeneous vs. Homogeneous Catalysts

Catalysts used in biomass transformation can be broadly classified into heterogeneous and homogeneous types (Table 1). Heterogeneous catalysts operate in a different phase from reactants, enabling their easy separation and reusability [12]. By contrast, homogeneous catalysts have the same phase as reactants, providing high selectivity and control over reaction pathways. Both types of catalysts play unique roles in biomass conversion, with their applications optimized for specific reaction requirements [28].

Table 1. Comparison of the heterogeneous and homogeneous catalysts in biomass transformation.

Characteristic	Heterogeneous Catalysts	Homogeneous Catalysts	References
Catalyst Phase	Solid catalyst (insoluble in the reaction mixture)	Liquid catalyst (soluble in the reaction mixture)	[29]
Reusability	Reusable; easy to separate after reaction	Nonreusable; difficult to separate and often requires regeneration	[30]
Reaction Conditions	Operates under milder conditions (low temperature, high pressure)	Typically requires more specific conditions (solvent, temperature)	[31]
Catalyst Deactivation	Can suffer from fouling or poisoning over time	Less prone to deactivation but may suffer from side reactions	[8]
Activity and Selectivity	Maybe less selective, requiring optimization of the surface area and structure	Generally, offers higher selectivity and faster reactions	[32]
Environmental Impact	Environmentally friendly, easier to separate and reuse	Can involve toxic solvents or reagents	[33]
Cost	Generally, less expensive, particularly for common metal catalysts	Often more expensive, particularly when using expensive metals or reagents	[34]
Typical Biomass Reactions	Suitable for catalytic cracking, hydrogenation, esterification, and pyrolysis	Typically used for reactions like dehydration, oxidation, and esterification	[35]

2.3.1. Differences in the Structure and Applications

Heterogeneous catalysts, such as solid-supported nickel or cobalt systems, are commonly employed in industrial-scale processes due to their stability and scalability. For instance, zeolite-supported catalysts are effective in cracking and reforming reactions, facilitating the breakdown of biomass into simpler hydrocarbons [36,37]. In contrast, homogeneous catalysts, typically metal complexes in solution, offer superior selectivity for complex transformations, such as the synthesis of fine chemicals [38]. However, their solubility presents challenges in recovery and reuse, which limits their practical application in cost-sensitive processes.

2.3.2. Stability and Operational Efficiency

Heterogeneous catalysts can encounter issues such as fouling, sintering, or poisoning, which compromise their long-term performance. Although homogeneous catalysts offer high efficiency and selectivity, their separation and recycling present significant challenges [39]. Recent advancements in hybrid catalytic systems aim to leverage the strengths of both heterogeneous and homogeneous catalysts, enhancing process stability, efficiency, and overall sustainability [40]. These innovations are essential for meeting the growing demand for scalable and environmentally friendly biomass conversion technologies.

2.4. Catalyst Supports and Promoters

The performance of metal catalysts in biomass conversion is greatly influenced by the choice of supports and promoters [41]. Supports provide structural stability and enhance the dispersion of active metal sites, while promoters alter the electronic and chemical properties of the catalysts, boosting their activity and selectivity [42]. Together, these components are crucial for optimizing catalytic systems and ensure efficient biomass upgrading.

2.4.1. Zeolites, MOFs, and Carbon-Based Supports

Zeolites, with their porous structure and inherent acidity, are commonly used as supports in cracking and hydrocracking reactions. MOFs, recognized for their tunable pore sizes and high surface areas, offer distinct benefits in adsorbing and activating specific biomass molecules [43]. Carbon-based supports, such as graphene and activated carbon, provide exceptional thermal stability and conductivity, making them ideal for high-temperature biomass conversion processes [44]. These supports not only enhance catalytic efficiency but also improve resistance to deactivation.

2.4.2. Role of Promoters in Enhancing Catalytic Activity

Promoters, such as alkali metals or sulfur compounds, enhance the activity and selectivity of metal catalysts by altering their electronic properties. For examples, potassium promoters improve the performance of iron catalysts in Fischer–Tropsch synthesis by suppressing undesired side reactions [45]. Phosphorus-based promoters increase the resistance of nickel catalysts to poisoning, ensuring sustained catalytic performance. By integrating advanced supports with effective promoters, researchers are developing next-generation catalytic systems that are optimized for efficient biomass transformation [46].

3. Biomass-Derived Feedstocks and Their Chemical Transformations

Biomass feedstocks are versatile and renewable resources for the production of fuels and chemicals. Their chemical composition and availability play a crucial role in determining the processes used to convert them into valuable products. Broadly, biomass feedstocks are classified into lignocellulosic biomass, algal biomass, and waste biomass (Table 2) [47]. Each category possesses distinct characteristics that necessitate tailored catalytic approaches for efficient valorization. Recent advancements in catalytic technologies have facilitated the depolymerization, reforming, and upgrading of these feedstocks into high-value platform chemicals, biofuels, and other renewable products [48]. Optimizing these processes positions biomass-derived feedstocks as sustainable solutions for energy and chemical production.

Table 2. Biomass Feedstocks and Their Chemical Composition.

Biomass Feedstock	Main Components	Component Percentage	References
Lignocellulosic Biomass	Cellulose, Hemicellulose, Lignin	Cellulose: 40–60%, Hemicellulose: 20–30%, Lignin: 15–30%	[49]
Algal Biomass	Lipids, Proteins, Carbohydrates	Lipids: 10–30%, Proteins: 40–60%, Carbohydrates: 20–30%	[50]
Agricultural Waste (e.g., Straw, Bagasse)	Cellulose, Hemicellulose, Lignin, Ash	Cellulose: 35–50%, Hemicellulose: 20–30%, Lignin: 15–25%, Ash: 3–5%	[51]

Table 2. *Cont.*

Biomass Feedstock	Main Components	Component Percentage	References
Wood Biomass	Cellulose, Hemicellulose, Lignin	Cellulose: 40–50%, Hemicellulose: 20–30%, Lignin: 20–30%	[52]
Marine Biomass (e.g., *Sargassum* sp.)	Polysaccharides, Proteins, Lipids	Polysaccharides: 30–60%, Proteins: 20–30%, Lipids: 10–20%	[53]

3.1. Lignocellulosic Biomass

Lignocellulosic biomass, the most abundant form of biomass, consists of cellulose, hemicellulose, and lignin. These components create a complex and recalcitrant structure that necessitates advanced catalytic strategies for effective conversion [54]. Depolymerizing these biopolymers is a pivotal step in unlocking the chemical potential of lignocellulosic biomass, facilitating the production of platform chemicals and renewable fuels [55]. Its widespread availability in agricultural and forestry residues makes lignocellulosic biomass a central focus of research in renewable energy and green chemistry [56].

3.1.1. Depolymerization of Cellulose, Hemicellulose, and Lignin

Depolymerization is the primary step in breaking down lignocellulosic biomass into its individual components. Cellulose, a polysaccharide made up of glucose units, typically undergoes hydrolysis to yield fermentable sugars using acid or enzymatic catalysts. Hemicellulose, a heteropolymer, undergoes hydrolysis to yield a mixture of sugars, including xylose and arabinose [57,58]. Lignin, an aromatic polymer that provides structural rigidity, is depolymerized through oxidative or reductive processes to produce phenolic compounds. Metal-based catalysts, such as those containing transition metals like Ni and Co, are crucial in enhancing the efficiency and selectivity of these depolymerization reactions [59].

3.1.2. Catalytic Valorization of Platform Chemicals

After depolymerization, the individual components of lignocellulosic biomass can be further processed into platform chemicals. Glucose derived from cellulose can be catalytically converted into 5-hydroxymethylfurfural (HMF), a versatile precursor for bioplastics [60]. Similarly, hemicellulose-derived xylose can be transformed into furfural, an important industrial solvent. Lignin valorization offers pathways to produce aromatic compounds, such as vanillin and phenol. Heterogeneous catalysts, including zeolites and metal-supported systems, are particularly effective in these transformations, ensuring high yields and selectivity [61,62].

3.2. Algal Biomass

Algal biomass, sourced from microalgae and macroalgae, is emerging as a promising sustainable feedstock due to its rapid growth rate, high lipid content, and minimal land-use requirements [63]. Unlike lignocellulosic biomass, algae bypass the needs for complex pretreatment processes, serving as a direct resource for biofuels and chemical production. The catalytic upgrading of algal lipids and carbohydrates has become a cornerstone in advancing algal biorefineries, enabling the production of biodiesel, biogas, and other value-added chemicals [64].

3.2.1. Lipid Extraction Techniques

Lipids in algal biomass are the primary feedstock for biodiesel production. Advanced extraction methods, including solvent extraction and supercritical fluid techniques, are employed to isolate these lipids from algal cells. Recent innovations, such as the adoption

of green solvents and ionic liquids, have significantly improved extraction efficiency while minimizing environmental impact [65].Following extraction, the lipids are converted into biodiesel through transesterification, a process typically catalyzed by alkali or acid catalysts. Additionally, the extracted lipid hold potential for the production of bio-based lubricants and polymers, broadening their applicability in sustainable industries [66].

3.2.2. Catalytic Upgrading to Biofuels

In addition to biodiesel, algal lipids and carbohydrates can be catalytically upgraded to produce advanced biofuels, such as renewable diesel and jet fuel. Hydroprocessing of algal oils, facilitated by metal-based catalysts like Ni–Mo and Co–Mo systems, effectively removes oxygen to yield hydrocarbon fuels [67,68]. Meanwhile, algal carbohydrates can be fermented into ethanol or converted into syngas through gasification, which can subsequently be transformed into fuels via Fischer–Tropsch synthesis. These catalytic highlight the versatility of algal biomass as a feedstock, offering sustainable solutions for diverse energy demands [69].

3.3. Waste Biomass

Waste biomass, encompassing agricultural residues, municipal solid waste, and industrial byproducts, represents an underutilized resource with substantial potential for generating energy and chemical [70]. Although its heterogeneous composition presents challenges, advancements in catalytic technologies have enabled its efficient conversion into biofuels and value-added products. Utilizing waste biomass not only alleviates environmental burdens but also promotes a circular economy by creating value from otherwise discarded materials [12].

3.3.1. Agricultural and Municipal Waste Utilization

Agricultural residues, such as corn stover and rice husks, are abundant sources of lignocellulose and can be transformed into biofuels and chemicals through catalytic depolymerization and upgrading methods. Municipal solid waste, which often includes organic fractions, can be subjected to gasification or pyrolysis to generate syngas and bio-oil [71]. Metal catalysts, such as iron and nickel-based systems, are instrumental in these processes, enhancing conversion efficiency and minimizing tar formation [72].

3.3.2. Metal-Catalyzed Conversion Strategies

Metal catalysts are essential for converting waste biomass into high-value products. For instance, nickel catalysts are employed in hydrothermal liquefaction to transform wet biomass into biocrude, which can be further upgraded to liquid fuels. Similarly, iron catalysts are effective in the gasification of mixed waste biomass, producing clean syngas for various downstream applications [73]. Recent developments in bimetallic and supported catalysts have enhanced their selectivity and stability, facilitating the efficient processing of diverse waste streams. These innovations underscore the potential of waste biomass as a renewable resource for sustainable energy production [74].

4. Metal-Catalyzed Processes for Renewable Fuel Production

Metal-catalyzed processes are pivotal for converting biomass into renewable fuels. These processes address the challenges posed by biomass, such as its high oxygen content and complex structure, by facilitating chemical reactions that transform biomass into energy-dense fuels (Figure 2) [11]. A key reaction in this transformation is hydrodeoxygenation (HDO), which removes oxygen from biomass-derived intermediates to produce hydrocarbons suitable for transportation fuels. The effectiveness of these catalytic processes depends on the careful selection of catalysts that offer high efficiency, selectivity, and

stability under industrial conditions [75]. By optimizing these reactions, metal-catalyzed processes support the sustainable production of renewable fuels, which can replace fossil fuels, lower greenhouse gas emissions, and enhance energy security [76].

