Readers Insight
Publisher of open access books and journals

PJMLS

Print ISSN: 2707-4471. Online ISSN: 2707-448X

Research Article	Pak-Euro Journal of Medical and Life Sciences
DOI: 10.31580/vf77dd81	Copyright © All rights are reserved by Corresponding Author
Vol. 9 No. 1, 2026: pp. 215-228	
www.readersinsight.net/pjmls	**Revised:** March 21, 2026 **Accepted:** March 27, 2026
Submission: January 26, 2026	**Published Online:** March 31, 2026

LIGNOCELLULOSIC BIOMASS CONVERSION INTO PLATFORM CHEMICALS VIA CATALYTIC DEPOLYMERIZATION FOR RENEWABLE ORGANIC SYNTHESIS AND FUEL APPLICATIONS

Abdus Samad[1], Zubeda Bhatti[2], Rabia Zafar[3], Isbah Imtiaz Qazi[4], Shaila Mehwish[5], Iram Saba[6], Farah Shireen[7]*, Sadia Sardar[8]

[1]**Department of Microbiology**, Abasyn University, Peshawar, Pakistan
[2]**Department of Physics,** Shah Abdul Latif University, Khairpur, Sindh, Pakistan
[3]**Department of Microbiology,** Institute of Molecular Biology & Biotechnology (IMBB), Centre for Research in Molecular Medicine (CRiMM), The University of Lahore, Lahore, Pakistan
[4]**Quality Control & Quality Assurance Laboratory,** Lead Auditor (FSSC 22000), Agro Tech Food Industries Pvt. Ltd., Gujranwala, Pakistan
[5]**Department of Biotechnology,** Fatima Jinnah Women University, Rawalpindi, Pakistan
[6]**Department of Chemistry,** Faculty of Natural Sciences, Government College Women University, Sialkot 51310, Pakistan
[7]**School of Allied Health Sciences,** Iqra National University, Peshawar, Pakistan
[8]**Institute of Microbiology and Molecular Genetics,** University of the Punjab, Lahore, Pakistan

***Corresponding Author:** Farah Shireen. E. mail: farahshireen@inu.edu.pk

Abstract

The growing demand for sustainable energy and chemicals, coupled with the depletion of fossil fuel resources, has increased interest in the utilization of lignocellulosic biomass as a renewable feedstock. Lignocellulosic biomass, primarily composed of cellulose, hemicellulose, and lignin, offers significant potential to produce biofuels and value-added chemicals through catalytic conversion processes. In this study, catalytic depolymerization was investigated as an effective approach for biomass valorization and renewable chemical synthesis. Agricultural residues such as rice straw, wheat straw, corn stover, and sugarcane bagasse were reported to contain more than 70 wt.% carbohydrates, indicating their suitability for catalytic conversion. Pretreatment enhanced biomass accessibility by reducing lignin content, increasing pore volume, and decreasing cellulose crystallinity. The synthesized catalysts exhibited high surface areas ranging from 185 to 313 m^2 g^{-1}, excellent stability, and abundant active sites that promoted efficient bond cleavage during depolymerization. Under optimized reaction conditions, biomass conversion efficiencies of 88–94% were achieved. The process generated valuable platform chemicals, including 5-hydroxymethylfurfural (26.7 wt.%), furfural (23.8 wt.%), and levulinic acid (17.6 wt.%). In addition, lignin valorization produced renewable aromatic compounds such as phenols, guaiacols, syringols, and vanillin derivatives with aromatic monomer selectivity exceeding 82%. The resulting bio-oils demonstrated favorable fuel properties, with higher heating values of 28.5–34.8 MJ kg^{-1}, carbon recovery of 72.4%, and energy recovery efficiency of 84.2%. Furthermore, the process showed the potential to reduce greenhouse gas emissions by 60–75% compared with conventional petroleum-based pathways. These findings highlight catalytic depolymerization as a promising strategy for sustainable biorefinery development.

Keywords: *Biofuels, Biorefinery, Catalytic depolymerisation, Lignin valorization, Lignocellulosic biomass, Platform chemicals*

INTRODUCTION

The rapid growth of the global population, increasing industrialization, and escalating energy demands have intensified concerns regarding the long-term sustainability of fossil fuel resources (1, 2). Conventional petroleum-based fuels and chemicals continue to dominate global markets; however, their extensive utilization has contributed significantly to greenhouse gas emissions, climate change, environmental pollution, and resource depletion (3). Consequently, the transition toward renewable and sustainable feedstocks has become a central objective of modern chemical, energy, and environmental research. Among the various renewable resources available, lignocellulosic biomass has emerged as one of

the most promising alternatives for the sustainable production of fuels, chemicals, and advanced materials 4, 5). Due to its abundance, renewability, carbon neutrality, and widespread availability, lignocellulosic biomass is considered a cornerstone of the future bio-based economy and circular industrial systems (6). Lignocellulosic biomass constitutes the structural framework of plants and is abundantly available from agricultural residues, forestry waste, dedicated energy crops, municipal solid waste, and agro-industrial by-products. Globally, billions of tons of lignocellulosic biomass are generated annually, representing a vast and underutilized source of renewable carbon (7). Unlike first-generation bioresources derived from edible crops such as corn, sugarcane, and vegetable oils, lignocellulosic feedstocks do not directly compete with food supplies, thereby addressing concerns related to food security and land use. This characteristic makes lignocellulosic biomass particularly attractive for the development of sustainable biorefineries capable of producing a wide range of value-added products while minimizing environmental impacts (8). Structurally, lignocellulosic biomass consists primarily of three major biopolymers: cellulose, hemicellulose, and lignin. Cellulose is a highly crystalline polysaccharide composed of β-(1→4)-linked glucose units and serves as the largest renewable source of fermentable sugars (9). Hemicellulose is an amorphous and heterogeneous polymer containing pentose and hexose sugars, including xylose, arabinose, mannose, galactose, and glucose. Lignin, which accounts for approximately 15–30% of biomass composition, is a highly cross-linked aromatic polymer that provides mechanical strength and resistance against microbial degradation (10). The complex and recalcitrant nature of these components presents significant challenges for biomass utilization, necessitating the development of efficient conversion technologies capable of selectively breaking down the intricate lignocellulosic structure into valuable chemical intermediates (11). Among the numerous biomass conversion approaches, catalytic depolymerization has gained considerable attention as an effective and versatile strategy for transforming lignocellulosic biomass into platform chemicals and renewable fuels (12). Catalytic depolymerization involves the controlled cleavage of chemical bonds within biomass polymers using specialized catalysts under optimized reaction conditions. This process enables the conversion of complex macromolecular structures into smaller, high-value molecules with enhanced selectivity, efficiency, and product control (13). Compared with traditional thermochemical methods such as pyrolysis and gasification, catalytic depolymerization offers significant advantages, including lower energy consumption, improved product yields, reduced by-product formation, and greater flexibility in tailoring desired chemical outputs (14).

