Conversion of Lignocellulosic Amazonian Biomass into Biochar: Applications in Supercapacitors and Catalysts— A review.

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***Abstract*— This article reviews the valorization of Amazonian biomass through its conversion into biochar, emphasing the primary technologies involved and their applications in supercapacitors and catalysts. Converting biomass into biochar is presented as a sustainable strategy for the reusing of agro-industrial waste, leading to the generation of high-value-added materials. The article discusses technologies such as hydrothermal carbonization, chemical activation, and pyrolysis, focusing on their ability to produce biochars with adjustable properties, including high surface area and porosity. One study highlighted indicates that açaí seed residues yield highly efficient biochars for supercapacitors, achieving capacitances of up to 346 F g^{-1} with excellent electrochemical stability after thousands of cycles. However, research on the potential of other Amazonian biomasses for similar applications remains scarce. Additionally, residues like tucumã peels have demonstrated high catalytic efficiency as catalysts in transesterification reactions, achieving up to 97.8% conversion in biodiesel production. Açaí seeds were also used to synthesize acid catalysts, achieving a 95% conversion rate of oleic acid to biodiesel. Furthermore, muruci seeds, after pyrolysis and sodium functionalization, resulted in a basic catalyst that achieved 97.2% conversion in biodiesel synthesis from vegetable oil. Murumuru almond shells and yellow passion fruit peels have also showed significant potential as catalysts in biodiesel production. In summary, biomass from the Amazon region, derived from agro-industrial waste, serve as a promising precursor for synthesizing high-value-added materials, such as supercapacitors and catalysts. This is attributed to the low cost and abundance of these residues, which are often improperly discarded. Utilizing these materials can enhance the regional bioeconomy and promote sustainability.**

***Keywords*— Biomass, Biochar, Supercapacitor, Catalyst, Sustainable Materials**

II. INTRODUCTION

Biochar, a carbon-rich material produced through the thermal decomposition of biomass, has emerged as a promising solution to address environmental challenges in an era of growing concern for sustainability [1]. Within the framework of bioeconomy and circular economy, the use of biomass residues for biochar production represents an essential approach that values renewable resources, reduces waste, and promotes more sustainable production cycles [2]. This process not only mitigates the environmental impact of waste but also generates new value-added products, aligning with the principles of the circular economy by transforming waste into valuable resources [3].

The production of biochar involves techniques such as pyrolysis, gasification, and hydrothermal carbonization, each yielding materials with distinct physicochemical characteristics, which are influenced by both the type of biomass and the production process parameters [4]. The use of plant, agricultural, and forestry residues, especially from biodiversity-rich regions like the Amazon, presents a unique opportunity to enhance the local bioeconomy while promoting environmental sustainability [5].

In addition to traditional applications of biochar, such as agricultural amendments to improve soil quality and carbon sequestration [6], it has also demonstrated effectiveness in more advanced technologies, such as water decontamination, where it acts as a pollutant adsorbent [7], and in enhancing the efficiency of industrial processes, where it serves as a catalyst [8]. More recently, biochar has been investigated as an electrode material in supercapacitors, energy storage devices that demand materials with high surface area and favorable electrochemical properties.

This article will review the methodologies of biochar production, characterization, and environmental applications, with a particular emphasis on the use of Amazonian biomass. The analysis will explore how the integration of these residues into biochar production can stimulate the regional bioeconomy and contribute to the circular economy. Additionally, the stydy will examine the potential of biochar as a material for supercapacitors and catalysts. In doing so, this work aims to promote the sustainable use of natural resources, addressing global demands for innovative and environmentally responsible solutions.

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III. BIOMASS

Biomass is defined as renewable organic matter derived from plants, animals, or microorganisms, which can be used as a source of energy or for the production of materials [9]. It is considered a renewable energy source because its regeneration occurs relatively quickly compared to fossil sources such as oil and coal. The energy contained in biomass is ultimately derived from photosynthesis, the process by which plants convert solar energy into chemical energy stored in the form of organic compounds [10]. Biomass can be used directly as fuel or converted into liquid biofuels, biogas, or value-added materials such as bioplastics, adsorbents, catalysts, and supercapacitors, as depicted in Figure 1 [11].

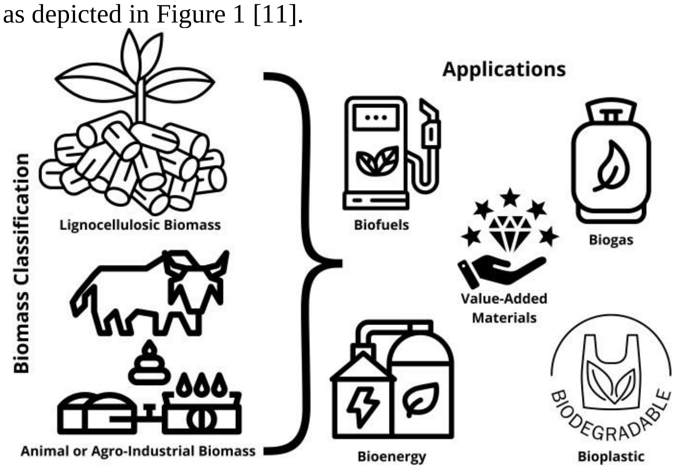


Figure 1. Classification of biomass and its corresponding applications.

