American Journal of Applied and Industrial Chemistry
2025, Vol. 9, No. 2, pp. 53–67
https://doi.org/10.11648/j.ajaic.20250902.13

Review Article

Turning Waste into Clarity: A Review of Sugarcane Bagasse-Based Activated Carbon in Juice Purification

Wabi Reggasa Bogale*, Gemechu Duguma Argessa

Department of Industrial Chemistry, Bule Hora University, Hagere Mariyam, Ethiopia

Abstract

The extraction of table sugar, predominantly sourced from sugarcane and sugar beet, necessitates the intricate separation of sucrose from various non-sugar components through elaborate clarification and purification techniques. Activated carbon (AC) is widely acknowledged for its remarkable adsorption capabilities, making it an effective agent for eliminating impurities from aqueous solutions, including sugarcane juice. However, the high costs associated with the production and regeneration of commercial activated carbon underscore the need for developing affordable and sustainable alternatives derived from agricultural by-products. In this regard, sugarcane bagasse, a lignocellulosic residue generated during sugar processing, emerges as a plentiful and cost-effective precursor for activated carbon synthesis. The studies reviewed predominantly utilize two-step activation processes that combine chemical and physical methods to enhance the textural and adsorptive characteristics of the produced carbon materials. Critical activation parameters, such as carbonization temperature, impregnation ratio, and activation duration, play a significant role in determining the surface area, pore structure, and adsorption performance of the final product. Although activated carbon has a wide range of applications, there is a notable scarcity of research specifically addressing its function in the clarification of sugarcane juice. Preliminary findings indicate that activated carbon derived from sugarcane bagasse possesses a greater surface area and total pore volume compared to other biomass sources, leading to enhanced efficiency in color and impurity removal. Consequently, this review emphasizes the potential of sugarcane bagasse-based activated carbon as a sustainable and economical clarifying agent for sugarcane juice, advocating for further investigation to refine its use as a viable alternative to traditional chemical flocculants.

Keywords

Activated Carbon, Activation, Bagasse, Clarification, Surface Area, and Pore Structure

1. Introduction

1.1. Background of the Study

Sucrose, widely recognized as table sugar, is primarily extracted from two main sources: sugarcane (*Saccharum officinarum*) and sugar beet (*Beta vulgaris*). The industrial production of sugar is a complex process that involves a series of meticulously designed steps aimed at separating sucrose from various non-sugar constituents. This intricate procedure typically encompasses advanced techniques for isolation and purification, as highlighted [1]. For sugarcane, the initial phase of production entails the clarification of sugarcane juice, which is accomplished through a combination of coagulation,

*Corresponding author: wabireg@gmail.com (Wabi Reggasa Bogale)

Received: 18 October 2025; **Accepted:** 30 October 2025; **Published:** 9 December 2025

flocculation, and precipitation methods. These techniques are essential for eliminating colloidal particles and pigmented materials, which are subsequently removed through processes such as decantation and filtration.

A critical component of the clarification process is the generation of an insoluble precipitate that plays a vital role in absorbing and extracting unwanted compounds from the juice [2]. This precipitate not only aids in the purification of the juice but also enhances the overall quality of the final sugar product. The effectiveness of these methods is crucial, as they ensure that the sucrose extracted is of high purity, free from impurities that could affect its taste and usability. The careful orchestration of these steps underscores the sophistication of sugar production, reflecting the importance of both traditional practices and modern technological advancements in achieving optimal results in the sugar industry.

In the sugar industry, milk of lime is frequently employed to enhance the clarification process. While liming can reduce turbidity, it may also lead to increased mud levels and slower settling of flocs if not managed properly. This can result in clarified juice that contains elevated levels of calcium, potentially causing scaling issues in evaporators [3]. Alternative methods for juice clarification include the use of synthetic acrylamide polymer additives, which promote the rapid settling of impurities. However, these synthetic agents are costly and raise concerns regarding their carcinogenic and neurotoxic effects on human health. Furthermore, the use of sulfur dioxide in the sulphitation process for producing white sugar has been increasingly discouraged in various countries due to the associated health risks linked to the consumption of sugar contaminated with residual sulfur [4].

The principal objective of clarification in sugar processing is to obtain clear juice with minimal concentrations of insoluble and soluble impurities, thereby maximizing sugar yield and improving color quality one of the most critical parameters in raw sugar assessment. Unclarified juice is prone to enzymatic degradation and non-enzymatic browning reactions during storage, which adversely affect both color and overall quality. Raw sugars produced in both large- and small-scale industries are often difficult to decolorize during clarification, leading to quality deterioration and economic loss for producers [4].

The use of adsorbents for sugarcane syrup clarification represents an innovative approach that efficiently removes color compounds from sugarcane syrup, significantly improving the purification process. Among various adsorbents, activated carbon (AC) is the most widely utilized at the industrial scale due to its high specific surface area, favorable pore structure, tunable surface chemistry, and robust mechanical properties [5]. These characteristics make it suitable not only for sugar purification but also for applications in catalysis, separation, and environmental remediation.

Agricultural by-products have emerged as promising low-cost precursors for activated carbon production because of their abundance, renewability, and carbon-rich composition. Such carbons exhibit high adsorption capacity, substantial mechanical strength, and low ash content [6]. Activated carbon can theoretically be produced from any carbonaceous material rich in elemental carbon, and in recent years, considerable attention has been directed toward synthesizing it from agricultural wastes. Among these, sugarcane bagasse a fibrous residue generated during sugarcane milling stands out as an abundant and renewable feedstock [7].

Laboratory-scale studies have demonstrated that sugarcane bagasse-derived activated carbon (BAC) can serve as an effective and cleaner substitute for conventional chemical and thermal treatments in raw sugar production. The adsorption performance of BAC depends on its porosity, surface chemistry, and various process parameters such as contact time, carbon dosage, solution concentration, viscosity, and temperature [8, 9]. Numerous researchers have explored the preparation and application of activated carbons from agricultural residues for diverse purposes, including colorant removal from sugar liquors, as well as treatment of drinking water and industrial wastewater [9].

Recent advances have also introduced nano-activated carbon, which consists of nanoscale carbon particles synthesized from cellulose-rich materials such as annatto peels and sugarcane bagasse [10]. Nano- and bio-based clarificants are increasingly recognized as potential alternatives for the clarification of raw sugar and jaggery, as well as for water treatment. Nanotechnology has demonstrated promising performance in wastewater purification and food industries, enabling the detection and removal of chemical and biological contaminants [4].

In recent years, there has been a growing interest in identifying inexpensive and effective alternatives to conventional clarifying and flocculating agents used in various industrial processes. The exploration of low-cost activated carbon derived from biomass, particularly sugarcane bagasse, presents an opportunity to enhance environmental sustainability while providing viable solutions for commercial applications. Research indicates that activated carbon produced from biomaterials can be significantly more cost-effective compared to its commercial counterparts [11].

Traditionally, the removal of impurities, specifically non-sugar components, from sugarcane juice has relied on clarification and flocculation techniques. These processes often involve carbonation (utilizing calcium oxide and CO_2), sulphitation (introducing SO_2), and phosphitation (using H_3PO_4), alongside polyelectrolytes as flocculants. However, these methods can be prohibitively expensive for many developing countries. Moreover, they pose health risks due to the residual chemicals such as sulfur and phosphorus left in the final product, which can persist even after the completion of cane juice processing. Additional challenges include the generation of large volumes of sludge and low coagulation efficiency, which complicate waste management and increase operational costs.

The financial burden associated with chemical treatments

and the environmental pollution resulting from sludge disposal have prompted the need to investigate alternatives, such as locally produced activated carbon from plant sources like sugarcane bagasse. The conversion of sugarcane bagasse into activated carbon offers a promising solution, as it effectively removes contaminants from both liquid and gas phases. This carbonaceous material serves as an efficient adsorbent for impurities, including colored pigments both natural and process-induced as well as inorganic constituents (ash) present in clarified juice [3]. Despite its potential, research specifically addressing the application of activated carbon from sugarcane bagasse for juice clarification remains limited. Therefore, this review emphasizes the necessity for comprehensive studies on the clarification capabilities of bagasse-based activated carbon in sugarcane juice, particularly in the absence of chemical flocculants.

1.2. Significance of the Review

Sugar, derived from sugarcane and sugar beet, is an essential product globally, serving as a sweetener in both domestic food preparations and the food processing industry. The clarification of sugarcane juice using activated carbon sourced from plants, such as sugarcane bagasse, represents an innovative approach to reducing impurities during processing. This method not only has the potential to lower processing costs but also to enhance the purity of the final products.

The purpose of this review is to recommend effective, cost-efficient, and eco-friendly clarifying agents for the purification of sugarcane juice. By highlighting the advantages of using plant-based activated carbon, this review aims to inform researchers, sugar producers, governmental bodies, and non-governmental organizations about its benefits. The findings are intended to promote a broader understanding of the application of activated carbon derived from sugarcane bagasse in juice purification processes, both nationally and internationally. This knowledge could facilitate the adoption of sustainable practices in the sugar industry and contribute to improved product quality and environmental stewardship.

