

SYNTHESIS OF BIOMASS-DERIVED CATALYSTS AND THEIR ORGANIC TRANSFORMATIONS

Saurabh Korake,*^{ORCID} Parin Gandhi,^{ORCID} Vijay Godse^{ORCID}

Department of Chemistry, Dahiwadi College Dahiwadi - 415508, Tal-Man, Dist – Satara, Maharashtra, India

Keywords

Biomass-derived catalysts,
Sustainable catalysis,
Lignocellulosic biomass,
Biomass-derived carbon,
Catalyst recyclability

Abstract

The increasing demand for a chemically sustainable and environmentally friendly chemical process has greatly increased the use of biomass-derived catalysts as substitutes to the traditional fossil based catalytic systems. The use of biomass as a resource is an advantage because it offers a low cost, abundant and less environmentally damaging alternative to petroleum that can effectively catalyze chemical reactions. The purpose of this chapter is to provide a comprehensive review of biomass resources, methods for synthesizing biomass derived catalysts, methods used to characterize biomass derived catalysts and mechanisms involved in biomass derived catalysts that are used in various organic transformations including oxidations, reductions, C-C bond forming reactions, esterification's and photocatalytic reactions. In addition to highlighting challenges associated with biomass derived catalysts, recyclability, advantages related to environmental issues and future research areas will be emphasized to show how biomass derived catalysts are a key component in the development of green chemistry and sustainable chemical production practices.

Received -
11th December 2025

Online Available -
13st January 2026

1. Introduction

Global pressure to reduce the environmental effects of fossil-based chemical processes and the rapid exhaustion of non-renewable resources has driven an international push to establish sustainable chemistry. Traditional chemical production is largely dependent upon petroleum feedstocks, energy-intensive process conditions and homogeneous catalysts that produce large amounts of waste. Catalysis will play a major role in reducing the environmental impacts of traditional chemical processes through efficient use of energy, improved selectivity and reduction of waste generation [1].

Biomass has been identified as one of the key elements of sustainable chemistry because it is renewable, available globally and has a wide diversity of chemical compositions. Plant, agricultural, forest and marine biomass can all be used as biomass. The functional groups present in biomass, including hydroxyl, carboxyl, phenolic and amino functionalities, enable intrinsic chemical reactivity and coordination ability that make biomass an attractive feedstock for the design of catalysts [2].

Biomass-derived catalysts demonstrate the convergence of renewable resources and green catalytic science. Depending on how biomass is prepared, biomass may act as a catalyst support, an active catalytic phase, a templating agent, or a sacrificial precursor for porous carbon and inorganic materials [3]. Biomass-derived catalysts have many potential benefits compared to traditional fossil-based catalysts, including lower costs, availability and environmental footprints.

Over the past few decades, the advancements in materials science and nanotechnology have greatly accelerated the development of biomass-derived catalysts with controlled physicochemical properties. Through control over carbonization, heteroatom doping and metal immobilization, researchers have developed biomass-derived catalysts with high surface areas and well-dispersed active sites [4]. These developments have also increased the range of applications of biomass-derived catalysts to include redox reactions, C-C bond forming reactions and even photocatalytic reactions.



*Correspond author E-mail address: saurabhkorake99@gmail.com

Copyright: © 2025 This chapter is an open access chapter distributed under the term of the Creative Commons

Attribution 4.0 International

Korake (2025) *Advances in Photocatalysis: Principles, Materials and Applications*, <https://doi.org/10.5281/zenodo.18231395>

Integration of biomass-derived catalysts into organic synthesis is particularly appealing for the fine chemicals and pharmaceutical industries. In addition to the simple transformation, researchers have demonstrated the effectiveness of using biomass-based magnetic copper catalysts for complex tasks, including base-free Chan-Lam coupling and the oxidation of hydrocarbons [5]. Additionally, the recycling of these materials is typically very good and the amount of metal leached during the reaction is generally very low, making them suitable replacements for homogeneous catalysts.

From an environmental point of view, the application of biomass-derived materials goes beyond simple transformations. Researchers have shown that engineered biochars have a high capacity to adsorb common pharmaceutical pollutants such as tetracycline and diclofenac, demonstrating their ability to participate in a closed-loop chemical economy [6]. Furthermore, biomass-derived carbon nanomaterials have been recently synthesized using low temperature hydrothermal carbonization (HTC) and activation to form high surface area supports (>3000 m²/g) for metal nanoparticles [7].

Although there remain numerous industrial challenges, such as the variability of feedstocks derived from plants, recent reviews have emphasized that biogenically mediated synthesis of plants and environmentally friendly catalytic methods are rapidly decreasing the gap between successful laboratory demonstrations and industrial viability [8].

2. Biomass Resources for Catalyst Design

2.1. Types of Biomass

Biomass can be broadly categorized based on the source of the biomass and the type of chemical compounds present in the biomass, each having different characteristics for catalyst synthesis:

Lignocellulosic Biomass:

Includes wood, agricultural residues (e.g., rice straw, wheat straw, corn stover) and forestry wastes. This is the largest group of biomass utilized for catalyst synthesis due to its high carbon content and renewability [9].

Agro-industrial By-product:

Examples include rice husks, sugarcane bagasses, coconut shells and fruit peels. Many of these have

both carbon and inorganic components such as silica that allow for the creation of hybrid catalysts [10].

Marine Biomass:

Algae and chitosan, a polysaccharide derived from crustacean shells. Marine biomass is special due to the presence of nitrogen in the biomolecules and inherent metal-chelating capabilities [11].