Biomass can originate from either animal or plant sources, with each category exhibiting distinct characteristics and chemical compositions. Plant-derived biomass, generally obtained from plants and agricultural residues, is rich in structural carbohydrates such as cellulose, hemicellulose, and lignin, with smaller proportions of lipids and proteins [12]. This type of biomass is frequently used in the production of biofuels and biological materials due to the abundance of lignocellulose, which can be converted into ethanol, bio-oils, biochar, and other chemical compounds [13]. In contrast, animal-derived biomass, obtained from livestock, aquaculture, and other zootechnical activities, is predominantly composed of proteins, lipids, and collagen, with a lower content of lignocellulosic compounds [14]. Animal biomass is often utilized in the production of biogas through anaerobic digestion, as well as in the production of by-products such as fertilizers and feed additives. This differentiation is crucial for determining the conversion process and the types of products that can be obtained from each biomass category [15].

Lignocellulosic biomass, originating from vascular plants, primarily consists of three polymers: cellulose, hemicellulose, and lignin, which together provide rigidity and structural strength to plant cell walls. Cellulose, accounting for about 40-60% of lignocellulosic biomass, is a linear polysaccharide composed of glucose units linked by β-1,4-glycosidic bonds. This structure gives cellulose high crystallinity and considerable resistance to chemical and biological degradation [16]. Hemicellulose, which comprises approximately 20-40% of biomass, is an amorphous heteropolysaccharide made up of various monosaccharide such as xylose, arabinose, mannose, and glucuronic acid. Unlike cellulose, hemicellulose has a branched structure and is less crystalline, making it more susceptible to hydrolysis [17]. Lignin, constituting between 15-30% of biomass, is an amorphous and highly branched polymer formed by phenylpropanoid units. Lignin provides rigidity to the cell wall and serves as a physical and chemical barrier against microbiological and enzymatic degradation [18].

The proportion and specific composition of these components vary among different types of plant biomass and are closely related to the characteristics of the source plant. In addition to the main components, lignocellulosic biomass also contains small amounts of extractives (essential oils, resins, waxes) and minerals (ash), which can influence both the conversion processes and the properties of the final products [19]. A detailed understanding of the chemical composition of lignocellulosic biomass is essential for developing efficient conversion technologies and for producing high-value-added products from renewable resources.

A. *Biomass from the Amazon Region*

The Amazon is one of the most biodiverse regions in the world, with a vast variety of plants and fruits. Among the region's natural resources, biomass from waste, such as the shells and seeds of exotic fruits, stands out as particularly significant. These wastes, often underutilized, are generated in large quantities during the processing of fruits for the food industry and can become problematic if not properly managed [20]. The main fruits whose residues have significant potential due to their annual production include açaí (Euterpe oleracea) with 1.6 tons per year, where 93% of the total national production is concentrated in the northern region, Brazil nuts (Bertholletia excelsa) with 35,000 tons per year, guaraná (Paullinia cupana) with 2,460 tons per year, cupuaçu (Theobroma grandiflorum) with an annual production average of 1.6 million tons, and tucumã (Astrocaryum vulgare) with 40 tons per year [21]. These wastes are rich in lignocellulosic compounds, vegetable oils, and other bioactive constituents, making them valuable for various industrial applications, especially in the production of porous materials, biofuels, and value-added chemicals. Figure 2 illustrates several examples of Amazonian biomass.

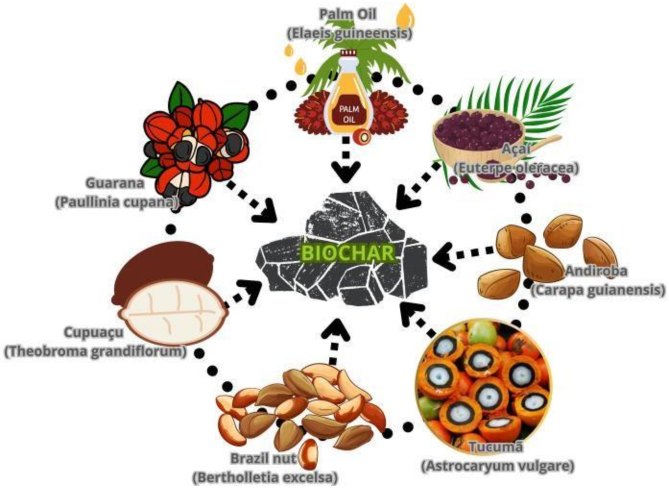


Figure 2. Types of Amazonian Biomass.

