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REVIEW ARTICLE

A comprehensive review of agricultural waste-derived activated carbon for carbon dioxide (CO_2) capture using PRISMA methodology

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ABSTRACT

The rising concentration of carbon dioxide (CO_2) in the atmosphere underscores the critical need to develop efficient, scalable, and sustainable carbon capture technologies. Activated carbon (AC) is one of the materials currently being widely developed for carbon capture. The effectiveness of AC for carbon capture depends on its characteristics, such as surface area and functional group content, which vary with the synthesis process. This comprehensive review presents an in-depth evaluation of the synthesis pathways for AC derived from agricultural waste, with particular attention to activation and modification techniques to enhance CO_2 adsorption. It also further examines key parameters influencing the physicochemical properties of these materials, including pore structure, surface area, and surface chemistry. The review process follows the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to ensure transparency and reproducibility. Inclusion and exclusion criteria were defined to identify the most relevant studies and to systematically collect and synthesize pertinent data. The review identified that chemical activation, particularly with KOH, H_3PO_4, and $ZnCl_2$, substantially enhances the surface area, pore development, and surface functionality of AC, thereby improving CO_2 adsorption capacity. Among various activation techniques, KOH activation consistently yields the highest specific surface areas and well-developed microporous structures suitable for CO_2 adsorption. Modification strategies, such as heteroatom doping and metal impregnation, further enhance the basicity and selectivity of AC toward CO_2 molecules by increasing the number of active sites and tuning surface chemistry.

Keywords: activated carbon; adsorption; biomass; CO_2 capture; PRISMA, pyrolysis

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1. Introduction

The United Nations has established seventeen Sustainable Development Goals (SDGs), endorsed by all member states, to serve as a comprehensive framework for achieving a more equitable and sustainable future. Among these goals, SDG 13 holds particular significance, as it focuses on combating climate change and its impacts, a priority made increasingly urgent by the continued rise in anthropogenic carbon dioxide (CO_2) emissions over the past two decades[1,2]. This rise is largely driven by industrial activities that have intensified since the Industrial Revolution, contributing to an average global temperature increase of approximately 0.17 °C per year[3]. Key sectors responsible for substantial CO_2 emissions include fossil fuel-based energy production, cement and chemical manufacturing, metal processing, and petroleum refining[4-7]. As a consequence, atmospheric CO_2 concentrations reached approximately 423 ppm in 2023[3]. The continued acceleration of emissions is a critical concern due to the central role of CO_2 in driving climate change and its adverse effects on public health, including respiratory disorders, hypertension, and increased heart rate[3]. To mitigate these impacts, various carbon capture technologies have been developed to reduce emissions from large point sources, such as power plants. Among these, membrane separation, chemical absorption, cryogenic distillation, and chemical looping have been explored[3,8]. However, many of these approaches are constrained by high energy requirements and operational costs. In contrast, adsorption has emerged as a promising and cost-effective alternative due to its low energy consumption and operational simplicity[1-3].

Adsorption has gained recognition as a practical and cost-effective method for carbon capture and storage[9]. Among various adsorbent materials, notable candidates include polymers, carbon-based materials, metal oxides, zeolites, and metal organic frameworks (MOFs). While zeolites are effective, their performance is often influenced by moisture, temperature, and pressure conditions. In contrast, carbon materials such as charcoal, biochar, carbon nanotubes, graphite, graphene, fullerenes, and activated carbon (AC) offer distinct advantages due to their chemical stability and versatility[10,11]. These materials are relatively easy to synthesize and modify, with well-developed pore networks and high specific surface areas that promote efficient CO_2 adsorption. Unlike MOFs, carbon materials exhibit strong resistance to moisture, enhancing their reliability under industrial conditions. The abundance and low cost of carbon precursors further support their large-scale application. Among various carbon materials, AC exhibits excellent adsorption performance over a wide temperature range, making it a robust option for diverse operational conditions. Given these characteristics, the development of AC remains a promising alternative for enhancing CO_2 capture efficiency in practical[1,2].

AC has gained considerable attention as a highly effective adsorbent for CO_2 capture, owing to its superior physicochemical, mechanical, thermal, and chemical stability. While a wide range of porous carbon-based materials are available, those derived from agricultural waste are particularly promising[12]. This preference is attributed to their advantageous textural properties, high CO_2 adsorption capacity, ease of preparation, low production costs, and the renewable and sustainable nature of the feedstocks[13].

Agricultural waste is an abundant, renewable feedstock that can be used either for direct heat production or converted into liquid and gaseous fuels via diverse thermochemical and biochemical pathways. Among these technologies, pyrolysis is among the most prominent thermochemical methods for transforming agricultural waste into value-added products such as biochar, tar, and permanent gases. During pyrolysis, agricultural waste is thermally degraded in the absence of oxygen, generally at intermediate temperatures, predominantly yielding biochar[14] as a solid product, as depicted in **Figure 1**.

A variety of pyrolysis approaches have been established, including slow and fast pyrolysis, operated under diverse temperature ranges and moisture conditions (i.e., dry and wet pyrolysis)[15]. Meanwhile, the fabrication of AC generally requires the incorporation of chemical activating agents either before or after the pyrolysis stage. For instance, an effective strategy has been reported for the pyrolysis of Arundo donax combined with single-step activation using potassium hydroxide (KOH)[16]. This method simplifies the conventional two-step activation procedure, thereby reducing processing time and improving operational efficiency. Both physical and chemical activation techniques are widely applied in the preparation of carbon materials, employing agents such as steam[17], CO_2[18], KOH[12], $ZnCl_2$[19], H_3PO_4[12], HNO_3[20], and H_2O_2[21]. Various pyrolysis parameters, such as precursor type and temperature, as well as activation parameters, such as activator type, exert a substantial influence on the yield, specific surface area, and surface chemistry of the resulting biochar. For example, Ighalo et al.[22] investigated pyrolysis within a temperature range of 250-650 °C and demonstrated that increasing temperature enhanced the specific surface area, as determined by Brunauer-Emmett-Teller (BET) analysis, while concurrently decreasing product yield[22]. Furthermore, both the synthesis route and the inherent characteristics of the agricultural waste feedstock govern the nature and concentration of surface functional groups present on the derived carbon materials. Thermal conversion of different agricultural waste types produces a spectrum of carbonaceous products, including carbon fibers and AC, each exhibiting distinct structural features and considerable potential for application in various industrial fields[23].