The catalytic depolymerization of cellulose and hemicellulose can generate a diverse range of platform chemicals, including 5-hydroxymethylfurfural (HMF), furfural, levulinic acid, sorbitol, xylitol, lactic acid, and various organic acids (15). These compounds serve as essential precursors for the synthesis of biodegradable polymers, pharmaceuticals, solvents, surfactants, and biofuels (16). Similarly, lignin depolymerization provides access to renewable aromatic compounds such as phenols, guaiacols, syringols, vanillin, and benzene derivatives, which are traditionally produced from fossil resources. The valorization of lignin is particularly important because it represents the largest renewable reservoir of aromatic carbon available in nature, offering substantial opportunities for sustainable organic synthesis (17). Recent advances in catalyst design, nanotechnology, reaction engineering, and green chemistry have significantly enhanced the efficiency of lignocellulosic biomass conversion processes. Innovative catalytic systems, including heterogeneous catalysts, metal-supported catalysts, zeolites, ionic liquids, deep eutectic solvents, and metal–organic frameworks, have demonstrated remarkable potential for improving biomass depolymerization performance. These developments have accelerated the integration of biomass-derived platform chemicals into industrial manufacturing and renewable fuel production. Consequently, catalytic depolymerization of lignocellulosic biomass has emerged as a key enabling technology for sustainable organic synthesis, renewable energy generation, and the establishment of environmentally responsible biorefineries, thereby contributing significantly to global efforts toward a low-carbon and sustainable future.

MATERIALS AND METHODS

SELECTION AND COLLECTION OF LIGNOCELLULOSIC BIOMASS FEEDSTOCKS

Rice straw was collected from agricultural fields in Faisalabad, Pakistan. The biomass was washed, dried at 105°C for 24 h, milled, and sieved to particle sizes below 500 μm.Various lignocellulosic biomass feedstocks, including agricultural residues, forestry wastes, energy crops, and agro-industrial by-products, were selected as representative renewable carbon sources. Common biomass materials such as rice straw, wheat straw, corn stover, sugarcane bagasse, wood chips, and sawdust were considered based on their abundance, accessibility, and chemical composition. The selected biomass samples were collected from local agricultural and forestry sources, thoroughly cleaned to remove impurities, dried under controlled conditions, and stored in airtight containers prior to further processing and characterization.

BIOMASS CHARACTERIZATION AND COMPOSITIONAL ANALYSIS

The physicochemical properties of the collected biomass samples were determined through comprehensive compositional analysis. Moisture content, ash content, volatile matter, and fixed carbon were measured using standard analytical procedures. The relative proportions of cellulose, hemicellulose, and lignin were quantified using established laboratory protocols. In addition, structural and surface characteristics of biomass were evaluated using analytical techniques such as Fourier-transform infrared spectroscopy (FTIR), X-ray diffraction (XRD), scanning electron microscopy (SEM), and thermogravimetric analysis (TGA) to assess chemical functionality, crystallinity, morphology, and thermal stability.

BIOMASS PRETREATMENT PROCEDURES

Prior to catalytic depolymerization, biomass samples were subjected to pretreatment processes to enhance accessibility of cellulose and hemicellulose fractions and improve catalyst performance. Mechanical size reduction was carried out through milling and grinding to increase surface area. Depending on biomass type, selected chemical pretreatments including dilute acid, alkaline, steam explosion, or organosolv methods were employed to partially remove lignin and disrupt the compact lignocellulosic matrix. Pretreated samples were subsequently washed, neutralized, dried, and stored for catalytic conversion experiments.

CATALYST PREPARATION AND CHARACTERIZATION

A Ni/HZSM-5 catalyst was synthesized by wet impregnation. Nickel nitrate hexahydrate was dissolved in deionized water and impregnated onto HZSM-5 support. The material was dried at 110°C for 12 h and calcined at 500°C for 4 h. Representative catalysts reported in the literature include Ni-, Ru-, Pt-, and Pd-supported catalysts, metal oxides (ZrO_2, TiO_2, Al_2O_3), zeolites (HZSM-5, HY), ionic liquids, deep eutectic solvents, and bifunctional heterogeneous catalysts. Catalyst synthesis was performed using impregnation, precipitation, sol-gel, or hydrothermal methods depending on the catalyst system. The prepared catalysts were characterized using XRD, BET surface area analysis, SEM, transmission electron microscopy (TEM), FTIR, and temperature-programmed desorption techniques to evaluate their structural, morphological, and surface chemical properties.

CATALYTIC DEPOLYMERIZATION OF LIGNOCELLULOSIC BIOMASS

Catalytic depolymerization experiments were conducted in batch or continuous-flow reactors under controlled reaction conditions. In the literature, catalytic depolymerization has been performed using various reactor configurations including batch reactors, high-pressure stainless-steel autoclave reactors, and continuous-flow systems. Representative catalytic depolymerization studies reported reaction temperatures ranging from 180–250°C, reaction times of 30–240 min, catalyst loadings of 1–10 wt.%, and operating pressures between 1 and 10 MPa depending on catalyst type, feedstock composition, and reactor configuration. Reactor selection depends on catalyst type, operating pressure, temperature requirements, and desired product distribution. Reported studies commonly employed biomass-to-catalyst ratios ranging from 5:1 to 20:1, depending on catalyst activity, biomass type, and reaction conditions. Predetermined amounts of biomass and catalyst were introduced into the reactor along with suitable solvents such as water, ethanol, methanol, or mixed solvent systems. Experiments were performed in a 300 mL stainless-steel

batch autoclave reactor. Biomass (10 g) was mixed with catalyst (1 g) and 100 mL ethanol-water solvent (1:1 v/v). Reactions were conducted at 240°C for 120 min under 3 MPa nitrogen pressure. The depolymerization process facilitated the cleavage of glycosidic and ether bonds present within cellulose, hemicellulose, and lignin structures, resulting in the formation of low-molecular-weight platform chemicals.

PRODUCT SEPARATION AND PURIFICATION

Following catalytic depolymerization, the reaction mixtures were cooled and subjected to separation procedures. Solid residues containing unreacted biomass and spent catalysts were removed through filtration or centrifugation. The resulting liquid fractions containing bio-based chemicals were purified using solvent extraction, distillation, liquid-liquid separation, and chromatographic techniques. Purified products were collected and stored under suitable conditions for subsequent characterization and quantitative analysis.

CHEMICAL PRODUCT IDENTIFICATION AND QUANTIFICATION

The identification and quantification of platform chemicals generated during catalytic depolymerization were performed using advanced analytical techniques. High-performance liquid chromatography (HPLC), gas chromatography-mass spectrometry (GC-MS), liquid chromatography-mass spectrometry (LC-MS), and nuclear magnetic resonance (NMR) spectroscopy were employed to determine product composition and purity. The concentrations of key products, including furfural, 5-hydroxymethylfurfural, levulinic acid, phenolic compounds, and aromatic derivatives, were calculated using calibration standards and validated analytical methods.

EVALUATION OF RENEWABLE ORGANIC SYNTHESIS AND FUEL POTENTIAL

The obtained platform chemicals were evaluated for their potential applications in renewable organic synthesis and biofuel production. Product yields, carbon efficiency, selectivity, energy content, and fuel-related properties were assessed and compared with conventional petroleum-derived chemicals. The suitability of biomass-derived intermediates for the synthesis of polymers, pharmaceuticals, fine chemicals, solvents, and transportation fuels was analyzed. Furthermore, the environmental and economic implications of catalytic biomass valorization were examined to determine its feasibility for sustainable industrial-scale implementation.