Improper disposal of fruit shells and seeds can lead to serious environmental problems. The accumulation of these organic wastes in landfills or their disposal in water bodies can cause pollution, the release of greenhouse gases, and soil and water contamination [22]. Additionally, the anaerobic decomposition of these materials can result in the emission of methane, a potent greenhouse gas, exacerbating climate change. Despite these environmental challenges, these wastes hold enormous potential as raw materials for industrial processes. Valorizing these wastes not only helps mitigate environmental impacts but also contributes to the sustainable development of the Amazon region [23].

Amazonian biomass residues have shown great potential in different contexts of energy production and storage. The açaí shell and seed, for example, are rich in lignin and cellulose and can be converted into high-quality activated carbon for use in supercapacitors and purification filters [24]. The Brazil nut shell and babaçu shell, in turn, have high oil content, making them viable raw materials for the production of biodiesel and bio-oils.

The chemical and thermal activation of residues such as cupuaçu shells and tucumã seeds can generate porous materials with high surface area, suitable for the adsorption of contaminants or as electrodes in energy storage devices such as batteries and electric double-layer supercapacitors. Additionally, extracts from these residues may contain antioxidant and antimicrobial compounds, adding value to the formulation of cosmetic and pharmaceutical products [25].

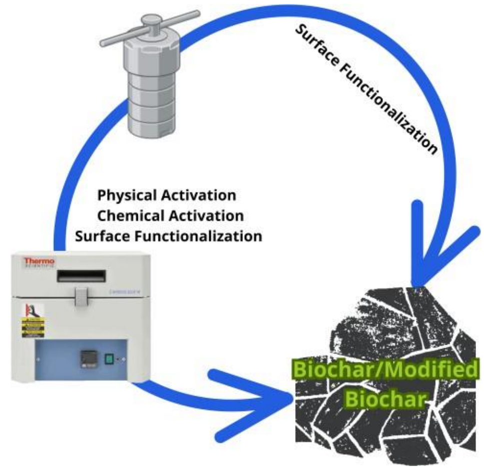
Another promising application is the use of these residues as precursors for the synthesis of nanomaterials, such as graphitic carbon and carbon nanotubes, which are essential in emerging energy technologies. The valorization of Amazonian residues in such applications not only boosts the circular economy in the region but also reduces dependence on fossil resources, promoting a cleaner and more sustainable energy matrix [26].

Amazonian biomass, especially the shells and seeds of exotic fruits, represents a renewable and underexplored source of materials for energy production and storage. Their utilization contributes to the mitigation of environmental problems and the development of sustainable technologies, aligning biodiversity conservation with technological innovation.

IV. BIOCHAR: PROPERTIES AND SYNTHESIS TECHNIQUES

Biochar is a carbonaceous material produced from the thermal decomposition of organic biomass under controlled low- oxygen or oxygen-free conditions, through processes such as pyrolysis. Its physical and chemical properties make it a versatile material used in various applications, including supercapacitors, catalysts, and soil improvement. Among its most remarkable characteristics, high surface area and adjustable porosity play pivotal roles in its performance, especially in adsorption processes and energy storage [27].

The surface area of biochar is directly influenced by the pyrolysis conditions, including temperature, residence time, and the type of biomass used. In many cases, biochar can achieve specific surface areas exceeding 1000 m^2/g, which is one of the reasons for its high efficiency in applications such as



adsorbents and electrodes in electrochemical devices [28]. The large surface area results from a complex porous structure, composed of micropores (diameter less than 2 nm), mesopores (between 2 and 50 nm), and, to a lesser extent, macropores (diameter greater than 50 nm). Micropores provide a significant active area for the adsorption of small molecules, while mesopores act as transport channels, facilitating the access of larger molecules or ions to the inner regions of the material [29].

Additionally, the porosity of biochar is adjustable, meaning it can be controlled during the production process by modifying pyrolysis conditions or applying post-treatments, such as chemical or physical activation. This adjustability is crucial for tailoring biochar to specific applications. For example, a biochar with a high fraction of micropores is ideal for energy storage systems, where a large surface area and adsorption capacity are required [30]. On the other hand, a balanced combination of mesopores and micropores is desirable for catalytic processes, in which both rapid reagent diffusion and a high active area are critical.

The effective surface area of biochar is also directly related to its morphology and texture. Roughness and pore distribution increase the available surface for interactions, making it highly efficient for electrostatic charge storage in supercapacitors or for pollutant adsorption in environmental applications [31].

Another relevant aspect of biochar is its electrical conductivity, which can be adjusted according to the production conditions. The conductivity of biochar increases as the pyrolysis temperature rises, since higher temperatures promote the aromatization of carbon structures and the formation of graphitic carbon networks. This makes biochar an attractive candidate for replacing traditional materials in energy storage devices, such as batteries and supercapacitors, where high electrical conductivity is required [32].