2. Sugarcane Processing and Various Products

Sugarcane is primarily cultivated for sugar production, but its processing yields various valuable by-products, including bagasse, brown sugar, molasses, syrup, and jaggery, in addition to table sugar. The large-scale processing of sugarcane for sugar production involves several key steps, as illustrated in Figure 1.

Initially, the cane is harvested, transported, and washed to remove dirt, soil, and other residues. The next step involves chopping the cane into smaller pieces using revolving knives in a shredder, a powerful hammer mill that transforms the cane into a fibrous material. At this stage, the cane stalks are ruptured, but no juice is extracted. The sugar juice is subsequently extracted through the use of mills or diffusers, separating the fibrous cellulosic matter known as bagasse, which can then be further processed into sugar [3].

Following juice extraction, clarification is performed through the addition of various chemicals. Lime is used to raise the pH, while sulfur dioxide (SO_2) is employed for decolorization during the sulphitation process. Additionally, caustic soda (NaOH) and soda ash (Na_2CO_3) are utilized to manage impurities in evaporators and vacuum pans, and the system is rinsed with hydrochloric acid (Eggleston, 2008).

The production of pure sugar involves several stages, including juice purification, concentration through evaporation, sucrose crystallization, and final separation and drying. The purification process, known as defecation, occurs at relatively high temperatures and involves the action of chemical agents, primarily calcium hydroxide ($Ca(OH)_2$) and magnesium hydroxide ($Mg(OH)_2$), in conjunction with heat [12]. This method is one of the most commonly used treatments for juice purification.

During this heating process, various compounds are formed, notably chromophoric impurities, which arise primarily from the alkaline degradation of sucrose. These impurities account for approximately 70% to 80% of the total mass of colored products in the juice. The development of these colored compounds is a prevalent issue in both the cane and beet sugar industries [13].

In light of these challenges, contemporary research is focused on enhancing the most widely used methods for clarifying raw sugarcane juice. The goal is to achieve greater efficiency in removing non-sugar compounds and color while minimizing sucrose loss [14].

Sugar is obtained through the refining of cane juice, but other unrefined sugarcane products, such as jaggery, brown sugar, and molasses, are also produced [15]. Sugar mills generate substantial quantities of solid waste and residual effluents during processing, many of which contain high pollutant loads. These by-products include bagasse, filter cake, soil matter, organic impurities, wastewater, and molasses. Notably, some of these materials, such as molasses and bagasse, have significant potential for recycling and reuse [16].

Sugarcane bagasse, a by-product of the sugarcane industry, is produced after juice extraction for sugar production. Approximately 54 million dry tons of bagasse are generated annually worldwide [8]. However, the treatment and disposal of bagasse pose challenges [17]. One promising approach is to utilize bagasse as an additive for the production of sludge-based adsorbents, thereby enhancing their adsorption capacity. The bagasse is obtained by crushing and squeezing the sugarcane to extract the juice, and is subsequently collected, dried at 105 ℃, ground, and sieved into various particle sizes [18].

In addition to its potential as an additive, sugarcane bagasse is currently used as fuel for boilers and as a raw material for manufacturing pulp, paper, and building boards. According to the previous research report, [19], bagasse in its natural state

is a poor adsorbent for organic compounds, such as sugar colorants and metal ions. To enhance its adsorptive properties toward these contaminants, although another researcher. suggested that bagasse must undergo physical or chemical modification. This transformation is effectively achieved through the conversion of bagasse into activated carbon, which has been identified as a suitable resource for the preparation of activated carbon [8].

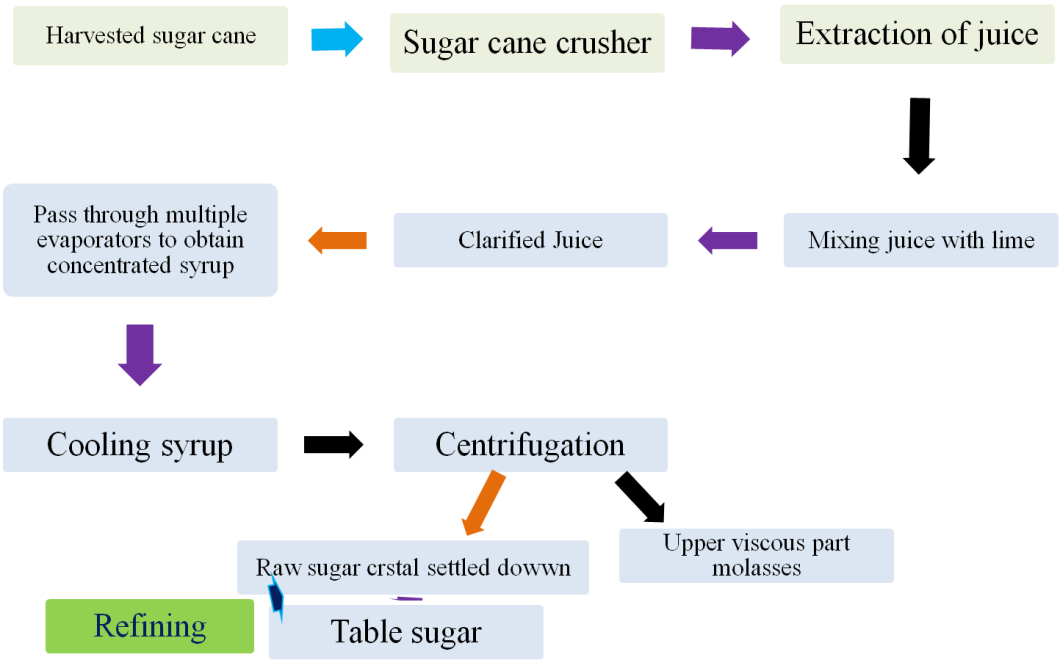

Figure 1. *Sugarcane products processing flow chart Source: [3].*

2.1. Sugar Production Status in Ethiopia

Ethiopia is among the sugar-producing countries that cultivate sugarcane, contributing approximately 0.18% of the total global sugar output. Commercial sugar production in the country began in 1954 with the establishment of the Wonji Sugar Factory, marking the inception of Ethiopia's modern sugar industry. Since then, sugar has been produced primarily from irrigated and semi-mechanized sugarcane plantations managed by state-owned sugar estates, alongside limited participation from smallholder out-growers' schemes.

Currently, Ethiopia maintains about 45,000 hectares of sugarcane cultivation, which supplies raw material to three operational factories Wonji, Metehara, and Finchaa. Together, these factories produce an estimated 460,000 tons of sugar annually. In addition to sugar, the Finchaa and Metehara sugar industries also engage in ethanol production, generating approximately 20 million and 15 million liters of ethanol per year, respectively. The ethanol is blended at 10% with gasoline for use in the transport sector, contributing to the country's renewable energy initiatives.

The Ethiopian sugar industry plays a significant role in the national economy by creating employment opportunities for over 28,000 people, while also supporting rural livelihoods and contributing to industrial development [20]. However, despite these contributions, the country's sugar production potential remains underutilized. Productivity has fluctuated from year to year due to the limited application of improved agronomic and manufacturing technologies. In contrast, other major sugar-producing countries have significantly enhanced production efficiency through technological innovation, research-based practices, and process optimization. Hence, Ethiopia's sugar sector would benefit from adopting advanced technologies to optimize both cane yield and sugar recovery efficiency [20].

2.2. The Composition of Sugarcane Juice

Sugarcane juice is well known raw material mainly for the production of raw and refined sugar. Raw cane juice and its subsequent form (mixed juice, MJ) are stable suspensions that contain large numbers of suspended particles. Sugarcane juice with its two separate sections contain sucrose and other soluble components (glucose, fructose, inorganic ions, organic acids, polysaccharides, proteins, starch, amino acids, vitamins, etc.) and insoluble matters (soil, sand lipids, gums and wax), chromophoric substance and non-sucrose components [3]. The chromophoric compounds are initially present in the juice as chlorophyll and polyphenols. Other colored substances and compounds are formed during the various stages of processing the juice, mainly during juice purification. The relative amounts of the components in cane juice is depend on the variety, maturity, and weather condition of the cane plant, soil

type, and the harvesting method and processing conditions [3].