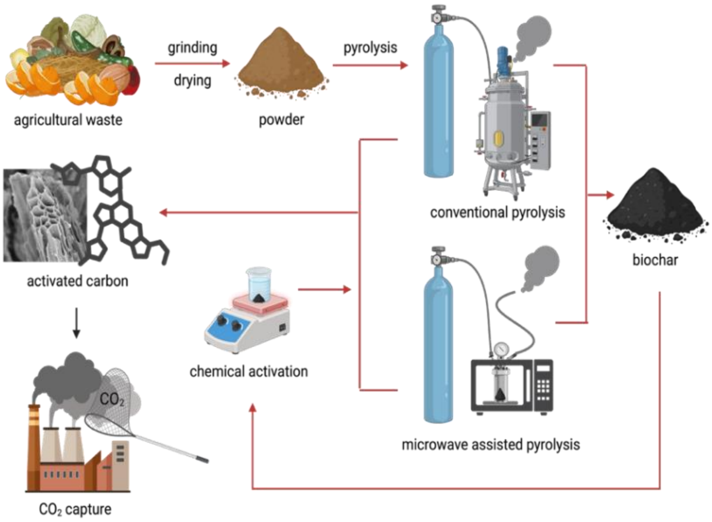

Figure 1. Preparation of AC derived from agricultural waste via chemical activation for CO_2 capture. The figure was created using BioRender (https://BioRender.com, accessed on June 27, 2025)

Numerous studies have demonstrated that unmodified biochar exhibits limited capacity for contaminant adsorption, prompting the exploration of various modification strategies. These include treatments with steam, acids, or bases, and the incorporation of heteroatoms into the carbon matrix[23]. Enhancing CO_2 capture performance requires introducing basic functional groups and increasing material porosity. One widely adopted approach is nitrogen doping, which involves integrating nitrogen-rich compounds such as polyethyleneimine (PEI) or triethylenephosphoramide (TEPA) into carbon structures. This process introduces nitrogen functionalities, such as pyridinic and pyrrolic nitrogen, which are known to significantly improve CO_2 adsorption efficiency[24,25]. For instance, the addition of chitosan to carbonized materials has been reported to increase CO_2 uptake to 5.83 mmol g^{-1} at 0 °C[26]. Furthermore, the addition of alkali metal oxides or hydroxides into the carbon framework increases its surface alkalinity, thereby enhancing the adsorption of acidic CO_2 molecules. Previous studies have shown that biochar produced from walnut shells and impregnated with metal nitrates, especially magnesium, exhibits superior CO_2 adsorption performance compared to other metal-doped biochar, such as iron or nickel[27]. Despite advances in modification strategies and their effectiveness for CO_2 capture, comprehensive reviews of the preparation and functionalization of AC derived from agricultural waste remain limited. This review aims to provide a comprehensive overview of the production of AC derived from agricultural waste, including fruit peel, vegetable, and nut peel. It also evaluates the most effective methods for producing AC from these plant-based by-products, with a particular focus on their application in CO_2 capture technologies.

2. Method

2.1. Data sources and search strategy

A systematic literature review was conducted using a comprehensive, structured approach to ensure rigorous selection of relevant studies. The review process followed the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines to enhance transparency and reproducibility (**Figure 2**). The adoption of a PRISMA-based approach is critical to ensuring methodological rigor, as it provides a standardized framework for systematically and traceably identifying, screening, and synthesizing literature. In contrast to conventional narrative reviews, which may be susceptible to subjective selection and bias, PRISMA enables the use of predefined inclusion and exclusion criteria, explicit search strategies, and consistent reporting procedures. This is particularly important in research areas characterized by rapidly expanding and heterogeneous outputs, where variations in methodologies and materials can complicate the interpretation of findings. Moreover, the PRISMA framework enhances the credibility of the review by enabling readers to assess the completeness of the literature selection and the validity of the synthesis.

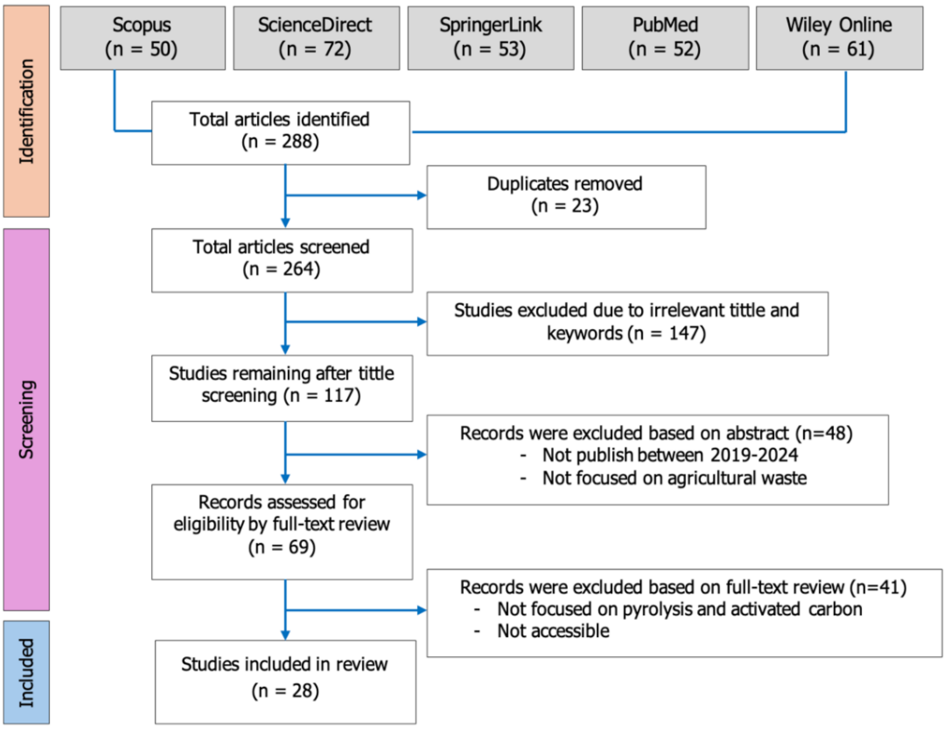

Figure 2. Preparation Overview of Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) flow chart.

Relevant publications were systematically identified through comprehensive searches across multiple databases, including Scopus, ScienceDirect, SpringerLink, PubMed, and Wiley Online. The search strategy was constructed using Boolean operators, whereby primary concepts were combined using ‘AND’ (e.g., ‘activated carbon’ AND ‘agricultural waste’ AND ‘CO_2 adsorption’), while synonymous or related terms were grouped using ‘OR’ (e.g., ‘activation’ OR ‘pyrolysis’) to capture relevant variations. This approach ensured both precision and comprehensiveness in retrieving relevant records. All identified references were imported into a reference management system, where duplicate entries were detected and removed. The remaining studies were then screened according to predefined inclusion and exclusion criteria, followed by systematic data extraction and synthesis, thereby ensuring a transparent, reproducible, and methodologically robust review process.

2.2. Study selection, inclusion, and exclusion criteria

Inclusion and exclusion criteria were predefined to ensure the systematic identification and selection of the most relevant studies. An initial pool of articles was retrieved from multiple databases, followed by a sequential screening process based on titles, abstracts, and full texts in accordance with the PRISMA framework (**Figure 2**). Studies were included if they met the following criteria: (i) published between 2019 and 2024; (ii) original research articles focusing on AC derived from agricultural waste for CO_2 capture; and (iii) provided detailed descriptions of preparation methods, including pyrolysis and activation processes, along with comprehensive characterization data such as Brunauer-Emmett-Teller (BET) surface area, pore volume, and pore size. Studies that did not meet these criteria, as well as review articles, meta-analyses, books, and other non-original research publications, were excluded.

As presented in the PRISMA flow chart (**Figure 2**), the initial search identified 288 relevant records through database queries. After removing duplicates, 264 records remained. These were screened based on predefined exclusion criteria. Specifically, 147 studies were excluded for irrelevant titles and keywords, and 48 were excluded for abstracts that fell outside the 2019 to 2024 publication range or did not focus on agricultural waste. Additionally, 41 articles were excluded for not addressing pyrolysis and activation processes or for being inaccessible. After applying these criteria, 28 articles were retained for review. These studies met the inclusion criteria, specifically focusing on the production of AC from agricultural waste, with an emphasis on CO_2 adsorption. The distribution of the selected studies by publication year and country of origin is shown in **Figure 3**.