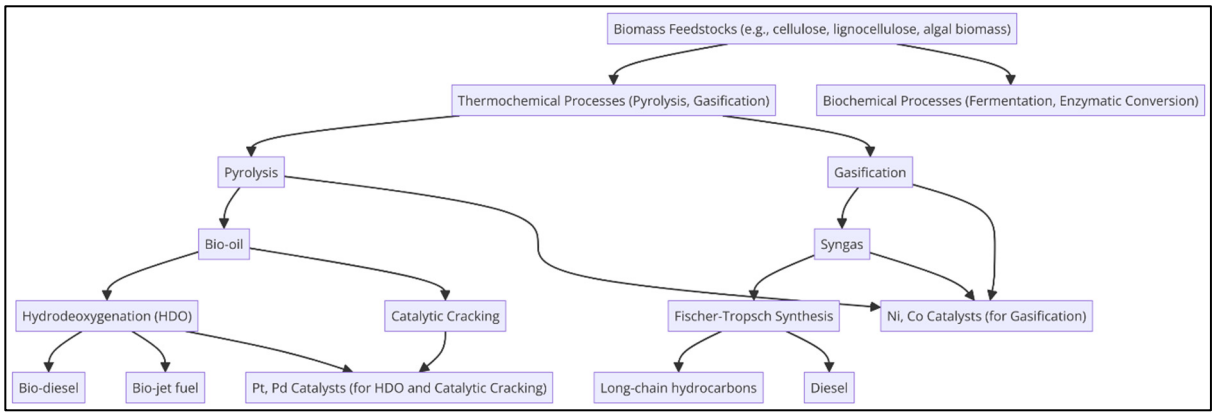

Figure 2. Catalytic Pathways in Biomass Conversion.

4.1. Hydrodeoxygenation (HDO)

Hydrodeoxygenation (HDO) is a critical reaction in the catalytic upgrading of biomass-derived intermediates, especially bio-oil. Bio-oil, produced through processes like pyrolysis and liquefaction, contains a high concentration of oxygenated compounds, which render it acidic, thermally unstable, and unsuitable for direct use as fuel [77]. HDO addresses these challenges by removing oxygen in the form of water or carbon dioxide, converting bio-oil into hydrocarbons with higher energy density and improved stability. This reaction is essential for transforming biomass into drop-in fuels, such as gasoline, diesel, and jet fuel, which are compatible with existing fuel infrastructure [78,79].

4.1.1. Mechanisms of HDO for Biomass

The mechanism of hydrodeoxygenation involves the catalytic activation of hydrogen, which then react with the oxygen-containing functional groups in biomass-derived compounds. This process typically follows two main pathways: direct hydrogenolysis and hydrogenation-dehydration [80]. In the direct hydrogenolysis pathway, the oxygen atom is removed from the molecule, usually as water, through the cleavage of C–O bonds. This pathway is particularly common in the conversion of phenolic compounds, a major component of bio-oil derived from lignin [81].

In the hydrogenation-dehydration pathway, oxygen-containing functional groups are initially hydrogenated to form intermediates such as alcohols, which are then dehydrated to produce hydrocarbons. This two-step mechanism is particularly effective for upgrading furans and carboxylic acids found in bio-oil [82]. Transition metal catalysts, such as Ni, Co, and Mo, are essential for these reactions as they facilitate hydrogen activation and promote selective bond cleavage [83]. The reaction conditions, including temperature, pressure, and hydrogen availability, play a crucial role in determining the efficiency and product distribution of the HDO process.

4.1.2. Common Catalysts for HDO

Various metal-based catalysts are developed for hydrodeoxygenation, each offering unique advantages in terms of activity, selectivity, and stability. Nickel-based catalysts are among the most widely used catalysts due to their cost-effectiveness and strong hydrogenation capabilities [19]. Supported nickel catalysts, typically combined with carriers (e.g., alumina or silica), are effective in deoxygenating phenolics and carboxylic acids. Cobalt cat-

alysts, often paired with molybdenum (CoMo), are also highly effective in HDO reactions, particularly for upgrading fatty acids and esters into diesel-range hydrocarbons [84].

Noble metals, such as platinum (Pt) and palladium (Pd), are highly efficient for HDO due to their superior hydrogen activation properties and resistance to deactivation. These catalysts are particularly useful in reactions requiring high selectivity and mild operating conditions [85]. However, their high cost limits their widespread use in industrial applications. To overcome this challenge, researchers are exploring bimetallic catalysts and advanced supports that reduce noble metal loading while maintaining catalytic performance [86]. For instance, Pt–Ni and Pd–Co systems improve activity and stability in HDO processes, providing a more cost-effective pathway for such processes [87].

The selection of a catalyst for HDO depends on factors, such as the feedstock composition, target product distribution, and economic viability. Continuous efforts to develop catalysts that are robust, selective, and cost-efficient are driving advancements in HDO technology, facilitating the large-scale production of renewable fuels [79].

4.2. Fischer–Tropsch Synthesis

Fischer–Tropsch synthesis (FTS) is a fundamental methodology for producing synthetic hydrocarbons, converting biomass-derived syngas into liquid fuels and chemicals. This catalytic process is particularly significant in biomass conversion as it provides a sustainable route for generating fuels that are compatible with existing transportation and energy infrastructures [88]. Utilizing biosyngas—a mixture of hydrogen (H_2) and carbon monoxide (CO)—FTS facilitates the production of long-chain hydrocarbons, including diesel, kerosene, and gasoline. This process not only reduces reliance on fossil fuels but also enhances carbon utilization efficiency, supporting greenhouse gas mitigation and energy sustainability [89].

4.2.1. Biosyngas Conversion to Hydrocarbons

Biosyngas, generated through the gasification of biomass, serves as the primary feedstock for FTS. This conversion process involves a series of surface catalytic reactions that combine carbon monoxide and hydrogen molecules to form hydrocarbons of different chain lengths [90]. The general reaction is represented by the following equation:

$$(2n+1)H_2 + nCO \rightarrow C_nH_{2n+2} + nH_2O \quad (1)$$

The reaction proceeds under moderate to high pressures (10–40 bar) and temperatures (200–350 °C) depending on the desired product distribution [91]. Low-temperature FTS (200–240 °C) promotes the formation of long-chain hydrocarbons, such as waxes and diesel, while high-temperature FTS (300–350 °C) produces short-chain hydrocarbons and olefins [92].

The success of FTS depends on the precise control of the reaction conditions and catalyst properties, which determine selectivity toward specific hydrocarbon products. The water–gas shift (WGS) reaction, which adjusts the H_2/CO ratio by converting CO and water into CO_2 and H_2, is a critical complementary reaction in FTS [93]. For biomass-derived syngas, which typically has a lower H_2/CO ratio than syngas acquired from fossil fuels, the WGS reaction is essential for optimizing feedstock utilization and ensuring efficient hydrocarbon production [16].

4.2.2. Role of Fe and Co Catalysts

Iron (Fe) and cobalt (Co) are the primary catalysts used in FTS, each offering distinct properties that make them suitable for specific feedstocks and process conditions. These catalysts are highly active in facilitating the polymerization of CO and H_2 into hydrocarbons,

with their activity and selectivity being influenced by the choice of support materials, promoters, and operating parameters [94].

Iron catalysts are versatile and commonly used in FTS due to their ability to catalyze the Fischer–Tropsch and WGS reactions. This dual functionality makes iron particularly effective for generating biomass-derived syngas, which often requires WGS activity to balance the H_2/CO ratio [95]. Iron catalysts are also cost-effective and abundant, further enhancing their suitability for large-scale applications. However, they are susceptible to deactivation through carbon deposition and sintering, which requires periodic regeneration and advanced formulations to enhance their stability [96].

Cobalt catalysts, in contrast, exhibit higher activity and selectivity for hydrocarbon production, particularly in low-temperature FTS. They are particularly suited for producing long-chain paraffins and diesel-range hydrocarbons. Supported cobalt catalysts, often combined with materials such as alumina, silica, or titanium dioxide, show excellent performance in FTS [97]. However, cobalt catalysts are more sensitive to syngas impurities, such as sulfur, and require a high H_2/CO ratio for optimal performance, making them less flexible than iron catalysts for producing biomass-derived syngas [95].

To improve the performance of Fe and Co catalysts, researchers have developed bimetallic systems and introduced promoters, such as potassium for iron and ruthenium for cobalt. These modifications enhance catalytic activity, selectivity, and resistance to deactivation [98]. For instance, potassium-promoted iron catalysts show increased WGS activity and hydrocarbon selectivity, while ruthenium-promoted cobalt catalysts exhibit enhanced hydrogenation activity. These advancements contribute to the development of more efficient and scalable Fischer–Tropsch processes optimized for producing renewable bio-syngas feedstocks [16].

4.3. Aqueous-Phase Reforming (APR)

Aqueous-phase reforming (APR) is an innovative catalytic process for producing hydrogen and value-added chemicals from biomass-derived oxygenated compounds, such as sugars, alcohols, and polyols. Unlike traditional reforming techniques that require high temperatures, APR operates in liquid water at moderate temperatures (200–250 °C) and pressures (20–50 bar) [99], making it an energy-efficient option. This characteristic is especially beneficial for processing wet biomass feedstocks, which would otherwise need extensive drying. APR leverages the unique chemistry of oxygenated compounds to produce hydrogen-rich syngas and hydrocarbons, positioning it a critical technology for sustainable hydrogen production and renewable fuel synthesis [89].

4.3.1. Pt and Ru Catalysts for Hydrogen Production

Platinum (Pt) and ruthenium (Ru) are the most widely used catalysts for APR due to their exceptional hydrogenation and reforming activity. These noble metals excel at breaking C–C and C–H bonds, effectively reforming biomass-derived molecules into hydrogen and carbon dioxide [100]. The catalytic surfaces of Pt and Ru facilitate the adsorption and activation of reactant molecules, enabling efficient bond cleavage and promoting hydrogen release [87].

For example, Pt catalysts are highly effective in the APR of alcohols such as glycerol and ethylene glycol, which are common intermediates in biomass conversion. Platinum supported on carbon or alumina exhibits high selectivity for hydrogen production while minimizing the formation of undesirable byproducts like methane [101]. Similarly, Ru catalysts excel at cleaving complex oxygenated compounds, making them well-suited for APR reactions involving polyols and sugars. The stability and robustness of Pt and Ru catalysts under aqueous conditions further enhance their suitability for this process [102].

Recent research has concentrated on optimizing Pt and Ru catalysts through the development of bimetallic systems and modifications to catalyst supports. For instance, Pt–Ni and Ru–Cu combinations have been investigated to enhance hydrogen yield while suppressing methane formation, thereby improving the overall efficiency of the process [103]. Innovations in catalyst design are paving the way for the scalable application of APR in hydrogen production, meeting the increasing demand for clean energy solutions.

4.3.2. Reaction Conditions for APR

The reaction conditions for APR are crucial in shaping the efficiency and selectivity of the process. Operating temperatures of 200–250 °C and pressures of 20–50 bar are ideal for maintaining water in the liquid phase while driving reforming reactions [104]. These moderate conditions enable the efficient conversion of biomass-derived feedstocks with minimal thermal energy input, establishing APR as an energy-efficient alternative to high-temperature gas-phase reforming [105].

The composition of the feedstock significantly affects APR performance. Oxygenated compounds such as sugars, glycerol, and sorbitol are preferred due to their high hydrogen content and ease of reforming. However, impurities like sulfur and nitrogen compounds can poison the catalyst surface, diminishing its activity [106]. To mitigate this issue, pretreatment steps, such as feedstock purification, are commonly employed.

The hydrogen-to-carbon monoxide (H_2/CO) ratio produced during APR is a critical parameter, as it significantly impacts the downstream utilization of syngas. APR inherently generates a high H_2/CO ratio, making it particularly suitable for hydrogen production and processes such as methanol synthesis and Fischer–Tropsch reactions [107]. Furthermore, the selection of the catalyst and its support plays a crucial role in influencing APR selectivity, allowing the reaction to be steered toward hydrogen or hydrocarbons depending on the desired end product [108,109].

To further enhance the performance of APR, process intensification strategies, such as integrating APR with complementary catalytic processes, are under active exploration. For instance, coupling APR with hydrodeoxygenation (HDO) or water–gas shift (WGS) reactions can significantly improve hydrogen yield and feedstock utilization [109]. These advancements highlights the potential of APR as a cornerstone technology in the transition toward sustainable hydrogen and renewable fuel production [110].

4.4. Pyrolysis and Catalytic Cracking

Pyrolysis and catalytic cracking are essential thermochemical processes for converting biomass into biofuels and chemicals. Pyrolysis involves the thermal decomposition of biomass at high temperatures, producing intermediates such as bio-oil, syngas, and char [111]. While raw bio-oil from pyrolysis is characterized by high oxygen content and chemical instability, catalytic cracking refines this intermediate by breaking down complex molecules and removing oxygen. This process yield hydrocarbons with properties comparable to conventional fossil fuels [112]. Integrating these processes into biorefineries offers transformative potential for biofuel production, fostering a circular and sustainable energy system.