The shelf life of sugarcane juice is limited due to high incidences of microbial contamination and enzymatic reactions, which begins immediately after extraction. Sugarcane juice is highly susceptible to spoilage due to the presence of sugars and high water content [21]. The researcher stated further, as to determine the quality of sugarcane juice extracted from stored canes, as well as change in quality of fresh juice stored at different temperatures. Cane stems were stored at 10 and 30 ℃ while the fresh juice was stored at 5 and 30 ℃. The parameters was studied are; juice yield, total soluble solids, total sugar content, titratable acidity, P^H, viscosity, total microbial count and sensory evaluation for colour and flavor. Results showed that low temperature storage (10 ℃) of canes was able to maintain the quality of juice for 10days, while low temperature storage (5 ℃) of juice could last for only 4days. Spoilage of cane stored at 30 ℃ occurred faster than that stored at 10 ℃ [21].

Microorganisms present in the sugarcane juice induce rapid microbial fermentation by conversion of sucrose into organic acid and ethanol, thus imparting sour taste within hours of extraction [22]. Another major problem in sugarcane juice processing is the enzymatic browning due to the activity of polyphenol oxidase and peroxidase [23]. hese problems associated with sugarcane juice possess serious challenges in processing and marketing sugarcane based beverages.

2.3. Use of Clarificant and Flocculants in Sugar Production

Sugarcane juice is the primary raw material used in the production of both raw and refined sugar. The extracted juice, often referred to as *mixed juice (MJ)*, is a stable suspension containing numerous soluble and insoluble components. Chemically, sugarcane juice consists mainly of sucrose, accompanied by other soluble constituents such as glucose, fructose, inorganic ions, organic acids, polysaccharides, proteins, starch, amino acids, and vitamins. It also contains insoluble materials including soil particles, sand, lipids, gums, and waxes, as well as chromophoric and non-sucrose compounds [3].

The chromophoric substances in sugarcane juice primarily originate from chlorophylls and polyphenolic compounds, while additional colored materials are formed during processing, particularly in the clarification and purification stages. The relative composition of cane juice components varies with several factors such as cane variety, maturity stage, climatic conditions, soil type, harvesting method, and processing parameters [3].

The shelf life of sugarcane juice is generally limited due to its high sugar and moisture content, which promote rapid microbial growth and enzymatic degradation immediately after extraction. Studies on juice storage under different temperature conditions revealed that storing sugarcane stems at 10 ℃ preserved juice quality for up to 10 days, whereas storing fresh juice at 5 ℃ extended its usability for only four days. In contrast, samples stored at 30 ℃ exhibited accelerated spoilage characterized by increased microbial load, acidity, and undesirable changes in color and flavor [21].

Microorganisms present in freshly extracted juice initiate fermentation, converting sucrose into organic acids and ethanol, which imparts a sour taste within hours of extraction [22]. In addition to microbial spoilage, enzymatic browning caused by the activity of polyphenol oxidase (PPO) and peroxidase (POD) enzymes represents another significant issue affecting juice quality and appearance [23]. Together, these microbial and enzymatic processes pose major challenges to the processing, storage, and commercialization of sugarcane juice and related beverages.

2.4. Activation of Activated Carbon

The term *activated carbon* originates from the combination of two words *carbon* and *active*. The term “carbon” refers to a material obtained after carbonization of a raw precursor, while “active” indicates that the carbon has undergone an activation process, which develops its porous structure and enhances its surface area, thereby improving its adsorption capacity [24]. Activated carbon can be produced from a wide range of carbonaceous materials containing organic carbon. Ideally, suitable raw materials should possess a high carbon content, low volatile and inorganic matter, and exhibit good mechanical and thermal stability. Economically, materials that are inexpensive and widely available are preferred for large-scale production [25].

Traditionally, activated carbon has been derived from coal and charcoal. However, growing environmental concerns and sustainability goals have motivated the use of renewable biomass resources as precursors. These include agricultural residues, plant stems, and other organic wastes. For example, Investigated the carbonization of plantain (*Musa paradisiaca*) stem at 400 ℃ for one hour, followed by chemical activation using phosphoric acid (H_3PO_4) and zinc chloride ($ZnCl_2$) to produce CPPAC (carbonized plantain phosphoric acid activated carbon) and CPZAC (carbonized plantain zinc chloride activated carbon), respectively [26]. Physicochemical analyses including pH, bulk density, moisture content, ash content, volatile matter, iodine number, and surface functional groups revealed that chemical activation induced significant structural and chemical transformations. CPPAC was found to be more suitable for liquid-phase adsorption due to its lower bulk density, reduced ash content, and higher iodine value, indicating enhanced microporosity and adsorption efficiency [26].

The preparation of activated carbon generally involves three main stages: pretreatment, carbonization, and activation. Pretreatment removes soluble impurities and residual nutrients from the biomass. During carbonization, lignin, cellulose, and hemicellulose are thermally decomposed to form carbonaceous char while eliminating water, oxygen, hydrogen,

sulfur, and volatile compounds. Typically, carbonization occurs above 400 ℃, leading to dehydration and the release of gaseous products such as H_2O, CO, and CO_2, which facilitate subsequent activation reactions. The activation stage further develops the pore network and increases surface area through chemical or physical means [27].

Recent research trends favor the use of non-woody agricultural wastes as precursors for activated carbon due to their favorable chemical composition and the potential to develop superior pore structures compared to woody materials. The selection of raw materials is guided by seven key criteria proposed by Menéndez-Díaz [28]. High carbon content; Low inorganic matter to minimize ash formation; High density and volatile matter content; Abundant and low-cost availability; High activation potential; Low degradation rate during storage; and Ability to yield a significant amount of activated carbon after processing.

However, most biomass residues inherently possess lower carbon content than fossil-based materials, which can limit their activation yield [29]. Despite this, biomass-derived activated carbon remains a cost-effective adsorbent with excellent textural properties and adsorptive performance. Traditionally, microporous activated carbons (pore width < 2 nm) have been utilized for various purification applications. More recently, mesoporous carbons (pore width between 2-50 nm) have gained growing attention because of their broader adsorption capacity and enhanced performance across a wider range of environmental and industrial applications [8].

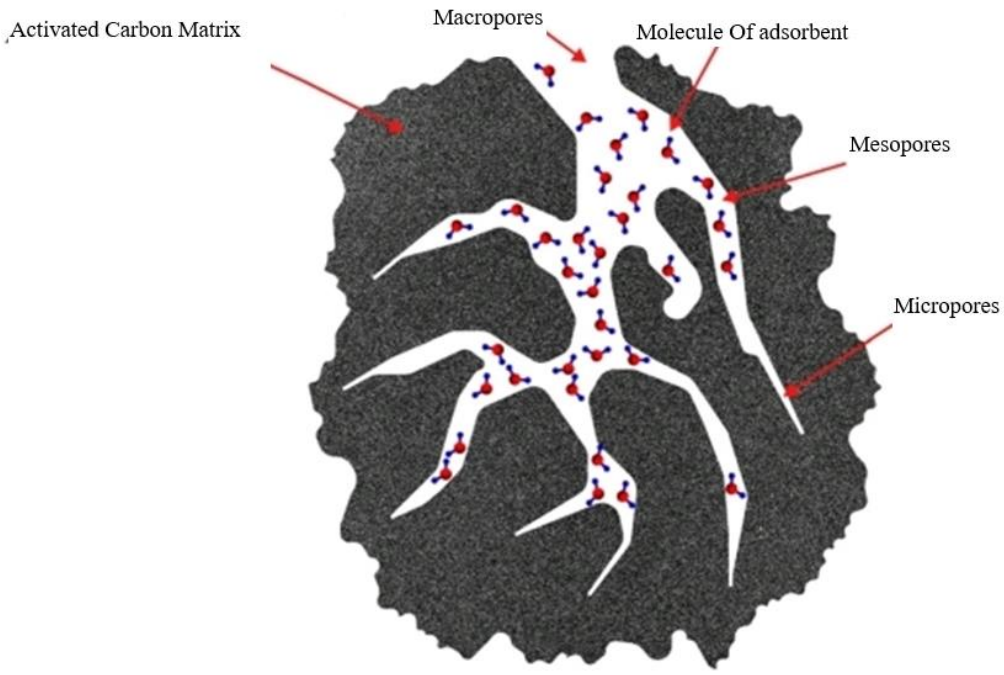

Figure 2. *Pore structures in activated carbon Source: [20].*

Porous carbon (Figure 2) is characterized by distinct physicochemical properties such as a large surface area, a wide range of pore sizes, and relatively low density. Activated carbon, on the other hand, refers to carbon materials whose surfaces have been modified or activated through processes such as surface functionalization, or metal and oxide deposition to enhance their performance for specific applications. While all activated carbons are porous carbons, not all porous carbons are activated. The pore size distribution of porous carbons spans a wide range, whereas activated carbons are predominantly microporous materials [30].

Though a fundamental difference exists between porous and activated carbons, the boundary between the two is sometimes indistinct, especially in terms of processing and application. During activation, both pore generation and surface modification occur simultaneously, resulting in enhanced surface characteristics and adsorption properties.