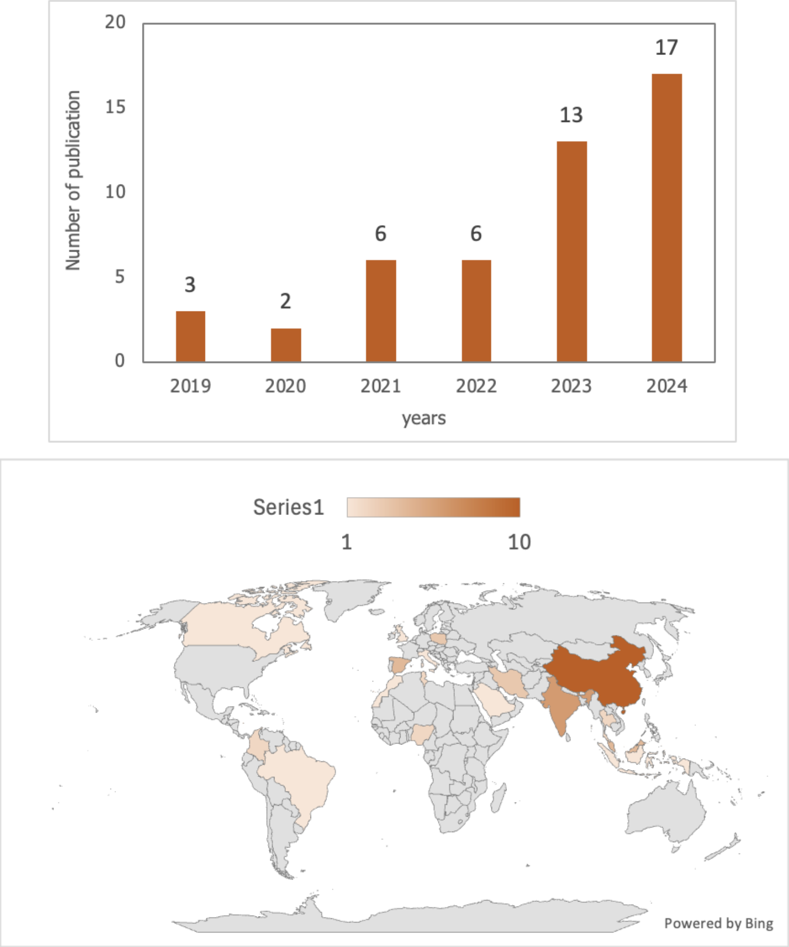

Figure 3. Overview of the distribution of selected studies based on (a) publication year and (b) country of origin.

2.3. Data extraction

Data extraction was conducted independently by the authors and subsequently cross-verified to ensure accuracy and consistency. Key information from the selected studies was systematically compiled into a summary table, including feedstock type, activating agent, BET surface area, pore volume, pore size, and CO_2 adsorption performance. This structured approach enabled consistent comparison across studies and facilitated a reliable synthesis of the findings.

2.4. Risk of bias assessment

To further ensure the robustness of the review, a risk of bias (RoB) assessment was performed using a systematic evaluation framework. Five domains of potential bias were assessed: (i) randomization process, (ii) deviations from intended procedures, (iii) completeness of outcome data, (iv) accuracy of outcome measurement, and (v) selective reporting of results. Each study was evaluated using a standardized scoring system, where a green score (+) indicated clearly reported and complete data, a yellow score (−) indicated minor or manageable limitations, and a red score (×) indicated significant bias or missing information. Based on the cumulative assessment, studies were categorized as low-, unclear-, or high-risk of bias.

Table 1. Bias analysis of selected articles on agricultural waste AC.

Study	D1	D2	D3	D4	D5	Overall
Acevedo et al. (2024)	+	+	+	+	+	+
Ahmad et al. (2020)	+	+	-	+	-	-
Aimikhe et al. (2024)	+	+	+	+	+	+
Alam et al. (2020)	+	+	+	+	+	+
Asadi-Sangachini et al. (2019)	+	-	+	+	+	+
Asgharizadeh et al. (2024)	+	-	+	+	+	+
Astuti et al. (2019)	+	+	+	+	+	+
Aziz et al. (2024)	-	-	+	+	-	-
Bai et al. (2023)	+	-	+	+	+	+
Cheng et al. (2024)	+	-	+	-	-	-
Fonseca-Bermudez et al. (2024)	+	+	+	+	+	+
Gao et al. (2022)	+	+	+	+	+	+
Goskula et al. (2024)	+	+	+	+	+	+
Hassan and Carr (2021)	+	+	+	+	+	+
Joshi et al. (2023)	+	-	+	+	+	+
Kanjana et al. (2024)	+	+	+	-	-	-
Khajonrit et al. (2022)	-	-	+	+	-	-
Khama et al. (2024)	+	+	-	-	+	-
Luo et al. (2023)	-	+	+	-	-	-
Pang et al. (2020)	+	+	+	+	+	+
Rashidi et al. (2022)	+	+	+	+	+	+
Saadi et al. (2024)	+	+	-	+	-	-
Serafin et al. (2021)	+	+	-	+	-	-
Serafin et al. (2023)	+	+	+	+	+	+
Siemak and Michalkiewicz (2024)	+	+	-	+	-	+
Tetteh et al. (2024)	+	+	+	+	+	+
Vega et al. (2024)	+	+	+	+	+	+
Zubbri et al. (2021)	+	+	+	+	+	+

The risk of bias (RoB) in studies on AC production from agricultural waste is summarized in **Table 1**. Overall, the assessment indicates predominantly low to unclear levels of bias across the evaluated parameters, with most studies demonstrating strong relevance and alignment with the objectives of the present review. More than 60% of the studies provided comprehensive descriptions of AC preparation using various precursors and activating agents, including sufficient detail in the abstracts, methodologies, and conclusions. In addition, over 85% of the studies employed reproducible methods that can be readily implemented in standard laboratory settings without specialized equipment. Nevertheless, some methodological limitations were identified that may influence the reliability of the reported outcomes. Collectively, this systematic RoB assessment enhances the transparency, consistency, and overall validity of the review.

3. Result and Discussion

3.1. Agricultural waste as a precursor in the activated carbon production

The use of agricultural waste as a precursor for AC production has attracted considerable attention due to its potential to deliver measurable economic and environmental benefits. The use of agricultural waste can reduce total production costs by approximately 30-70%, as these feedstocks are often available at minimal or no cost and generally require lower energy input during processing[19]. In contrast, coal-based precursors may account for approximately 30-50% of total production costs due to mining, transportation, and preprocessing expenses. Overall, the production cost of AC derived from agricultural waste is typically reported at $1-3 per kg, compared to $3-6 per kg for coal-based AC, depending on processing conditions and scale. Furthermore, the utilization of agricultural waste can offset waste management costs and generate additional economic value, reinforcing its attractiveness as a sustainable raw material. Despite these advantages, optimization of the agricultural waste supply chain remains a complex challenge due to the multiple interconnected stages involved, including production, harvesting, collection, storage, transportation, conversion, and distribution. For example, agricultural waste densification can reduce transportation costs. However, it may increase carbon-equivalent emissions due to additional energy consumption during processing. Conversely, pretreatment methods can enhance the properties of agricultural waste by increasing calorific value, bulk density, and energy density, while also improving combustion behavior. In this context, AC produced through thermochemical conversion can be integrated into existing industrial systems.