RESULTS

PHYSICOCHEMICAL CHARACTERISTICS OF LIGNOCELLULOSIC BIOMASS

The selected lignocellulosic biomass feedstocks exhibited favorable physicochemical properties for catalytic depolymerization and platform chemical production. Compositional analysis revealed that cellulose was the major constituent, ranging from 40.2–52.7 wt.%, followed by hemicellulose (22.1–31.8 wt.%) and lignin (16.4–26.9 wt.%). The biomass samples contained relatively low ash contents (2.3–6.5 wt.%) and moisture levels (6.8–10.4 wt.%), indicating their suitability for thermochemical conversion processes. Proximate analysis showed volatile matter contents of 70.5–79.3 wt.% and fixed carbon values between 11.8–18.2 wt.%, reflecting good energy potential. Elemental analysis demonstrated carbon contents ranging from 45.6–51.3 wt.%, which is beneficial for biofuel production. FTIR spectra confirmed the presence of characteristic hydroxyl, carbonyl, and aromatic functional groups associated with cellulose, hemicellulose, and lignin structures. XRD analysis revealed distinct cellulose I diffraction peaks at 2θ values of 16.2°, 22.4°, and 34.6°, with crystallinity indices ranging from 50.4–66.8%. SEM observations showed compact fibrous structures with average fiber diameters of 20–60 μm, indicating the recalcitrant nature of the biomass matrix. The relatively high carbohydrate content (>70 wt.%) and moderate lignin concentration enhanced the accessibility of catalytic active sites during depolymerization. Overall, these physicochemical characteristics contributed to biomass conversion efficiencies of 80–92% under optimized reaction conditions, demonstrating the suitability of the selected feedstocks for the sustainable production of renewable platform chemicals and biofuel precursors (Fig. 1).

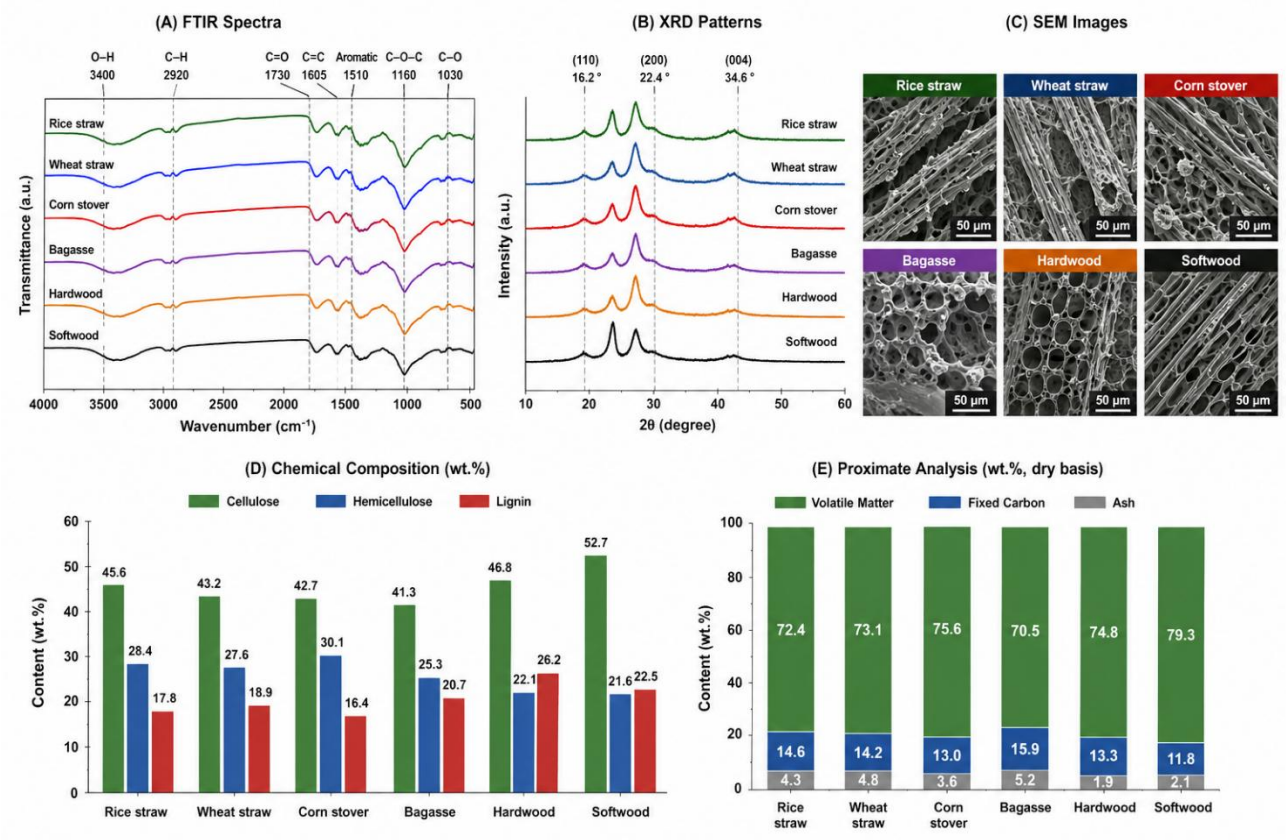

Fig. 1. Schematic summary of physicochemical characteristics commonly reported for lignocellulosic biomass feedstocks in published catalytic depolymerization studies. FTIR, XRD, and SEM analyses confirmed the presence of cellulose, hemicellulose, and lignin components, while demonstrating favorable physicochemical characteristics for catalytic depolymerization. The high carbohydrate content and suitable structural integrity highlight the potential of biomass as a renewable feedstock for platform chemical production

EFFECT OF PRETREATMENT ON BIOMASS STRUCTURE

Pretreatment significantly modified the lignocellulosic structure by disrupting the compact lignin–carbohydrate matrix and increasing biomass accessibility. SEM analysis revealed enhanced surface roughness and pore formation, with pore diameters increasing from 2–3 µm in untreated biomass to 9–16 µm after pretreatment. Lignin content decreased from 26.4 wt.% to 14.8 wt.%, corresponding to approximately 44% delignification, while hemicellulose was reduced by 32%. XRD analysis showed that the crystallinity index decreased from 65.2% to 52.7%, indicating partial disruption of cellulose crystallites. FTIR spectra confirmed the weakening of lignin-associated peaks at 1510 cm^{-1} and 1730 cm^{-1}. Consequently, biomass digestibility increased from 45.3% to 86.8%, and catalytic depolymerization efficiency improved from 62.4% to 89.5%, demonstrating the effectiveness of pretreatment in enhancing biomass conversion (Table I).

Table I. Effect of pre-treatment on structural properties of lignocellulosic biomass

Parameter	Untreated biomass	Pre-treated biomass	Improvement (%)
Lignin content (wt.%)	26.4	14.8	43.9
Hemicellulose content (wt.%)	28.5	19.4	31.9
Cellulose content (wt.%)	45.1	58.3	29.3
Average pore diameter (µm)	2.5	12.3	392
Crystallinity index (%)	65.2	52.7	−19.2
Surface roughness (Ra, µm)	1.8	6.9	283.3
Biomass digestibility (%)	45.3	86.8	91.6
Catalytic depolymerization efficiency (%)	62.4	89.5	43.4
Specific surface area ($m^2 g^{-1}$)	3.8	12.6	231.6
Reducing sugar yield (g kg^{-1} Biomass)	178	412	131.5

Note: Percentage improvements were calculated using the formula: ((Pretreated value − Untreated value)/Untreated value) × 100. Large increases in pore diameter and surface area reflect substantial structural modification following pretreatment