Dedicated Energy Crops:

Switch grass and miscanthus are two examples of dedicated energy crops that can provide a reliable feedstock supply, however, their use raises concerns about competition for arable land.

Valorizing Waste Streams

Residues from agriculture and forestry are particularly useful for transforming waste into value-added materials while minimizing the environmental consequences associated with burning biomass. For example, sugarcane bagasse and rice husks are both good candidates for producing mesoporous materials and carbon-silica hybrids [12]. Similarly, fruit peels and nutshells, which are both high in lignin, are good precursors for synthesizing activated carbons with hierarchical porosity.

Unique Properties of Marine Biomass

Marine biomass is another renewable resource that offers some unique properties. Chitin and chitosan both contain many amino and hydroxyl functional groups, which endow the molecules with basicity. This makes marine biomass particularly well-suited for base-catalyzed reactions and enantioselective transformations without requiring extensive chemical treatment [13].

Chemical composition of the biomass is one of the factors that governs the catalytic potential of it. As mentioned above, lignocellulosic biomass, which represents the main part of all the terrestrial biomass, is composed mainly of three biopolymers; namely; Cellulose, Hemicellulose and Lignin [13].

- Carbohydrate polymers called cellulose are composed of β -(1 \rightarrow 4)-D-glucose linked units forming a linear chain. Strong hydrogen bonding is possible between cellulose's numerous hydroxyl group. Cellulose can thus be converted into oxygen rich-surface functionalized carbonaceous material after heat treatment or modification of cellulose. It facilitates acid catalyzed reaction and immobilizing metals.

- Amorphous heteropolysaccharide, hemicellulose is formed from many types of sugar monomers

including xylose, mannose and arabinose. Hemicellulose's branched structure and lower thermal stability than cellulose makes it easily degradable during pyrolysis. Pyrolysis of hemicellulose generates micropores and mesopores in the biomass derived carbons and contributes to surface acidity and porosity.

- Lignin is an aromatic polymer with three-dimensional structure having phenolic, methoxy and aliphatic hydroxyl groups. Due to its high carbon content and aromatic structure, lignin is very favorable to produce graphitic and heteroatom doped carbon catalysts from it. Phenolic groups in the materials derived from lignin can serve as intrinsic redox sites or strongly interact with metal particles.

In addition to the three main compounds of biomass, there are also some minor components; e.g., proteins, lipids, extracts and inorganic minerals (e.g., alkali and alkaline earth metals). These minor components can greatly affect the properties of catalysts. They can function as natural doping agent, pore-forming agent, or catalytic promoter.

The multiple functional groups present in biomass; e.g., hydroxyl, carboxyl, phenolic, amino and ether groups can function as effective anchoring site for metal nanoparticles, acid-base functionality and redox active center. Therefore, the inherent chemical diversity of biomass enables the direct production of functional catalysts without the need for outside modifications and hence biomass is an excellent and versatile raw material for the production of catalysts [7,8,9,10].

Thus, the type and amount of biomass will not only determine whether a catalyst can be synthesized from it, but it will also determine the characteristics of the active sites, stability and catalytic performance of the catalyst. Understanding the relationship between the characteristics of biomass and those of the catalyst will allow us to develop biomass derived catalysts tailored for a particular organic transformation and therefore, improve the efficiency and sustainability of the catalytic process.

3. Biomass Derived Catalysts

Biomass-derived catalysts represent an important innovation in heterogeneous catalysis, in which renewable biological resources are used as a component of the catalytic system [14]. Biomass-derived catalysts are made from either whole

biomass, processed biomass or intermediate materials produced from biomass and are designed to perform organic transformations efficiently while producing less waste and less harmful effects to the environment. The concept of biomass-derived catalysts combines aspects of materials science, catalysis and green chemistry to meet the increasing demands for sustainable chemical processes.

Depending on how biomass functions within the catalytic system, biomass-derived catalysts can be categorized broadly. Biomass or its derivative can function as a support for active catalytic species, as a catalytically active component itself, as a template, or as a sacrificial precursor for the synthesis of new catalytic materials.

3.1 Biomass as Catalyst Support

Probably the most commonly used aspect of biomass in the design of catalysts is as a support for active catalytic species. The surface functional groups of biopolymers such as cellulose, lignin, chitosan and starch are sufficient to form strong interactions with metal ions and metal nanoparticles. Such strong interactions enhance metal dispersion, inhibit metal particle agglomeration and prevent leaching of metal species during the catalytic reaction [9-10].

For example, Pd, Cu, Ni and Fe metal nanoparticles supported on cellulose were found to demonstrate good catalytic activity and recyclability in hydrogenation, oxidation and coupling reactions. The amino functional groups of chitosan based supports provide additional chelation sites resulting in higher catalyst stability and selectivity [15]. In many cases, the catalytic performance of biomass-supported catalysts was better than that of the corresponding inorganic supports because of the tunable surface chemistry and adjustable hydrophilicity of biomass.

3.2 Biomass as Catalytically Active Component

In some cases, biomass-derived materials themselves can act as catalytically active phases. Carbonaceous materials produced from pyrolysis or hydrothermal carbonization of biomass exhibit intrinsic catalytic activity due to surface oxygen-containing functional groups, defects and heteroatom dopants. For example, sulfonated biomass-derived carbons can act as solid acid catalysts in esterification, dehydration and condensation reactions, providing environmentally friendly alternatives to liquid mineral acids [16].

Similarly, alkali-rich biomass ash can act as a solid base catalyst for transesterification and C-C bond-

forming reactions. The use of biomass-derived materials as active phases eliminates the need for additional catalytically active species, reducing the complexity of catalyst preparation and improving the overall sustainability of the process.