Byamba-Ochir reported that activated carbon can be produced either through direct activation of dried raw precursors or via a two-stage process involving initial carbonization followed by activation. In the two-stage process, raw materials such as walnut shells, wood, bone, sugarcane bagasse, or coal are first carbonized at elevated temperatures (typically below 700 ℃) in the absence of oxygen [31]. This carbonization process, essentially a pyrolytic reaction, drives off volatile hydrocarbons, yielding a solid carbon-rich residue known as char or biochar. Subsequent activation using physical or chemical methods develops the internal porosity, creating fine cavities and enhancing the material's adsorption capacity [29].

2.5. Clarification of Sugarcane Juice and Its Challenges

Clarification is a crucial stage in sugar processing that directly affects the purity, color, and overall yield of sugar. The primary objective of juice clarification is to remove suspended and colloidal impurities, including organic acids, proteins, polysaccharides, colorants, and inorganic materials such as mud and silica. These impurities, if not removed effectively, lead to poor crystallization, darker color, and reduced sugar quality in the final product [1].

Conventionally, clarification involves a combination of chemical and physical processes, typically including lime treatment, heating, and sedimentation or filtration. Lime (calcium hydroxide) is commonly added to adjust the pH of the juice to around 7.0-7.2, which promotes the precipitation of non-sugar substances and stabilizes sucrose. The clarified juice is then separated from the precipitated impurities, referred to as *press mud*. However, this conventional process requires precise control of temperature, pH, and chemical dosage to ensure effective impurity removal without causing sucrose loss or re-coloration of the juice [32].

Despite its widespread use, the traditional clarification method faces several challenges. Excessive use of lime can lead to scaling in evaporators, sucrose inversion, and increased production costs. Moreover, the disposal of lime mud poses environmental concerns. Additionally, the chemical clarifiers used in some plants may introduce secondary contaminants or residual color, which compromise product quality. These limitations have driven research toward alternative and eco-friendly clarification methods [4].

In recent years, adsorption-based clarification using activated carbon (AC) and other bio-based adsorbents has gained attention as a sustainable and efficient approach. Activated carbon effectively removes colorants, organic impurities, and colloidal materials from sugarcane juice through surface adsorption and pore diffusion mechanisms. The efficiency of adsorption depends on parameters such as carbon dosage, contact time, pore structure, surface chemistry, and juice viscosity [8]. However, the high cost of commercially produced activated carbon limits its large-scale application in the sugar industry.

To overcome this barrier, researchers have explored the production of low-cost activated carbon from agricultural by-products, particularly sugarcane bagasse, which is abundantly available in sugar mills. Bagasse-derived activated carbon (BAC) has shown promising results in removing colorants and turbidity from sugarcane juice, offering an environmentally friendly alternative to conventional clarification techniques [9].

Nevertheless, the application of sugarcane bagasse-based activated carbon in juice clarification remains underexplored, and further studies are needed to optimize its production parameters, regeneration methods, and performance consistency. The integration of such green technologies could significantly enhance the sustainability of sugar manufacturing while reducing dependence on chemical clarifiers and minimizing waste generation.

2.6. The Activation Methods of Carbon Materials

The activation of carbon materials plays a pivotal role in converting raw precursors into high-performance porous adsorbents characterized by extensive surface areas and diverse functional groups. This transformation is primarily achieved through two predominant techniques: physical (or thermal) activation and chemical activation [29, 33]. Each method is designed to improve the porosity, surface reactivity, and overall adsorption capacity of the carbon materials. However, they diverge significantly in their operational conditions, underlying mechanisms, and the environmental consequences associated with their application. For instance, physical activation typically involves the use of high temperatures in the presence of activating agents such as steam or carbon dioxide, while chemical activation employs chemical agents like phosphoric acid or potassium hydroxide at lower temperatures, leading to different structural and chemical properties in the resulting adsorbents.

The choice between physical and chemical activation is influenced by various factors, including the desired characteristics of the final product and the specific applications for which the adsorbents are intended. Physical activation generally results in a more uniform pore structure and higher thermal stability, making it suitable for applications requiring robust materials. In contrast, chemical activation often yields a higher surface area and greater functionalization, which can enhance the material's affinity for specific adsorbates. Understanding these differences is essential for optimizing the production of carbon-based adsorbents tailored to meet the demands of various environmental and industrial applications, thereby contributing to advancements in fields such as water treatment, air purification, and energy storage.

2.6.1. Physical Activation Method

Physical activation, also known as thermal activation, is a two-step process consisting of carbonization (pyrolysis) followed by gasification or activation. In the first stage, the organic precursor is carbonized in an inert atmosphere (usually nitrogen or argon) at moderate temperatures to remove volatile compounds and obtain a carbon-rich char. In the second stage, the carbonized material is exposed to oxidizing gases such as steam, carbon dioxide (CO_2), or air mixtures at elevated temperatures typically ranging from 800 to 1100 ℃ [33].

During this stage, partial gasification occurs, leading to the development of porosity through the controlled removal of carbon atoms. The process enlarges existing pores and generates new micro- and mesopores within the carbon matrix. This results in a product with good mechanical strength, low

ash content, and high structural stability.

One of the main advantages of the physical activation process is its chemical-free nature, making it an environmentally friendly and green approach for producing activated carbon [31]. Moreover, it is cost-effective and suitable for large-scale industrial applications, especially when inexpensive carbonaceous feedstocks such as coconut shells, sawdust, or sugarcane bagasse are used.

However, several limitations are associated with this method. Physical activation generally requires long activation times and high energy input, leading to increased operational costs. Furthermore, the resulting activated carbons often exhibit lower adsorption capacity compared to chemically activated ones due to less-developed microporosity [29]. Despite these drawbacks, physical activation remains widely used because of its simplicity, absence of chemical waste, and production of mechanically robust carbon materials.

2.6.2. Chemical Activation Method

In contrast to physical activation, chemical activation combines carbonization and activation into a single step, where both processes occur simultaneously in the presence of a chemical activating agent. The precursor is impregnated or mixed with an activating compound and then heated under an inert atmosphere (usually nitrogen). During heating, the activating agent promotes dehydration, oxidation, and structural rearrangements that result in the development of a highly porous carbon network [34, 35].

In this process, the raw material is first saturated with dehydrating and oxidizing agents such as phosphoric acid (H_3PO_4), zinc chloride ($ZnCl_2$), potassium hydroxide (KOH), or sodium hydroxide (NaOH). After impregnation, the suspension is dried and subsequently heated to temperatures between 400 ℃ and 900 ℃, depending on the precursor and activating chemical. At these temperatures, cellulose and other biopolymers decompose, forming a cross-linked carbon framework. The resulting solid is repeatedly washed to remove residual activating agents and soluble by-products, yielding clean, porous activated carbon [36].

Chemical activation agents act primarily as dehydrating catalysts, preventing the formation of tar or bituminous materials during pyrolysis and thus increasing carbon yield. They facilitate the formation of fine micropores and mesopores by deeply penetrating the carbon structure and reacting with carbon atoms to liberate gaseous products [37, 38]. This reaction pathway enables enhanced surface area development and improved adsorption properties.

Unlike physical activation, which typically requires two separate furnaces for carbonization and activation, chemical activation is conducted in a single reactor, reducing energy consumption and process complexity [36]. The effectiveness of the activation process depends on several parameters, including:

1) Type of activating agent
2) Impregnation ratio (mass of activating agent to dry precursor)
3) Activation temperature and time
4) Heating rate and atmosphere
5) Precursor composition and particle size [39, 40].

Chemical activation is generally considered more efficient than physical activation because it produces carbons with larger surface areas, higher porosity, and superior adsorption capacity at lower activation temperatures and shorter times [41]. Furthermore, the yield of activated carbon is often higher, and the process allows better control over pore size distribution.

Nevertheless, the method also presents notable disadvantages. The post-activation washing step, necessary to remove residual chemicals, is often time-consuming and water-intensive. The resulting wastewater may contain toxic residues (e.g., Zn^{2+} , Cl^- , or phosphate ions), posing environmental challenges and requiring secondary treatment before disposal [42].

The main activating chemicals used include alkaline agents such as KOH, NaOH, $CaCl_2$, and K_2CO_3; acidic agents like H_3PO_4 and H_2SO_4; and neutral metal salts such as $ZnCl_2$ [43]. Depending on their physical state, activating agents can be mixed with the precursor either through dry blending or wet impregnation. During activation, these agents act as oxidizing, dehydrating, and structural templating agents, facilitating the formation of an interconnected porous matrix [44].

In summary, physical activation presents a straightforward and environmentally friendly approach to producing carbon materials. This method is characterized by its simplicity and minimal environmental impact, making it an attractive option for various applications. However, it is important to note that while physical activation is advantageous in terms of sustainability, the resulting carbon materials may not possess the advanced textural and surface characteristics required for certain high-performance applications. These applications include adsorption processes, catalytic reactions, and energy storage systems, where specific properties such as surface area, porosity, and chemical reactivity are crucial for optimal performance.