From a technical perspective, the growing preference for agricultural waste is also driven by its tunable physicochemical properties and its competitive performance relative to coal-based materials[28]. Agricultural waste can produce AC with a high specific surface area and well-developed pore structure due to its lignocellulosic (lignin, cellulose, and hemicellulose) composition and high volatile content, which facilitates pore formation during pyrolysis and activation[19]. Biomass sources such as peanut shells (*Arachis hypogaea*)[2], oil palm shells (*Elaeis guineensis*)[10], and corn stalks (*Zea mays*)[6] are particularly promising due to the presence of intrinsic heteroatoms (e.g., O and N), which promote the formation of surface functional groups and enhance adsorption performance. Quantitatively, AC derived from agricultural waste typically exhibits BET surface areas of 1000-2500 m^2/g, with some studies reporting values exceeding 3000 m^2/g under optimized activation conditions[6,10,29]. These values are comparable to, or in some cases higher than, those of conventional coal-derived AC, which typically range from 500-1500 m^2/g depending on the activation method[30,31]. In addition, these materials generally exhibit good thermal stability and predominantly microporous structures, which are advantageous for adsorption applications. The physicochemical properties of AC derived from agricultural waste are summarized in **Figure 4**.

As is known, pyrolysis conditions play a crucial role in determining the yield, specific surface area, and surface chemistry of AC. For example, Ighalo et al.[22] investigated pyrolysis over a temperature range of 250-650 °C and reported that increasing the temperature significantly enhanced the specific surface area of the produced AC, as confirmed by BET analysis, while simultaneously decreasing the overall product yield. From a performance perspective, these materials have demonstrated effective CO_2 adsorption capacities of 2.3-7.3 mmol/g under ambient conditions, driven by a combination of physisorption in micropores and chemisorption via surface functional groups[1,2,6,7]. However, variability in precursor composition, pyrolysis conditions, and activation conditions can lead to inconsistencies in pore structure and adsorption performance, highlighting the need for process optimization and standardization[9,12]. Overall, the use of agricultural waste as a precursor not only supports circular economy principles by valorizing biomass residues but also provides a technically viable and economically competitive pathway for producing high-performance adsorbents[19]. Utilizing agricultural waste as a precursor for AC production thus offers dual benefits: (1) mitigating solid waste disposal challenges and (2) providing a cost-effective adsorbent for environmental remediation, thereby supporting the principles of the circular economy.

Figure 4. Properties of activated carbon derived from agricultural waste.

3.2. Pyrolysis technologies of agricultural waste

Pyrolysis is a thermochemical conversion process conducted in the absence of oxygen, enabling the transformation of biomass, including agricultural waste, into value-added products such as biochar, bio-oil, and syngas through high-temperature treatment[32]. Depending on the operating temperature, heating rate, and vapor residence time, pyrolysis can be classified into slow, fast, and flash pyrolysis. Slow pyrolysis is characterized by relatively low heating rates (0.1-2 °C s^{-1}), moderate temperatures of approximately 500 °C, and long vapor residence times. Under these conditions, biochar is the dominant product, typically accounting for 30-50% of the initial biomass mass[33]. In contrast, flash pyrolysis operates at moderate temperatures (400-600 °C), with extremely rapid heating rates and vapor residence times of less than 2 s, leading to lower tar and gas yields than in slow pyrolysis. Fast pyrolysis, meanwhile, is primarily designed to maximize the production of bio-oil and combustible gases. This process generally operates at temperatures around 500 °C or higher, with high heating rates and vapor residence times below 3 s, followed by rapid cooling of the pyrolysis vapors. In some cases, temperatures may reach up to 1000 °C when syngas production is prioritized.

Agricultural waste is mainly composed of cellulose, hemicellulose, and lignin, together with smaller amounts of inorganic mineral constituents[34,35]. These components possess distinct chemical structures and undergo different thermal degradation pathways during pyrolysis. Among the operational parameters, temperature is considered the most critical factor because it strongly influences the pore structure, surface chemistry, and overall physicochemical properties of the resulting AC. Agricultural waste pyrolysis generally proceeds through sequential decomposition stages. Initially, moisture is removed through evaporation, followed by hemicellulose degradation at approximately 200-350 °C. Cellulose decomposition occurs at higher temperatures, while lignin decomposes gradually over a broader temperature range, typically above 400 °C, due to its highly aromatic, thermally stable structure. Optimizing pyrolysis temperature is therefore essential, as higher temperatures can enhance pore development and volatile release, thereby improving the surface characteristics of AC. However, excessively high temperatures may reduce solid yield due to extensive carbon burn-off. Despite its advantages, conventional pyrolysis still faces several limitations, including inefficient heat transfer, prolonged heating times, and relatively high energy consumption, which may increase operational costs.

Microwave-assisted pyrolysis has emerged as an attractive alternative to conventional thermal conversion methods due to its ability to provide rapid and homogeneous heating. This approach significantly shortens reaction times, enhances overall process efficiency, and lowers energy requirements. In addition, because water readily absorbs microwave radiation, high-moisture agricultural waste can be processed directly without preliminary drying, offering a practical advantage for feedstocks with substantial water content. Comparative studies indicate that microwave pyrolysis can produce biochar with a higher specific surface area and greater porosity than biochar obtained by conventional pyrolysis at comparable temperatures. Nevertheless, conventional pyrolysis often yields higher biochar yields. This difference is partly attributed to the more extensive thermal cracking and gas evolution typically associated with conventional heating, which can influence the distribution of biochar and bio-oil products. A key distinction of microwave pyrolysis lies in its heating mechanism. Conventional systems rely primarily on heat transfer by conduction and convection from external sources, such as heating elements, and are therefore limited by the thermal conductivity and surface temperature gradients within the material. In contrast, microwave irradiation induces internal heating through interactions between electromagnetic waves and polar molecules in biomass, leading to volumetric energy absorption. This internal heat generation promotes more uniform temperature profiles and consistent thermal treatment throughout the material, thereby improving thermal efficiency. Thus, microwave-assisted pyrolysis is characterized by enhanced energy utilization, faster processing rates, and the ability to achieve high heating rates and elevated temperatures[36], highlighting its advantages over conventional pyrolysis technologies.

3.3. Degradation behavior of agricultural waste

A comprehensive understanding of pyrolysis requires a clear characterization of the stepwise thermal degradation behavior of the three major biomass constituents: cellulose, hemicellulose, and lignin. Elucidating the transformation pathways of these biopolymers during heating provides deeper insight into the mechanisms governing the conversion of agricultural waste. Such knowledge is crucial not only for advancing the fundamental science of pyrolysis but also for identifying the most appropriate agricultural waste feedstocks. By correlating feedstock composition with pyrolytic behavior, researchers can more effectively select suitable agricultural waste to enhance the conversion efficiency of biomass into value-added products. Ultimately, a detailed mechanistic understanding of pyrolysis contributes to the optimization of bioenergy technologies and promotes the sustainable utilization of agricultural waste resources.