4.4.1. Ni-Based Catalysts for Bio-Oil Upgrading

Nickel (Ni)-based catalysts are widely employed for upgrading bio-oil due to their cost-effectiveness, high activity, and strong deoxygenation capabilities [15]. Bio-oil derived from pyrolysis contains a diverse array of oxygenated compounds, such as acids, alcohols, ketones, and phenolics, which contribute to its corrosive nature and low energy density. Ni catalysts effectively facilitate hydrodeoxygenation (HDO) and cracking reactions, convert-

ing these oxygen-rich compounds into hydrocarbons with enhanced stability and calorific value [113].

Nickel catalysts operated by adsorbing and activating oxygen-containing compounds on their surface, facilitating the selective removal of oxygen as water or carbon dioxide. For instance, Ni-supported on alumina or silica effectively converts phenolic compounds, commonly found in lignin-derived bio-oil, into aromatic hydrocarbons [114]. Beyond deoxygenation, Ni catalysts promote the cracking of larger molecules into shorter-chain hydrocarbons, which are more suitable for fuel applications [115]. This dual functionality—integrating deoxygenation and cracking—renders Ni catalysts indispensable for bio-oil upgrading processes.

Advances in catalyst design have significantly improved the performance of Ni-based systems. For example, bimetallic catalysts, such as Ni–Co or Ni–Mo, enhance activity and resistance to poisoning by impurities in bio-oil, such as sulfur [103]. Additionally, modifying the catalyst support with materials like zeolites or mesoporous silica can increase the dispersion of active sites, boosting catalytic efficiency and selectivity [116]. These innovations are facilitating the widespread adoption of Ni-based catalysts in bio-oil upgrading applications.

4.4.2. Integration with Biorefineries

The integration of pyrolysis and catalytic cracking processes into biorefineries marks a significant step toward establishing a sustainable and circular bioeconomy. Biorefineries are implemented to process diverse biomass feedstocks into various products, including fuels, chemicals, and power, thereby optimizing resource utilization and minimizing waste [117]. By incorporating pyrolysis and catalytic cracking, these facilities efficiently convert lignocellulosic biomass into liquid hydrocarbons, aligning with the goals of sustainable energy production [118].

In a biorefinery setup, pyrolysis acts as the initial stage, converting biomass into bio-oil, syngas, and char. The resulting bio-oil is subsequently refined through catalytic cracking using Ni-based or zeolite-supported catalysts to produce high-value fuels, such as gasoline and diesel [119]. Char generated during pyrolysis can be used as a solid fuel or as a feedstock for activated carbon production, while syngas can be employed for power generation or chemical synthesis via Fischer–Tropsch or methanol synthesis processes [16]. This integrated approach not only maximizes the yield of valuable products but also enhances energy efficiency by utilizing all byproducts of the respective processes.

Additionally, biorefineries offer flexibility to customize catalytic processes based on specific feedstocks and market demands (Figure 3). For example, agricultural residues with a high lignin content can be optimized for bio-oil production, while algal biomass may be better suited for lipid extraction and hydroprocessing [120]. The modular nature of biorefineries facilitates the integration of emerging catalytic technologies, such as bimetallic systems or hybrid catalysts, to improve efficiency and product quality. This integration demonstrates the transformative potential of combining pyrolysis, catalytic cracking, and biorefinery processes for developing a sustainable future [121,122].

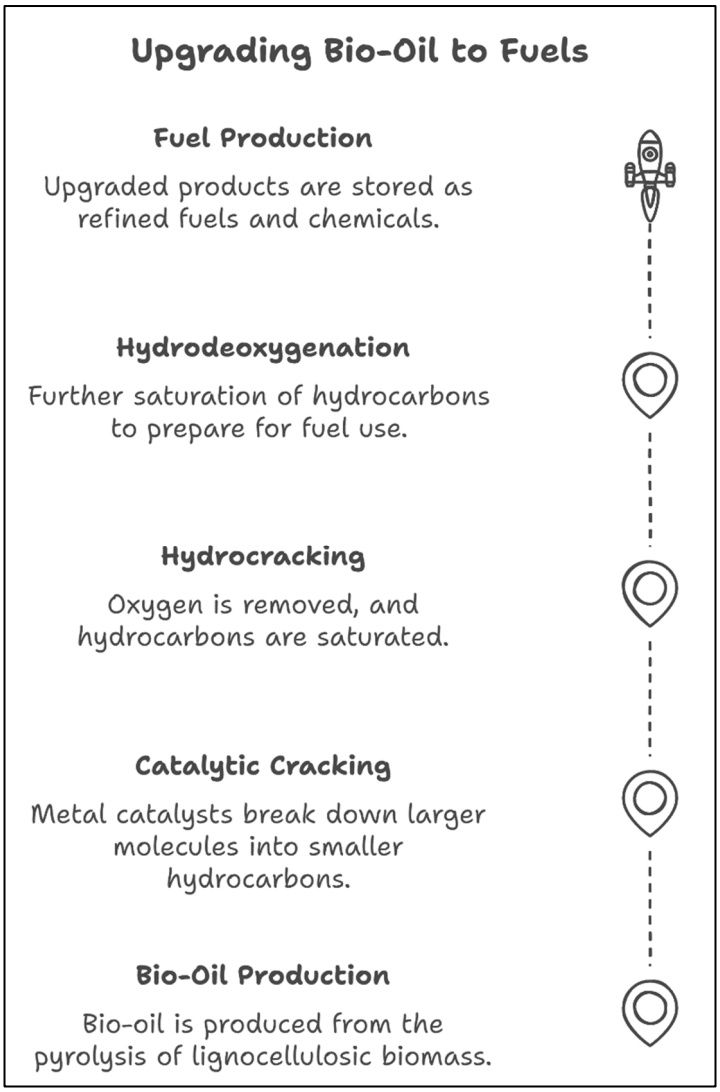

Figure 3. Catalytic Cracking Process in Biorefineries.

5. Catalytic Production of Chemicals from Biomass

The catalytic conversion of biomass into chemicals represents a transformative strategy for developing renewable alternatives to fossil-based products. Biomass-derived chemicals form the basis for diverse applications, including bioplastics, pharmaceuticals, and bio-based solvents [4]. Valorizing biomass into platform chemicals is a fundamental pillar of the bioeconomy, enabling the sustainable production of high-value intermediates with minimal environmental impact. Advances in catalytic technologies have significantly enhanced this process, improving efficiency, selectivity, and scalability [12]. Through the use of catalysts, complex biomass molecules can be effectively transformed into versatile chemical building blocks, thereby reducing dependence on finite fossil resources [123].

5.1. Platform Chemicals

Platform chemicals are intermediate compounds derived from biomass that serve as precursors for a wide range of end-use products. Examples include 5-hydroxymethylfurfural (5-HMF), furfural, and bio-based aromatics, which are critical building blocks in the shift toward a bio-based economy [124]. Catalytic processes are integral to the production of these chemicals, facilitating the selective conversion of lignocellulosic biomass into high-value products [54]. The advancement of efficient catalytic pathways has established platform chemicals as essential components of sustainable industrial processes (Table 3).

Table 3. Biomass-derived platform chemicals and their catalytic pathways.

Biomass-Derived Platform Chemicals	Catalytic Pathways	Reaction Type	Catalysts	Source
Furfural	Hydrodeoxygenation, Hydrogenation	Reduction	Ni/Al_2O_3, Ru/C, Pd/C	[125]
Levulinic acid	Reduction, Hydrogenation	Hydrogenation, Dehydration	Ru/Al_2O_3, Rh/SiO_2	[126]
Acetic acid	Esterification, Hydrogenation	Dehydration, Hydrogenation	Pd/Al_2O_3, Cu/ZnO, Fe_3O_4	[17]
Bioethanol	Dehydration, Hydrogenation, and Oxidation	Hydrogenation	Cu/ZnO, Ru/Al_2O_3	[127]
Lactic acid	Hydrogenation, Oxidation	Hydrogenation, Reduction	Ru/Al_2O_3, Pd/C	[128]
Hydroxyacetaldehyde	Hydrogenation, Oxidation	Reduction, Oxidation	Pd/C, CuO/TiO_2	[129]
Glycerol	Hydrogenation, reforming, and oxidation	Hydrogenation, Dehydration	Pt/C, Pd/C	[130]
HMF (5-Hydroxymethylfurfural)	Hydrogenation, Hydrodeoxygenation	Hydrogenation, Reduction	Ru/Al_2O_3, Pd/C	[131]
Succinic acid	Hydrogenation, Dehydration	Reduction, Dehydration	Ru/Al_2O_3, Cu/ZnO	[132]
2,5-Furandicarboxylic acid (FDCA)	Hydrogenation, Oxidation	Reduction, Oxidation	Ru/C, Pd/C	[133]

5.1.1. Production of 5-HMF and Furfural

The catalytic conversion of biomass-derived carbohydrates, such as glucose and xylose, into 5-HMF and furfural is a pivotal step in biomass valorization. 5-HMF, produced from hexose sugars, is a highly versatile platform chemical used in the manufacture of bioplastics, biofuels, and fine chemicals [134]. Its synthesis involves the acid-catalyzed dehydration of sugars, employing catalysts such as HCl or sulfuric acid, or heterogeneous systems like zeolites and metal-organic frameworks (MOFs). Recent advancements have introduced bifunctional catalysts that integrate acid and metal sites, significantly enhancing both the yield and selectivity of 5-HMF production [135].

Furfural, another key platform chemical, is derived from pentose sugars like xylose, which are abundant in hemicellulose. Catalysts such as alumina-supported metals or solid acids enables the dehydration of xylose into furfural. This versatile compound is extensively used in the production of resins, solvents, and bio-based fuels [136]. Advances in catalyst design, including the development of renewable catalysts and the application of green solvents, have enhanced the sustainability and efficiency of furfural production processes, solidifying its role as a cornerstone in lignocellulosic biomass valorization [137].

5.1.2. Methyl Oleate Valorization

Methyl oleate serves as a representative compound for studies on biomass-derived fatty acid methyl esters. Catalytic transformation using transition metals such as Ru and Pd facilitates the selective production of high-value products like bio-lubricants, detergents, and surfactants. Hydrogenation and oxidative cleavage pathways exemplify how such conversions support industrial sustainability efforts [138,139]. Furthermore, the efficient valorization of methyl oleate underscores its role in advancing biomass conversion technologies

5.1.3. Bio-Based Aromatics

Bio-based aromatics, produced through the catalytic conversion of lignin and other biomass fractions, serve as crucial intermediates for manufacturing polymers, adhesives, and pharmaceuticals. Aromatic compounds like benzene, toluene, and xylene, can be obtained by depolymerizing lignin using oxidative or reductive catalytic processes [55]. Transition metal catalysts, such as those based on nickel and cobalt, are particularly effective in breaking down the complex aromatic structure of lignin into smaller, usable molecules.

Zeolites and supported metal catalysts are essential for converting lignin-derived intermediates into bio-aromatics with high selectivity. For instance, zeolite-supported nickel catalysts exhibit exceptional performance in hydrodeoxygenation, enabling the production of aromatic hydrocarbons with minimal byproducts [140]. Furthermore, advancements in bimetallic and bifunctional catalyst design have significantly enhanced the efficiency of bio-aromatic production, solidifying these compounds as sustainable alternatives to their petroleum-derived counterparts [141].

5.2. Biopolymers and Their Precursors

Biopolymers and their precursors derived from biomass are emerging as sustainable alternatives to petroleum-based materials. These bio-derived materials not only reduce reliance on finite fossil resources but also offer advantages such as improved biodegradability and reduced environmental impact [142]. The production of biopolymers leverages catalytic processes to transform biomass-derived intermediates—such as sugars, organic acids, and alcohols—into polymer precursors like lactones, diols, and other monomers. These precursors can then be polymerized into bioplastics, resins, and biodegradable materials [118]. Advances in catalytic strategies are enhancing the efficiency and scalability of these processes, advancing the transition toward a more sustainable materials industry.