On the other hand, chemical activation is a more complex process that typically results in carbons with enhanced textural and surface properties. This method allows for greater control over the characteristics of the final product, making it particularly suitable for applications that demand high efficiency and effectiveness. The decision between utilizing physical or chemical activation ultimately hinges on several factors, including the specific requirements of the intended application, the type of feedstock available, and the environmental implications of each method. Therefore, a careful assessment of these elements is essential for selecting the most appropriate carbon production technique.considerations.

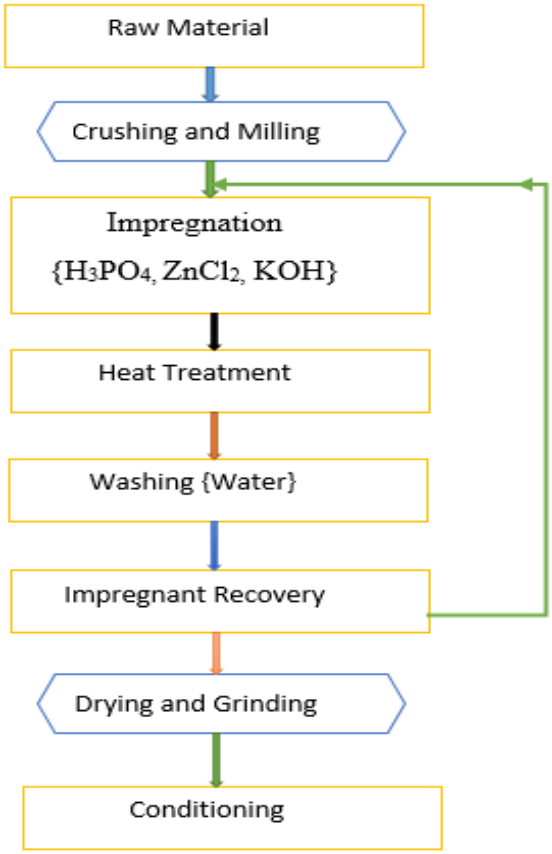

Figure 3. *Chemical activation process of activated carbon, Source: [40].*

(i). Preparation of Activated Carbon Using Phosphoric Acid

Phosphoric acid (H_3PO_4) stands out as one of the most widely utilized activating agents for lignocellulosic biomass, primarily due to its remarkable efficiency and the relatively gentle conditions it requires for activation [29]. The activation process facilitated by phosphoric acid is characterized by a series of chemical transformations, including depolymerization, dehydration, and the redistribution of key biopolymers such as cellulose, hemicellulose, and lignin found in lignocellulosic materials [45]. These transformations are crucial for breaking down the complex structure of biomass, thereby enhancing its reactivity and suitability for subsequent applications.

As the activation progresses, phosphoric acid engages with the hydroxyl groups present in the carbonaceous precursor, which fosters cross-linking reactions while simultaneously mitigating the formation of excessive tar. With an increase in temperature, the process generates volatile byproducts that facilitate the development of micropores and mesopores in areas previously occupied by decomposed biomass [46]. This transformation not only improves the porous architecture of the activated carbon but also significantly increases its surface area, making it more effective for various applications, including adsorption and catalysis. The intricate interplay of these chemical reactions underscores the importance of phosphoric acid in optimizing the properties of activated carbon derived from lignocellulosic sources.

Additionally, phosphoric acid treatment increases the concentration of acidic surface functional groups, such as phosphate and carboxyl groups, which enhance the hydrophilicity and ion-exchange capacity of the carbon surface [45]. These surface modifications improve the adsorbent's affinity for polar and ionic species in aqueous systems, making H_3PO_4-activated carbons highly effective in water purification and sugar decolorization applications.

However, excessive impregnation with phosphoric acid may lead to the formation of polyphosphate layers on the carbon surface, which can block pore openings and reduce the overall porosity [47]. Therefore, optimization of the acid concentration, impregnation ratio, and activation temperature is crucial to achieving a balance between porosity development and carbon yield.

(ii). Preparation of Activated Carbon Using Zinc Chloride

Zinc chloride ($ZnCl_2$) is widely recognized as an effective activating agent for the production of activated carbon from lignocellulosic and cellulosic sources, as noted [48]. In the activation process, $ZnCl_2$ serves a dual purpose: it acts as a dehydrating agent and promotes the swelling of the biomass. This interaction is crucial as it aids in the disintegration of lignocellulosic materials into smaller carbon-rich fragments. The thermal decomposition of biomass in the presence of $ZnCl_2$ leads to the release of various volatile gases, including carbon monoxide (CO), carbon dioxide (CO_2), methane (CH_4), and aldehydes. These gases play a significant role in developing a porous structure within the activated carbon, as highlighted [49].

Moreover, zinc chloride is instrumental in maintaining the integrity of the pore structure throughout the activation process by moderating the expulsion of volatile substances. The effectiveness of $ZnCl_2$ in enhancing the activation process is closely linked to the mass ratio of the activating agent to the raw material. An increase in the concentration of $ZnCl_2$ facilitates the easier release of volatile compounds, which in turn enhances nitrogen adsorption capabilities and increases the overall pore volume of the resulting activated carbon, as discussed [48]. This relationship underscores the importance of optimizing the $ZnCl_2$ concentration to achieve the desired characteristics of activated carbon.

However, an excessive amount of $ZnCl_2$ may cause structural cracking and collapse, converting micropores into mesopores and thereby reducing the overall carbon yield [50]. Additionally, higher $ZnCl_2$ concentrations tend to decrease the number of acidic surface functional groups, including phenolic and carboxylic sites, while increasing lactonic groups, which can influence the adsorption selectivity of the final product [51].

Despite these drawbacks, $ZnCl_2$ activation is widely preferred for its ability to generate mesoporous carbons with large surface areas and uniform pore distributions, suitable for applications in gas adsorption, catalysis, and dye removal.

(iii). Activated Carbon Preparation by Potassium Hydroxide

In recent years, there has been a growing interest in alkali metal salts, particularly potassium hydroxide (KOH) and potassium carbonate (K_2CO_3), as potent activators for the synthesis of high surface area activated carbons at relatively moderate temperatures. Research indicates that KOH is particularly effective in producing activated carbons characterized by well-developed microporous and mesoporous structures, a uniform distribution of pores, and minimal levels of impurities. This makes KOH a preferred choice among researchers and industry professionals aiming to optimize the properties of activated carbons for various applications, including adsorption and catalysis.

The activation process using KOH typically involves a careful preparation stage where the precursor material, which can either be carbonized biomass or raw biomass, is mixed with KOH at a predetermined impregnation ratio. This mixture is then subjected to thermal treatment in an inert atmosphere at temperatures ranging from 600 ℃ to 900 ℃. During this thermal activation, a series of chemical reactions occur, resulting in the generation of metallic potassium, water vapor, and gaseous byproducts such as hydrogen (H_2) and carbon dioxide (CO_2). These gaseous products play a crucial role in the activation process, as they penetrate the carbon lattice, facilitating the formation of new pores and the enlargement of existing ones. This intricate interplay of reactions not only enhances the surface area of the activated carbon but also significantly improves its structural characteristics, making it suitable for a wide range of applications. This method generally results in activated carbons with exceptionally high surface areas (up to 2500 m^2/g) and high microporosity, but the yield is often low (typically 10-40%) due to carbon consumption during activation [52]. Furthermore, KOH-activated carbons exhibit excellent adsorption performance for gases and small organic molecules, though their microporous nature may limit their ability to adsorb larger macromolecular pollutants.

Nevertheless, environmental concerns exist regarding the toxicity and corrosiveness of KOH, as well as the need for extensive washing to remove residual potassium compounds. These factors can lead to wastewater pollution if not properly [53]. Therefore, while KOH activation remains a highly effective method for preparing superior-quality activated carbon, careful process optimization and waste management are necessary to ensure sustainability.

2.7. Physicochemical Properties of Activated Carbon

Activated carbon is renowned for its exceptional physicochemical characteristics, which render it an extremely effective adsorbent for a variety of applications, including the removal of pollutants, the purification of gases, and the clarification of sugar juice. Its remarkable high surface area, coupled with a diverse range of pore sizes, allows for the accommodation of various contaminants. Additionally, the presence of chemically active surface functional groups enhances its ability to form strong interactions with both organic and inorganic substances, making it a preferred choice in environmental remediation and industrial processes [8, 9].

The versatility of activated carbon is further underscored by its adaptability to different treatment scenarios. In the context of pollutant removal, it can effectively capture a wide array of harmful compounds, including volatile organic compounds and heavy metals, thereby improving air and water quality. In gas purification, activated carbon plays a crucial role in eliminating undesirable odors and toxic gases, contributing to safer and more pleasant environments. Furthermore, its application in sugar juice clarification not only enhances the quality of the final product but also optimizes the overall production process. These multifaceted capabilities highlight the significance of activated carbon in both environmental and industrial applications, establishing it as a critical material in the pursuit of sustainability and efficiency.