Cellulose is a linear polysaccharide consisting of D-glucose monomers interconnected through β-(1-4) glycosidic linkages, forming long chains that may contain several hundred to several thousand repeating units. Upon pyrolysis, cellulose undergoes a series of intricate thermal decomposition reactions, with biochar representing the principal solid residue. The degradation process is initiated by dehydration, during which water is released as the polymeric structure fragments into smaller molecular species. These intermediates subsequently undergo depolymerization and cross-linking reactions, generating a complex mixture of volatile compounds, including permanent gases and condensable organic vapors, as well as solid carbonaceous residues. Under slow pyrolysis conditions, thermal decomposition typically commences at temperatures below 250 °C, leading to a reduction in polymer chain length and the emission of gases including H_2O, CO_2, and CO. As the temperature exceeds 250 °C, cellulose converts to a tar-like intermediate enriched in organic constituents, while a dark char residue forms. Hydroxyl (–OH) groups play a crucial role during the initial stages of char development, strongly affecting the hydrophilic properties of the resulting material. A temperature of approximately 440 °C is considered a pivotal transition point, at which the abundance of –OH functionalities and aliphatic C–H bonds reaches a maximum. Beyond this temperature, typically between 460 °C and 700 °C, significant structural evolution occurs, characterized by the breakdown of oxygen-containing functional groups and the formation of condensed aromatic carbon structures. This aromatization markedly enhances the hydrophobic character of the biochar. Prior to this structural transition, the relatively hydrophilic surface of biochar is particularly advantageous for serving as a support matrix that facilitates the uniform dispersion of metal species[3].

Hemicellulose, the second-most prevalent biopolymer in agricultural waste, plays a crucial role in maintaining the structural stability of plant cell walls. It consists of a heterogeneous assembly of polysaccharides, including glucoxylan, glucomannans, glucuronoxylan, and xylan. This compositional complexity arises from the presence of various monosaccharide units, such as xylose, glucose, galactose, mannose, and arabinose[37]. Owing to its diverse sugar constituents, hemicellulose exhibits an amorphous architecture that complements and supports the crystalline structure of cellulose. During pyrolysis, hemicellulose initially undergoes depolymerization, yielding oligosaccharide fragments in a manner comparable to cellulose decomposition. Individual fractions, such as glucomannans and xylan, degrade into intermediates, including levoglucosenone and levomannosan. These intermediate species may subsequently convert into syngas and bio-oil or participate in secondary condensation and polymerization reactions that contribute to the formation of the biochar framework. The overall transformation is largely governed by aromatization, dehydration, and decarboxylation reactions, which promote the formation of thermally stable, structurally robust carbonaceous materials.

Lignin is an intricate, amorphous biopolymer primarily constructed from p-hydroxyphenyl, syringyl, and guaiacyl structural units. Its highly irregular three-dimensional network is attributed to differences in the relative abundance of these monolignol units and the diversity of interunit connections, which include both ether (–O–) and carbon–carbon (C–C) linkages[38]. The abundance of functional groups, including methoxy (–OCH_3), hydroxyl (–OH), carboxyl (–COOH), and carbonyl (C=O), imparts considerable polarity to lignin molecules. Owing to its structural heterogeneity, lignin decomposes over a wide temperature interval during pyrolysis. Among its various linkages, β-O-4 ether bonds are the most prevalent, accounting for approximately 60% of the overall structure[38]. Thermal cleavage of these bonds generates highly reactive radical intermediates, which subsequently undergo condensation and repolymerization reactions, ultimately contributing to the formation of a stable biochar framework[39]. Furthermore, the breakdown of methoxy substituents leads to the evolution of methane gas. The inherent complexity of lignocellulosic biomass, together with the distinct thermal degradation behaviors of cellulose, hemicellulose, and lignin, makes the comprehensive elucidation of the pyrolysis mechanism particularly challenging. Achieving a thorough understanding of the pathways for transforming agricultural residues into activated porous carbon materials is an even more demanding scientific and technological endeavor.

The composition of hemicellulose, cellulose, and lignin in agricultural waste significantly influences the physicochemical properties of biochar, a solid product of pyrolysis. Among these components, cellulose plays a critical role in pore development during pyrolysis, as its thermal decomposition promotes the formation of porous carbon structures. Consequently, agricultural waste with higher cellulose content generally produces biochar with a larger specific surface area. For example, pineapple crown leaf waste, containing approximately 70.42% cellulose, was reported to produce biochar with a BET surface area of 11.51 m^2/g; after activation with $ZnCl_2$, the resulting AC exhibited a specific surface area of 750.12 m^2/g. In contrast, cocoa shell waste, which contains only 21.20% cellulose, yielded biochar with a lower surface area of 8.92 m^2/g, and after $ZnCl_2$ activation, the resulting AC exhibited a specific surface area of 392.71 m^2/g[19]. In contrast, lignin primarily contributes to the development of surface functional groups and influences the pore size distribution due to its highly aromatic and thermally stable structure. Agricultural waste with higher lignin content tends to produce biochar with larger pore diameters and enhanced structural stability. For instance, coconut shell, which contains approximately 36.51% lignin, produced biochar with average pore diameters of 2.12 and 3.05 nm, whereas pineapple crown leaves, with a lignin content of only 4.33%, produced biochar with average pore diameters of 1.93 and 2.33 nm[19]. These findings indicate that the intrinsic biochemical composition of agricultural waste is a key factor governing the textural and surface properties of biochar and AC, thereby influencing their adsorption performance and suitability for environmental applications.

3.4. Key factors impacting the structure of the pyrolysis product

As pyrolysis remains the principal method for converting agricultural waste into biochar, this section examines the diverse factors that govern the formation and evolution of carbon structures during pyrolysis. Beyond the inherent characteristics of the agricultural waste precursor, significant emphasis is placed on optimizing key operational parameters. Process variables, including pyrolysis temperature, residence time, heating rate, and the reaction atmosphere, play decisive roles in determining both the yield and the properties of the resulting biochar. These parameters influence not only the amount of biochar produced but also its physicochemical attributes, such as specific surface area, pore structure, and surface chemistry (e.g., pH and functional groups). The chemical composition and structural features of agricultural waste, particularly its primary constituents: cellulose, hemicellulose, and lignin, strongly affect the distribution and nature of pyrolysis products. Elevated proportions of cellulose and hemicellulose generally favor the formation of volatile compounds, whereas lignin is widely regarded as the main precursor for biochar formation[40]. In addition, the presence of inorganic mineral matter significantly alters pyrolysis pathways and product distribution, often exerting catalytic effects on thermal decomposition reactions[41].

Operating pressure is a critical parameter that significantly influences the structural and physicochemical properties of the pyrolysis product. Elevated pressures can promote structural rearrangement, alter pore development, and improve the mechanical strength of the resulting material. Although the overall hydrochar framework tends to remain relatively stable under high-pressure conditions, smaller, more uniformly distributed particles are often obtained, highlighting the role of pressure in regulating particle morphology and microstructure. In pyrolysis systems, increased pressure prolongs vapor residence time, thereby encouraging secondary carbonization reactions and enhancing the structural stability of the produced biochar. Furthermore, pressure exerts a substantial impact on both the fixed carbon content and the energy density of biochar. High-pressure pyrolysis conditions are generally associated with higher carbon enrichment and improved fuel properties, leading to enhanced performance characteristics of the final carbonaceous material[42].

Temperature is a fundamental variable governing the formation, structural evolution, and functional performance of carbon materials. It strongly influences properties such as pore development, specific surface area, surface chemistry, and overall reactivity. Variations in pyrolysis temperature produce markedly different outcomes, with higher temperatures generally enhancing the specific surface area and alkalinity (pH) of the resulting biochar while simultaneously reducing biochar yield due to intensified devolatilization and mass loss. Nevertheless, excessively high temperatures may adversely affect material integrity by inducing pore shrinkage, structural collapse, or partial melting of the carbon matrix. These effects arise from extensive thermal decomposition and structural rearrangement of the original biomass components. The observed increase in pH at elevated temperatures is primarily attributed to the enrichment and concentration of alkaline inorganic species, such as sodium and potassium, during high-temperature treatment. In addition, higher pyrolysis temperatures promote the removal of volatile compounds, thereby facilitating the formation of more developed and accessible pore networks. Lahijani et al.[43] reported that increasing the pyrolysis temperature significantly improved the CO_2 adsorption capacity. This enhancement was associated with greater particle fragmentation, reduced average pore diameter, and the formation of abundant micropores, all of which contribute to stronger adsorbate–adsorbent interactions and improved CO_2 uptake.