5.2.1. Conversion to Lactones and Diols

The catalytic conversion of biomass-derived intermediates into lactones and diols is fundamental for numerous biopolymer applications. Lactones, such as γ-valerolactone (GVL), are versatile building blocks for the production of biodegradable plastics, solvents, and biofuels [143]. These compounds are synthesized from levulinic acid, a platform chemical obtained through the catalytic breakdown of cellulose or hemicellulose. Metal-based catalysts, such as Ru and Pt supported on carbon or alumina, are commonly used for the hydrogenation of levulinic acid to GVL [144]. Bifunctional catalysts that integrate acidic and metallic sites enhance the efficiency and selectivity of this conversion process.

Diols, such as 1,3-propanediol and 1,4-butanediol, are key precursors for polyesters, polyurethanes, and other bioplastics. These compounds are typically produced from biomass-derived sugars and glycerol through hydrogenolysis or fermentation processes. Catalysts, including Cu-based or bimetallic Ru–Cu systems, facilitate the selective hydrogenation of intermediates, such as glycerol or sorbitol, into diols [145]. Recent advancements in the catalyst design have focused on enhancing the stability and reducing the costs of these systems to enable the large-scale production of biopolymer precursors [146].

5.2.2. Precursors for Sustainable Polymers

Beyond lactones and diols, other biomass-derived compounds are essential precursors for sustainable polymers. For example, furancarboxylic acid (FDCA), synthesized from 5-hydroxymethylfurfural (HMF), is a bio-based alternative to terephthalic acid, a key monomer in polyethylene terephthalate (PET) production [147]. The catalytic oxidation of HMF using metal catalysts, like Pt, Au, or Ru, yields FDCA with high selectivity, providing

a route for producing bio-based plastics with comparable performance to their fossil-based counterparts [148].

Lactic acid, another biomass-derived precursor, is polymerized to produce polylactic acid (PLA), a biodegradable plastic commonly used in packaging, medical devices, and textiles. The catalytic conversion of sugars into lactic acid can be accomplished using acid catalysts or enzymatic processes [149]. The scalability of these methods makes PLA one of the most commercially successful bioplastics [150,151]. Advances in the catalyst design, particularly those enhancing reaction efficiency and product purity, continue to broaden the range of sustainable polymers derived from biomass.

5.3. Green Hydrogen Production

Green hydrogen, produced through renewable methods, is essential for a sustainable energy system. Biomass conversion provides a promising pathway for hydrogen production by utilizing catalytic processes to transform biomass into hydrogen-rich intermediates or directly extract hydrogen [152]. These approaches include water electrolysis powered by renewable energy and the reforming of biomass-derived syngas. Metal-based catalysts play a crucial role in ensuring high efficiency, selectivity, and scalability, establishing green hydrogen as a pivotal enabler of the hydrogen economy [153].

5.3.1. Metal Catalysts in Electrolysis

Water electrolysis is an established method for hydrogen production, using renewable electricity to split water into hydrogen and oxygen. Metal catalysts are essential for improving the efficiency of this process by lowering the energy required for water splitting. In alkaline electrolysis, nickel-based catalysts are commonly used for their affordability and high performance in the oxygen evolution reaction (OER) [154]. For proton exchange membrane electrolysis, noble metals such as platinum (Pt) and iridium (Ir) are employed due to their excellent activity in both the hydrogen evolution reaction and OER [155].

Recent advances in catalyst development aim to reduce dependence on costly noble metals by exploring earth-abundant alternatives, such as cobalt-iron alloys or transition metal phosphides [156]. Furthermore, innovations in electrode design, including the use of nanostructured catalysts or hybrid materials, have improved the efficiency and durability of electrolyzers [157]. These developments are propelling the adoption of electrolysis as a scalable and sustainable solution for green hydrogen production.

5.3.2. Hydrogen from the Biomass-Derived Syngas

Biomass-derived syngas, a mixture of hydrogen (H_2), carbon monoxide (CO), and carbon dioxide (CO_2), is another renewable source of hydrogen. It is typically produced through biomass gasification, a process where high temperatures and limited oxygen convert solid biomass into a gaseous mixture [158]. Catalysts are essential for refining of syngas to maximize hydrogen yield and purity. For instance, nickel-based catalysts are commonly employed in steam reforming, which converts CO and hydrocarbons in syngas into additional H_2 and CO_2 [159].

The water–gas shift (WGS) reaction is a crucial step in hydrogen production from syngas, where CO reacts with water to form CO_2 and H_2. Iron-based catalysts, often enhanced with chromium or copper, are commonly utilized in high-temperature WGS reactions, while Cu–Zn catalysts are effective at lower temperatures [160]. Advances in catalyst design, such as bimetallic systems and supported metal nanoparticles, have improved the efficiency and selectivity of these processes, enabling the scalable production of hydrogen from biomass-derived syngas [161]. Biomass-based hydrogen production provides significant environmental benefits by utilizing renewable resources and reducing carbon emissions. When coupled with carbon capture technologies, this process further

enhances sustainability, positioning it as a key element in the transition to a low-carbon energy future [162].

6. Challenges and Future Perspectives

The catalytic transformation of biomass into renewable fuels and chemicals presents immense opportunities for sustainable development. However, several challenges must be overcome to fully realize its potential. One major issue is the stability and deactivation of catalysts [11]. Over time, catalysts lose their activity due to factors, such as poisoning, sintering, and fouling. Poisoning occurs when impurities in biomass, such as sulfur and nitrogen compounds, bind to the active sites on the catalyst, rendering them inactive. Sintering, particularly at high temperatures, causes metal particle aggregation, thereby reducing the available surface area for catalytic reactions [8]. Fouling involves the accumulation of carbonaceous deposits or biomass residues on the catalyst surface, further diminishing its effectiveness. To address these challenges, innovative strategies are required, thereby enhancing catalyst longevity. This includes modifying the catalyst chemical composition to improve catalyst resistance to poisoning, developing thermal stabilization techniques to mitigate sintering, and optimizing process conditions to minimize fouling [163]. Additionally, employing regenerating and self-cleaning catalysts as well as advanced materials, such as nanostructured supports, can considerably improve catalyst stability and operational lifespan [164].

Scalability and economic feasibility are major concerns when translating biomass conversion technologies from laboratory scales to industrial scales. The high cost of noble metal catalysts, intense energy demands of processing steps, and variability in biomass feedstocks pose notable obstacles to commercialization. Industrial applications often require catalysts that maintain consistent performance under various conditions, a challenge arising due to the heterogeneous nature of biomass [165]. Additionally, the logistics involved in biomass collection, transportation, and storage further complicate and increase costs in the supply chain. Strategies to reduce costs and enhance scalability include developing low-cost catalysts using earth-abundant materials, such as transition metals or metal oxides, and designing modular processing units that can operate near biomass sources [165,166]. Furthermore, process intensification techniques, such as combining multiple catalytic steps into a single reactor, can improve energy efficiency and reduce overall costs. Integrating catalytic processes into existing biorefineries can also enhance resource utilization and create economic synergies, making biomass conversion technologies more viable for large-scale applications [167].

Emerging catalytic technologies present promising solutions to overcome current challenges and advance biomass conversion. Hybrid catalysts, which integrate the characteristics of heterogeneous and homogeneous catalysts, exhibit potential for enhancing reaction efficiency and selectivity [168]. Bimetallic systems, where two metals work synergistically, are another innovative approach that improves stability and activity compared to single-metal catalysts. For example, Ni–Co or Pt–Ru combinations demonstrate superior performance for hydrodeoxygenation and reforming reactions [169].

Metathesis reactions stand as transformative advancements in the valorization of biomass. By utilizing ruthenium-based catalysts like Grubbs' systems, these processes efficiently redistribute carbon-carbon double bonds in fatty acids, enabling the production of bio-based olefins, lubricants, and polymers. The specificity and efficiency of metathesis reactions make them a cornerstone of sustainable biomass conversion technologies, particularly in improving economic viability [170–173]. Moreover, the use of artificial intelligence (AI) and machine learning in the catalyst design is revolutionizing the field. These technologies enable the rapid screening of catalyst formulations, prediction of reaction

outcomes, and optimization of process parameters, greatly accelerating the development of next-generation catalytic systems [174]. The combination of computational tools and experimental research is driving the development of more efficient, cost-effective, and scalable biomass conversion technologies.

Environmental impacts and sustainability are essential factors in the development and implementation of biomass conversion technologies. Lifecycle analysis (LCA) that estimates metrics, such as the carbon footprint, energy consumption, and resource efficiency, is a powerful tool for evaluating the environmental performance of catalytic processes [175]. LCA helps identify hotspots in process chains and guide improvements to minimize environmental impacts. For example, decreasing the use of fossil-derived hydrogen in hydroprocessing or optimizing reaction conditions to reduce energy inputs can greatly enhance the sustainability of biomass conversion [176]. Sustainability metrics, including water use, land use, and greenhouse gas emissions, are essential for assessing the overall impact of biomass conversion technologies. Integrating renewable energy sources, such as solar or wind, into biomass processing and developing closed-loop systems for recycling catalysts and byproducts can further enhance the environmental profile of biomass-derived fuels and chemicals [4]. By tackling these challenges and adopting innovative strategies, biomass conversion technologies can contribute to a sustainable and circular bioeconomy [177,178].

7. Conclusions

Advances in metal-based catalysts have revolutionized the transformation of biomass into renewable fuels and chemicals, paving the way for sustainable energy and material production. These catalysts, which include transition metals, noble metals, and hybrid systems, demonstrate remarkable efficiency in breaking down complex biomass structures and producing high-value products. Transition metals, like nickel, cobalt, and iron, are effective in processes, such as pyrolysis, gasification, and hydrodeoxygenation, offering cost-effective solutions for large-scale applications. Noble metals, including platinum and palladium, exhibit unparalleled selectivity and activity, particularly for reactions requiring precise control, such as hydrogenation and reforming. Innovations in the catalyst design, including the use of bimetallic and supported catalysts, have considerably improved performance while addressing challenges, such as deactivation, poisoning, and cost constraints. These advancements, along with the integration of catalytic technologies into biorefineries, underscore the transformative potential of metal-based catalysts in fostering a renewable and sustainable bioeconomy.

The future outlook for achieving sustainability in biomass conversion is promising and challenging. A key priority is addressing the scalability and economic feasibility of catalytic processes. Developing low-cost catalysts using earth-abundant materials and reducing dependence on expensive noble metals will be essential for making these technologies viable at an industrial scale. Advances in hybrid and bimetallic catalysts, along with AI-driven design approaches, are poised to drive the next generation of catalytic systems, enhancing efficiency, selectivity, and stability. Environmental considerations will be pivotal in shaping future developments. Integrating LCA and sustainability metrics into the process design can help minimize the carbon footprint and resource consumption associated with biomass conversion. The incorporation of renewable energy sources into catalytic processes and optimization of reaction conditions for energy efficiency will further enhance the environmental benefits of biomass-derived products. By addressing current challenges and adopting innovative approaches, metal-based catalysts can facilitate a sustainable shift toward a circular bioeconomy, reducing reliance on fossil fuels and mitigating climate change.