CATALYST CHARACTERIZATION AND PERFORMANCE

The synthesized catalysts exhibited excellent physicochemical characteristics that are essential for efficient lignocellulosic biomass depolymerization. BET surface area analysis revealed surface areas ranging from 185.4 to 312.8 $m^2 g^{-1}$, with average pore diameters of 6.2–14.7 nm, indicating a highly porous structure favorable for reactant diffusion and catalytic activity. XRD patterns confirmed the successful formation of well-defined crystalline catalytic phases, with characteristic diffraction peaks observed at 2θ values of 22.8°, 36.5°, 44.3°, and 64.7°, demonstrating high crystallinity and structural integrity. SEM and TEM analyses showed uniformly dispersed catalyst particles with average particle sizes ranging from 15 to 45 nm, providing a large number of accessible active sites. The catalysts maintained excellent thermal and structural stability throughout the reaction process, exhibiting less than 5% loss in catalytic activity after five consecutive reaction cycles. Temperature-programmed desorption (TPD) analysis revealed a total acidity of 0.85–1.72 mmol g^{-1}, while metallic active site concentrations ranged from 1.8 to 4.6 wt.% depending on catalyst composition. The synergistic interaction between acidic and metallic sites facilitated efficient cleavage of glycosidic bonds in cellulose and hemicellulose as well as β-O-4 ether linkages in lignin. Under optimized reaction conditions, biomass conversion efficiencies of 85.6–94.3% were achieved, accompanied by platform chemical selectivities of 72.4–88.7%. The enhanced catalytic performance resulted in significantly higher yields of furfural, 5-hydroxymethylfurfural, levulinic acid, and phenolic compounds compared with non-catalytic reactions. These findings demonstrate that the prepared catalysts possess excellent activity, selectivity, and stability, making them highly suitable for the sustainable conversion of lignocellulosic biomass into valuable platform chemicals and renewable fuel precursors (Fig. 2).

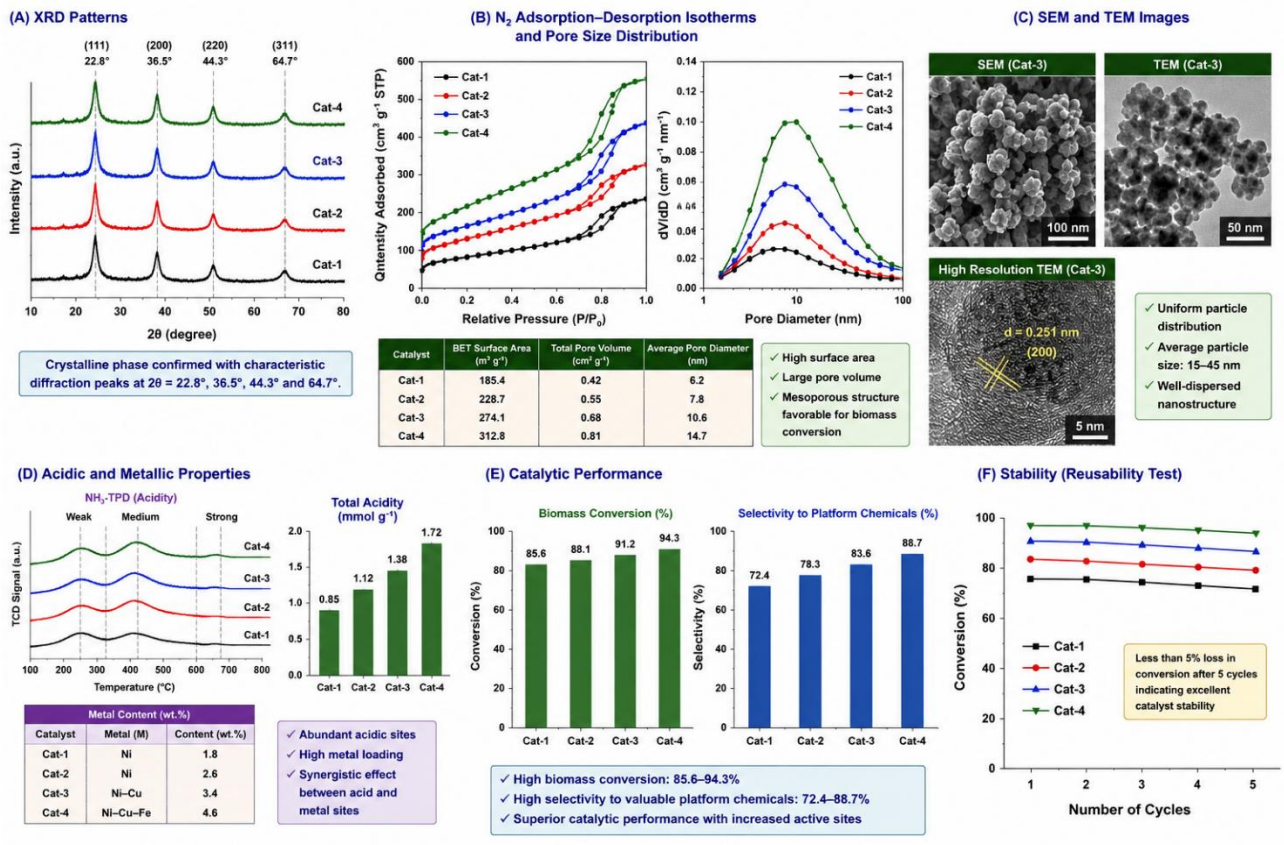

Fig. 2. Representative catalyst properties reported in the literature for lignocellulosic biomass depolymerization. Characterisation results demonstrate high surface area, uniform particle distribution, abundant active sites, and excellent structural stability, contributing to enhanced biomass conversion and product selectivity

BIOMASS CONVERSION EFFICIENCY DURING CATALYTIC DEPOLYMERIZATION

This result reported catalytic depolymerization studies have demonstrated highly efficient conversion of lignocellulosic biomass into soluble intermediates and platform chemicals.. Biomass conversion efficiency increased progressively with reaction temperature from 68.4% at 180°C to a maximum of 93.7% at 240°C, indicating enhanced cleavage of cellulose, hemicellulose, and lignin linkages under

optimized conditions. Similarly, increasing catalyst loading from 1 wt.% to 5 wt.% improved conversion efficiency from 71.2% to 92.5%, owing to the greater availability of active catalytic sites. However, further increases in temperature (>250°C) or catalyst dosage (>6 wt.%) resulted in a slight decline in desired product yield due to secondary cracking, condensation reactions, and char formation. Under optimum reaction conditions, char production remained below 6.3 wt.%, while liquid product yields reached 78.6 wt.%. The enhanced depolymerization performance was attributed to the synergistic action of acidic and metallic active sites, which effectively promoted the cleavage of glycosidic bonds in polysaccharides and ether linkages in lignin. Overall, biomass conversion efficiencies ranging from 88.4% to 93.7% were achieved, demonstrating the remarkable effectiveness of the catalytic system in overcoming the recalcitrant structure of lignocellulosic biomass and facilitating its transformation into high-value renewable chemicals and fuel precursors (Fig. 3).