3.3 Biomass as Template and Sacrificial Precursor

Biological materials are also widely used as templates or sacrificial precursors for the synthesis of structured inorganic catalysts. Natural biopolymers such as cellulose fibers, starch granules and lignin aggregates can direct the formation of porous metal oxides and composite materials. After calcination or chemical removal of the biomass template, highly ordered hierarchical pore structures with large surface area can be generated.

This template method has been successfully applied to the synthesis of mesoporous TiO₂, ZnO, CeO₂ and ferrite materials, exhibiting enhanced mass transport, increased light harvesting and improved catalytic performance [17]. The hierarchical structure of biomass can provide an additional advantage compared to synthetic templates, which are usually expensive and environmentally undesirable.

3.4 Alignment with Green Chemistry Principles

The development of biomass-derived catalysts follows many of the principles of green chemistry, especially the use of renewable feedstock, safer chemicals, waste reduction and energy efficiency [18]. Biomass-derived catalysts replace the need to utilize the limited availability of mined inorganic resources and fossil-based feedstocks through the utilization of naturally abundant and biodegradable materials.

In addition, biomass-derived catalysts can often cause organic reactions to occur at milder conditions and result in reduced amounts of solvents and energy consumed and easier recoveries and recycling of catalysts. Often times, biomass-derived catalysts are prepared using environmentally friendly techniques such as aqueous processing, low temperature treatments and plant extract mediated reductions that increase the environmental compatibility of the process [7].

3.5 Biomass-Derived Catalysts Compared to Traditional Catalysts

Compared to traditional catalysts that are generally synthesized from nonrenewable metals and inorganic supports, biomass-derived catalysts have advantages of being more sustainable and having less

environmental impact. Traditional catalysts are often prepared at elevated temperatures and involve the use of toxic reagents and energy intensive processes. On the other hand, biomass-based systems take advantage of naturally occurring structures and functionalities of the biomass to prepare catalysts using simpler and greener pathways [19].

Furthermore, the tunability of biomass chemistry allows for the selective manipulation of catalyst properties such as acidity, basicity and redox behavior. This versatility allows for the rational design of catalysts optimized for specific organic transformations such as fine chemical synthesis, biomass conversion and environmental cleanup.

A holistic approach to sustainable catalysis is offered by using biomass-derived catalysts to integrate renewable feedstocks and functional catalytic designs. A unique feature of biomass-derived catalysts is their multifunctionality and their compatibility with both the environment and economics; therefore, they will be important to the next generation of catalytic technologies [5] as the chemical industry evolves to adopt greener processes and practices.

There are multiple ways in which biomass may be converted to a catalytically useful material depending upon the desired catalytic properties. Biomass may be used directly as a catalyst, converted to a carbonaceous material via thermal conversion processes (pyrolysis or hydrothermal carbonization) to create a functional carbon material, or chemically modified to incorporate active catalytic species [9].

4. Biomass as a catalyst and derived carbon catalysts

Multiple strategies to convert biomass to a catalytically useful material, two strategies have received particular attention: using biomass directly as a catalyst and preparing biomass-derived carbon catalysts. These strategies were chosen because of the simplicity, environmental-friendliness and cost-effectiveness of each.

4.1 Biomass Used Directly as Catalysts

Certain types of biomass can serve directly as catalysts for specific types of chemical reactions without requiring extensive chemical modifications. These types of catalysts owe their potential as catalysts to their inherent mineral content and surface functional groups. Many types of plant ash,

agricultural residue and bio-waste materials have substantial levels of alkali and alkaline earth metals, such as potassium, calcium, magnesium and sodium, which can be present as oxides, carbonates, or hydroxides [21]. The presence of these metal oxides can generate strong basic sites on the surface of the material; thus, it can act as a solid-base catalyst for base-catalyzed organic transformations.

Plant-ash catalysts made from the controlled-burning of biomass residues have been extensively tested as solid-base catalysts for base-catalyzed organic transformations. For example, plant ashes that are rich in potassium oxide and calcium oxide have shown exceptional activity as catalysts for transesterification reactions for the production of biodiesel [13, 14]. Transesterification reactions involve the conversion of vegetable oils and waste cooking oils to fatty-acid-methyl esters (FAME). FAME is used as the fuel component of biodiesel. The transesterification reaction occurs under mild conditions when the vegetable oils and waste cooking oils are treated with methanol over a catalyst. The primary mechanism of action for this type of catalyst is thought to be the generation of surface basic sites by the metal oxides, which activate the alcohol molecules and facilitate nucleophilic attack on the triglyceride.

Untreated bio-residue materials, such as banana peels, eggshells and agricultural husks, have also been found to be effective catalysts. This is likely due to the presence of naturally occurring inorganic phases and functional groups in these materials. Eggshells, which are primarily composed of calcium carbonate, can be thermally transformed into calcium oxide. Calcium oxide can then be used as an efficient heterogeneous base catalyst. Rice husk contains silica and has exhibited catalytic properties for condensation and esterification reactions [22].

Direct use of biomass as catalysts has many advantages. It does not require much processing; requires little energy; and generates very little chemical waste. However, these catalysts do suffer some drawbacks. They can be difficult to reproduce consistently; generally have lower surface areas than synthetic catalysts; and can degrade quickly if exposed to extreme reaction conditions. Therefore, although direct biomass catalysts could be ideal for low-cost and large-scale applications, they often need

to be modified to increase their consistency and long-term durability.