In addition to its structural characteristics, biochar is also known for its thermal and chemical stability. Due to its highly aromatized and carbon-rich structure, it exhibits excellent thermal resistance, being capable of withstanding temperatures above 400°C without significant degradation. Chemically, biochar is stable across a wide pH range, making it ideal for harsh environments, such as those found in heterogeneous catalysis applications [33]. The chemical stability of the material also makes it reusable in multiple reaction cycles, an important attribute in sustainable industrial processes. Thus, the combination of high surface area, adjustable porosity, electrical conductivity, and thermal and chemical stability makes biochar a material of great interest for a wide range of technological and environmental applications [34]

The utilization of biomass in the production of high-value materials, such as catalysts and supercapacitors, involves a series of technological processes aimed at maximizing the structural and chemical properties of the final products. Some these technologies are illustrated in Figure 3. Among these technologies, physical and chemical activation processes, as well as surface functionalization, are fundamental for producing carbonaceous materials with high surface area, controlled porosity, and specific catalytic properties [35].

Figure 3. Technologies for Biomass Conversion into Biochar.

A. *Physical Activation*

Physical activation of biomass is one of the initial steps in converting organic materials into activated carbon, which can be used in both catalysts and supercapacitors. There are two main methods of physical activation: hydrothermal carbonization and tubular furnace carbonization.

Hydrothermal Carbonization**:** This process involves treating biomass in an aqueous medium under conditions of high temperature and pressure (usually between 180°C and 250°C) for an extended period. During this process, the biomass is dehydrated and depolymerized, resulting in the formation of hydrochar, a precursor to activated carbon. Hydrothermal carbonization is particularly effective for wet and heterogeneous biomass, such as agricultural residues, as it promotes the dehydration and aromatization of carbon chains, preparing the material for subsequent activation [36].

Tubular Furnace Carbonization: This is a thermal process in which biomass is heated in an inert atmosphere (usually nitrogen or argon) at temperatures ranging from 400 °C to 1000 °C. During this process, biomass undergoes pyrolysis, i.e., the thermal decomposition of organic components, resulting in the formation of carbon with a porous structure. Pyrolysis may generate by-products such as gases and liquids, including bio-oil. The process can be classified as slow, fast, or instantaneous, depending on the heating rate and the residence time of the biomass in the reactor. The tubular furnace allows for precise control of temperature and residence time, which is crucial for optimizing the porosity and surface area of the resulting carbon. This carbon can be used directly or subjected to additional chemical activation processes [37].

Gasification and Torrefaction: These are thermal methods that, although they produce biochar, are not widely used for this purpose due to their limitations. Gasification occurs at temperatures above 700°C in a low-oxygen environment and focuses on the production of syngas, generating biochar as a by-product, usually with lower porosity and surface area. Torrefaction, conducted at moderate temperatures between 200 °C and 300 °C, aims to improve the biomass's properties as a fuel, resulting in denser and less porous biochar. Both processes produce biochar with less favorable characteristics for applications requiring high adsorption and surface area, making them less preferred compared to pyrolysis and hydrothermal carbonization [38].

The main purpose of physical activation is to remove volatile materials from the biomass, resulting in the formation of a carbonaceous structure with high thermal and mechanical stability, making it suitable for applications such as adsorbents and electrodes in energy storage devices.

B. *Chemical Activation*

Chemical activation is a subsequent or complementary step to physical activation, and its primary goal is to introduce and enhance the porosity of the carbonaceous material, as well as increase its surface area. This process involves impregnating the biomass or pre-carbonized charcoal with activating chemical agents, followed by heating under controlled conditions. The most common activating agents include potassium hydroxide (KOH), zinc chloride ($ZnCl_2$), and phosphoric acid (H_3PO_4), each playing specific roles in developing the porous structure [39].

Potassium Hydroxide (KOH): Promotes severe activation, resulting in the formation of micropores and mesopores with high surface area. KOH reacts with biomass during heating, forming potassium oxides that, when removed in the washing step, leave a network of pores [40]. Zinc chloride ($ZnCl_2$), on the other hand, acts as a dehydrating agent that facilitates carbonization at lower temperatures, promoting the formation of a porous structure with a predominance of micropores[41]. Phosphoric acid (H_3PO_4) acts as a dehydrating agent and favors the formation of phosphocarbonic bonds in the carbonaceous structure, resulting in materials with high surface acidity and adsorption capacity [42].

Chemical activation methods generally involve impregnating the biomass or pre-carbonized charcoal with the activating agent solution, followed by drying and heating in a tubular furnace under an inert atmosphere. The activation temperature varies depending on the chemical agent used, but generally occurs between 400 °C and 900 °C. After activation, the material is subjected to washing to remove chemical residues, exposing the porous structure created during the process [43].

Chemical activation is essential for producing materials with highly controlled porosity, which is crucial for applications in catalysts, where high surface area favors the adsorption of reagents and the acceleration of chemical reactions, and in supercapacitors, where the porous structure optimizes the storage capacity of electric charge.