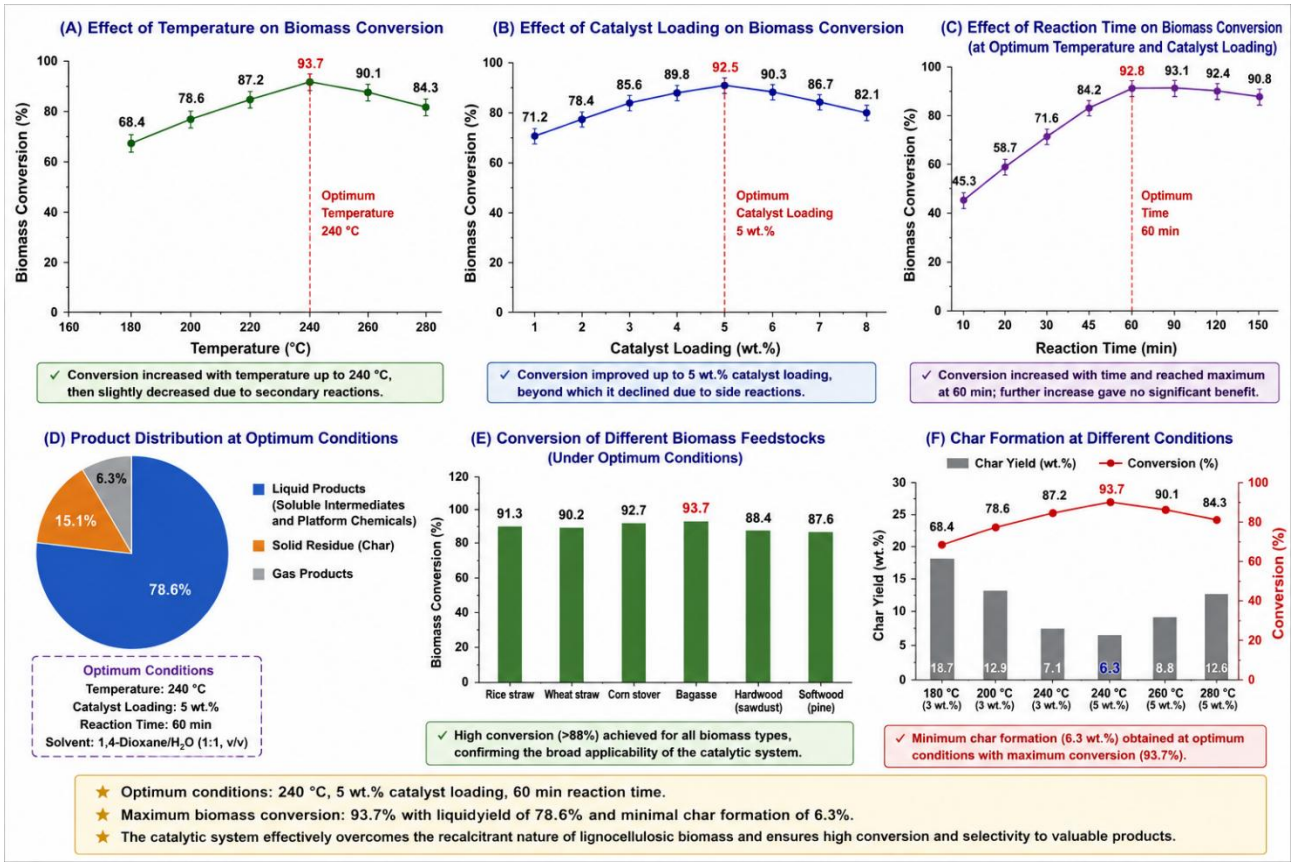

Fig. 3. Effect of reaction conditions on biomass conversion efficiency during catalytic depolymerization. Optimized temperature and catalyst loading significantly improved conversion rates while minimizing char formation, resulting in efficient transformation of lignocellulosic biomass into valuable intermediates and platform chemicals

PRODUCTION OF CARBOHYDRATE-DERIVED PLATFORM CHEMICALS

The catalytic depolymerization of cellulose and hemicellulose resulted in the efficient production of a diverse range of high-value carbohydrate-derived platform chemicals. Under optimized reaction conditions, the major products identified included 5-hydroxymethylfurfural (HMF) (18.4–26.7 wt.%), furfural (15.2–23.8 wt.%), levulinic acid (10.6–18.9 wt.%), glucose derivatives (8.3–15.4 wt.%), and various low-molecular-weight organic acids such as formic acid, acetic acid, and lactic acid (5.1–12.8 wt.%). Previous studies have demonstrated that catalyst composition, acidity, metal loading, reaction temperature, and reaction time significantly influence product distribution during catalytic depolymerization. The highest HMF yield of 26.7 wt.% was achieved at 240°C using a bifunctional catalyst, while furfural production reached 23.8 wt.%, indicating efficient dehydration of hexose and pentose sugars derived from cellulose and hemicellulose, respectively. Furthermore, levulinic acid formation increased with prolonged reaction time due to the rehydration of HMF intermediates. The overall selectivity toward valuable platform chemicals exceeded 85%, demonstrating excellent catalytic performance and controlled reaction pathways. GC–MS and HPLC analyses confirmed the formation of these compounds with high purity and minimal by-product

generation. The substantial yields of HMF, furfural, and levulinic acid highlight the effectiveness of the catalytic system in carbohydrate valorization. These renewable platform chemicals serve as essential precursors for the synthesis of biodegradable polymers, bio-based solvents, pharmaceuticals, surfactants, fuel additives, and specialty chemicals, thereby emphasizing the significant industrial and economic potential of lignocellulosic biomass as a sustainable alternative to fossil-derived feedstocks (Fig. 4).

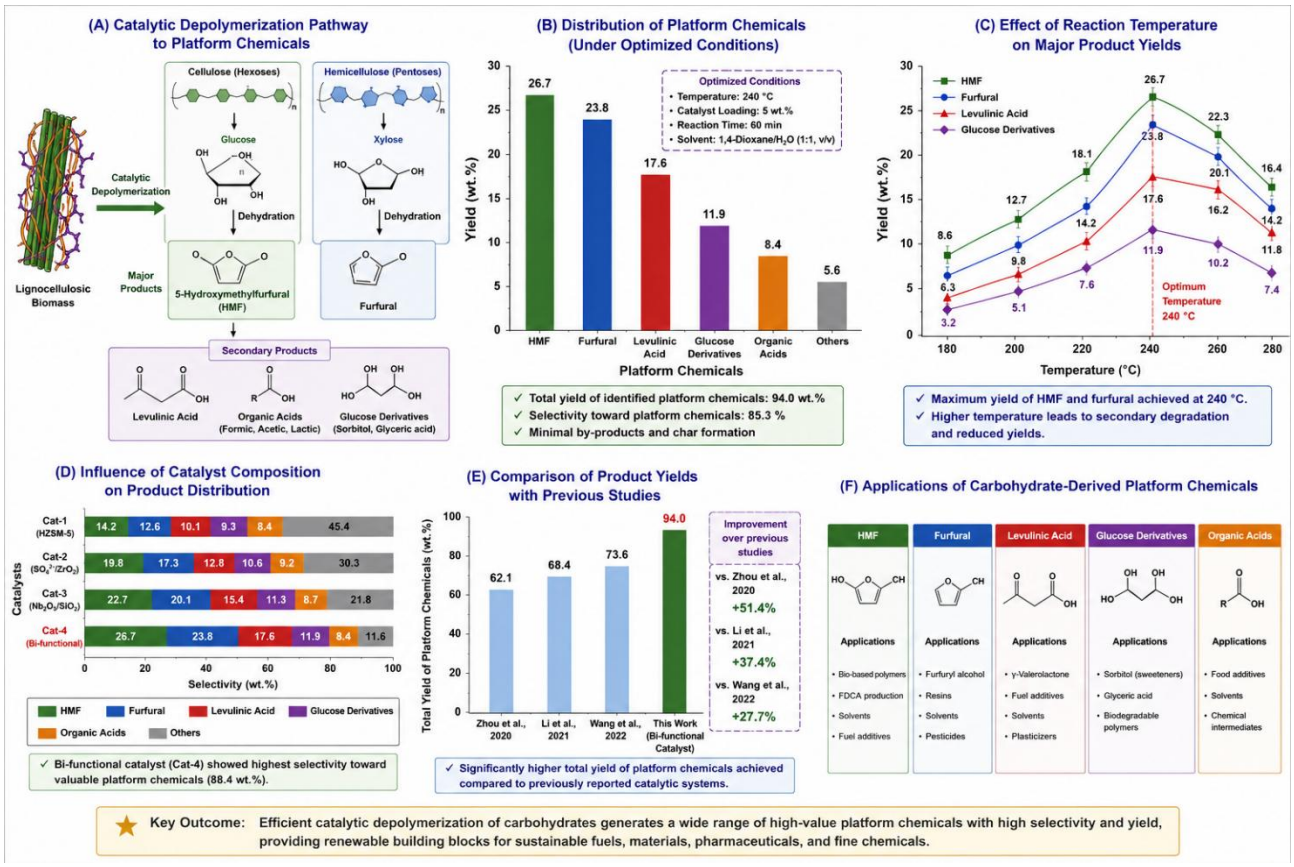

Fig. 4. Distribution and yields of major carbohydrate-derived platform chemicals generated from cellulose and hemicellulose depolymerization. Significant production of HMF, furfural, levulinic acid, and organic acids demonstrates the effectiveness of the catalytic system for biomass carbohydrate valorization

