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**Review Article**

# $CO_2$ methanation: a bibliometric analysis and review of activated carbon-based materials (2014–24)

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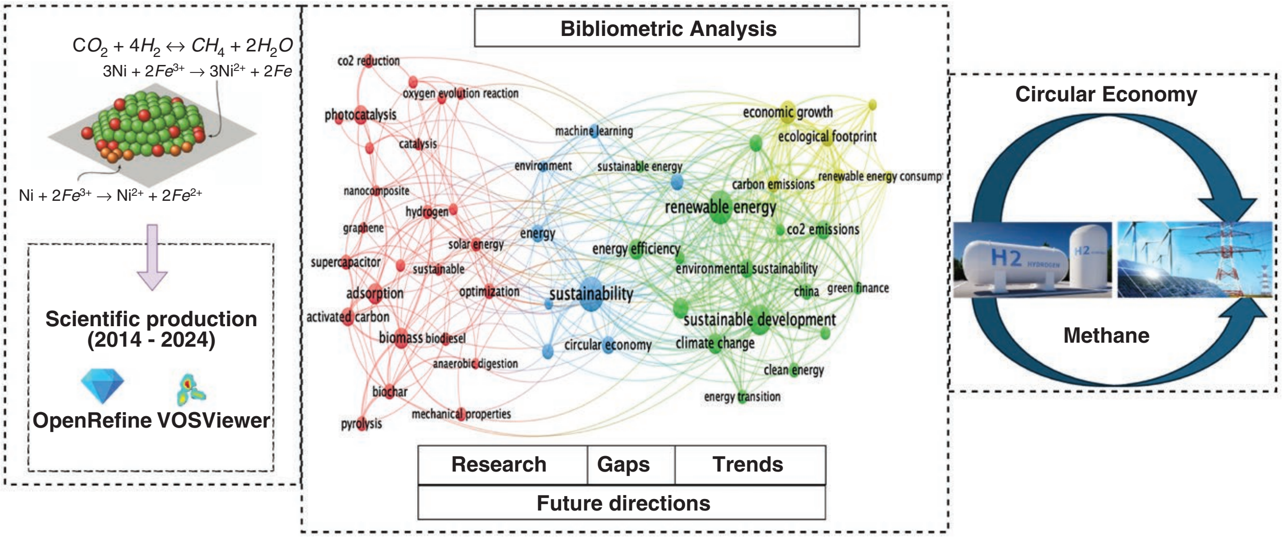
## Abstract

This study highlights the significant potential of activated carbon (AC)-based materials in environmental remediation and energy production, particularly in converting carbon dioxide ($CO_2$) and hydrogen ($H_2$) into methane ($CH_4$) and water ($H_2O$) using transition metal-based catalysts. It emphasizes the role of porous AC in waste reduction and resource utilization, examining various applications of $CO_2$ and evaluating environmental impacts. The research explores commercialization opportunities and specifically investigates $CO_2$ methanation using AC-based materials. Using bibliometric analyses of 4196 articles from the Web of Science database, the study identifies a growing research interest in porous AC-related $CO_2$ methanation from 2014 to 2024. The top three journals in this field are *Environment Development and Sustainability*, *Biomass Conversion and Biorefinery*, and *Journal of Environment Science and Pollution*. However, there is limited inter-institutional collaboration in this field, suggesting room for development towards commercializing sustainable $CH_4$ production pathways. $CH_4$ is highlighted as a crucial intermediate in industrial processes, and research directions are identified through co-occurring author keywords analysis. The study suggests the need for a comprehensive approach integrating AC materials into carbon-neutral energy processes while addressing the potential adverse effects of AC nanoparticles on biological and environmental factors. Ultimately, it clarifies the potential uses and commercialization prospects for porous AC materials, especially in conjunction with carbon capture and utilization technologies, promoting sustainable practices in energy production and environmental management.

## Graphical abstract



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## 1. Introduction

The emission of $CO_2$ poses a significant challenge for both society and industry, prompting substantial efforts to mitigate its production and release into the atmosphere. The current focus is on promoting processes that involve underground storage and capture of $CO_2$ [1]. However, converting $CO_2$ into high-value molecules is increasingly recognized as a crucial approach for regulating atmospheric emissions in the future [2]. Many scientists argue that low-temperature methanation could potentially reduce reliance on underground $CO_2$ storage [3–5]. This process requires hydrogen, obtainable through water electrolysis or from industries with surplus hydrogen production. Electricity needed for these processes can come from "green" sources like biomass, wind, or solar energy. In addition to converting $CO_2$ into a high-value molecule, this conversion process offers the advantage of transforming hydrogen ($H_2$) into a more easily usable energy source, exemplified by the production of $CH_4$. Furthermore, the produced $CH_4$ can synthetic natural gas (SNG) in the chemical and petrochemical sectors, thereby lowering natural gas consumption. Ecologically and environmentally, converting $CO_2$ and $H_2$ into $CH_4$ presents a viable alternative.