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References

1. Demirbas, A. Combustion characteristics of different biomass fuels. *Prog. Energy Combust. Sci.* **2004**, *30*, 219–230. [CrossRef]
2. Poorter, H.; Nagel, O. The role of biomass allocation in the growth response of plants to different levels of light, CO_2, nutrients and water: A quantitative review. *Funct. Plant Biol.* **2000**, *27*, 1191. [CrossRef]
3. Antar, M.; Lyu, D.; Nazari, M.; Shah, A.; Zhou, X.; Smith, D.L. Biomass for a sustainable bioeconomy: An overview of world biomass production and utilization. *Renew. Sustain. Energy Rev.* **2021**, *139*, 110691. [CrossRef]
4. Mika, L.T.; Cséfalvay, E.; Németh, Á. Catalytic conversion of carbohydrates to initial platform chemicals: Chemistry and sustainability. *Chem. Rev.* **2018**, *118*, 505–613. [CrossRef]
5. Gallezot, P. Conversion of biomass to selected chemical products. *Chem. Soc. Rev.* **2012**, *41*, 1538–1558. [CrossRef] [PubMed]
6. Tian, S.; Wang, Z.; Gong, W.; Chen, W.; Feng, Q.; Xu, Q.; Chen, C.; Chen, C.; Peng, Q.; Gu, L. Temperature-controlled selectivity of hydrogenation and hydrodeoxygenation in the conversion of biomass molecule by the Ru1/mpg-C3N4 catalyst. *J. Am. Chem. Soc.* **2018**, *140*, 11161–11164. [CrossRef]
7. Ruddy, D.A.; Schaidle, J.A.; Ferrell, J.R., III; Wang, J.; Moens, L.; Hensley, J.E. Recent advances in heterogeneous catalysts for bio-oil upgrading via "ex situ catalytic fast pyrolysis": Catalyst development through the study of model compounds. *Green Chem.* **2014**, *16*, 454–490. [CrossRef]
8. Argyle, M.D.; Bartholomew, C.H. Heterogeneous catalyst deactivation and regeneration: A review. *Catalysts* **2015**, *5*, 145–269. [CrossRef]
9. Laskar, D.D.; Tucker, M.P.; Chen, X.; Helms, G.L.; Yang, B. Noble-metal catalyzed hydrodeoxygenation of biomass-derived lignin to aromatic hydrocarbons. *Green Chem.* **2014**, *16*, 897–910. [CrossRef]
10. Lu, Y.; Jiang, Y.; Gao, X.; Wang, X.; Chen, W. Strongly coupled Pd nanotetrahedron/tungsten oxide nanosheet hybrids with enhanced catalytic activity and stability as oxygen reduction electrocatalysts. *J. Am. Chem. Soc.* **2014**, *136*, 11687–11697. [CrossRef]
11. Sudarsanam, P.; Peeters, E.; Makshina, E.V.; Parvulescu, V.I.; Sels, B.F. Advances in porous and nanoscale catalysts for viable biomass conversion. *Chem. Soc. Rev.* **2019**, *48*, 2366–2421. [CrossRef] [PubMed]
12. Sudarsanam, P.; Zhong, R.; Van den Bosch, S.; Coman, S.M.; Parvulescu, V.I.; Sels, B.F. Functionalised heterogeneous catalysts for sustainable biomass valorisation. *Chem. Soc. Rev.* **2018**, *47*, 8349–8402. [CrossRef] [PubMed]
13. Nzihou, A.; Stanmore, B.; Sharrock, P. A review of catalysts for the gasification of biomass char, with some reference to coal. *Energy* **2013**, *58*, 305–317. [CrossRef]
14. Long, J.; Song, H.; Jun, X.; Sheng, S.; Lun-Shi, S.; Kai, X.; Yao, Y. Release characteristics of alkali and alkaline earth metallic species during biomass pyrolysis and steam gasification process. *Bioresour. Technol.* **2012**, *116*, 278–284. [CrossRef]
15. Koike, N.; Hosokai, S.; Takagaki, A.; Nishimura, S.; Kikuchi, R.; Ebitani, K.; Suzuki, Y.; Oyama, S.T. Upgrading of pyrolysis bio-oil using nickel phosphide catalysts. *J. Catal.* **2016**, *333*, 115–126. [CrossRef]
16. dos Santos, R.G.; Alencar, A.C. Biomass-derived syngas production via gasification process and its catalytic conversion into fuels by Fischer Tropsch synthesis: A review. *Int. J. Hydrogen Energy* **2020**, *45*, 18114–18132. [CrossRef]
17. Yu, W.; Tang, Y.; Mo, L.; Chen, P.; Lou, H.; Zheng, X. One-step hydrogenation–esterification of furfural and acetic acid over bifunctional Pd catalysts for bio-oil upgrading. *Bioresour. Technol.* **2011**, *102*, 8241–8246. [CrossRef] [PubMed]
18. Nolte, M.W.; Shanks, B.H. A perspective on catalytic strategies for deoxygenation in biomass pyrolysis. *Energy Technol.* **2017**, *5*, 7–18. [CrossRef]
19. Ambursa, M.M.; Juan, J.C.; Yahaya, Y.; Taufiq-Yap, Y.; Lin, Y.-C.; Lee, H.V. A review on catalytic hydrodeoxygenation of lignin to transportation fuels by using nickel-based catalysts. *Renew. Sustain. Energy Rev.* **2021**, *138*, 110667. [CrossRef]
20. Yuan, M.; Long, Y.; Yang, J.; Hu, X.; Xu, D.; Zhu, Y.; Dong, Z. Biomass sucrose-derived cobalt@ nitrogen-doped carbon for catalytic transfer hydrogenation of nitroarenes with formic acid. *ChemSusChem* **2018**, *11*, 4156–4165. [CrossRef] [PubMed]
21. Sinfelt, J.H.; Yates, D.J. Catalytic hydrogenolysis of ethane over the noble metals of Group VIII. *J. Catal.* **1967**, *8*, 82–90. [CrossRef]

22. Yang, L.; Chen, Z.G.; Dargusch, M.S.; Zou, J. High performance thermoelectric materials: Progress and their applications. *Adv. Energy Mater.* **2018**, *8*, 1701797. [CrossRef]
23. Fu, J.; Lym, J.; Zheng, W.; Alexopoulos, K.; Mironenko, A.V.; Li, N.; Boscoboinik, J.A.; Su, D.; Weber, R.T.; Vlachos, D.G. C–O bond activation using ultralow loading of noble metal catalysts on moderately reducible oxides. *Nat. Catal.* **2020**, *3*, 446–453. [CrossRef]
24. Marshall, S.T.; O'Brien, M.; Oetter, B.; Corpuz, A.; Richards, R.M.; Schwartz, D.K.; Medlin, J.W. Controlled selectivity for palladium catalysts using self-assembled monolayers. *Nat. Mater.* **2010**, *9*, 853–858. [CrossRef]
25. Michel, C.; Gallezot, P. Why is ruthenium an efficient catalyst for the aqueous-phase hydrogenation of biosourced carbonyl compounds? *ACS Catal.* **2015**, *5*, 4130–4132. [CrossRef]
26. Xue, Z.; Liu, Q.; Wang, J.; Mu, T. Valorization of levulinic acid over non-noble metal catalysts: Challenges and opportunities. *Green Chem.* **2018**, *20*, 4391–4408. [CrossRef]
27. Han, X.; Zhang, W.; Ma, X.; Zhong, C.; Zhao, N.; Hu, W.; Deng, Y. Identifying the activation of bimetallic sites in NiCo2S4@ g-C3N4-CNT hybrid electrocatalysts for synergistic oxygen reduction and evolution. *Adv. Mater.* **2019**, *31*, 1808281. [CrossRef] [PubMed]
28. Dawes, G.J.S.; Scott, E.L.; Le Nôtre, J.; Sanders, J.P.; Bitter, J.H. Deoxygenation of biobased molecules by decarboxylation and decarbonylation–a review on the role of heterogeneous, homogeneous and bio-catalysis. *Green Chem.* **2015**, *17*, 3231–3250. [CrossRef]
29. Ono, Y. Solid base catalysts for the synthesis of fine chemicals. *J. Catal.* **2003**, *216*, 406–415. [CrossRef]
30. Kazemi, M.; Ghobadi, M.; Mirzaie, A. Cobalt ferrite nanoparticles (CoFe2O4 MNPs) as catalyst and support: Magnetically recoverable nanocatalysts in organic synthesis. *Nanotechnol. Rev.* **2018**, *7*, 43–68. [CrossRef]
31. Bédard, A.-C.; Adamo, A.; Aroh, K.C.; Russell, M.G.; Bedermann, A.A.; Torosian, J.; Yue, B.; Jensen, K.F.; Jamison, T.F. Reconfigurable system for automated optimization of diverse chemical reactions. *Science* **2018**, *361*, 1220–1225. [CrossRef] [PubMed]
32. Pena-Pereira, F.; Kloskowski, A.; Namieśnik, J. Perspectives on the replacement of harmful organic solvents in analytical methodologies: A framework toward the implementation of a generation of eco-friendly alternatives. *Green Chem.* **2015**, *17*, 3687–3705. [CrossRef]
33. Thomas, P.A.; Marvey, B.B. Room temperature ionic liquids as green solvent alternatives in the metathesis of oleochemical feedstocks. *Molecules* **2016**, *21*, 184. [CrossRef]
34. Liu, X.; Dai, L. Carbon-based metal-free catalysts. *Nat. Rev. Mater.* **2016**, *1*, 16064. [CrossRef]
35. Rahman, M.M.; Liu, R.; Cai, J. Catalytic fast pyrolysis of biomass over zeolites for high quality bio-oil–a review. *Fuel Process. Technol.* **2018**, *180*, 32–46. [CrossRef]
36. Olvera, D.; Rodriguez, J.A.; Perez-Silva, I.; Chavez-Esquivel, G.; Tavizon-Pozos, J.A. Catalytic evaluation of Li and K supported on CaO in the transesterification of triolein, triestearin, and tributyrin. *Chem. Pap.* **2022**, *76*, 6287–6295. [CrossRef]
37. Westerhaus, F.A.; Jagadeesh, R.V.; Wienhöfer, G.; Pohl, M.-M.; Radnik, J.; Surkus, A.-E.; Rabeah, J.; Junge, K.; Junge, H.; Nielsen, M. Heterogenized cobalt oxide catalysts for nitroarene reduction by pyrolysis of molecularly defined complexes. *Nat. Chem.* **2013**, *5*, 537–543. [CrossRef]
38. Dupont, J.; de Souza, R.F.; Suarez, P.A. Ionic liquid (molten salt) phase organometallic catalysis. *Chem. Rev.* **2002**, *102*, 3667–3692. [CrossRef]
39. Ye, R.; Zhukhovitskiy, A.V.; Deraedt, C.V.; Toste, F.D.; Somorjai, G.A. Supported dendrimer-encapsulated metal clusters: Toward heterogenizing homogeneous catalysts. *Acc. Chem. Res.* **2017**, *50*, 1894–1901. [CrossRef]
40. Lim, K.R.G.; Handoko, A.D.; Nemani, S.K.; Wyatt, B.; Jiang, H.-Y.; Tang, J.; Anasori, B.; Seh, Z.W. Rational design of two-dimensional transition metal carbide/nitride (MXene) hybrids and nanocomposites for catalytic energy storage and conversion. *ACS Nano* **2020**, *14*, 10834–10864. [CrossRef]
41. Li, D.; Tamura, M.; Nakagawa, Y.; Tomishige, K. Metal catalysts for steam reforming of tar derived from the gasification of lignocellulosic biomass. *Bioresour. Technol.* **2015**, *178*, 53–64. [CrossRef]
42. Schumann, J.; Eichelbaum, M.; Lunkenbein, T.; Thomas, N.; Alvarez Galvan, M.C.; Schlögl, R.; Behrens, M. Promoting strong metal support interaction: Doping ZnO for enhanced activity of Cu/ZnO: M (M= Al, Ga, Mg) catalysts. *ACS Catal.* **2015**, *5*, 3260–3270. [CrossRef]
43. Martens, J.A.; Verboekend, D.; Thomas, K.; Vanbutsele, G.; Pérez-Ramírez, J.; Gilson, J.-P. Hydroisomerization and hydrocracking of linear and multibranched long model alkanes on hierarchical Pt/ZSM-22 zeolite. *Catal. Today* **2013**, *218*, 135–142. [CrossRef]
44. Deng, J.; Li, M.; Wang, Y. Biomass-derived carbon: Synthesis and applications in energy storage and conversion. *Green Chem.* **2016**, *18*, 4824–4854. [CrossRef]
45. Xiong, H.; Motchelaho, M.A.; Moyo, M.; Jewell, L.L.; Coville, N.J. Effect of Group I alkali metal promoters on Fe/CNT catalysts in Fischer–Tropsch synthesis. *Fuel* **2015**, *150*, 687–696. [CrossRef]
46. Wang, Y.; Yao, L.; Wang, S.; Mao, D.; Hu, C. Low-temperature catalytic CO_2 dry reforming of methane on Ni-based catalysts: A review. *Fuel Process. Technol.* **2018**, *169*, 199–206. [CrossRef]