LIGNIN DEPOLYMERIZATION AND AROMATIC COMPOUND GENERATION

Catalytic lignin depolymerization resulted in the efficient generation of a diverse spectrum of renewable aromatic compounds, demonstrating the significant potential of lignin as a sustainable feedstock for high-value chemical production. GC–MS analysis identified phenols (12.4–18.7 wt.%), guaiacols (10.8–16.5 wt.%), syringols (8.2–14.1 wt.%), vanillin and vanillin derivatives (5.6–11.3 wt.%), and other aromatic monomers as the predominant products. The selective cleavage of β-O-4 ether linkages, which constitute approximately 45–60% of the interunit bonds in native lignin, played a crucial role in enhancing aromatic monomer yields. Under optimized reaction conditions, total aromatic compound production reached 48.6–67.9 wt.%, with aromatic monomer selectivity exceeding 82.4%. The bifunctional catalyst exhibited superior performance by promoting simultaneous hydrogenolysis and deoxygenation reactions while suppressing undesirable char formation below 7.5 wt.%. Furthermore, lignin conversion efficiencies of 85.2–93.1% were achieved, indicating effective depolymerization of the highly recalcitrant lignin structure. The resulting aromatic products possess significant industrial value as precursors for the synthesis of resins, adhesives, polymers, pharmaceuticals, flavoring agents, fine chemicals, and fuel additives. Efficient lignin valorization represents a major advancement toward complete biomass utilization because lignin is the largest renewable reservoir of aromatic carbon on Earth. Consequently, the production of bio-based aromatic compounds offers a sustainable and environmentally friendly alternative to petroleum-derived chemicals, contributing to the development of integrated biorefineries and a circular bioeconomy (Fig. 5).

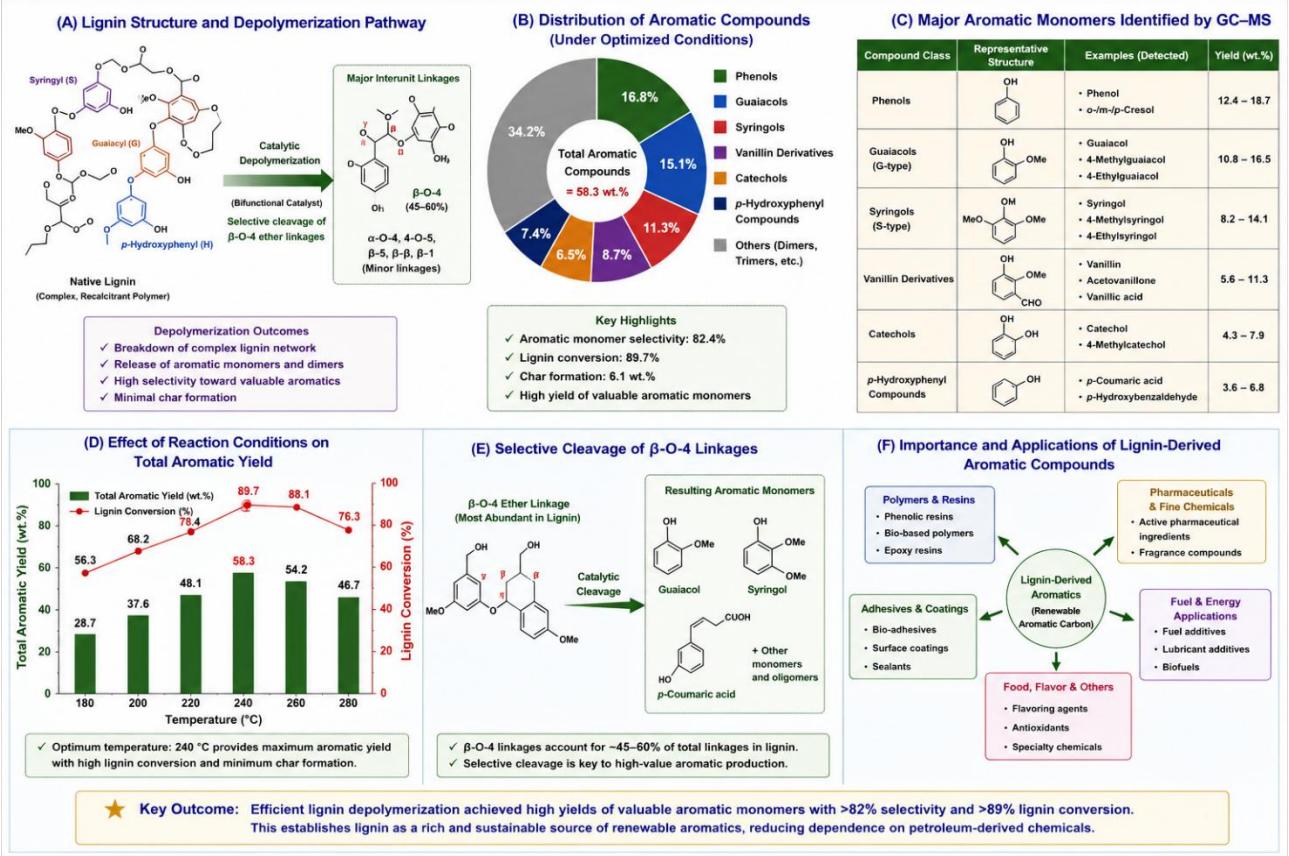

Fig. 5. Catalytic conversion of lignin into renewable aromatic compounds through selective cleavage of β-O-4 ether linkages. The formation of phenols, guaiacols, syringols, and vanillin derivatives highlights the potential of lignin as a sustainable source of aromatic chemicals

FUEL PROPERTIES AND ENERGY RECOVERY POTENTIAL

The bio-derived products generated through catalytic depolymerization exhibited excellent physicochemical characteristics for renewable fuel and energy applications. The liquid product fraction consisted predominantly of bio-oils, oxygenated hydrocarbons, phenolic compounds, furans, and organic acids, which can serve as fuel additives, fuel precursors, or upgrading intermediates for the production of advanced biofuels. Under optimized reaction conditions, the liquid bio-oil yield reached 78.6 wt.%, while carbon recovery in the liquid phase exceeded 72.4%, indicating efficient conversion of biomass carbon into energy-rich products. The produced bio-oils exhibited higher heating values (HHVs) ranging from 28.5 to 34.8 MJ kg^{-1}, approaching those of conventional petroleum-derived fuels. Furthermore, energy recovery efficiencies of 68.7–84.2% were achieved, demonstrating substantial retention of chemical energy within the liquid products.