C. *Surface Functionalization*

Surface functionalization is a critical step in adapting the properties of carbonaceous materials for specific applications, such as catalysts or supercapacitor electrodes. Functionalization involves introducing functional groups (acidic, basic, or other) onto the material's surface, which can enhance its catalytic activity or improve its energy storage capacity [44]. Two main functionalization methods are highlighted:

Acidic Functionalization: This involves treating the carbonaceous material with strong acids, such as sulfuric acid (H_2SO_4) or nitric acid (HNO_3). Through this process, acidic functional groups (such as carboxylic, sulfonic, and nitro groups) are introduced onto the material's surface, increasing surface acidity. This can be advantageous for catalysts in esterification reactions or to improve interaction with electrolytes in supercapacitors [45].

Basic Functionalization: In this method, the material is treated with strong bases, such as sodium hydroxide (NaOH) or ammonium hydroxide (NH_4OH). This treatment introduces basic groups, such as amines or hydroxyls, onto the carbon surface, which can enhance catalytic capacity in base reactions or increase ion adsorption in supercapacitors [46].

Surface functionalization is crucial for increasing the selectivity and efficiency of catalysts, enabling specific interaction with reagents. For supercapacitors, proper functionalization can improve capacitance, cycle stability, and the overall energy efficiency of the device.

In conclusion, physical and chemical activation technologies, along with surface functionalization, play fundamental roles in converting biomass into high-performance carbonaceous materials. These technologies enable the production of materials with adjustable properties, optimized for applications in catalysis and energy storage, contributing to the development of sustainable and efficient solutions.

V. Supercapacitors Applications

A. Carbon Electrodes in Supercapacitors

A supercapacitor, or ultracapacitor, is an energy storage device known for its ability to store and release energy rapidly, with a power density significantly higher than that of conventional batteries. Unlike batteries, which store energy through chemical reactions, supercapacitors rely on the separation of charges at electrode- electrolyte interfaces. This allows for fast charge/discharge cycles, high efficiency, and long lifespan [47]. Supercapacitors are used in applications requiring rapid power surges, such as electric vehicles and backup power systems [48]. Supercapacitors operate through two primary types of capacitance:

Electrical Double-Layer Capacitance (EDLC): EDLC occurs at the interface between the electrode and the electrolyte, where a voltage applied to the system causes electrolyte ions to be are adsorbed onto the electrode surface. The efficiency of EDLC is largely determined by specific surface area of the electrode and its ion adsorption capacity, making porous carbons materials particularly effective [49].

Pseudocapacitance: Pseudocapacitance arises from rapid and reversible electrochemical reactions, such as Faradaic charge transfer between the electrode and electrolyte ions. These reactions, which involve redox process, ion adsorption, or intercalation, increase the charge storage capacity beyond what is achievable by EDLC alone. Materials like metal oxides and conductive polymers are known for their high pseudocapacitance properties [50].

Porous carbons, especially those derived from biomass, have gained prominence as materials for supercapacitor electrodes due to their cost-effectiveness, sustainability, and superior electrochemical performance. These materials exhibit a highly developed porous structure, which is essencial for efficient ion adsorption at the electrode-electrolyte interface - a key process in supercapacitoy energy storage [51].

The efficiency of supercapacitors is strongly influenced by surface area of the electrodes. In EDLC, the capacitance is directly proportional to the number of ions adsorbed on the electrode surfaces. Biomass-derived porous carbons, with their extensive network of micropores (diameter < 2 nm) and mesopores (diameter between 2 nm and 50 nm) are highly effective in this regard [52].

When a voltage is applied to a supercapacitor, ions in the electrolyte migrate towards the porous carbon electrodes. On the positively charged electrode, anions from the electrolyte are attracted and adsorbed, while cations migrate to the negative charged electrode. This separation of charges at the electrode-electrolyte interface forms the electrical double layer, where electrostatic attraction between the opposite charges generates the capacitance [53].

The presence of micropores in carbon electrodes is critical for maximizing capacitance density, as these small pores provide an immerse active surface area within a confined space. However, ion accessibility to these micropores is equally important, and mesopores facilitate this by serving as ion transport channels. Mesopores enable ions to diffuse quickly through the material, reaching the micropores for adsorption [54].

The balance between micropores and mesopores is crucial for optimal performance, as a poorly distributed pore structure can lead to ion blockage, particularly in small or tortuous pores. Well-distributed mesopores help create an efficient transport network, ensuring rapid ion diffusion during charge and discharge cycles, which is essential for maintaining both high power density and device stability [55].

This optimized porous architecture not only enhances the specific capacitance of the supercapacitors but also contributes to their long-term stability, enabling consistent performance over thousands of cycles. Additionally, using biomass-derived porous carbons supports the sustainability of supercapacitor production, reducing the environmental impact associated whit traditional electrochemical materials.

B. Synthesis of Carbon Electrodes and Electrochemical Testing

The brush method is a widely used technique for synthesizing carbon electrodes from biomass. In this process, the biomass is first converted into activated carbon through carbonization, followed by chemical or physical activation, resulting in a material with high porosity and specific surface area. The activated carbon is then mixed with an appropriate solvent, which may contain a binder to improve the material's adherence to the substrate [56]. The resulting suspension is applied to the conductive substrate using a brush or a similar coating technique. After application, the electrode undergoes a drying and thermal treatment process to consolidate the carbon layer, ensuring good adhesion and electrical continuity. This method allows for the fabrication of electrodes with controlled thickness and optimized properties for supercapacitor applications.