4.2 Biomass-Derived Carbon Catalysts

Carbonaceous catalysts produced through the thermal conversion of biomass are one of the most researched classes of biomass-derived catalytic materials. Both pyrolysis and hydrothermal carbonization can be used to produce biomass-derived carbon catalysts. Pyrolysis converts biomass into biochar, which is a highly carbonaceous material with developed porosity and a variety of surface functional groups. Hydrothermal carbonization produces hydrochar, which is a material produced through the treatment of biomass in an aqueous medium at temperatures of 180°C to 250°C and autogenously-generated pressure. Hydrochar has higher levels of oxygen in its surface functional groups than biochar and is more hydrophilic [23].

Biomass-derived carbon catalysts possess many properties that make them well-suited for use as catalysts for a variety of organic transformations. These properties include:

- High surface areas, which provide a large number of active sites for catalytic reactions to occur.
- Tunable pore sizes, which allow reactants and products to move easily through the catalyst.
- Surface functional groups, such as hydroxyl (-OH), carboxyl (-COOH), sulfonic (-SO₃H) and amino (-NH₂) groups, which contribute to acid-base and redox catalytic activity.

The above characteristics make biomass-derived carbon catalysts suitable for a wide range of organic transformations, including esterification, oxidation, reduction and C-C bond forming reactions.

Additionally, the catalytic performance of biomass-derived carbon catalysts can be further improved through heteroatom doping. Heteroatom doping involves incorporating atoms such as nitrogen, sulfur and phosphorus into the carbon framework. For example, nitrogen-doped carbon catalysts exhibit enhanced basicity and electron-donating capability compared to undoped carbon catalysts. These enhancements make nitrogen-doped carbon catalysts more effective for oxidative and coupling reactions. Sulfur and phosphorus doping add new acid and redox-active sites to the carbon framework, respectively, making these doped carbon catalysts more applicable to a broader range of catalytic applications [9, 11].

Biomass precursors that are rich in proteins, amino acids, or sulfur-containing compounds are particularly suited for heteroatom doping. This is because the atoms being doped are already part of the biomass precursor prior to thermal conversion. Therefore, no additional dopants need to be added to the system; this reduces the overall sustainability of the catalyst synthesis process [24].

In summary, biomass-derived carbon catalysts are a versatile and environmentally friendly class of materials that provide a link between traditional heterogeneous catalysts and renewable resources. The tunability of their structure, the multifunctionality of their surface chemistry and the compatibility of their production method with green synthesis procedures make them central to the development of next-generation sustainable catalytic systems.

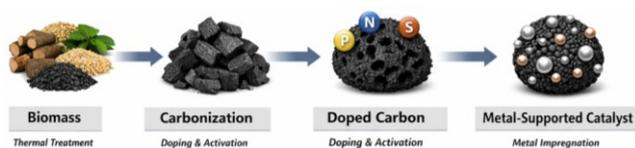


Fig. 1: Schematic illustration of the synthesis of biomass-derived carbon catalysts through thermal conversion

5. Characterization of Biomass-Derived Catalysts

Establishing unambiguous structure-catalyst activity relationships for biomass-derived catalysts requires comprehensive characterization of the catalyst. Since biomass-derived catalysts consist of heterogeneous precursors and complex surface functionalities, a combination of structural, morphological, chemical and thermal techniques must be used to fully elucidate the catalyst's properties. Beyond confirming the success of catalyst synthesis, these characterization techniques provide valuable insight into the distribution of active sites, the interaction between metal species and supports and the stability of the catalyst under reaction conditions.

5.1 Structural Characterization

X-ray diffraction (XRD) is commonly used to determine the crystalline phases in biomass-derived catalysts. For metal-supported systems, XRD identifies the formation of metallic or oxide phases and evaluates crystallite size based on peak broadening [25]. In addition, XRD of carbon-based catalysts derived from biomass usually shows broad diffraction peaks indicative of amorphous or

turbostratic carbon structures. Sharp diffraction peaks may also indicate a degree of graphitization and/or successful incorporation of heteroatoms.

5.2 Surface Chemistry and Functional Group Analysis

Fourier Transform-Infrared Spectroscopy (FTIR) is a critical analytical tool for characterizing the surface functional groups in biomass-derived catalysts. The common functional groups identified by FTIR include hydroxyl (-OH), carboxyl (-COOH), sulfonic (-SO₃H) and amino (-NH₂) groups. The presence of these functional groups is responsible for the binding of metal nanoparticles and contributes to the acid-base behavior of the catalyst. In addition, changes in FTIR spectra between before and after the catalytic reaction provide valuable insights into the interactions between the catalyst and substrates, as well as the deactivation of the catalyst [26].

Raman Spectroscopy complements FTIR by providing information regarding the carbon structure and defect density in biomass-derived carbon catalysts. The ID/IG ratio, where ID represents the relative intensity of the D band and IG represents the relative intensity of the G band, indicates the degree of disorder and the presence of defects sites, which are often associated with enhanced catalytic activity [27].

5.3 Morphology and Texture

Scanning Electron Microscopy (SEM), Transmission Electron Microscopy (TEM), Surface Area Analysis (e.g., Brunauer–Emmett–Teller (BET)) and other analytical methods provide a detailed understanding of the physical and chemical characteristics of the catalyst. For example, SEM and TEM allow one to assess the morphology, size and dispersion of the metal phase, while BET surface area analysis enables an evaluation of the accessible surface area and the pore structure of the catalyst. Biomass-derived catalysts usually show a hierarchical pore structure that improves the mass transport and the accessibility of the active sites of the catalyst. Higher BET surface areas and optimal pore structures are usually associated with better catalytic performances in both liquid and gas phase reactions.