The efficiency of activated carbon depends largely on its structural, textural, and chemical properties, including surface area, pore volume, pore size distribution, surface functional groups, and ash content [54, 55]. These parameters determine the accessibility and strength of adsorption sites during physicochemical interactions with solutes.

2.7.1. Ash Content of Activated Carbon

The ash content of activated carbon is a critical parameter that reflects its purity and overall quality. This metric indicates the amount of inorganic mineral residue that remains after the complete combustion of the carbon material. A higher ash content signifies a greater presence of these non-carbonaceous materials, which can interfere with the carbon's structural integrity. Specifically, elevated levels of ash can obstruct the pore structures within the activated carbon, leading to a significant reduction in the accessible surface area. This diminished surface area directly impacts the material's adsorption capacity, which is essential for its effectiveness in various applications, such as air and water purification [32, 65].

The implications of high ash content extend beyond mere physical obstruction; they can also affect the performance of activated carbon in practical scenarios. When the pore structures are compromised, the material's ability to adsorb contaminants is severely hindered, resulting in less efficient filtration and purification processes. This reduction in adsorption capacity can lead to increased operational costs and decreased effectiveness in applications where activated carbon is employed. Therefore, understanding and controlling ash

content is vital for manufacturers and users alike, as it plays a pivotal role in determining the suitability of activated carbon for specific uses, ensuring that it meets the required performance standards in various environmental and industrial contexts [32].

Moreover, excessive ash can alter the surface chemistry, decreasing the availability of active binding sites for pollutant removal. Therefore, high-quality activated carbon typically exhibits low ash content and high fixed carbon content, which together contribute to improved adsorption performance and chemical stability.

2.7.2. Pore Size and Yield of Activated Carbon

The activation temperature and duration strongly influence both the yield and pore structure of activated carbon. As temperature increases, volatile substances are expelled, and the decomposition of cellulose and hemicellulose occurs, leading to a reduction in yield but a significant enhancement of surface area and micropore volume.

The specific surface area of activated carbon increased with activation temperature, reaching a maximum of 995 m^2/g at 800 ℃, after which it slightly declined due to pore collapse. Prolonged activation times initially enhance pore development but may later cause structural degradation [56]. Thus, an optimal balance between temperature, time, and activating agent concentration is essential to achieve desirable textural properties and economic yield.

2.8. Studies on the Preparation and Applications of Activated Carbon

Activated carbon is extensively utilized across various industries due to its affordability, adaptability, and exceptional adsorption capabilities. The characteristics of activated carbon can differ significantly based on the type of feedstock used and the specific activation process employed [57]. This material's unique properties make it particularly valuable in environmental engineering applications, where it is commonly used for the purification of water and air, treatment of industrial effluents, and adsorption of gases. Beyond environmental applications, activated carbon is also integral to food processing, sugar refining, and controlling odors, highlighting its multifaceted utility in both industrial and consumer contexts [58].

A notable example of activated carbon's effectiveness is illustrated by Kim [30], who demonstrated the successful production of granular activated carbon from walnut shells through a $ZnCl_2$ activation process. This method not only enhanced the material's adsorption capacity but also facilitated the efficient removal of Cu^{2+} ions from synthetic wastewater. Such advancements underscore the potential of utilizing agricultural by-products for the creation of high-performance activated carbon, thereby contributing to sustainable practices in waste management and resource recovery. The ongoing research and development in this field continue to reveal new applications and improvements, further solidifying activated carbon's role as a critical component in addressing environmental challenges [58]. Investigated activated carbons derived from agricultural residues such as strawberry and pistachio shells, demonstrating that adsorption capacity depends on both the adsorbent structure and the physicochemical nature of the pollutant.

Prepared activated carbon from sugarcane bagasse (SCB) using H_2SO_4 activation at 600 ℃ for 2 hours [58, 64]. The resulting carbon exhibited strong adsorption capacity for organic pollutants, validating its potential for industrial wastewater purification.

Furthermore, the evaluated bagasse-based activated carbon (BAC) for raw sugarcane juice clarification, achieving approximately 87% color removal at ambient temperature, indicating that BAC can serve as a viable and sustainable alternative to conventional clarifying agents in the sugar industry [9].

Table 1. *Activated carbon derived from different agricultural waste and its application.*

Raw material	Application	References
Oil palm empty fruit bunches	Phenol adsorption	[59]
Industrial sludge	Methylene blue removal	[60]
Sugarcane Bagasse	Sugar juice decolorization	[61]
Maize tassel	Removal of heavy metal water	[62]
Biomass	Adsorbent for CO2	[63]
Walnut shell	Methylene blue removal	[52]

3. Conclusion

This review provides an in-depth examination of the various methods for preparing activated carbon, its physicochemical properties, and its diverse applications, with a particular emphasis on sugarcane bagasse. A wide array of low-cost and readily available natural materials around the globe can serve as precursors for the production of activated carbon, including agricultural residues, lignocellulosic biomass, and industrial by-products. Among these materials, sugarcane bagasse stands out as a particularly advantageous raw material due to its favorable characteristics, such as a high carbon content, minimal ash content, and its renewable nature, making it an attractive option for sustainable activated carbon production.

The production of activated carbon from sugarcane bagasse can be accomplished through two primary methods: physical activation and chemical activation. Physical activation in-

volves thermal treatment in either inert or oxidizing environments, while chemical activation entails the impregnation of the biomass with activating agents like phosphoric acid (H_3PO_4), zinc chloride ($ZnCl_2$), potassium hydroxide (KOH), or potassium carbonate (K_2CO_3), followed by pyrolysis. Although both approaches yield porous carbon structures, chemical activation is often favored due to its ability to produce materials with higher surface areas, enhanced pore development, lower activation temperatures, reduced processing times, and superior adsorption capacities. Each activating agent plays a distinct role in influencing the pore structure, surface functionalization, and overall adsorption properties of the resulting activated carbon.

Activated carbon produced from sugarcane bagasse exhibits a high surface area, substantial total pore volume, and well-defined micro- and mesoporous structures, which contribute to its effectiveness in various adsorption applications. While research on its application for clarifying sugarcane juice is still in its infancy, initial studies suggest that activated carbon derived from bagasse can efficiently eliminate colorants and impurities from raw juice. This finding highlights its potential as a sustainable and chemical-free alternative to traditional clarifying agents. In summary, sugarcane bagasse emerges as a cost-effective, environmentally friendly, and renewable resource for activated carbon production, particularly in the context of sugarcane juice purification, presenting a promising direction for future research and application.

Abbreviations

AC	Activated Carbon
BAC	Bagasse-Derived Activated Carbon
CPZAC	Carbonized Plantain Zinc Chloride Activated Carbon
MJ	*Mixed Juice*
POD	Peroxidase
PPO	Polyphenol Oxidase
SCB	Sugarcane Bagasse

Conflicts of Interest

The author of this review paper titled “Turning Waste into Clarity: A Review of Sugarcane Bagasse-Based Activated Carbon in Juice Purification" hereby declare that: The paper has no financial, professional, or personal conflicts of interest that could inappropriately influence or bias the publication of this review. No competing interests exist on the paper and any individuals, institutions, or organizations that could affect the integrity of the review findings.

References

[1] Eggleston, G. (2008). Sucrose and Related Oligosaccharides. In: Fraser-Reid, B. O., Tatsuta, K., Thiem, J. (eds) Glycoscience. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-30429-6_26

[2] Prati, P., & Moretti, R. H. (2010). Study of clarification process of sugar cane juice for consumption. Food Science and Technology, 30, 776-783. https://doi.org/10.1016/j.lwt.2009.07.020

[3] Doherty, W. O. (2011). Improved sugar cane juice clarification by understanding calcium oxide-phosphate-sucrose systems. Journal of Agricultural and Food Chemistry, 59(5), 1829-1836. https://doi.org/10.1021/jf1043212

[4] Majur, M. M., Ramesh, D., & Birhanu, T. (2019). Clarifying capacity of eco-friendly nano CaO and okra (Abelmoschus esculentus) extract on the processing of sugarcane juice: A review. International Research Journal of Science and Technology, 1(1), 21-30. https://doi.org/10.46378/irjst.2019.010104

[5] Walker, G., & Weatherley, L. R. (2000). Prediction of bisolute dye adsorption isotherms on activated carbon. Process Safety and Environmental Protection, 78(3), 219-223. https://doi.org/10.1205/095758200530673

[6] Avova, D., Apak, E., Ekinci, E., Yardim, F., Petrov, N., Budinova, T., & Minkova, V. (2001). Biomass conversion to carbon adsorbents and gas. Biomass and Bioenergy, 21(2), 133-142. https://doi.org/10.1016/S0961-9534(01)00027-7