47. Binder, J.B.; Raines, R.T. Simple chemical transformation of lignocellulosic biomass into furans for fuels and chemicals. *J. Am. Chem. Soc.* **2009**, *131*, 1979–1985. [CrossRef] [PubMed]
48. Zhang, Z.; Song, J.; Han, B. Catalytic transformation of lignocellulose into chemicals and fuel products in ionic liquids. *Chem. Rev.* **2017**, *117*, 6834–6880. [CrossRef] [PubMed]
49. Kobayashi, H.; Fukuoka, A. Synthesis and utilisation of sugar compounds derived from lignocellulosic biomass. *Green Chem.* **2013**, *15*, 1740–1763. [CrossRef]
50. Laurens, L.M.; Dempster, T.A.; Jones, H.D.; Wolfrum, E.J.; Van Wychen, S.; McAllister, J.S.; Rencenberger, M.; Parchert, K.J.; Gloe, L.M. Algal biomass constituent analysis: Method uncertainties and investigation of the underlying measuring chemistries. *Anal. Chem.* **2012**, *84*, 1879–1887. [CrossRef] [PubMed]
51. Shaikh, H.M.; Pandare, K.V.; Nair, G.; Varma, A.J. Utilization of sugarcane bagasse cellulose for producing cellulose acetates: Novel use of residual hemicellulose as plasticizer. *Carbohydr. Polym.* **2009**, *76*, 23–29. [CrossRef]
52. Tribot, A.; Amer, G.; Alio, M.A.; de Baynast, H.; Delattre, C.; Pons, A.; Mathias, J.-D.; Callois, J.-M.; Vial, C.; Michaud, P. Wood-lignin: Supply, extraction processes and use as bio-based material. *Eur. Polym. J.* **2019**, *112*, 228–240. [CrossRef]
53. Li, D.; Chen, L.; Xu, D.; Zhang, X.; Ye, N.; Chen, F.; Chen, S. Preparation and characteristics of bio-oil from the marine brown alga Sargassum patens C. *Agardh. Bioresour. Technol.* **2012**, *104*, 737–742. [CrossRef] [PubMed]
54. Zhou, C.-H.; Xia, X.; Lin, C.-X.; Tong, D.-S.; Beltramini, J. Catalytic conversion of lignocellulosic biomass to fine chemicals and fuels. *Chem. Soc. Rev.* **2011**, *40*, 5588–5617. [CrossRef]
55. Sun, Z.; Fridrich, B.; De Santi, A.; Elangovan, S.; Barta, K. Bright side of lignin depolymerization: Toward new platform chemicals. *Chem. Rev.* **2018**, *118*, 614–678. [CrossRef] [PubMed]
56. Woiciechowski, A.L.; Neto, C.J.D.; de Souza Vandenberghe, L.P.; de Carvalho Neto, D.P.; Sydney, A.C.N.; Letti, L.A.J.; Karp, S.G.; Torres, L.A.Z.; Soccol, C.R. Lignocellulosic biomass: Acid and alkaline pretreatments and their effects on biomass recalcitrance–Conventional processing and recent advances. *Bioresour. Technol.* **2020**, *304*, 122848. [CrossRef]
57. Sun, Y.; Cheng, J. Hydrolysis of lignocellulosic materials for ethanol production: A review. *Bioresour. Technol.* **2002**, *83*, 1–11. [CrossRef]
58. Jørgensen, H.; Kristensen, J.B.; Felby, C. Enzymatic conversion of lignocellulose into fermentable sugars: Challenges and opportunities. *Biofuels Bioprod. Biorefining* **2007**, *1*, 119–134. [CrossRef]
59. Zhai, Y.; Li, C.; Xu, G.; Ma, Y.; Liu, X.; Zhang, Y. Depolymerization of lignin via a non-precious Ni–Fe alloy catalyst supported on activated carbon. *Green Chem.* **2017**, *19*, 1895–1903. [CrossRef]
60. Zhang, Z.; Zhao, Z.K. Microwave-assisted conversion of lignocellulosic biomass into furans in ionic liquid. *Bioresour. Technol.* **2010**, *101*, 1111–1114. [CrossRef] [PubMed]
61. vom Stein, T.; Grande, P.M.; Leitner, W.; Domínguez de María, P. Iron-catalyzed furfural production in biobased biphasic systems: From pure sugars to direct use of crude xylose effluents as feedstock. *ChemSusChem* **2011**, *4*, 1592–1594. [CrossRef]
62. Sahu, R.; Dhepe, P.L. A one-pot method for the selective conversion of hemicellulose from crop waste into C5 sugars and furfural by using solid acid catalysts. *ChemSusChem* **2012**, *5*, 751–761. [CrossRef] [PubMed]
63. Adeniyi, O.M.; Azimov, U.; Burluka, A. Algae biofuel: Current status and future applications. *Renew. Sustain. Energy Rev.* **2018**, *90*, 316–335. [CrossRef]
64. Krohn, B.J.; McNeff, C.V.; Yan, B.; Nowlan, D. Production of algae-based biodiesel using the continuous catalytic Mcgyan® process. *Bioresour. Technol.* **2011**, *102*, 94–100. [CrossRef] [PubMed]
65. Halim, R.; Gladman, B.; Danquah, M.K.; Webley, P.A. Oil extraction from microalgae for biodiesel production. *Bioresour. Technol.* **2011**, *102*, 178–185. [CrossRef] [PubMed]
66. Tran, D.-T.; Chen, C.-L.; Chang, J.-S. Effect of solvents and oil content on direct transesterification of wet oil-bearing microalgal biomass of Chlorella vulgaris ESP-31 for biodiesel synthesis using immobilized lipase as the biocatalyst. *Bioresour. Technol.* **2013**, *135*, 213–221. [CrossRef]
67. Kordulis, C.; Bourikas, K.; Gousi, M.; Kordouli, E.; Lycourghiotis, A. Development of nickel based catalysts for the transformation of natural triglycerides and related compounds into green diesel: A critical review. *Appl. Catal. B Environ.* **2016**, *181*, 156–196. [CrossRef]
68. Nakagawa, Y.; Tamura, M.; Tomishige, K. Recent development of production technology of diesel-and jet-fuel-range hydrocarbons from inedible biomass. *Fuel Process. Technol.* **2019**, *193*, 404–422. [CrossRef]
69. Chen, W.-H.; Lin, B.-J.; Huang, M.-Y.; Chang, J.-S. Thermochemical conversion of microalgal biomass into biofuels: A review. *Bioresour. Technol.* **2015**, *184*, 314–327. [CrossRef] [PubMed]
70. Demirbaş, A. Biomass resource facilities and biomass conversion processing for fuels and chemicals. *Energy Convers. Manag.* **2001**, *42*, 1357–1378. [CrossRef]
71. Sipra, A.T.; Gao, N.; Sarwar, H. Municipal solid waste (MSW) pyrolysis for bio-fuel production: A review of effects of MSW components and catalysts. *Fuel Process. Technol.* **2018**, *175*, 131–147. [CrossRef]

72. Li, D.; Koike, M.; Wang, L.; Nakagawa, Y.; Xu, Y.; Tomishige, K. Regenerability of hydrotalcite-derived nickel–iron alloy nanoparticles for syngas production from biomass tar. *ChemSusChem* **2014**, *7*, 510–522. [CrossRef]
73. Chen, X.; Che, Q.; Li, S.; Liu, Z.; Yang, H.; Chen, Y.; Wang, X.; Shao, J.; Chen, H. Recent developments in lignocellulosic biomass catalytic fast pyrolysis: Strategies for the optimization of bio-oil quality and yield. *Fuel Process. Technol.* **2019**, *196*, 106180. [CrossRef]
74. Alonso, D.M.; Wettstein, S.G.; Dumesic, J.A. Bimetallic catalysts for upgrading of biomass to fuels and chemicals. *Chem. Soc. Rev.* **2012**, *41*, 8075–8098. [CrossRef] [PubMed]
75. Zacher, A.H.; Olarte, M.V.; Santosa, D.M.; Elliott, D.C.; Jones, S.B. A review and perspective of recent bio-oil hydrotreating research. *Green Chem.* **2014**, *16*, 491–515. [CrossRef]
76. Kuhl, K.P.; Hatsukade, T.; Cave, E.R.; Abram, D.N.; Kibsgaard, J.; Jaramillo, T.F. Electrocatalytic conversion of carbon dioxide to methane and methanol on transition metal surfaces. *J. Am. Chem. Soc.* **2014**, *136*, 14107–14113. [CrossRef]
77. Saidi, M.; Samimi, F.; Karimipourfard, D.; Nimmanwudipong, T.; Gates, B.C.; Rahimpour, M.R. Upgrading of lignin-derived bio-oils by catalytic hydrodeoxygenation. *Energy Environ. Sci.* **2014**, *7*, 103–129. [CrossRef]
78. Cheng, S.; Wei, L.; Julson, J.; Rabnawaz, M. Upgrading pyrolysis bio-oil through hydrodeoxygenation (HDO) using non-sulfided Fe-Co/SiO_2 catalyst. *Energy Convers. Manag.* **2017**, *150*, 331–342. [CrossRef]
79. Chen, S.; Zhou, G.; Miao, C. Green and renewable bio-diesel produce from oil hydrodeoxygenation: Strategies for catalyst development and mechanism. *Renew. Sustain. Energy Rev.* **2019**, *101*, 568–589. [CrossRef]
80. Bu, Q.; Lei, H.; Zacher, A.H.; Wang, L.; Ren, S.; Liang, J.; Wei, Y.; Liu, Y.; Tang, J.; Zhang, Q. A review of catalytic hydrodeoxygenation of lignin-derived phenols from biomass pyrolysis. *Bioresour. Technol.* **2012**, *124*, 470–477. [CrossRef] [PubMed]
81. Van den Bosch, S.; Schutyser, W.; Vanholme, R.; Driessen, T.; Koelewijn, S.-F.; Renders, T.; De Meester, B.; Huijgen, W.; Dehaen, W.; Courtin, C. Reductive lignocellulose fractionation into soluble lignin-derived phenolic monomers and dimers and processable carbohydrate pulps. *Energy Environ. Sci.* **2015**, *8*, 1748–1763. [CrossRef]
82. Xu, C.; Paone, E.; Rodríguez-Padrón, D.; Luque, R.; Mauriello, F. Recent catalytic routes for the preparation and the upgrading of biomass derived furfural and 5-hydroxymethylfurfural. *Chem. Soc. Rev.* **2020**, *49*, 4273–4306. [CrossRef] [PubMed]
83. Su, B.; Cao, Z.-C.; Shi, Z.-J. Exploration of earth-abundant transition metals (Fe, Co, and Ni) as catalysts in unreactive chemical bond activations. *Acc. Chem. Res.* **2015**, *48*, 886–896. [CrossRef]
84. Kamaruzaman, M.F.; Taufiq-Yap, Y.H.; Derawi, D. Green diesel production from palm fatty acid distillate over SBA-15-supported nickel, cobalt, and nickel/cobalt catalysts. *Biomass Bioenergy* **2020**, *134*, 105476. [CrossRef]
85. Gutierrez, A.; Kaila, R.K.; Honkela, M.L.; Slioor, R.; Krause, A.O.I. Hydrodeoxygenation of guaiacol on noble metal catalysts. *Catal. Today* **2009**, *147*, 239–246. [CrossRef]
86. Guczi, L. Bimetallic nano-particles: Featuring structure and reactivity. *Catal. Today* **2005**, *101*, 53–64. [CrossRef]
87. Bjelić, A.; Grilc, M.; Huš, M.; Likozar, B. Hydrogenation and hydrodeoxygenation of aromatic lignin monomers over Cu/C, Ni/C, Pd/C, Pt/C, Rh/C and Ru/C catalysts: Mechanisms, reaction micro-kinetic modelling and quantitative structure-activity relationships. *Chem. Eng. J.* **2019**, *359*, 305–320. [CrossRef]
88. Zhang, Q.; Kang, J.; Wang, Y. Development of novel catalysts for Fischer–Tropsch synthesis: Tuning the product selectivity. *ChemCatChem* **2010**, *2*, 1030–1058. [CrossRef]
89. Zhou, W.; Cheng, K.; Kang, J.; Zhou, C.; Subramanian, V.; Zhang, Q.; Wang, Y. New horizon in C1 chemistry: Breaking the selectivity limitation in transformation of syngas and hydrogenation of CO_2 into hydrocarbon chemicals and fuels. *Chem. Soc. Rev.* **2019**, *48*, 3193–3228. [CrossRef] [PubMed]
90. Jiao, F.; Li, J.; Pan, X.; Xiao, J.; Li, H.; Ma, H.; Wei, M.; Pan, Y.; Zhou, Z.; Li, M. Selective conversion of syngas to light olefins. *Science* **2016**, *351*, 1065–1068. [CrossRef]
91. Aida, T.M.; Tajima, K.; Watanabe, M.; Saito, Y.; Kuroda, K.; Nonaka, T.; Hattori, H.; Smith, R.L., Jr.; Arai, K. Reactions of d-fructose in water at temperatures up to 400 C and pressures up to 100 MPa. *J. Supercrit. Fluids* **2007**, *42*, 110–119. [CrossRef]
92. Ding, M. Syngas Conversion to Lower Olefins via Facet Regulating. *Prog. Chem.* **2017**, *29*, 5.
93. Porosoff, M.D.; Yan, B.; Chen, J.G. Catalytic reduction of CO_2 by H_2 for synthesis of CO, methanol and hydrocarbons: Challenges and opportunities. *Energy Environ. Sci.* **2016**, *9*, 62–73. [CrossRef]
94. Santos, V.P.; Wezendonk, T.A.; Jaén, J.J.D.; Dugulan, A.I.; Nasalevich, M.A.; Islam, H.-U.; Chojecki, A.; Sartipi, S.; Sun, X.; Hakeem, A.A. Metal organic framework-mediated synthesis of highly active and stable Fischer-Tropsch catalysts. *Nat. Commun.* **2015**, *6*, 6451. [CrossRef]
95. Abelló, S.; Montané, D. Exploring iron-based multifunctional catalysts for Fischer–Tropsch synthesis: A review. *ChemSusChem* **2011**, *4*, 1538–1556. [CrossRef] [PubMed]
96. Abdulrasheed, A.; Jalil, A.A.; Gambo, Y.; Ibrahim, M.; Hambali, H.U.; Hamid, M.Y.S. A review on catalyst development for dry reforming of methane to syngas: Recent advances. *Renew. Sustain. Energy Rev.* **2019**, *108*, 175–193. [CrossRef]