To assess the electrochemical performance of the carbon electrodes, a three-electrode system is used in conjunction with a potentiostat. The three-electrode system consists of a working electrode, a counter electrode, and a reference electrode. The working electrode is the synthesized carbon electrode where electrochemical reactions occur. The counter electrode, usually a platinum rod, completes the electrical circuit. The reference electrode, such as Ag/AgCl or Hg/HgO, provides a constant and known potential, serving as a reference for all measurements [57]. The potentiostat controls and measures the potential applied between the working electrode and the reference electrode while recording the current generated during the process.

C. *Electrochemical Characterization Techniques Used in Supercapacitors*

The electrochemical characterization of supercapacitors involves several techniques, each providing specific insights into the performance and efficiency of the electrodes.

Cyclic Voltammetry (CV) is a fundamental technique for evaluating the electrochemical behavior of the electrode. In this technique, the current is measured as a function of the potential applied to the electrode. The resulting voltammetric curve is analyzed to determine the electrode's capacity to store and release charge. In efficient supercapacitors, the CV curve presents a rectangular shape, indicating that ion adsorption and desorption occur rapidly and effectively, which is characteristic of a device with high storage capacity and good efficiency [58][59].

Galvanostatic Charge and Discharge (GCD) is another crucial technique for measuring the supercapacitor's capacity. In this approach, a constant current is applied to the electrode, and the variation in potential is recorded over time. The resulting curve shows how the supercapacitor's capacity varies with charge and discharge time. For supercapacitors, the GCD curve typically exhibits a triangular shape, reflecting the linearity of the relationship between potential and time, which is characteristic of ideal capacitive behavior [60][61].

Electrochemical Impedance Spectroscopy (EIS) provides detailed information about the internal resistance and capacitance of the supercapacitor. In this technique, a small, variable frequency wave is applied, and the system's response is measured to determine resistance and capacitance at different frequencies. The Nyquist plot generated by EIS shows the relationship between the real resistance (Z') and the imaginary resistance (Z") of the supercapacitor. For high-performance supercapacitors, the plot features a curve forming an angle close to 90° with the Z" axis at low frequencies. This shape indicates low internal resistance and high capacitance, which is desirable for an efficient supercapacitor.

These combined techniques provide a comprehensive analysis of the electrochemical performance of porous carbon electrodes, allowing for the evaluation of their efficiency in energy storage applications [62][63][64].

D. *Carbon Electrodes from Amazonian Biomass*

Souza et al. (2021) highlighted the use of açaí seeds as a precursor biomass for the production of carbon materials for supercapacitor electrodes [65]. The methodology employed involved carbonization and chemical activation with KOH, which resulted in porous carbons with adjustable pore structures, ranging from micropores to mesopores, depending on the activation degree. The key results indicated that the electrodes derived from this biomass exhibited a high specific capacitance of 346 Fg^{-1} at 1 $mAcm^{-2}$ and excellent electrochemical stability, retaining 88% of capacitance after 5000 cycles.

These findings underscore the potential of açaí waste as a sustainable and effective solution for the development of supercapacitors.

Although açaí waste has been successfully used in the synthesis of electrodes, the literature reveals a scarcity of studies investigating the potential of other Amazonian biomass for similar application. This underscores a vast, unexplored area with significant potential for new research and innovation.

However, the limited number of studies in this area can be attributed to several factors, including logistical challenges in accessing remote regions of the Amazon, the high costs associated with the extraction and processing of biomaterials, and a lack of investment or incentives for scientific research in this region. Moreover, environmental conservation policies sometimes impose restrictions that can complicate large-scale exploration and utilization of these natural resources. These barriers highlight the need for stronger research support and collaborative efforts between governmental, academic, and industrial sectors to unlock the full potential of Amazonian biomaterials.

Additionally, there is a gap in the comparative analysis between Amazonian biomass and more conventional materials used in the production of supercapacitor electrodes. Future studies should aim to evaluate the performance, cost-effectiveness, and scalability of these biomaterials in comparison with widely used materials such as activated carbon derived from coconut shells or synthetic sources. A better understanding of the unique properties of Amazonian biomass, such as its high porosity, natural abundance, and potential synergies with local environmental sustainability efforts, could help position these materials as viable alternatives in global energy storage technologies.

Table 1 presents a selection of Amazonian biomass types that have already been used as adsorbents for pollutant removal, suggesting that these raw materials could also be promising for the synthesis of carbon electrodes. This would broaden the scope of applications for these materials in both energy and environment fields.

Table 1. Amazonian biomass types that have already been used as adsorbents.