Residence time, defined as the time the feedstock remains at a given temperature within the reactor, is a key operational parameter that affects the structural and physicochemical characteristics of the resulting carbon materials. Prolonged residence times generally promote further carbonization, leading to increased energy density and the formation of more condensed, polyaromatic carbon structures associated with secondary char development. Conversely, shorter residence times tend to favor higher biochar yields by limiting secondary reactions and reducing devolatilization. In addition, residence time significantly influences the textural evolution of biochar by regulating processes such as polymerization, depolymerization, and secondary recondensation reactions, which ultimately affect micropore formation and pore size distribution. Surface area typically increases with extended residence time as pore networks become more developed. However, excessively long residence times, particularly beyond approximately 150 minutes, may result in a decrease in surface area, likely due to structural shrinkage and partial collapse of the carbon framework caused by over-carbonization[3].

The heating rate is a key operational parameter that significantly affects carbonization efficiency, surface structure, and the chemical composition of the resulting carbon materials. Rapid heating generally yields higher effective carbonization temperatures and favors fast pyrolysis, leading to pronounced structural transformations and altered surface morphology. In contrast, lower heating rates enable more gradual and controlled thermal degradation, often yielding carbon materials with distinct surface functional groups and more stable structural features. Moreover, the heating rate strongly influences the pyrolysis reaction pathway and consequently determines the physicochemical characteristics of the produced biochar. Elevated heating rates enhance the thermal cracking of organic constituents and volatile compounds, thereby increasing gas evolution and altering product distribution.

3.5. Modification techniques of biochar to activated carbon

AC refers to carbonaceous materials characterized by a strong carbon framework, high specific surface area, and a well-developed internal pore network. AC derived from agricultural waste exhibits improved physicochemical properties, particularly upon chemical or physical activation. The activation process increases porosity by generating new pores and enlarging existing ones, thereby substantially improving the specific surface area. Chemical activating agents (e.g., KOH, NaOH, H_3PO_4, $ZnCl_2$) primarily operate via two mechanisms: (1) selective etching of carbon atoms, which leads to pore enlargement, and (2) removal of mineral impurities and tar residues that obstruct pore access. This dual mechanism significantly enhances the accessibility of adsorption sites and increases the number of active sites on the AC surface[44]. Moreover, the concentration of the activating agent and the mass ratio of activator to precursor significantly influence the resulting surface area, as summarized in **Table 2**. Higher concentrations of activating agents generally promote the development of a larger surface area, as more extensive removal of organic matter and tar facilitates the formation of additional pore structures[45,46]. Kielbasa et al.[47] reported that KOH-AC from lemon peel achieved a BET surface area of 2159 m^2/g, while Luo et al.[48] synthesized AC from grape seed waste with a BET surface area of 3314.5 m^2/g. BET analysis further revealed that samples activated with KOH exhibited significantly higher specific surface areas than those activated with H_3PO_4, thereby enhancing gas adsorption performance[49]. Additionally, the pores produced via KOH activation tend to be more uniform and highly interconnected, improving pore accessibility and the adsorption capacity of the carbon material[50]. The redox interaction between KOH and carbon (C) begins at approximately 400 °C, leading to the formation of potassium carbonate (K_2CO_3). As the temperature increases to around 600 °C, KOH is fully converted into K_2CO_3. When the temperature exceeds 700 °C, K_2CO_3 thermally decomposes to produce carbon dioxide (CO_2) and potassium oxide (K_2O). At higher temperatures, both K_2CO_3 and K_2O may undergo further reduction to metallic potassium (K). The resulting potassium vapor can diffuse into the carbon framework, promoting the development of micropores and contributing to the formation of a highly porous structure. KOH activation also enhances the surface chemistry of carbon materials by generating functional groups such as –OH, C=O, C–C, and =C–H. However, as the activation temperature increases, oxygen-containing functionalities progressively decompose, releasing CO and CO_2[51]. Considering the acidic character of CO_2, the introduction of Lewis basic sites on the carbon surface has been shown to improve CO_2 adsorption capacity. The sequence of reactions involved in KOH activation is summarized in Eqs. (1)-(5).

Table 2. Properties of ACs from various precursors and activating agents.

Feedstock	Activator (A)	Ratio char : A	BET surface area (m^2/g)	Pore volume (cm^3/g)	Pore size (nm)	Surface functionalities	References
Date seeds	KOH	1:1	675	0.515	2.2	-OH, C=O,	[5]
Corn stalk	$KHCO_3$-KCl	1:3	2512	1.296	1.95	C=O, -COOH, C-OH, C-O-C	[6]
Palm shell	$CaCl_2$	1:2	1334	0.55	2.27	Phenolic groups, carboxylic acids, C-O	[10]
Grape seed	$NaNH_2$	1:3	3315	1.45	-	-OH, N-H, C-N, C=O, C-O	[48]
Mangosteen	KOH	1:5	1039	0.635	2.43	C=O, C-O	[64]
Walnut Shell	H3PO4	1:2.5	1513	0.99	0.9	-OH, C=O, C-O, C-OH, C-O-C	[63]
Fruit waste	KOH	2:1	2004	0.79	0.93	-	[65]
Pineapple crown leaf	KOH	1:3	314	0.1098	1.79	Carbonyl, -OH	[66]
Asparagus waste	ZnCl2	1:2	1516	1.24	3.6	-	[67]
Pomegranate peel	KOH	1:1	1047	0.472	0.8	-	[68]
Cantaloupe peel	KOH	1:1	1958	1.18	1.9	-OH, C=O,	[69]
Rambutan peel	CO_2	1:0.7	0.75	0.0001	2.33	-OH, C-O	[70]
Karanja shell	KOH	1:3	997	0.82	0.82	-OH, C=O, C-O, O-C-O	[71]
Avocado seed	KOH	1:1	2024	0.926	0.6	-	[72]
Pomelo peel	K_2CO_3	1:2	1371	0.54	1.3	-OH, C=O, COOH, C-O, C-N	[73]
Ripe plantain peel	H_3PO_4	1:1	1062	0.554	2.82	-OH, N-H, C=O	[74]
Almond seed shell	KOH	1:4	292	0.17	2.13	-OH, -COO, SCN	[75]
Mango seed shell	KOH	1:4	629	0.28	2.12	-OH, SCN, C≡N	[75]
Coconut shell	KOH	1:1	1726	0.75	-	Oxygen functional group	[76]
Rice husk	Potassium acetate	1:1.5	80	0.58	3.0	Carboxylic, -OH	[77]
Rice husk	H_3PO_4	1:1	1500	0.8	2.5	High oxygen content	[78]
Coconut shell	Potassium citrate	1:2	1050	0.62	2.5	High oxygen content, acetic groups	[79]
Cashew nut shell	K_2CO_3	1:1	1693	0.839	1.63	-OH, C=O, COOH	[80]
Rambutan peel	KOH	1:1	2500	0.313	2.8	High oxygen content	[81]
Agricultural residue	KOH	1:3	1800	1.2	3.0	-OH, C=O,	[82]
Hazelnut shell	KOH	1:1	1696	0.7	3.5	Pyridinic-N, -OH, C=O	[83]
Sugarcane bagasse	Potassium oxalate	1:2	1250	0.78	2.7	Carboxyl, phosphate, lactone group	[84]
Olive stone	KOH solution	1:1	969	0.443	-	-OH, C=O,	[1]
Olive stone	Bioorganic solution	1:1	915	0.444	-	-OH, C=O,	[1]
Olive stone	H_3PO_4	1:1	849	0.339	-	-OH, C=O,	[1]
Sunflower seed hull	$ZnCl_2$	1:4	1956	0.28	1.12	-OH, C=O,	[85]