5.4 Thermal and Chemical Stability

Thermal Degradation Studies (Thermogravimetry (TGA)) are typically carried out to study the thermal stability of biomass-derived catalysts. TGA helps to identify the decomposition temperatures of the

organic components of the biomass and the functional groups attached to it. TGA also gives additional information regarding the metal loading and the resistance of the organic component towards oxidative degradation. The stability of the catalyst during operation is very important for its recyclability and long term applicability.

5.5 Acid – Base and Redox Properties

For reactions like esterification, condensation and transesterification, the acid-base properties of the biomass-derived catalysts play a crucial role. Various techniques such as NH₃-TPD and CO₂-TPD are commonly used to measure the number of acidic and basic sites, respectively. These measurements help to establish a relationship between the surface acidity/basicity of the catalyst and the observed catalytic activity.

Redox properties of the catalysts are also very important for oxidation and reduction reactions. For this purpose various techniques like H₂-TPR and cyclic voltammetry are used to study the reducibility of the metal, the oxidation state of the metal and the metal-support interactions. Biomass-derived carbon support and metal nanoparticles show strong redox interactions that increase the catalytic efficiency and stability of the catalyst [28].

5.6 Structure – Activity Relationship

By combining the data obtained from different analytical techniques, researchers can establish clear relationships between the structural properties of the catalyst and their performance. Establishing these relationships is fundamental to develop rationally designed catalysts and therefore to predict the catalytic behavior of the catalysts in certain organic transformations.

6. Green Chemistry Transformations Catalyzed by Biomass Derived Catalysts

Biomass-derived catalysts have shown great versatility in the promotion of a wide variety of organic transformations. Due to their adjustable surface chemistry, high functional group density and strong interactions between metal particles and carbon support, they are particularly useful in green and sustainable syntheses. Below we describe the most important reaction types catalyzed by biomass-derived catalysts.

6.1 Oxidation Reactions

In recent years, biomass-derived catalysts were found to be effective for the selective oxidation of alcohols to aldehydes or ketones. The oxidant is often molecular oxygen or hydrogen peroxide. High selectivities can be achieved at low pressures and moderate temperatures using supported copper and iron catalysts based on lignin [16].

The phenolic and aromatic functionalities present in lignin contribute to the ability of lignin to strongly coordinate with transition metals. This facilitates the electron transfer and maintains the catalytically active center of the metal. Moreover, the phenolic and aromatic functionalities prevent the oxidation of alcohols to carboxylic acids, which is a problem encountered in alcohol oxidation. Additionally, the use of biomass-derived catalysts prevents the leaching of the transition metals and allows the catalyst to be recovered and reused. Therefore, the use of biomass-derived catalysts addresses two main problems associated with the use of homogeneous oxidation catalysts [28].

6.2 Reduction Reactions

Reduction reactions, such as transfer hydrogenation and hydrogenation of carbonyl compounds, nitroarenes and unsaturated bonds have been efficiently catalyzed by biomass-supported metals such as Pd, Ni and Cu. With these systems, hydrogenation reactions can be performed without the need for high-pressure molecular hydrogen using alternative hydrogen-donor molecules such as alcohols or formic acid [16].

The porous structure and functionalized surface of biomass supports promote the uniform dispersion of the metal phase and the adsorption of the substrate. In addition, biomass-supported catalysts frequently demonstrate higher chemoselectivity than solution-based catalysts, thus making them highly attractive in pharmaceutical and fine chemical synthesis, where the selective reduction of functional groups within a molecule is crucial.

6.3 C-C Bond-Forming Reactions

Carbon-carbon bond-forming reactions, such as aldol, Knoevenagel and Michael additions, are efficiently promoted by solid acid and base catalysts derived from biomass. Carbon-carbon bond forming reactions are fundamental in the preparation of pharmaceuticals, agrochemicals and specialty chemicals [17, 19].

Acidic sites provided by sulfonated biomass-derived carbons activate carbonyl substrates. Alkali treated biomass materials provide basic sites for the formation of enolates. The heterogeneous nature of these catalysts permits an easy separation and reuse, avoids the need for stoichiometric bases or acids and reduces waste. In addition, biomass-derived catalysts often perform the reaction under solvent-free or aqueous conditions, which further increases the sustainability of the process.

6.4 Esterification and Transesterification

Esterification and transesterification reactions are among the most important applications of biomass-derived solid acid catalysts. These catalysts are primarily used in the production of biodiesel through the conversion of free fatty acids and triglycerides into fatty acid methyl esters under relatively mild conditions [29].

Compared to traditional homogeneous catalysts, biomass-derived acid catalysts exhibit superior water-tolerance and lower corrosion of equipment. High acid-site density and flexible pore structures of biomass-derived acids permit an efficient interaction with bulky fatty acid substrates, leading to high conversion efficiencies and a long lifetime of the catalysts.

Photocatalytic and photo-assisted transformations using biomass-derived materials have been demonstrated to be viable means for achieving a variety of organic transformations using visible light (e.g., oxidation, reduction and coupling) [30].

The incorporation of biomass-derived materials into photocatalytic systems enables the use of renewable energy sources and reduces the need for severe reaction conditions and/or excessive energy inputs.

Biomass-derived carbon materials function both as a support matrix and an electron transfer mediator which enhances charge separation and diminishes recombination.

Mechanisms of biomass-derived catalysts involve the synergistic combination of factors, including:

- Surface functional groups that promote substrate adsorption and activation;
- Metal-support interactions that stabilize catalytically active species and inhibit metal sintering; and
- Electronic structure of biomass-derived carbon matrices which influences the rate of electron transfer.