[7] Kalderis, D., Bethanis, S., Paraskeva, P., & Diamadopoulos, E. (2008). Production of activated carbon from bagasse and rice husk by a single-stage chemical activation method at low retention times. Bioresource Technology, 99(15), 6809-6816. https://doi.org/10.1016/j.biortech.2008.01.041

[8] Qureshi, K., Bhatti, I., Kazi, R., & Ansari, K. A. (2008). Physical and chemical analysis of activated carbon prepared from sugarcane bagasse and use for sugar decolorisation. International Journal of Chemical and Biomolecular Engineering, 1(3), 145-149. https://doi.org/10.5281/zenodo.1077315

[9] Sol ís-Fuentes, J. A., Gal án-M éndez, F., Hern ández-Medel, M. D. R., *et al.* (2019) Effectiveness of Bagasse Activated Carbon in Raw Cane Juice Clarification. *Food Bioscience*, 32, Article 100437. https://doi.org/10.1016/j.fbio.2019.100437

[10] Riyanto, C. A., Ampri, M. S., & Martono, Y. (2020). Synthesis and Characterization of Nano Activated Carbon from Annatto Peels (Bixa orellana L.) Viewed from Temperature Activation and Impregnation Ratio of H3PO4. *EKSAKTA: Journal of Sciences and Data Analysis*, *20*(1), 44-50. https://doi.org/10.20885/EKSAKTA.VOL1.ISS1.ART7

[11] Arulkumar, M., Sathishkumar, P., & Palvannan, T. (2011). Optimization of Orange G dye adsorption by activated carbon of Thespesia populnea pods using response surface methodology. *Journal of hazardous materials*, *186*(1), 827-834. https://doi.org/10.1016/j.jhazmat.2010.11.067

[12] Eggleston, G., Legendre, D., Pontif, K., & Gober, J. (2014). Improved control of sucrose losses and clarified juice turbidity with lime saccharate in hot lime clarification of sugarcane juice and other comparisons with milk of lime. *Journal of Food Processing and Preservation*, *38*(1), 311-325. https://doi.org/10.1111/j.1745-4549.2012.00779.x

[13] Baunsgaard, D. (2000). Analysis of color impurities in sugar processing using flourescence spectroscopy and chemometrics.*Royal Veterinary and Agricultural University, Department of Dairy and Food.*

[14] Kimatu, B. M., Faraj, A. K. and Mahungu, S. M. (2015). Effect of incorporating alum in cane juice clarification efficiency and sucrose losses. *International Journal of Food Studies*. 4(1). https://doi.org/10.7455/ijfs/4.1.2015.a5

[15] Singh, A., Lal, U., Mukhtar, H., Singh, P., Shah, G., & Dhawan, R. (2015). Phytochemical profile of sugarcane and its potential health aspects. Pharmacognosy Reviews, 9(17), 45-54. https://doi.org/10.4103/0973-7847.156340

[16] Basanta, R., Delgado, M. A. G., Mart ínez, J. E. C., V ázquez, H. M., & V ázquez, G. B (2007). sustainable recycling of waste from sugarcane agroindustry*: A review. CYTA-Journal of Food.* 5(4), 293-305. https://doi.org/10.1080/19476330903123202

[17] Inal, I. I. G., Holmes, S. M., Banford, A., & Aktas, Z. (2015). The performance of supercapacitor electrodes developed from chemically activated carbon produced from waste tea. Applied Surface Science, 357, 696-703. https://doi.org/10.1016/j.apsusc.2015.09.067

[18] Lubis, R. A. F., Nasution, H. I., & Zubir, M. (2020). Production of Activated Carbon from Natural Sources for Water Purification. Indonesian Journal of Chemical Science and Technology (IJCST), 3(2), 67-73. https://doi.org/10.24114/ijcst.v3i2.19531

[19] Marshall, W. E., & Champagne, E. T. (1995). Agricultural byproducts as adsorbents for metal ions in laboratory prepared solutions and in manufacturing wastewater. Journal of Environmental Science and Health. Part A: Environmental Science and Engineering and Toxicology, 30(2), 241-261. https://doi.org/10.1080/10934529509376198

[20] Dengia, A., Tsegaye, T., & Bekele, A. (2023). Analysis of declining trends in sugarcane yield at Wonji-Shoa Sugar Estate, Central Ethiopia. Experimental Results, 2023, 1-7. https://doi.org/10.1017/exp.2023.4

[21] Krishnakumar, T., Thamilselvi, C., & Devadas, C. T. (2013). Effect of delayed extraction and storage on quality of sugarcane juice. African Journal of Agricultural Research, 8(10), 930-935. https://doi.org/10.5897/AJAR12.1807

[22] Yusof, S., Shian, L. S., & Osman, A. (2000). Changes in quality of sugar-cane juice upon delayed extraction and storage. Food Chemistry, 68(4), 395-401. https://doi.org/10.1016/S0308-8146(99)00180-6

[23] Sreedevi, P., Jayachandran, L. E., & Rao, P. S. (2018). Browning and bioactive composition of sugarcane juice (Saccharum officinarum) as affected by high hydrostatic pressure processing. Journal of Food Measurement and Characterization, 12(3), 1962-1971. https://doi.org/10.1007/s11694-018-9811-7

[24] Nadzirah, Z., H. N. Haslina, and M. M. Adib. (2015) Studies on the preparation of activated carbon sugarcane bagasse on removal of chemical oxygen demand, alkalinity and oil and grease of car wash wastewater. *Advances in Environmental Biology*. 9(12), 15-21.

[25] Zielińska, A., Oleszczuk, P., Charmas, B., Skubiszewska-Zięba, J., & Pasieczna-Patkowska, S. (2015). Effect of sewage sludge properties on the biochar characteristic. Journal of Analytical and Applied Pyrolysis, 112, 201-213. https://doi.org/10.1016/j.jaap.2015.01.025

[26] Ekpete, O., Marcus, A., & Osi, V. (2017). Preparation and characterization of activated carbon obtained from plantain (Musa paradisiaca) fruit stem. Journal of Chemistry, 2017, Article 8635615. https://doi.org/10.1155/2017/8635615

[27] Yang, H. M., Zhang, D. H., Chen, Y., Ran, M. J., & Gu, J. C. (2017). Study on the application of KOH to produce activated carbon to realize the utilization of distiller's grains. IOP Conference Series: Earth and Environmental Science, 69, 012051. https://doi.org/10.1088/1755-1315/69/1/012051

[28] Men éndez-D áz, J. A., & Mart ín-Gull ón, I. (2006). Types of carbon adsorbents and their production. In T. J. Bandosz (Ed.), Interface Science and Technology: Vol. 7. Activated carbon surfaces in environmental remediation (pp. 1-47). https://doi.org/10.1016/S1573-4285(06)80010-4

[29] Yahya, M. A., Al-Qodah, Z., & Ngah, C. Z. (2015). Agricultural bio-waste materials as potential sustainable precursors used for activated carbon production: A review. Renewable & Sustainable Energy Reviews, 46, 218-235. https://doi.org/10.1016/j.rser.2015.02.051

[30] Kim, J. W., Sohn, M. H., Kim, D. S., Sohn, S. M., & Kwon, Y. S. (2001). Production of granular activated carbon from waste walnut shell and its adsorption characteristics for Cu^{2+} ion. Journal of Hazardous Materials, 85(3), 301-315. https://doi.org/10.1016/S0304-3894(01)00239-4

[31] Byamba-Ochir, N., Shim, W. G., Balathanigaimani, M. S., & Moon, H. (2016). Highly porous activated carbons prepared from carbon rich Mongolian anthracite by direct NaOH activation. Applied Surface Science, 379, 331-337. https://doi.org/10.1016/j.apsusc.2016.04.082

[32] Chowdhury, Z. Z., Zain, S. M., Khan, R. A., Niya, A. A., and Khalid, k. (2012). Process variables optimization for preparation and characterization of novel adsorbent from lignocellulosic waste. *BioResource*, 7(3), 3732-3754.