$$2C + 6KOH \rightarrow 2K + 2K_2CO_3 + 3H_2 \quad (1)$$

$$2K_2CO_3 \rightarrow K_2O + CO_2 \quad (2)$$

$$C + CO_2 \rightarrow 2CO \quad (3)$$

$$2C + K_2CO_3 \rightarrow 2K + 3CO \quad (4)$$

$$C + K_2O \rightarrow 2K + CO \quad (5)$$

In comparison, chemical activation with NaOH exhibits strong oxidizing properties and is often considered a more environmentally favorable approach. Previous studies have demonstrated that the redox interactions between NaOH and the carbon precursor promote the development of both microporous and mesoporous frameworks within the carbon matrix. During activation, NaOH generates reactive species such as CO, CO_2, and H_2, while facilitating the penetration of metallic sodium (Na) and sodium carbonate (Na_2CO_3) into the carbon structure. The intercalation of these species induces lattice expansion, thereby increasing the specific surface area and pore size. Nevertheless, excessive NaOH loading can intensify gasification reactions, potentially diminishing the effective surface area. Elevated NaOH concentrations may also initiate a series of reactions involving carbon and sodium-containing species (e.g., C–NaOH, C–Na_2CO_3, C–Na_2O, C–Na, C–CO_2, and C–CO), which promote the cleavage of C–C and C–O–C bonds and consequently reduce overall carbon yield[3]. Furthermore, NaOH activation has been reported to enhance the aromatic character of biochar, thereby strengthening π–π interactions during the adsorption of pollutants. The principal reaction pathways associated with NaOH activation are summarized as follows:

$$2C + 6NaOH \rightarrow 2Na + 2Na_2CO_3 + 3H_2 \quad (6)$$

$$2C + Na_2CO_3 \rightarrow 2Na + 3CO \quad (7)$$

$$2Na + CO_2 \rightarrow Na_2O + CO \quad (8)$$

Chemical activation with acids is a well-established method for modifying the structural framework and surface chemistry of carbon-based materials, resulting in notable enhancements in specific surface area, pore structure, and surface functionalization, thereby improving adsorption performance. This technique typically involves treating carbon precursors, such as activated carbon (AC) and biochar, with strong inorganic acids, including H_3PO_4, H_2SO_4, and HNO_3. Such treatment stimulates the formation of new pores and the expansion of existing ones, resulting in a highly developed porous structure that is crucial for effective adsorption applications. Among these activating agents, phosphoric acid (H_3PO_4) is the most frequently applied in the preparation of activated carbons for carbon capture purposes. In addition to promoting extensive pore formation, H_3PO_4 introduces phosphorus-containing surface functionalities. For instance, impregnation of Lantana camara biomass with an 85 wt% H_3PO_4 solution significantly enhanced the specific surface area of the resulting activated biochar from 117 to 1177 m^2/g and increased the pore volume by nearly twentyfold compared to the unmodified biochar[52]. X-ray photoelectron spectroscopy (XPS) further confirmed a higher oxygen content and identified surface groups, including C–PO_3, C–P_2O_6, and C–P_2O_5. Consistent findings were reported by Bong et al.[53], who detected functional groups, including C–O–PO_3 and C–PO_3, in biochar produced by H_3PO_4 activation at temperatures ranging from 400 to 600°C[53]. Nevertheless, the generation of acidic phosphorus oxide species (P_xO_y) during H_3PO_4 activation may hinder CO_2 chemisorption on carbon surfaces. Throughout the activation process, H_3PO_4 is converted into polyphosphate compounds, which significantly contribute to the evolution of the porous network.

$$2P_2O_5 + 5C \rightarrow P_4 + 5CO_2 \quad (9)$$

$$2H_2P_2O_7^{2-} \rightarrow P_4 + 6O_2 + 2H_2O \quad (10)$$

Zinc chloride ($ZnCl_2$) is widely recognized as an effective activating agent, primarily due to its strong dehydrating capability. The $ZnCl_2$-assisted activation process during pyrolysis generally occurs in three stages. In the initial stage, thermal decomposition of the biomass leads to the formation of smaller molecular fragments and volatile compounds. Subsequently, $ZnCl_2$ interacts with these intermediates, promoting the formation of char, tar, and additional volatiles through a series of chemical reactions[3]. In the final stage, the char undergoes further reaction with $ZnCl_2$, leading to substantial pore development. $ZnCl_2$ activation enhances the formation of mesopore and macropore structures, which is attributed to the deep penetration of molten $ZnCl_2$ into the carbon matrix, facilitating the expansion and restructuring of the pore network.

$$ZnCl_2 + C \rightarrow Zn + Cl_2 + CO \qquad (11)$$

3.6. Application of activated carbon for CO_2 storage

Activated carbon is widely recognized as an effective adsorbent for carbon dioxide (CO_2) capture, owing to its advantageous properties, including a high specific surface area and well-developed porosity, which provide abundant active sites for CO_2 adsorption. commonly performed with CO_2 or steam, is widely used to enhance the development of microporosity in carbon materials. This process significantly increases the specific surface area and, consequently, improves CO_2 adsorption capacity. The physicochemical characteristics of the activated carbon are strongly influenced by the selection of the biomass precursor and the pyrolysis parameters, including activation temperature and residence time. For instance, CO_2 activation generally favors the formation of well-developed microporous structures with relatively uniform pore size distributions, which are particularly suitable for gas-phase adsorption. In contrast, steam activation tends to generate a broader pore size distribution, including mesopores and macropores, thereby facilitating the diffusion of CO_2 molecules into the internal pore network[54]. In addition to physical activation, chemical activation offers an effective approach to further enhance pore development and surface functionality. Chemical activating agents such as KOH and $ZnCl_2$ promote the formation of hierarchical pore structures and introduce surface functional groups that can interact favorably with CO_2 molecules, thereby increasing adsorption efficiency[55,56].

Furthermore, advanced surface modification approaches, such as acid or alkaline treatment, heteroatom doping (e.g., nitrogen or sulfur incorporation), and metal impregnation, can effectively tailor the surface chemistry of activated carbon and strengthen specific interactions with CO_2, thereby enhancing capture performance. The efficiency of these modification strategies is highly dependent on the selection of activating agents, as well as activation temperature and duration. For example, one study examined the production of porous carbon from tobacco stems using KOH activation at different temperatures and found that increasing the activation temperature led to a higher specific surface area and micropore volume, which initially improved CO_2 adsorption capacity until a saturation threshold was reached[57]. This behavior was attributed to the reduction of oxygen-containing functional groups at elevated temperatures, which generally favors CO_2 adsorption. In another investigation, activated carbon derived from corn stover was prepared using H_3PO_4, CO_2, and H_2O as activating agents. Among these, H_3PO_4-AC exhibited the highest CO_2 capture capacity of 10.9 mmol g^{-1}, owing to its well-developed microporous structure and large specific surface area achieved through chemical activation[58]. Additionally, nanoporous carbon synthesized from walnut shells and doped with urea demonstrated enhanced CO_2 adsorption with increasing nitrogen doping levels[59]. Similarly, the incorporation of metal oxides such as NiO and CuO into AC significantly improved CO_2 uptake, highlighting the beneficial role of metal impregnation in promoting adsorption performance[60].