Carbon-based systems have defect sites and heteroatom dopants that improve electron transfer rates, thus increasing redox activity. Cooperative interaction between biomass-derived carbon matrices and metal nanoparticles can provide increased catalytic activity and selectivity. Therefore, understanding these mechanisms will be important in designing and optimizing the next generation of biomass-derived catalysts [20].

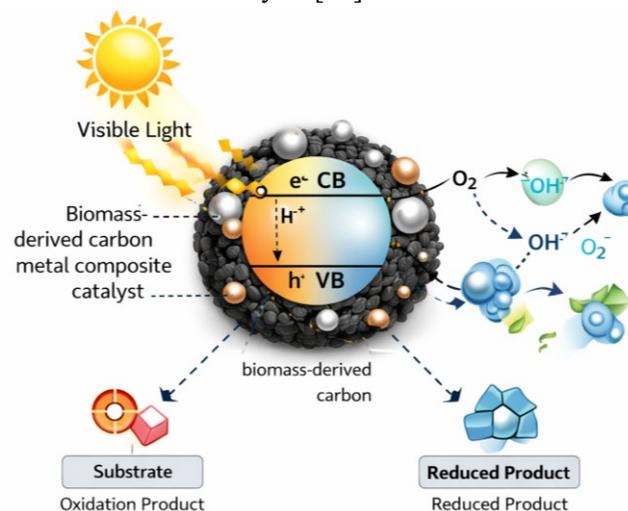


Fig. 2: Photocatalytic mechanism over biomass-derived carbon–metal catalysts under visible light.

7. Recycling, Stability and Reusability of Biomass-Derived Catalysts

A major benefit of biomass-derived catalysts is their ability to recycle and operate stably over many reaction cycles with little to no decrease in activity and virtually no metal leaching [18].

Due to their heterogeneous nature, biomass-derived catalysts can be easily separated via filtration or magnetic separation, thereby minimizing downstream processing costs.

Factors affecting thermal and chemical stability include the nature of the biomass precursor, synthesis method and the type of active species present. Optimizing catalyst design should ensure that it is resistant to deactivation and therefore suitable for long-term and industrial-scale applications.

8. Environmental and Economic Impact

Studies utilizing life cycle assessments indicate that biomass-derived catalysts typically have lower carbon footprints and reduced energy requirements compared to traditional fossil-derived catalysts and

they also produce fewer environmental impacts [1, 15].

Utilizing agricultural or industrial wastes to produce biomass-derived catalysts contributes to waste valorization and circular economy models [1, 15].

From a purely economic perspective, the low cost and wide availability of biomass feedstocks makes them a desirable choice for large-scale implementations. Combining this with the recyclability of biomass-derived catalysts and the reduced waste generated through their utilization, biomass-derived catalysts represent a highly competitive option for the sustainable development of chemical processes.

9. Challenges and Limitations

While biomass-derived catalysts have many benefits, there are still significant scientific and technological hurdles that need to be addressed before they can be widely adopted. Some of the primary issues associated with the adoption of biomass-derived catalysts include:

- The inherent variability of biomass feedstocks. The composition of biomass can vary based on a number of factors including the source, geographic location, seasonal factors and processing history. This variability can result in differences in the composition of the catalyst, the distribution of surface functionality and ultimately the catalytic performance of the resulting catalyst, all of which can complicate the reproduction and scale-up of biomass-derived catalysts [31].
- Reproducibility of catalyst synthesis. Unlike well-characterized synthetic supports, biomass-derived materials tend to have complex structures and distributions of functional groups, making it much more challenging to precisely control the properties of the resultant catalyst. Small changes in variables such as carbonization temperature, activation conditions and chemical modifications can have significant effects on the catalytic performance of the resulting catalyst [31].
- Long-term stability of the catalyst under the extreme conditions found in many chemical reactions. Biomass-derived supports can degrade structurally, lose functional groups, or release metal ions during extended periods of operation, especially under high-temperature, strongly acidic/alkaline, or oxidative conditions [31].

To address the challenges described above, it will be necessary to develop methods to standardize the processing of biomass, control the synthesis parameters of biomass-derived catalysts and develop new approaches to designing and creating advanced materials. Approaches such as controlled activation of biomass, surface functionalization of biomass-derived materials, creation of hybrid materials that incorporate both biomass-derived materials and other functional components and application of protective coatings to extend the longevity of biomass-derived catalysts are examples of the types of methods that researchers are exploring to improve the stability and reproducibility of biomass-derived catalysts [12].

10. Future Research Directions

Future research on biomass-derived catalysts is likely to focus on the development of hybrid catalytic systems that integrate biomass-derived materials with advanced functional components. For example, the integration of biomass-derived carbons with semiconductor photocatalysts and plasmonic materials could create novel solar-driven organic transformation and environmental remediation platforms.

Another area of future research is focused on developing metal-free catalytic materials from biomass alone. Examples of promising directions include the use of heteroatom doped carbons, enzyme-inspired biocatalytic frameworks and defective carbon materials for catalyzing redox and coupling reactions without relying on scarce or toxic metals.

Integrating biomass-derived catalysts with flow chemistry and continuous processing would be an important step towards commercializing biomass-derived catalysts. For example, immobilizing biomass-derived catalysts in fixed bed or microreactors could allow for enhanced mass transport, efficient heat management and scalable green chemical production.

Finally, advances in computational modeling, in-situ characterization and machine learning guided catalyst design are expected to further accelerate the rational development of high-performance biomass-derived catalysts. Overall, biomass-derived catalysis is expected to become a foundation for sustainable chemical technology in the future.