97. Jeske, K.; Kizilkaya, A.C.; López-Luque, I.; Pfänder, N.; Bartsch, M.; Concepción, P.; Prieto, G. Design of cobalt Fischer–Tropsch catalysts for the combined production of liquid fuels and olefin chemicals from hydrogen-rich syngas. *ACS Catal.* **2021**, *11*, 4784–4798. [CrossRef] [PubMed]
98. Willis, J.J.; Goodman, E.D.; Wu, L.; Riscoe, A.R.; Martins, P.; Tassone, C.J.; Cargnello, M. Systematic identification of promoters for methane oxidation catalysts using size-and composition-controlled Pd-based bimetallic nanocrystals. *J. Am. Chem. Soc.* **2017**, *139*, 11989–11997. [CrossRef]
99. Huber, G.W.; Dumesic, J.A. An overview of aqueous-phase catalytic processes for production of hydrogen and alkanes in a biorefinery. *Catal. Today* **2006**, *111*, 119–132. [CrossRef]
100. Coronado, I.; Stekrova, M.; Reinikainen, M.; Simell, P.; Lefferts, L.; Lehtonen, J. A review of catalytic aqueous-phase reforming of oxygenated hydrocarbons derived from biorefinery water fractions. *Int. J. Hydrogen Energy* **2016**, *41*, 11003–11032. [CrossRef]
101. Maris, E.P.; Davis, R.J. Hydrogenolysis of glycerol over carbon-supported Ru and Pt catalysts. *J. Catal.* **2007**, *249*, 328–337. [CrossRef]
102. Chang, A.C.-C.; Louh, R.; Wong, D.; Tseng, J.; Lee, Y. Hydrogen production by aqueous-phase biomass reforming over carbon textile supported Pt–Ru bimetallic catalysts. *Int. J. Hydrogen Energy* **2011**, *36*, 8794–8799. [CrossRef]
103. Bian, Z.; Das, S.; Wai, M.H.; Hongmanorom, P.; Kawi, S. A review on bimetallic nickel-based catalysts for CO_2 reforming of methane. *ChemPhysChem* **2017**, *18*, 3117–3134. [CrossRef] [PubMed]
104. Reynoso, A.; Ayastuy, J.; Iriarte-Velasco, U.; Gutiérrez-Ortiz, M. Cobalt aluminate spinel-derived catalysts for glycerol aqueous phase reforming. *Appl. Catal. B Environ.* **2018**, *239*, 86–101. [CrossRef]
105. Fasolini, A.; Cucciniello, R.; Paone, E.; Mauriello, F.; Tabanelli, T. A short overview on the hydrogen production via aqueous phase reforming (APR) of cellulose, C6-C5 sugars and polyols. *Catalysts* **2019**, *9*, 917. [CrossRef]
106. Bion, N.; Duprez, D.; Epron, F. Design of nanocatalysts for green hydrogen production from bioethanol. *ChemSusChem* **2012**, *5*, 76–84. [CrossRef] [PubMed]
107. Ross, M.B.; Dinh, C.T.; Li, Y.; Kim, D.; De Luna, P.; Sargent, E.H.; Yang, P. Tunable Cu enrichment enables designer syngas electrosynthesis from CO_2. *J. Am. Chem. Soc.* **2017**, *139*, 9359–9363. [CrossRef] [PubMed]
108. Coronado, I.; Stekrova, M.; Moreno, L.G.; Reinikainen, M.; Simell, P.; Karinen, R.; Lehtonen, J. Aqueous-phase reforming of methanol over nickel-based catalysts for hydrogen production. *Biomass Bioenergy* **2017**, *106*, 29–37. [CrossRef]
109. Davda, R.; Shabaker, J.; Huber, G.; Cortright, R.; Dumesic, J.A. A review of catalytic issues and process conditions for renewable hydrogen and alkanes by aqueous-phase reforming of oxygenated hydrocarbons over supported metal catalysts. *Appl. Catal. B Environ.* **2005**, *56*, 171–186. [CrossRef]
110. Vaidya, P.D.; Lopez-Sanchez, J.A. Review of hydrogen production by catalytic aqueous-phase reforming. *ChemistrySelect* **2017**, *2*, 6563–6576. [CrossRef]
111. Ma, Z.; Troussard, E.; Van Bokhoven, J.A. Controlling the selectivity to chemicals from lignin via catalytic fast pyrolysis. *Appl. Catal. A Gen.* **2012**, *423*, 130–136. [CrossRef]
112. French, R.; Czernik, S. Catalytic pyrolysis of biomass for biofuels production. *Fuel Process. Technol.* **2010**, *91*, 25–32. [CrossRef]
113. Sankaranarayanan, T.M.; Berenguer, A.; Ochoa-Hernández, C.; Moreno, I.; Jana, P.; Coronado, J.M.; Serrano, D.P.; Pizarro, P. Hydrodeoxygenation of anisole as bio-oil model compound over supported Ni and Co catalysts: Effect of metal and support properties. *Catal. Today* **2015**, *243*, 163–172. [CrossRef]
114. Mortensen, P.M.; Grunwaldt, J.-D.; Jensen, P.A.; Jensen, A.D. Screening of catalysts for hydrodeoxygenation of phenol as a model compound for bio-oil. *ACS Catal.* **2013**, *3*, 1774–1785. [CrossRef]
115. Santillan-Jimenez, E.; Morgan, T.; Lacny, J.; Mohapatra, S.; Crocker, M. Catalytic deoxygenation of triglycerides and fatty acids to hydrocarbons over carbon-supported nickel. *Fuel* **2013**, *103*, 1010–1017. [CrossRef]
116. Yang, M.; Liu, J.; Lee, S.; Zugic, B.; Huang, J.; Allard, L.F.; Flytzani-Stephanopoulos, M. A common single-site Pt (II)–O (OH) x–species stabilized by sodium on "active" and "inert" supports catalyzes the water-gas shift reaction. *J. Am. Chem. Soc.* **2015**, *137*, 3470–3473. [CrossRef] [PubMed]
117. Dahiya, S.; Kumar, A.N.; Sravan, J.S.; Chatterjee, S.; Sarkar, O.; Mohan, S.V. Food waste biorefinery: Sustainable strategy for circular bioeconomy. *Bioresour. Technol.* **2018**, *248*, 2–12. [CrossRef] [PubMed]
118. Liu, C.; Wang, H.; Karim, A.M.; Sun, J.; Wang, Y. Catalytic fast pyrolysis of lignocellulosic biomass. *Chem. Soc. Rev.* **2014**, *43*, 7594–7623. [CrossRef]
119. Bridgwater, A. Production of high grade fuels and chemicals from catalytic pyrolysis of biomass. *Catal. Today* **1996**, *29*, 285–295. [CrossRef]
120. Chew, T.L.; Bhatia, S. Catalytic processes towards the production of biofuels in a palm oil and oil palm biomass-based biorefinery. *Bioresour. Technol.* **2008**, *99*, 7911–7922. [CrossRef] [PubMed]
121. Li, H.; Fang, Z.; Smith, R.L., Jr.; Yang, S. Efficient valorization of biomass to biofuels with bifunctional solid catalytic materials. *Prog. Energy Combust. Sci.* **2016**, *55*, 98–194.