CO_2 adsorption on AC proceeds through a combination of physical and chemical mechanisms, governed by the nature and strength of interactions between CO_2 molecules and the adsorbent surface[61]. Physical adsorption (physisorption) is a reversible process driven mainly by weak intermolecular forces, such as van der Waals interactions. Its effectiveness is largely determined by the textural properties of the carbon material, including surface area, pore volume, and pore architecture. By contrast, chemical adsorption (chemisorption) involves the formation of stronger covalent or ionic bonds between CO_2 molecules and active sites on the carbon surface. These interactions are typically associated with Lewis acid–base behavior, hydrogen bonding, and specific surface functionalities. In this regard, the abundance of micropores, oxygen- and nitrogen-containing functional groups, and the structural aromaticity of the carbon framework play decisive roles in enhancing CO_2 capture performance. Although a high specific surface area and overall porosity generally promote greater CO_2 uptake, pore size distribution is often more critical than total surface area alone. Micropores with diameters in the range of approximately 0.5–0.7 nm are particularly effective for CO_2 adsorption, especially under low-pressure conditions, due to enhanced confinement effects and stronger adsorbate–adsorbent interactions. Physisorption is also sensitive to temperature; while higher temperatures can improve CO_2 diffusion kinetics, they typically weaken intermolecular interactions and reduce adsorption capacity. Chemisorption, on the other hand, depends on the availability of reactive surface groups and alkali metal species that facilitate bond formation, with hydrogen bonding and Lewis acid–base interactions playing especially important roles in the overall adsorption mechanism.

Numerous investigations have highlighted the importance of hydroxyl (–OH) groups in promoting CO_2 adsorption. Surface modification using nitrogen-containing polymers has also been widely explored to enhance the basicity and electron-donating capacity of carbon materials, thereby strengthening Lewis acid–base interactions with CO_2 molecules. In addition, the formation of covalent coordination bonds between CO_2 and reactive surface sites contributes to chemisorption. Recent progress has focused on the design of heteroatom-doped porous carbons, particularly N,P co-doped materials characterized by high specific surface areas and well-developed microporosity and mesoporosity. The incorporation of nitrogen and phosphorus functionalities has been shown to substantially improve CO_2 adsorption performance[62]. For example, nitrogen-enriched porous carbon derived from lotus stalk exhibited enhanced CO_2 uptake, with nitrogen functionalities playing a dominant role, especially at elevated temperatures and low pressures. However, excessive addition of modifying agents, such as melamine, may lead to pore obstruction and a consequent decline in specific surface area, ultimately reducing CO_2 capture efficiency. More broadly, the introduction of heteroatoms such as nitrogen, oxygen, and sulfur into activated carbon during the activation process alters its electronic structure and surface chemistry, thereby improving adsorption capacity and selectivity toward CO_2. Although micropores are essential for effective CO_2 capture due to their strong confinement effects, they may also adsorb other gases, such as CH_4 and N_2, leading to competitive adsorption and reduced selectivity. Heteroatom doping helps overcome this limitation by introducing functional groups that preferentially interact with CO_2 molecules. In particular, incorporating basic or electron-rich species, such as nitrogen, into the carbon framework increases the density of active sites capable of binding weakly acidic CO_2 molecules, thereby enhancing both adsorption capacity and selectivity.

3.7. Work limitation and future direction

This study provides a comprehensive overview of current approaches for the synthesis and surface modification of agricultural waste-derived AC intended for CO_2 capture applications. It discusses the fundamental conversion routes for transforming diverse agricultural waste precursors into AC and highlights the principal factors governing their physicochemical properties. In particular, both the intrinsic properties of the selected biomass and the processing conditions significantly influence the structural and chemical features of the resulting carbon materials. The review further summarizes various activation techniques and underscores their critical role in tailoring pore architecture and introducing functional groups to enhance CO_2 adsorption performance. Although considerable progress has been achieved, important challenges and knowledge gaps remain. A key issue is the limited understanding of the complex interplay between pore structure development and parameters such as feedstock composition, pyrolysis conditions, and activation strategies. Optimizing pore characteristics using chemical activating agents, such as KOH and $ZnCl_2$, remains a central approach for improving CO_2 capture efficiency. Nevertheless, several limitations persist in this research area. Differences in activating agents, activation temperature, and treatment duration complicate the standardization of synthesis protocols, thereby making direct comparisons among studies difficult. Furthermore, the geographic origin of agricultural biomass can substantially affect its chemical composition, particularly the relative proportions of lignin, cellulose, and hemicellulose, posing additional challenges in establishing broadly applicable conclusions regarding the pyrolysis behavior of agricultural residues. To advance the development of agricultural waste-based AC, future studies should adopt more systematic and comparative methodologies that account for these variables, thereby enabling a more comprehensive understanding of the potential of agricultural waste for CO_2 capture.

Furthermore, one of the principal limitations in the synthesis of AC is the unavoidable production of CO_2 during pyrolysis and activation, particularly when conventional physical or chemical activation methods are employed. To address this challenge, several strategies can be implemented. First, adopting low-temperature or microwave-assisted activation techniques can significantly reduce carbon loss and associated CO_2 emissions by improving energy efficiency and shortening processing time. Second, the use of alternative activating agents with lower oxidative potential, such as potassium carbonate or bio-derived salts, may help minimize excessive carbon burn-off. Third, integrating closed-loop systems that capture and reutilize emitted CO_2, either for in situ activation enhancement or for downstream applications, can further mitigate environmental impact. Additionally, employing biomass precursors with inherently high carbon yield and optimizing process parameters, such as heating rate and residence time, can suppress unnecessary oxidation reactions. Collectively, these approaches provide a promising pathway toward more sustainable and environmentally benign production of AC materials.

4. Conclusion

This systematic review provides a comprehensive understanding of the synthesis, activation, and modification of agricultural waste-derived AC for CO_2 capture. The findings demonstrate that agricultural residues are promising, sustainable, and cost-effective precursors for AC production due to their abundance, high carbon content, and renewable nature. The review identified that chemical activation, particularly with KOH, H_3PO_4, and $ZnCl_2$ substantially enhances the surface area, pore development, and surface functionality of AC, thereby improving CO_2 adsorption capacity. Among various activation techniques, KOH activation consistently yields the highest specific surface areas and well-developed microporous structures suitable for CO_2 adsorption.

Modification strategies, such as heteroatom doping and metal impregnation, further enhance the basicity and selectivity of AC toward CO_2 molecules by increasing the number of active sites and tuning surface chemistry. The review also emphasizes that process parameters, including pyrolysis temperature, residence time, heating rate, and activating agent concentration, play critical roles in determining the physicochemical properties and adsorption performance of the resulting materials.

Author contributions

Conceptualization and methodology, Widi Astuti; investigation and data curation, Dwi Puti S. Aritonang and Maya Anggraeni; writing-original draft preparation, Nagistra Tiwa Lira and Dian Ratri Pramudhita; supervision and validation, Irene Nindita Pradnya; writing-review and editing, Triastuti Sulistyaningsih and Megawati; software, formal analysis, and visualization, Zulfa Ajrina Fitri. All authors have read and agreed to the published version of the manuscript.

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Conflict of interest

The authors declare no conflict of interest.

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