11. Conclusion

Biomass-derived catalysts represent a powerful and sustainable alternative to fossil fuel derived catalysts. By utilizing renewable biomass feedstocks that are capable of forming a wide array of surface chemistries and providing diverse catalytic functionalities, biomass-derived catalysts can be utilized to facilitate a wide array of organic transformations under environmentally benign conditions.

As a result of their versatility, low environmental impact and compatibility with the principles of green chemistry, biomass-derived catalysts represent a powerful tool for the sustainable manufacture of chemicals. While there are several challenges to be addressed regarding the reproducibility, stability and standardization of biomass-derived catalysts, advancements in materials science and process integration are anticipated to resolve these limitations. As research continues, biomass-derived catalysts are expected to be at the forefront of advancing the field of green chemistry and sustainable organic synthesis.

References

- 1) Beena Unni, A., & Muringayil Joseph, T. (2024). Enhancing Polymer Sustainability: Eco-Conscious Strategies. *Polymers*, 16(13), 1769. <https://doi.org/10.3390/polym16131769>
- 2) Chai, Y. D., Pang, Y. L., Lim, S., Chong, W. C., Lai, C. W., & Abdullah, A. Z. (2022). Recent Progress on Tailoring the Biomass-Derived Cellulose Hybrid Composite Photocatalysts. *Polymers*, 14(23), 5244. <https://doi.org/10.3390/polym14235244>
- 3) Urso, M., Ju, X., Nittoor-Veedu, R., Lee, H., Zaoralová, D., Otyepka, M., & Pumera, M. (2025). Single Atom Engineering for Electrocatalysis: Fundamentals and Applications. *ACS catalysis*, 15(13), 11617–11663. <https://doi.org/10.1021/acscatal.4c08027>
- 4) Jayaramulu, K., Mukherjee, S., Morales, D. M., Dubal, D. P., Nanjundan, A. K., Schneemann, A., Masa, J., Kment, S., Schuhmann, W., Otyepka, M., Zbořil, R., & Fischer, R. A. (2022). Graphene-Based Metal-Organic Framework Hybrids for Applications in Catalysis, Environmental and Energy Technologies. *Chemical reviews*, 122(24), 17241–17338. <https://doi.org/10.1021/acs.chemrev.2c00270>
- 5) Shetty, A., Molahalli, V., Sharma, A., & Hegde, G. (2023). Biomass-Derived Carbon Materials in Heterogeneous Catalysis: A Step towards Sustainable Future. *Catalysts*, 13(1), 20. <https://doi.org/10.3390/catal13010020>
- 6) Gonçalves, J. O., Leones, A. R., de Farias, B. S., da Silva, M. D., Jaeschke, D. P., Fernandes, S. S., Ribeiro, A. C., Cadaval, T. R. S., Jr., & Pinto, L. A. d. A. (2025). A Comprehensive Review of Agricultural Residue-Derived Bioadsorbents for Emerging Contaminant Removal. *Water*, 17(14), 2141. <https://doi.org/10.3390/w17142141>
- 7) Almaraz-Vega, E., Morales-Vargas, A. I., Gómez Delgado, G., Castellanos-Arteaga, L., Iñiguez Gómez, O., & Flores Salcedo, C. C. (2026). Sustainable Carbon Nanomaterials from Biomass Precursors: Green Synthesis Strategies and Environmental Applications. *Nanomaterials*, 16(1), 75. <https://doi.org/10.3390/nano16010075>
- 8) Radulescu, D.-M., Surdu, V.-A., Ficai, A., Ficai, D., Grumezescu, A.-M., & andronescu, E. (2023). Green Synthesis of Metal and Metal Oxide Nanoparticles: A Review of the Principles and Biomedical Applications. *International Journal of Molecular Sciences*, 24(20), 15397. <https://doi.org/10.3390/ijms242015397>
- 9) Woźniak, A., Kuligowski, K., Świerczek, L., & Cenian, A. (2025). Review of Lignocellulosic Biomass Pretreatment Using Physical, Thermal and Chemical Methods for Higher Yields in Bioethanol Production. *Sustainability*, 17(1), 287. <https://doi.org/10.3390/su17010287>
- 10) September, L. A., Kheswa, N., Seroka, N. S., & Khotseng, L. (2023). Green synthesis of silica and silicon from agricultural residue sugarcane bagasse ash - a mini review. *RSC advances*, 13(2), 1370–1380. <https://doi.org/10.1039/d2ra07490g>
- 11) Jiménez-Gómez, C. P., & Cecilia, J. A. (2020). Chitosan: A Natural Biopolymer with a Wide and Varied Range of Applications. *Molecules (Basel, Switzerland)*, 25(17), 3981. <https://doi.org/10.3390/molecules25173981>
- 12) Lamponi, S., Barletta, R., & Santucci, A. (2025). Agricultural and Agro-Industrial Residues as Sustainable Sources of Next-Generation