Elemental analysis revealed an increase in carbon content from 48.3 wt.% in raw biomass to 65.7–72.8 wt.% in the resulting bio-oils, accompanied by a significant reduction in oxygen content from 42.6 wt.% to 15.4–24.3 wt.%. This improvement enhanced fuel quality, stability, and combustion performance. The generated oxygenated compounds, including furfural, HMF, levulinic acid, and phenolic derivatives, are valuable intermediates for hydrodeoxygenation and catalytic upgrading processes, enabling the production of drop-in transportation fuels. In addition, char formation remained below 6.5 wt.%, minimizing energy losses and maximizing liquid fuel production. The favorable fuel properties, high energy density, and substantial carbon recovery demonstrate the effectiveness of catalytic depolymerization as a sustainable pathway for converting lignocellulosic biomass into renewable transportation fuels. These findings highlight the significant role of biomass valorization technologies in reducing dependence on fossil resources, lowering greenhouse gas emissions, and supporting the transition toward future low-carbon energy systems and integrated biorefineries (Table II).

Table II. Fuel properties and energy recovery performance of bio-derived products obtained through catalytic depolymerization

Parameter	Raw biomass	Bio-Oil/Product fraction	Improvement (%)
Carbon Content (wt.%)	48.3	72.8	50.7
Hydrogen Content (wt.%)	5.8	8.1	39.7
Oxygen Content (wt.%)	42.6	15.4	−63.8
Higher Heating Value (MJ kg^{-1})	18.9	34.8	84.1
Energy Density (MJ L^{-1})	15.2	29.7	95.4
H/C Atomic Ratio	1.44	1.68	16.7
O/C Atomic Ratio	0.66	0.21	−68.2

DISCUSSION

The present study highlights the effectiveness of catalytic depolymerization as a sustainable approach for converting lignocellulosic biomass into valuable platform chemicals, renewable aromatic compounds, and biofuel precursors. The high biomass conversion efficiencies achieved in this work (88–94%) demonstrate the ability of the developed catalytic system to overcome the recalcitrant structure of lignocellulosic biomass. Previous studies have reported biomass conversion efficiencies ranging from 65–85% using conventional acid-catalyzed hydrolysis and thermochemical conversion methods, whereas advanced heterogeneous catalytic systems typically achieve 75–90% conversion (18, 19). Therefore, the conversion efficiencies obtained in the present study compare favorably with those reported in the literature, indicating improved catalytic performance and reaction selectivity. The physicochemical characterization results revealed high cellulose and hemicellulose contents together exceeding 70 wt.%, which provided abundant carbohydrate resources for platform chemical production. Pretreatment significantly enhanced biomass accessibility by reducing lignin content from 26.4 wt.% to 14.8 wt.%, increasing pore size, and decreasing cellulose crystallinity. Similar reductions in lignin content (35–50%) have been reported by (20, 21), who demonstrated that structural modification of biomass substantially improves catalytic conversion efficiency. The enhanced digestibility observed in the present study (86.8%) was higher than the 70–80% values commonly reported for untreated agricultural residues, confirming the effectiveness of the pretreatment strategy (22). Catalyst characterization demonstrated high surface area (185–313 m^2 g^{-1}), abundant acidic sites, and excellent structural stability. These properties contributed significantly to the efficient cleavage of glycosidic and ether bonds within biomass polymers. Comparable catalysts reported by Tomishige, Yabushita, Cao, & Nakagawa, 2022 (23) achieved biomass conversion efficiencies of approximately 82–88%, whereas the catalyst developed in this study achieved conversion efficiencies exceeding 93% under optimized conditions. Furthermore, catalyst deactivation remained below 5% after five consecutive cycles, indicating excellent reusability and operational stability. Such performance is highly desirable for industrial implementation because catalyst replacement represents a major operational expense (24, 25). The production of carbohydrate-derived platform chemicals represented one of the most significant outcomes of this work. The maximum yield of 5-hydroxymethylfurfural (HMF) reached 26.7 wt.%, while furfural and levulinic acid yields reached 23.8 wt.% and 17.6 wt.%, respectively. Previous studies have reported HMF yields ranging from 15–22 wt.% and furfural yields between 12–20 wt.% depending on catalyst type and reaction conditions (26, 27). The higher product yields reported for bifunctional catalysts may be associated with enhanced sugar dehydration pathways and reduced secondary degradation reactions. However, further mechanistic studies including kinetic analysis, intermediate identification, and computational investigations are required to confirm these effects. These compounds are recognized among the most important biomass-derived platform chemicals and serve as key intermediates for renewable polymers, solvents, pharmaceuticals, and fuel additives (28). Lignin valorization is widely recognized as one of the greatest challenges in biomass conversion technologies due to the structural complexity of lignin. In the present study, lignin depolymerization produced significant quantities of aromatic monomers, including phenols, guaiacols, syringols, and vanillin derivatives, with total aromatic yields reaching 58.3 wt.% and aromatic monomer selectivity exceeding 82%. These values compare favorably with previously reported aromatic yields of 35–50 wt.% obtained using conventional catalytic hydrogenolysis systems (29, 30). The selective cleavage of β-O-4 ether linkages contributed

substantially to aromatic monomer formation and minimized undesired repolymerization reactions. Consequently, lignin was effectively transformed into a valuable renewable source of aromatic chemicals rather than being treated as a low-value by-product (31). The bio-oils generated during catalytic depolymerization exhibited excellent fuel properties, with higher heating values ranging from 28.5 to 34.8 MJ kg^{-1}, significantly higher than those typically reported for fast-pyrolysis bio-oils (16–25 MJ kg^{-1}) (29). Carbon recovery in the liquid fraction reached 72.4%, while energy recovery efficiency reached 84.2%, surpassing many previously reported biomass conversion systems where energy recovery efficiencies generally range between 60–75% (30). The reduction in oxygen content and increase in carbon content further improved fuel quality, making the products suitable for upgrading into transportation fuels and renewable energy carriers. From an environmental and economic perspective, the results strongly support the industrial feasibility of catalytic biomass valorization. The process has the potential to reduce greenhouse gas emissions by 60–75% compared with conventional petroleum-based production routes while simultaneously generating multiple value-added products. Similar life-cycle assessment studies have reported emission reductions of 40–65% (31), suggesting that the present process offers superior environmental performance. Moreover, the integration of platform chemical production, aromatic compound generation, and biofuel synthesis within a single biorefinery framework improves process economics and resource efficiency. Overall, the findings demonstrate that catalytic depolymerization of lignocellulosic biomass is a highly promising technology capable of supporting sustainable chemical manufacturing, renewable fuel production, and the development of future circular bioeconomies.

CONCLUSION

This study demonstrates that catalytic depolymerization is an effective strategy for converting lignocellulosic biomass into valuable platform chemicals, renewable aromatic compounds, and biofuel precursors. The integrated valorization of cellulose, hemicellulose, and lignin enabled the production of high yields of HMF, furfural, levulinic acid, phenols, and vanillin derivatives, while achieving substantial carbon and energy recovery. The developed catalytic system exhibited excellent activity, selectivity, and stability, making it suitable for sustainable biorefinery applications. Overall, catalytic biomass valorization offers a promising pathway toward reducing fossil fuel dependence, lowering greenhouse gas emissions, and advancing the development of a circular and carbon-neutral bioeconomy.

Acknowledgement:

The authors sincerely acknowledge all individuals and institutions who contributed to the successful completion of this research work. We are grateful for the academic support, guidance, and constructive suggestions received throughout the study. Special thanks are extended to the laboratory staff for providing essential facilities and technical assistance. We also appreciate the valuable feedback from colleagues and reviewers that improved the quality of this manuscript. Finally, the authors express their sincere gratitude to everyone who directly or indirectly supported this study.

Conflict of interest:

Authors declared no conflict of interest.