Biomass	Synthesis method	Specific surface area (m2/g)	adsorbate	Reference
Brazil nut	tubular furnace / activation KOH	1121	Fe and Mn	[66]
Andiroba bark	Hydrothermal/ CO2 physical activation	1937	CO2	[67]
Tucumã seed	tubular furnace activation KOH	1318	2-nitrophenol	[68]
Pupunha seed	muffle furnace	874	tartrazine yellow dyes	[69]
Babaçu seeds	tubular furnace/ physically activated with CO2	1101.26	phenol	[70]

CATALYSIS APPLICATION

A. *Heterogeneous Carbon Catalyst*

Heterogeneous carbon catalysts are widely used in industrial processes due to their ability to promote chemical reactions without being consumed in the reaction. These catalysts, often based on porous carbon materials such as activated carbon or graphene, offer a variety of advantages, including a high surface area, thermal and chemical stability, and reusability. The catalytic process in a heterogeneous carbon catalyst involves several critical steps [71].

First, the reagents adsorb onto the catalyst surface. Adsorption is a fundamental process where reagent molecules physically or chemically attach to the catalyst surface. This step is crucial because the interaction of the reagents with the catalyst can significantly influence the efficiency and selectivity of the reaction. The porous structure of carbon catalysts provides a large surface area and active sites that facilitate this adsorption [72][73].

After adsorption, mass transfer occurs. This process refers to the movement of reagents and products in and out of the catalyst's pores and between the liquid or gas phase and the solid surface. The efficiency of this transfer is vital for the reaction rate and depends on the accessibility of the active sites in the catalyst and the diffusion of the reagents through the porous structure [74].

Catalyst selectivity refers to the ability to promote a desired reaction while minimizing parallel or secondary reactions. Carbon catalysts can be designed to exhibit high selectivity by adjusting the pore structure, surface chemistry, and distribution of active sites. This is achieved through surface functionalization and modification processes, which can introduce specific functional groups to direct the reaction of interest [75].

B. *Catalytic Testing and Characterizations*

To evaluate the performance of heterogeneous carbon catalysts, catalytic tests are conducted in various experimental setups, including controlled pressure reactors and bath flasks. In controlled pressure reactors, the catalyst is placed in an environment where pressure and temperature can be precisely adjusted. This type of reactor is ideal for studying reactions that occur under specific pressure and temperature conditions, as well as for assessing the stability and efficiency of the catalyst under realistic operating conditions. Experimental parameters, such as pressure and temperature, are carefully monitored and adjusted to optimize catalytic performance and ensure reproducible results [76][77].

Bath flasks are used to perform reactions under controlled temperature conditions. In this arrangement, the catalyst is mixed with the reagents in a reaction flask, which is placed in a thermal bath to maintain a constant temperature during the process. This setup is useful for preliminary studies of reactivity and for determining the efficiency of the catalyst over a wide range of temperatures [78].

To characterize heterogeneous carbon catalysts, several morphological, structural, and surface characterization techniques are employed:

Morphological Characterization: Techniques such as Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) are used to examine the morphology of the catalysts. SEM provides detailed images of the catalyst surface, while TEM allows for high-resolution visualization of the internal structure. These techniques help identify the shape, size, and distribution of pores in the catalyst [79].

Structural Characterization: X-ray Diffraction (XRD) is utilized to determine the crystalline structure and phase of the carbon materials. XRD provides information on the arrangement of atoms in the catalyst and can identify structural changes that affect catalytic activity.

Surface Characterization: Techniques such as Low-Pressure Nitrogen Adsorption (BET) and X-ray Photoelectron Spectroscopy (XPS) are employed to analyze the surface area and surface chemistry of the catalyst. The BET method measures specific surface area and pore size distribution, while XPS provides information on the functional groups present on the surface and their concentrations [80][81].

These characterization techniques provide a comprehensive view of the physical and chemical properties of carbon catalysts, allowing for the optimization and development of new catalytic materials with improved performance and efficiency.

C. *Amazonian Biomass Used as Acidic and Basic Catalysts*

Amazonian biomass has proven to be a promising source for the production of efficient catalysts in biodiesel synthesis, as evidenced by studies on tucumã, açaí, muruci, murumuru, passion fruit, and cupuaçu. These materials, considered agroindustrial waste, have been processed in various ways to optimize their catalytic properties and make the biodiesel production process more sustainable.

Tucumã shells were calcined at 800 °C, producing a heterogeneous catalyst rich in K, P, Ca, and Mg. This catalyst demonstrated high efficiency in the transesterification of soybean oil with methanol, achieving a conversion of 97.3% to biodiesel. The catalyst could be reused up to five times, with only a slight reduction in catalytic activity [82].

Açaí seed residues were used to synthesize solid acid catalysts functionalized with sulfonic groups through an in-situ functionalization method. This catalyst, prepared at 130 °C for 6 hours, exhibited a conversion of 95% of oleic acid to biodiesel. Additionally, the catalyst maintained its effectiveness for up to five reaction cycles, demonstrating high structural stability [83].