- Biomedical Materials: Advances, Challenges and Perspectives. *Life*, 15(12), 1908. <https://doi.org/10.3390/life15121908>
- 13) Almeida, M., & Vieira, H. (2025). Marine-Derived Collagen and Chitosan: Perspectives on Applications Using the Lens of UN SDGs and Blue Bioeconomy Strategies. *Marine drugs*, 23(8), 318. <https://doi.org/10.3390/md23080318>
 - 14) Villora-Picó, J. J., González-Arias, J., Baena-Moreno, F. M., & Reina, T. R. (2024). Renewable Carbonaceous Materials from Biomass in Catalytic Processes: A Review. *Materials (Basel, Switzerland)*, 17(3), 565. <https://doi.org/10.3390/ma17030565>
 - 15) Nasrollahzadeh, M., Sajjadi, M., Irvani, S., & Varma, R. S. (2021). Starch, cellulose, pectin, gum, alginate, chitin and chitosan derived (nano)materials for sustainable water treatment: A review. *Carbohydrate polymers*, 251, 116986. <https://doi.org/10.1016/j.carbpol.2020.116986>
 - 16) Villora-Picó, J. J., González-Arias, J., Baena-Moreno, F. M., & Reina, T. R. (2024). Renewable Carbonaceous Materials from Biomass in Catalytic Processes: A Review. *Materials*, 17(3), 565. <https://doi.org/10.3390/ma17030565>
 - 17) Niu, B., Wang, X., Wu, K., He, X., & Zhang, R. (2018). Mesoporous Titanium Dioxide: Synthesis and Applications in Photocatalysis, Energy and Biology. *Materials (Basel, Switzerland)*, 11(10), 1910. <https://doi.org/10.3390/ma11101910>
 - 18) Martinengo, B., Diamanti, E., Uliassi, E., & Bolognesi, M. L. (2024). Harnessing the 12 Green Chemistry Principles for Sustainable Antiparasitic Drugs: Toward the One Health Approach. *ACS infectious diseases*, 10(6), 1856–1870. <https://doi.org/10.1021/acsinfecdis.4c00172>
 - 19) Alsaiani, N. S., Alzahrani, F. M., Amari, A., Osman, H., Harharah, H. N., Elboughdiri, N., & Tahooun, M. A. (2023). Plant and Microbial Approaches as Green Methods for the Synthesis of Nanomaterials: Synthesis, Applications and Future Perspectives. *Molecules (Basel, Switzerland)*, 28(1), 463. <https://doi.org/10.3390/molecules28010463>
 - 20) Ncube, S., Tian, Z., Lin, J., Zhang, H., Wang, S., & Tian, W. (2025). Sustainable Biomass-Derived Single-Atom Catalysts for Fenton-Like Catalysis. *Small (Weinheim an der Bergstrasse, Germany)*, 21(35), e2504746. <https://doi.org/10.1002/sml.202504746>
 - 21) Jha, M. K., Joshi, S., Sharma, R. K., Kim, A. A., Pant, B., Park, M., & Pant, H. R. (2021). Surface Modified Activated Carbons: Sustainable Bio-Based Materials for Environmental Remediation. *Nanomaterials*, 11(11), 3140. <https://doi.org/10.3390/nano11113140>
 - 22) Khanyile, N., Dlamini, N., Masenya, A., Madlala, N. C., & Shezi, S. (2024). Preparation of Biofertilizers from Banana Peels: Their Impact on Soil and Crop Enhancement. *Agriculture*, 14(11), 1894. <https://doi.org/10.3390/agriculture14111894>
 - 23) Igliński, B., Kujawski, W., & Kielkowska, U. (2023). Pyrolysis of Waste Biomass: Technical and Process Achievements and Future Development—A Review. *Energies*, 16(4), 1829. <https://doi.org/10.3390/en16041829>
 - 24) Gao, Y., Wang, Q., Ji, G., Li, A., & Niu, J. (2021). Doping strategy, properties and application of heteroatom-doped ordered mesoporous carbon. *RSC advances*, 11(10), 5361–5383. <https://doi.org/10.1039/d0ra08993a>
 - 25) Bulavchenko, O. A., & Vinokurov, Z. S. (2023). In Situ X-ray Diffraction as a Basic Tool to Study Oxide and Metal Oxide Catalysts. *Catalysts*, 13(11), 1421. <https://doi.org/10.3390/catal13111421>
 - 26) Pasieczna-Patkowska, S., Cichy, M., & Flieger, J. (2025). Application of Fourier Transform Infrared (FTIR) Spectroscopy in Characterization of Green Synthesized Nanoparticles. *Molecules (Basel, Switzerland)*, 30(3), 684. <https://doi.org/10.3390/molecules30030684>
 - 27) Wang, T., Jiang, Y., Feng, H., Liu, L., Deng, Q., Liu, D., & Wang, C. (2025). Recent Advances in Raman Spectroscopy for Resolving Material Surfaces/Interfaces. *Catalysts*, 15(12), 1131. <https://doi.org/10.3390/catal15121131>
 - 28) Wang, Y., Wei, L., Hou, Q., Mo, Z., Liu, X., & Li, W. (2023). A Review on Catalytic Depolymerization of Lignin towards High-Value Chemicals: Solvent and Catalyst. *Fermentation*, 9(4), 386. <https://doi.org/10.3390/fermentation9040386>

- 29) Vasić, K., Hojnik Podrepšek, G., Knez, Ž., & Leitgeb, M. (2020). Biodiesel Production Using Solid Acid Catalysts Based on Metal Oxides. *Catalysts*, 10(2), 237. <https://doi.org/10.3390/catal10020237>
- 30) Son, B. T., Long, N. V., & Nhat Hang, N. T. (2021). The development of biomass-derived carbon-based photocatalysts for the visible-light-driven photodegradation of pollutants: a comprehensive review. *RSC advances*, 11(49), 30574–30596. <https://doi.org/10.1039/d1ra05079f>
- 31) Li, A., Lei, S., Chen, S., Zhou, X., Wu, Z., Jiang, F., Zheng, P., Hu, L., & Deng, H. (2025). Review on manganese carbon interactions in manganese oxide-modified biochar for environmental remediation. *iScience*, 28(12), 113991. <https://doi.org/10.1016/j.isci.2025.113991>