122. Wen, Y.; Wei, Z.; Ma, C.; Xing, X.; Li, Z.; Luo, D. MXene boosted CoNi-ZIF-67 as highly efficient electrocatalysts for oxygen evolution. *Nanomaterials* **2019**, *9*, 775. [CrossRef] [PubMed]
123. Geilen, F.M.; Engendahl, B.; Harwardt, A.; Marquardt, W.; Klankermayer, J.; Leitner, W. Selective and flexible transformation of biomass-derived platform chemicals by a multifunctional catalytic system. *Angew. Chem.* **2010**, *32*, 5642–5646. [CrossRef]
124. Isikgor, F.H.; Becer, C.R. Lignocellulosic biomass: A sustainable platform for the production of bio-based chemicals and polymers. *Polym. Chem.* **2015**, *6*, 4497–4559. [CrossRef]
125. Sitthisa, S.; Resasco, D.E. Hydrodeoxygenation of furfural over supported metal catalysts: A comparative study of Cu, Pd and Ni. *Catal. Lett.* **2011**, *141*, 784–791. [CrossRef]
126. Cao, W.; Luo, W.; Ge, H.; Su, Y.; Wang, A.; Zhang, T. UiO-66 derived Ru/ZrO 2@ C as a highly stable catalyst for hydrogenation of levulinic acid to γ-valerolactone. *Green Chem.* **2017**, *19*, 2201–2211. [CrossRef]
127. Liang, B.; Ma, J.; Su, X.; Yang, C.; Duan, H.; Zhou, H.; Deng, S.; Li, L.; Huang, Y. Investigation on deactivation of Cu/ZnO/Al_2O_3 catalyst for CO_2 hydrogenation to methanol. *Ind. Eng. Chem. Res.* **2019**, *58*, 9030–9037. [CrossRef]
128. Geilen, F.M.; Engendahl, B.; Hölscher, M.; Klankermayer, J.r.; Leitner, W. Selective homogeneous hydrogenation of biogenic carboxylic acids with [Ru (TriPhos) H]+: A mechanistic study. *J. Am. Chem. Soc.* **2011**, *133*, 14349–14358. [CrossRef]
129. McDonald, R.I.; Liu, G.; Stahl, S.S. Palladium (II)-catalyzed alkene functionalization via nucleopalladation: Stereochemical pathways and enantioselective catalytic applications. *Chem. Rev.* **2011**, *111*, 2981–3019. [CrossRef]
130. Miyazawa, T.; Kusunoki, Y.; Kunimori, K.; Tomishige, K. Glycerol conversion in the aqueous solution under hydrogen over Ru/C+ an ion-exchange resin and its reaction mechanism. *J. Catal.* **2006**, *240*, 213–221. [CrossRef]
131. Alamillo, R.; Tucker, M.; Chia, M.; Pagán-Torres, Y.; Dumesic, J. The selective hydrogenation of biomass-derived 5-hydroxymethylfurfural using heterogeneous catalysts. *Green Chem.* **2012**, *14*, 1413–1419. [CrossRef]
132. Minh, D.P.; Besson, M.; Pinel, C.; Fuertes, P.; Petitjean, C. Aqueous-phase hydrogenation of biomass-based succinic acid to 1, 4-butanediol over supported bimetallic catalysts. *Top. Catal.* **2010**, *53*, 1270–1273. [CrossRef]
133. Wan, X.; Zhou, C.; Chen, J.; Deng, W.; Zhang, Q.; Yang, Y.; Wang, Y. Base-free aerobic oxidation of 5-hydroxymethyl-furfural to 2, 5-furandicarboxylic acid in water catalyzed by functionalized carbon nanotube-supported Au–Pd alloy nanoparticles. *ACS Catal.* **2014**, *4*, 2175–2185. [CrossRef]
134. Nikolla, E.; Román-Leshkov, Y.; Moliner, M.; Davis, M.E. "One-pot" synthesis of 5-(hydroxymethyl) furfural from carbohydrates using tin-beta zeolite. *ACS Catal.* **2011**, *1*, 408–410. [CrossRef]
135. Li, L.; Ding, J.; Jiang, J.-G.; Zhu, Z.; Wu, P. One-pot synthesis of 5-hydroxymethylfurfural from glucose using bifunctional [Sn, Al]-Beta catalysts. *Chin. J. Catal.* **2015**, *36*, 820–828. [CrossRef]
136. Dutta, S.; De, S.; Saha, B.; Alam, M.I. Advances in conversion of hemicellulosic biomass to furfural and upgrading to biofuels. *Catal. Sci. Technol.* **2012**, *2*, 2025–2036. [CrossRef]
137. Cai, C.M.; Nagane, N.; Kumar, R.; Wyman, C.E. Coupling metal halides with a co-solvent to produce furfural and 5-HMF at high yields directly from lignocellulosic biomass as an integrated biofuels strategy. *Green Chem.* **2014**, *16*, 3819–3829. [CrossRef]
138. Torres Galvis, H.M.; de Jong, K.P. Catalysts for Production of Lower Olefins from Synthesis Gas: A Review. *ACS Catal.* **2013**, *3*, 2130–2149. [CrossRef]
139. Zacharopoulou, V.; Lemonidou, A.A. Olefins from Biomass Intermediates: A Review. *Catalysts* **2018**, *8*, 2. [CrossRef]
140. Wang, H.; Ruan, H.; Feng, M.; Qin, Y.; Job, H.; Luo, L.; Wang, C.; Engelhard, M.H.; Kuhn, E.; Chen, X. One-pot process for hydrodeoxygenation of lignin to alkanes using Ru-based bimetallic and bifunctional catalysts supported on zeolite Y. *ChemSusChem* **2017**, *10*, 1846–1856. [CrossRef] [PubMed]
141. Wang, Y.; Tan, L.; Tan, M.; Zhang, P.; Fang, Y.; Yoneyama, Y.; Yang, G.; Tsubaki, N. Rationally designing bifunctional catalysts as an efficient strategy to boost CO_2 hydrogenation producing value-added aromatics. *ACS Catal.* **2018**, *9*, 895–901. [CrossRef]
142. Asgher, M.; Qamar, S.A.; Bilal, M.; Iqbal, H.M. Bio-based active food packaging materials: Sustainable alternative to conventional petrochemical-based packaging materials. *Food Res. Int.* **2020**, *137*, 109625. [CrossRef]
143. Borghs, J.C.; Lebedev, Y.; Rueping, M.; El-Sepelgy, O. Sustainable manganese-catalyzed solvent-free synthesis of pyrroles from 1, 4-diols and primary amines. *Org. Lett.* **2018**, *21*, 70–74. [CrossRef] [PubMed]
144. Xin, J.; Zhang, S.; Yan, D.; Ayodele, O.; Lu, X.; Wang, J. Formation of C–C bonds for the production of bio-alkanes under mild conditions. *Green Chem.* **2014**, *16*, 3589–3595. [CrossRef]
145. Zhang, X.; Cui, G.; Feng, H.; Chen, L.; Wang, H.; Wang, B.; Zhang, X.; Zheng, L.; Hong, S.; Wei, M. Platinum–copper single atom alloy catalysts with high performance towards glycerol hydrogenolysis. *Nat. Commun.* **2019**, *10*, 5812. [CrossRef] [PubMed]
146. Ai, L.; Jiang, J. Catalytic reduction of 4-nitrophenol by silver nanoparticles stabilized on environmentally benign macroscopic biopolymer hydrogel. *Bioresour. Technol.* **2013**, *132*, 374–377. [CrossRef] [PubMed]
147. Koopman, F.; Wierckx, N.; de Winde, J.H.; Ruijssenaars, H.J. Efficient whole-cell biotransformation of 5-(hydroxymethyl) furfural into FDCA, 2, 5-furandicarboxylic acid. *Bioresour. Technol.* **2010**, *101*, 6291–6296. [CrossRef]
148. Villa, A.; Schiavoni, M.; Campisi, S.; Veith, G.M.; Prati, L. Pd-modified Au on carbon as an effective and durable catalyst for the direct oxidation of HMF to 2, 5-furandicarboxylic acid. *ChemSusChem* **2013**, *6*, 609–612. [CrossRef]

149. Castro-Aguirre, E.; Iniguez-Franco, F.; Samsudin, H.; Fang, X.; Auras, R. Poly (lactic acid)—Mass production, processing, industrial applications, and end of life. *Adv. Drug Deliv. Rev.* **2016**, *107*, 333–366. [CrossRef] [PubMed]
150. Karamanlioglu, M.; Preziosi, R.; Robson, G.D. Abiotic and biotic environmental degradation of the bioplastic polymer poly (lactic acid): A review. *Polym. Degrad. Stab.* **2017**, *137*, 122–130. [CrossRef]
151. Nagarajan, V.; Mohanty, A.K.; Misra, M. Perspective on polylactic acid (PLA) based sustainable materials for durable applications: Focus on toughness and heat resistance. *ACS Sustain. Chem. Eng.* **2016**, *4*, 2899–2916. [CrossRef]
152. Czernik, S.; Evans, R.; French, R. Hydrogen from biomass-production by steam reforming of biomass pyrolysis oil. *Catal. Today* **2007**, *129*, 265–268. [CrossRef]
153. Wang, T.; Xie, H.; Chen, M.; D'Aloia, A.; Cho, J.; Wu, G.; Li, Q. Precious metal-free approach to hydrogen electrocatalysis for energy conversion: From mechanism understanding to catalyst design. *Nano Energy* **2017**, *42*, 69–89. [CrossRef]
154. Gong, M.; Wang, D.-Y.; Chen, C.-C.; Hwang, B.-J.; Dai, H. A mini review on nickel-based electrocatalysts for alkaline hydrogen evolution reaction. *Nano Res.* **2016**, *9*, 28–46. [CrossRef]
155. Shi, Q.; Zhu, C.; Du, D.; Lin, Y. Robust noble metal-based electrocatalysts for oxygen evolution reaction. *Chem. Soc. Rev.* **2019**, *48*, 3181–3192. [CrossRef] [PubMed]
156. Callejas, J.F.; Read, C.G.; Roske, C.W.; Lewis, N.S.; Schaak, R.E. Synthesis, characterization, and properties of metal phosphide catalysts for the hydrogen-evolution reaction. *Chem. Mater.* **2016**, *28*, 6017–6044. [CrossRef]
157. Sun, H.; Tian, C.; Fan, G.; Qi, J.; Liu, Z.; Yan, Z.; Cheng, F.; Chen, J.; Li, C.P.; Du, M. Boosting activity on Co4N porous nanosheet by coupling CeO_4 for efficient electrochemical overall water splitting at high current densities. *Adv. Funct. Mater.* **2020**, *30*, 1910596. [CrossRef]
158. Molino, A.; Chianese, S.; Musmarra, D. Biomass gasification technology: The state of the art overview. *J. Energy Chem.* **2016**, *25*, 10–25. [CrossRef]
159. Yao, D.; Yang, H.; Chen, H.; Williams, P.T. Investigation of nickel-impregnated zeolite catalysts for hydrogen/syngas production from the catalytic reforming of waste polyethylene. *Appl. Catal. B Environ.* **2018**, *227*, 477–487. [CrossRef]
160. Zhu, M.; Wachs, I.E. Iron-based catalysts for the high-temperature water–gas shift (HT-WGS) reaction: A review. *ACS Catal.* **2016**, *6*, 722–732. [CrossRef]
161. Gao, Y.; Jiang, J.; Meng, Y.; Yan, F.; Aihemaiti, A. A review of recent developments in hydrogen production via biogas dry reforming. *Energy Convers. Manag.* **2018**, *171*, 133–155. [CrossRef]
162. Florin, N.H.; Harris, A.T. Enhanced hydrogen production from biomass with in situ carbon dioxide capture using calcium oxide sorbents. *Chem. Eng. Sci.* **2008**, *63*, 287–316. [CrossRef]
163. Chaplin, B.P.; Shapley, J.R.; Werth, C.J. Regeneration of sulfur-fouled bimetallic Pd-based catalysts. *Environ. Sci. Technol.* **2007**, *41*, 5491–5497. [CrossRef] [PubMed]
164. Chng, L.L.; Erathodiyil, N.; Ying, J.Y. Nanostructured catalysts for organic transformations. *Acc. Chem. Res.* **2013**, *46*, 1825–1837. [CrossRef]
165. Bridgwater, A. The technical and economic feasibility of biomass gasification for power generation. *Fuel* **1995**, *74*, 631–653. [CrossRef]
166. Rentizelas, A.A.; Tolis, A.J.; Tatsiopoulos, I.P. Logistics issues of biomass: The storage problem and the multi-biomass supply chain. *Renew. Sustain. Energy Rev.* **2009**, *13*, 887–894. [CrossRef]
167. Chuah, L.F.; Klemeš, J.J.; Yusup, S.; Bokhari, A.; Akbar, M.M. A review of cleaner intensification technologies in biodiesel production. *J. Clean. Prod.* **2017**, *146*, 181–193. [CrossRef]
168. Iris, K.; Tsang, D.C. Conversion of biomass to hydroxymethylfurfural: A review of catalytic systems and underlying mechanisms. *Bioresour. Technol.* **2017**, *238*, 716–732.
169. Wawrzetz, A.; Peng, B.; Hrabar, A.; Jentys, A.; Lemonidou, A.; Lercher, J. Towards understanding the bifunctional hydrodeoxygenation and aqueous phase reforming of glycerol. *J. Catal.* **2010**, *269*, 411–420. [CrossRef]
170. Yan, W.; You, Z.; Meng, K.; Du, F.; Zhang, S.; Jin, X. Cross-metathesis of biomass to olefins: Molecular catalysis bridging the gap between fossil and bio-energy. *Chin. J. Chem. Eng.* **2022**, *48*, 44–60. [CrossRef]
171. Antonio Del, V.; Marc, M. Challenges in biomass valorization by olefin metathesis. *C. R. Chim.* **2024**, *27*, 179–195.
172. Nieres, P.D.; Zelin, J.; Trasarti, A.F.; Apesteguia, C.R. Valorisation of vegetable oils by heterogeneous catalysis via metathesis reactions. *Curr. Opin. Green Sustain. Chem.* **2018**, *10*, 1–5. [CrossRef]
173. Rouen, M.; Queval, P.; Borré, E.; Falivene, L.; Poater, A.; Berthod, M.; Hugues, F.; Cavallo, L.; Baslé, O.; Olivier-Bourbigou, H.; et al. Selective Metathesis of α-Olefins from Bio-Sourced Fischer–Tropsch Feeds. *ACS Catal.* **2016**, *6*, 7970–7976. [CrossRef]
174. Remón, J.; Giménez, J.; Valiente, A.; García, L.; Arauzo, J. Production of gaseous and liquid chemicals by aqueous phase reforming of crude glycerol: Influence of operating conditions on the process. *Energy Convers. Manag.* **2016**, *110*, 90–112. [CrossRef]
175. Singh, A.; Pant, D.; Korres, N.E.; Nizami, A.-S.; Prasad, S.; Murphy, J.D. Key issues in life cycle assessment of ethanol production from lignocellulosic biomass: Challenges and perspectives. *Bioresour. Technol.* **2010**, *101*, 5003–5012. [CrossRef]

176. Osman, A.I.; Mehta, N.; Elgarahy, A.M.; Al-Hinai, A.; Al-Muhtaseb, A.A.H.; Rooney, D.W. Conversion of biomass to biofuels and life cycle assessment: A review. *Environ. Chem. Lett.* **2021**, *19*, 4075–4118. [CrossRef]
177. Ubando, A.T.; Felix, C.B.; Chen, W.-H. Biorefineries in circular bioeconomy: A comprehensive review. *Bioresour. Technol.* **2020**, *299*, 122585. [CrossRef] [PubMed]
178. Sherwood, J. The significance of biomass in a circular economy. *Bioresour. Technol.* **2020**, *300*, 122755. [CrossRef]

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