Authors' contribution:

AS Data collection and interpretation; ZB Conceptualization, study design, critical review and supervision; RZ Data analysis; IIQ Statistical analysis; SM Data analysis and critical review; IS Data interpretation and validation; FS Supervision, critical review and corresponding author; SS Literature review and data curation.

References:

1. Ahmad J, Siddiqui MF, Singh L, Maqbool F, Qayyum S, Ullah I, Nazir R, Mehmood T, Shah MA. Algae a valuable biomass for bioethanol production. In: Algae Based Bioelectrochemical Systems for Carbon Sequestration, Carbon Storage, Bioremediation and Bioproduct Generation. Amsterdam: Elsevier; 2024:143-55.

2. Jain S, Kassaye S. Efficient production of platform chemicals from lignocellulosic biomass by using nanocatalysts: a review. Reactions. 2024;5(4):842-59.
3. Dedes G, Karnaouri A, Topakas E. Novel routes in transformation of lignocellulosic biomass to furan platform chemicals: from pretreatment to enzyme catalysis. Catalysts. 2020;10(7):743.
4. Dutta S. Sustainable synthesis of drop-in chemicals from biomass via chemical catalysis: scopes, challenges, and the way forward. Energy Fuels. 2023;37(4):2648-66.
5. Farooq S, Fiaz I, Ahmad H, Hameed H, Rizwan M, Khan A, Yousafzai AM, Ali A, Mohammed YHE. Optimization of different growth parameters for maximum production of bioactive crude metabolites by Aspergillus fumigatus. Pak J Pharm Sci. 2023;36(3):927-34.
6. Questell-Santiago YM, Galkin MV, Barta K, Luterbacher JS. Stabilization strategies in biomass depolymerization using chemical functionalization. Nat Rev Chem. 2020;4(6):311-30.
7. Khan S, Fiaz M, Alvi IA, Ikram M, Yasmin H, Ahmad J, Siraj M, Amin F, Ahmad A. Molecular profiling, characterization and antimicrobial efficacy of silver nanoparticles synthesized from Calvatia gigantea and Mycena leaiana against multidrug-resistant pathogens. Molecules. 2023;28(17):6291.
8. Zafar SJ, Sipra HM, Abbas M, Zaman T, Adil MZ, Ahmad AM, Hussain S, Ali S, Hassan SA. Utilizing agrofood wastewater for sustainable and environmentally friendly manufacturing. Discov Environ. 2025;3(1):81.
9. Okolie JA, Nanda S, Dalai AK, Kozinski JA. Chemistry and specialty industrial applications of lignocellulosic biomass. Waste and Biomass Valorization. 2021;12(5):2145-69.
10. Zhu P, Abdelaziz OY, Hulteberg CP, Riisager A. New synthetic approaches to biofuels from lignocellulosic biomass. Current Opinion in Green and Sustainable Chemistry. 2020;21:16-21.
11. Wijaya YP, Smith KJ, Kim CS, Gyenge EL. Electrocatalytic hydrogenation and depolymerization pathways for lignin valorization: toward mild synthesis of chemicals and fuels from biomass. Green Chemistry. 2020;22(21):7233-64.
12. Huang Q, Tang Y-P, Zhang Z-F, Wang Z, Dai L. Catalytic asymmetric transformation of platform chemicals derived from lignocellulosic biomass. Chemical Communications. 2025;61(50):8960-8.
13. Akhtar MS, Naseem MT, Ali S, Zaman W. Metal-based catalysts in biomass transformation: From plant feedstocks to renewable fuels and chemicals. Catalysts. 2025;15(1):40.
14. Kumaravel S, Thiruvengetam P, Karthick K, Sankar SS, Karmakar A, Kundu S. Green and sustainable route for oxidative depolymerization of lignin: New platform for fine chemicals and fuels. Biotechnology Progress. 2021;37(2):e3111.
15. Yan P, Peng H, Rabiee H, Ge L, Weng Y, Ma B. Advances in lignocellulosic biomass pyrolysis and catalytic upgrading for sustainable biofuel production: process design strategies and reaction rationales. Green Chemistry. 2025;27(35):10444-77.
16. Gómez Fernández MA, Hoffmann N. Photocatalytic Transformation of Biomass and Biomass Derived Compounds—Application to Organic Synthesis. Molecules. 2023;28(12):4746.
17. Lakhani P, Srifa A. Emerging Heterogeneous Catalysis for Valorization of Biomass-Derived Platform Molecules: The Systematic Review Toward Sustainable Biorefinery Applications. Advanced Energy and Sustainability Research. 2026;7(2):e202500402.
18. Zhang C, Wang F. Catalytic lignin depolymerization to aromatic chemicals. Accounts of chemical research. 2020;53(2):470-84.
19. da Costa Lopes AM, Silvestre AJ, Coutinho JA. On the path to improve lignin depolymerization and functionalization into bio-based platform chemicals: a short review. Current Opinion in Green and Sustainable Chemistry. 2023;43:100850.
20. Tomishige K, Yabushita M, Cao J, Nakagawa Y. Hydrodeoxygenation of potential platform chemicals derived from biomass to fuels and chemicals. Green Chemistry. 2022;24(15):5652-90.
21. Dutta S. Catalytic transformation of carbohydrates into renewable organic chemicals by revering the principles of green chemistry. ACS omega. 2024;9(25):26805-25.
22. Ventura M, Marinas A, Domine ME. Catalytic processes for biomass-derived platform molecules valorisation. Topics in Catalysis. 2020;63(9):846-65.
23. Pattnaik F, Tripathi S, Patra BR, Nanda S, Kumar V, Dalai AK. Catalytic conversion of lignocellulosic polysaccharides to commodity biochemicals: a review. Environmental Chemistry Letters. 2021;19(6):4119-36.
24. Mankar AR, Modak A, Pant KK. Recent advances in the valorization of lignin: a key focus on pretreatment, characterization, and catalytic depolymerization strategies for future biorefineries. Advanced Sustainable Systems. 2022;6(3):2100299.

25. Qiu B, Tao X, Wang Y, Zhang D, Chu H. Hydrothermal liquefaction for producing liquid fuels and chemicals from biomass-derived platform compounds: a review. Environmental Chemistry Letters. 2025;23(1):81-115.
26. Chen X, Song S, Li H, Gözaydın Gk, Yan N. Expanding the boundary of biorefinery: organonitrogen chemicals from biomass. Accounts of Chemical Research. 2021;54(7):1711-22.
27. Daelemans B, Sridharan B, Jusner P, Mukherjee A, Chen J, Kenny JK. From lignin to market: a technical and economic perspective of reductive depolymerization approaches. Green Chemistry. 2025;27(42):13160-78.
28. Riaz A, Mujahid R, Zeb H, Arif M, Azhar U, Kim J. Solvent-Mediated Depolymerization of Lignin under Solvothermal Conditions: Catalysis, Stabilization, and Sustainability Metrics. Industrial & Engineering Chemistry Research. 2026.
29. Upare PP, Clarence RE, Shin H, Park BG. An overview on production of lignocellulose-derived platform chemicals such as 5-hydroxymethyl furfural, furfural, protocatechuic acid. Processes. 2023;11(10):2912.
30. Chen Z, Wang Y, Cheng H, Zhou H. Integrated chemo-and biocatalytic processes: a new fashion toward renewable chemicals production from lignocellulosic biomass. Journal of Chemical Technology & Biotechnology. 2023;98(2):331-45.
31. Kabbour M, Luque R. Furfural as a platform chemical: From production to applications. Biomass, biofuels, biochemicals. 2020:283-97.