[33] Bouchelta, C., Medjram, M. S., Bertrand, O., & Bellat, J. P. (2008). Preparation and characterization of activated carbon from date stones by physical activation with steam. Journal of Analytical and Applied Pyrolysis, 82(1), 70-77. https://doi.org/10.1016/j.jaap.2007.12.009

[34] Gan, Y. X. (2021). Activated Carbon from Biomass Sustainable Sources. C - Journal of Carbon Research, 7(2), 39. https://doi.org/10.3390/c7020039

[35] Njoku, V. O., Foo, K. Y., Asif, M., & Hameed, B. H. (2014). Preparation of activated carbons from rambutan (Nephelium lappaceum) peel by microwave-induced KOH activation for Acid Yellow 17 dye adsorption. Chemical Engineering Journal, 250, 198-204. https://doi.org/10.1016/j.cej.2014.03.115

[36] Samsuri, A. W., Sadegh-Zadeh, F., & Seh-Bardan, B. J. (2014). Characterization of biochars produced from oil palm and rice husks and their adsorption capacities for heavy metals. International Journal of Environmental Science & Technology, 11(4), 967-976. https://doi.org/10.1007/s13762-013-0291-3

[37] Molina-Sabio, M., & Rodr guez-Reinoso, F. (2004). Role of chemical activation in the development of carbon porosity. Colloids and Surfaces A: Physicochemical and Engineering Aspects, 241(1-3), 15-25. https://doi.org/10.1016/j.colsurfa.2004.04.007

[38] Gratuito, M. K. B., Panyathanmaporn, T., Chumnanklang, R.-A., Sirinuntawittaya, N., & Dutta, A. (2008). Production of activated carbon from coconut shell: Optimization using response surface methodology. Bioresource Technology, 99(11), 4887-4895. https://doi.org/10.1016/j.biortech.2007.09.042

[39] Nowicki, P., Kuszyńska, I., Przepi órski, J., & Pietrzak, R. (2013). The effect of chemical activation method on properties of activated carbons obtained from pine cones. Central European Journal of Chemistry, 11(1), 78-85. https://doi.org/10.2478/s11532-012-0140-0

[40] Yorgun, S., Yıldız, D., & Şimşek, Y. E. (2016). Activated carbon from paulownia wood: Yields of chemical activation stages. Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, 38(14), 2035-2042. https://doi.org/10.1080/15567036.2015.1030477

[41] Cui, X. Y., Jia, F., 2, Y. X., & Gan, J. (2011). Influence of single-walled carbon nanotubes on microbial availability of phenanthrene in sediment. *Ecotoxicology*. 20(6), 1277-1285.

[42] Baodeng Wang, Chenming Zhu, Zhongzheng Zhang, Weili Zhang, Xinqing Chen, Nannan Sun, Wei Wei, Yuhan Sun, Haifeng Ji, H. (2016). Facile, low-cost, and sustainable preparation of hierarchical porous carbons from ion exchange resin: An improved potassium activation strategy, *Fuel*,. 179, 274-280. https://doi.org/10.1016/j.fuel.2016.03.088.

[43] Balajii, M., Niju, S. Biochar-derived heterogeneous catalysts for biodiesel production. *Environ Chem Lett* 17, 1447-1469 (2019). https://doi.org/10.1007/s10311-019-00885-x

[44] Girgis, B. S. and El-Hendawy, A.-N. A. (2002) Porosity Development in Activated Carbons Obtained from Date Pits under Chemical Activation with Phosphoric Acid. Microporous and Mesoporous Materials, 52, 105-117. https://doi.org/10.1016/S1387-1811(01)00481-4

[45] Abdelnaeim, M. Y., El Sherif, I. Y., Attia, A. A., Fathy, N. A., & El-Shahat, M. F. (2016). Impact of chemical activation on the adsorption performance of common reed towards Cu(II) and Cd(II). International Journal of Mineral Processing, 157, 80-88. https://doi.org/10.1016/j.minpro.2016.05.010

[46] de Yuso, A. M., Rubio, B., & Izquierdo, M. T. (2014). Influence of activation atmosphere used in the chemical activation of almond shell on the characteristics and adsorption performance of activated carbons. Fuel Processing Technology, 119, 74-80. https://doi.org/10.1016/j.fuproc.2013.11.025

[47] Zhong, Z.-Y., Yang, Q., Li, X.-M., Luo, K., Liu, Y., & Zeng, G.-M. (2012). Preparation of peanut hull-based activated carbon by microwave-induced phosphoric acid activation and its application in Remazol Brilliant Blue R adsorption. Industrial Crops & Products, 37(1), 178-185. https://doi.org/10.1016/j.indcrop.2011.12.015

[48] Arami-Niya, A., W. M. A. W. Daud, and F. S. Mjalli, (2010). Using granular activated carbon prepared from oil palm shell by $ZnCl_2$ and physical activation for methane adsorption. *Journal of Analytical and Applied Pyrolysis*. 89 (2), 197-203. https://doi.org/10.1016/j.jaap.2010.08.006

[49] Anisuzzaman, S. M., Joseph, C. G., Krishnaiah, D., Bono, A., Suali, E., Abang, S., & Fai, L. M. (2016). Removal of chlorinated phenol from aqueous media by guava seed (Psidium guajava) tailored activated carbon. *Water resources and industry*, *16*, 29-36. https://doi.org/10.1016/j.wri.2016.10.001

[50] Gundogdu, A., Duran, C., Senturk, H. B., Soylak, M., Imamoglu, M., & Onal, Y. (2013). Physicochemical characteristics of a novel activated carbon produced from tea industry waste. *Journal of Analytical and Applied Pyrolysis*, *104*, 249-259. https://doi.org/10.1016/j.jaap.2013.07.008

[51] Angin, D. (2014). Production and characterization of activated carbon from sour cherry stones by zinc chloride. *Fuel*, *115*, 804-811. https://doi.org/10.1016/j.fuel.2013.04.060

[52] Yang, J., & Qiu, K. (2010). Preparation of activated carbons from walnut shells via vacuum chemical activation and their application for methylene blue removal. *Chemical Engineering Journal*, *165*(1), 209-217. https://doi.org/10.1016/j.cej.2010.09.018

[53] Hui, T. S., & Zaini, M. A. A. (2015). Potassium hydroxide activation of activated carbon: A commentary. *Carbon Letters*, *16*(4), 275-280. https://doi.org/10.5714/CL.2015.16.4.275

[54] Zayadi, N. B. (2017.) performance of powdered and granular sugarcane bagasse activated carbon in removing pollutants of car wash wastewater.

[55] Argessa, G. D., Megersa, S., Kabato, W., Reggasa, W. (2025). Phytochemical Analysis and Antimicrobial Activity of Carica Papaya Seed and Bark Against Selected Pathogens, in Case of Southern Ethiopia. American Journal of Chemical Engineering, 13(3), 66-75. https://doi.org/10.11648/j.ajche.20251303.12

[56] Zhou, J., Luo, A., & Zhao, Y. (2018). Preparation and characterisation of activated carbon from waste tea by physical activation using steam. *Journal of the Air & Waste Management Association*, *68*(12), 1269-1277. https://doi.org/10.1080/10962247.2018.1508973

[57] Soleimani, M., & Kaghazchi, T. (2007). Agricultural waste conversion to activated carbon by chemical activation with phosphoric acid. *Chemical Engineering & Technology*, *30*(5), 649-654. https://doi.org/10.1002/ceat.200600293

[58] Chaiwon, T., Jannoey, P., & Channei, D. (2017) Preparation of Activated Carbon from Sugarcane Bagasse Waste for the Adsorption Equilibrium and Kinetics of Basic Dye. *Journal of Materials Science and Technology*.

[59] Blachnio, M., Deryło-Marczewska, A., Charmas, B., Zienkiewicz-Strzałka, M., Bogatyrov, V., & Galaburda, M. (2020). Activated carbon from agricultural wastes for adsorption of organic pollutants. *Molecules, 25*(21), 5105. https://doi.org/10.3390/molecules25215105

[60] Alam, M. Z., Ameem, E. S., Muyibi, S. A., & Kabbashi, N. A. (2009). The factors affecting the performance of activated carbon prepared from oil palm empty fruit bunches for adsorption of phenol. *Chemical Engineering Journal, 155*(1-2), 191-198. https://doi.org/10.1016/j.cej.2009.08.021

[61] Mahapatra, K., Ramteke, D. S., & Paliwal, L. J. (2012). Production of activated carbon from sludge of food processing industry under controlled pyrolysis and its application for methylene blue removal. *Journal of Analytical and Applied Pyrolysis, 95*, 79-86. https://doi.org/10.1016/j.jaap.2012.01.009

[62] Guan, B. T., Latif, P. A., & Yap, T. Y. (2013). Physical preparation of activated carbon from sugarcane bagasse and corn husk and its physical and chemical characteristics. *Int. J. Eng. Res. Sci. Technol. 2*, 1-14.

[63] Olorundare, O. F., Krause, R. W. M., Okonkwo, J. O., & Mamba, B. B. (2012). Potential application of activated carbon from maize tassel for the removal of heavy metals in water. Physics and Chemistry of the Earth, 50, 104-110. https://doi.org/10.1016/j.pce.2012.06.001

[64] Hao, W., Björkman, E., Lilliestråle, M., & Hedin, N. (2013). Activated carbons prepared from hydrothermally carbonized waste biomass used as adsorbents for CO_2. *Applied Energy, 112*, 526-532. https://doi.org/10.1016/j.apenergy.2013.02.028

[65] Argessa, G. D. (2025). Development and Nutritional Optimization of a Healthy Snack Bar for Children Using Locally Available Ingredients. Science Frontiers, 6(3), 34-56. https://doi.org/10.11648/j.sf.20250603.11