Muruci seeds were subjected to pyrolysis to generate a biochar, which was then functionalized with sodium, resulting in a basic catalyst. The 15Na/BCAM catalyst achieved a 97.2% conversion in the synthesis of biodiesel from vegetable oil, with high stability after several cycles of use, being effectively regenerated to maintain its activity [84].

Murumuru almond shells were used to produce an acidic biochar, which was applied in the transesterification of jupati oil. Although the catalyst initially showed good efficiency, the chlorophyll present in the oil deactivated the catalyst. This problem was mitigated by using an adsorbent from murumuru shells, which removed 92.5% of the chlorophyll, allowing the catalyst to be reused with 80% of catalytic activity retained [85]

Ashes from yellow passion fruit shells, rich in potassium, were used as a catalyst in the transesterification of cupuaçu butter, a byproduct with a lipid profile suitable for biodiesel production. The synthesis was optimized, resulting in a 97.8% conversion, highlighting the feasibility of using passion fruit and cupuaçu waste as bioresources for biodiesel [86].

These studies demonstrate that residues from different Amazonian biomasses can be processed to generate efficient catalysts, which not only contribute to the sustainable production of biodiesel but also offer an eco-friendly alternative for repurposing agroindustrial waste. The methodologies applied - including calcination, pyrolysis, in-situ functionalization, and hydrothermal treatment - were crucial for obtaining catalysts with high catalytic activity and reuse potential, reinforcing the economic and environmental viability of these materials in biofuel production.

VI. Future Prospects

The exploration of Amazonian biomass for the synthesis of supercapacitors and catalysts represents an emerging frontier in the bioeconomy and materials science. The Amazonia, with its vast biodiversity and abundance of plant waste, offers significant potential for the production of high-quality biochar. This carbonaceous material, when properly processed, can serve as a precursor for the manufacture of efficient supercapacitors and innovative catalysts.

Supercapacitors, known for their high energy storage capacity and rapid response time, are becoming essential components in advanced technologies, such as electric vehicles and portable electronic devices. The use of biochar derived from Amazonian biomass can not only reduce production costs but also contribute to a more sustainable approach to manufacturing these devices. The porosity and electrical conductivity of biochar, which are critical characteristics for the efficiency of supercapacitors, can be optimized through chemical and physical activation techniques tailored to the specific properties of Amazonian biomass.

Furthermore, biochar possesses catalytic properties that can be explored in a variety of chemical reactions, including those involved in reducing environmental pollutants and producing clean fuels. The presence of surface functional groups and the structural modification capability of biochar allow for its customization for specific applications. This opens up new possibilities for the integration of biochar-based catalysts in sustainable industrial processes, positively impacting both the regional economy and climate change mitigation.

Future prospects for the exploration of these biomasses include the development of more efficient and economically viable production processes that can be implemented on an industrial scale without compromising environmental sustainability. Continuous research into the characterization of the physical and chemical properties of biochar, derived from different Amazonian plant species will be crucial for identifying the best biomass sources and the optimal pyrolysis conditions.

Moreover, integrating these technologies into a circular economy, where agricultural and forestry waste is converted into high-value-added products, can boost the regional bioeconomy. Collaboration between universities, research centers, and industries will be essential for knowledge and technology transfer, ensuring that innovations derived from Amazonian biomass can be practically and effectively applied.

In summary, the exploration of Amazonian biomass for the synthesis of supercapacitors and catalysts offers a promising path for the development of advanced and sustainable technologies. By aligning with global demands for innovative and environmentally responsible solutions, this approach can transform the Amazonia into a hub of technological innovation, contributing to environmental preservation and the economic development of the region.

VII. CONCLUSION

The conversion of lignocellulosic biomass from the Amazon region, such as açaí seeds, tucumã peels, and Brazil nut shells, has proven to be a sustainable and efficient solution for the production of high-value carbon materials, particularly biochar. These underexplored biomasses offer significant potential for advanced technological applications, including the production of supercapacitors and catalysts. The agro-industrial residues from Amazonia, often improperly discarded, can be transformed into biochar with optimized properties such as high surface area and adjustable porosity. These materials have demonstrated high efficiency as electrodes in energy storage devices and as catalysts in chemical reactions, including biodiesel synthesis.

Despite the successful utilization of certain biomasses, such as açaí and tucumã, the vast biodiversity of the Amazonia presents a wealth of other biomass resources remain to be explored for these and other technological applications. Future research should prioritize expanding investigations into various types of Amazonian biomass using conversion techniques such as pyrolysis, hydrothermal carbonization, and chemical activation. This approach could unlock new possibilities for developing materials tailored to specific needs, including renewable energy devices and more efficient catalytic processes.

The valorization of these biomasses not only contributes to the regional bioeconomy but also promotes sustainability by repurposing organic waste into cutting-edge technological materials. Therefore, the utilization of Amazonian biomass reinforces the region's potential as a hub of innovation and sustainability, bolstering the circular economy and driving the development of solutions to global energy and environmental challenges.

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