The $CO_2$ methanation reaction ($4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$, $\Delta H_{298\ K} = -164$ kJ/mol) remains highly advantageous thermodynamically, significantly outpacing other reactions that produce hydrocarbons or alcohols [6]. Known as the Sabatier reaction, it holds promise for industrial implementation, contingent upon hydrogen sourced from renewables. $CO_2$ methanation is not only a pivotal catalytic process of academic interest but also shows potential for commercial applications [7–9]. With dwindling interest in large-scale SNG production from coal gasification byproducts [10], $CO_2$ methanation finds utility in industries like fuel cells and ammonia ($NH_3$) synthesis, removing trace CO from $H_2$-rich streams and preventing catalyst poisoning [11]. Furthermore, the Sabatier reaction holds potential applications in human space colonization on Mars, as acknowledged by the National Aeronautics and Space Administration (NASA) [8]. Moreover, NASA explores the Sabatier reaction for potential applications in future manned missions to Mars, converting Martian $CO_2$ into $CH_4$ and $H_2O$ for propellant and life support systems facilitated by transporting hydrogen from Earth [12]. Effective catalysts are crucial for achieving high selectivity and conversion rates in these processes [13–16]. Carbon-based catalysts, particularly porous activated carbon (AC), have emerged as promising candidates for $CO_2$ methanation due to their unique properties. AC has an exceptional adsorption capacity as a support, with a large specific surface area, a rich pore structure, and cost efficiency [17]. These attributes enhance catalytic stability, supported by efficient combustion for recycling metal-supported carbon carriers. Moreover, the surface functional groups, pore structure, and surface area of AC play pivotal roles in enhancing the $CO_2$ methanation reaction.

In this context, Wei and Jinlong [18] provided an extensive overview of $CO_2$ methanation, focusing on porous supports. Their article highlights recent advancements in catalytic materials, novel reactors, and the underlying reaction mechanisms. They emphasized how the catalytic properties of active metal sites can be influenced by interactions between the metal and its support. Similarly, Jwa *et al.* [19] investigated the hydrogenation of carbon oxides ($CO_2$ and CO) into $CH_4$ using Ni/$\beta$-zeolite catalysts, emphasizing the importance of enhancing $CO_2$ delivery to the catalyst surface to improve methanation efficiency. Numerous studies have explored nickel catalysts supported on materials such as porous alumina [20] or MCM41 [21, 22] catalysts. These investigations consistently demonstrate that the porous structure of these supports enhances nickel dispersion and prevents the sintering of nickel species. AC, known for its substantial surface area, surface functionalization, and low regeneration energy requirements, has received significant research interest. AC has proven effective as an adsorbent for $CO_2$ under ambient conditions [23–25]. For example, Vargas *et al.* [23] impregnated African palm shell-derived AC monoliths and found they could adsorb up to 5.8 mmol $CO_2$/g at 273 K and 1 bar. Wickramaratne and Jaroniec [25] reported AC spheres achieving high $CO_2$ uptakes of 8.9 mmol/g at 0°C and 4.55 mmol/g at 25°C under atmospheric pressure. Additionally, studies by Li *et al.* [26] showed that pine cone shell-based AC exhibited notable $CO_2$ adsorption capacities, achieving 7.63 mmol/g at 0°C under 1 bar and 2.35 mmol/g under 0.15 bar pressure. Previous work by our team [27] employed mesoporous AC-supported bimetallic Ni–Mo catalysts to investigate $CO_2$ methanation, highlighting AC's capability to adsorb $CO_2$ effectively. The composition and structure of the catalyst, including specific surface area and pore characteristics, significantly influence its catalytic performance. Supported nickel catalysts with high dispersion on AC, known for their developed pore structures and large specific surface area (>1000 $m^2$/g), exhibit promising catalytic properties. AC serves as an effective support for modifying surface properties to enhance nickel catalyst activity for $CO_2$ hydrogenation, positioning it favorably despite the current absence of reported porous AC-related $CO_2$ methanation studies.

A bibliometric review, sometimes referred to as science mapping or scientometrics, involves the analysis and visualization of different bibliometric networks based on the outputs of academic literature in a given scientific field using text and data mining techniques [28, 29]. According to Pritchard's original definition [30], this analysis uses statistical techniques and mathematical applications. Citations are fundamental to the dynamics of scientific and technological progress, creating connections between researchers, their ideas, publications, and institutions [31]. Eugene Garfield first proposed the concept of the Science Citation Index [32, 33]. Since then, bibliometrics has been used to evaluate research performance and allocate research funding at various levels, from individuals and groups to institutions and universities [34]. For a detailed overview of the history of scientometrics and bibliometrics, readers are referred to the following studies: [31, 33, 35, 36]. A bibliometric review can overcome the subjectivity often seen in narrative and systematic reviews [37] as well as in peer reviews, which is a significant advantage [34]. Additionally, bibliometric mapping helps professionals deepen their understanding of a particular field [38], provides a comprehensive visual reference platform for new researchers, and aids in understanding the evolutionary and historical changes in a research area [39]. Fields such as microbial fuel cells [40], library and information science [38], medicine [41], computational intelligence [42], materials engineering [29], and conversion technologies for $CO_2$ [43] have all benefited from bibliometric analyses.

Furthermore, researchers can visualize collaborations and networks within specific domains by analyzing co-authorship patterns, affiliations, and collaboration networks [38]. These data are invaluable for fostering interdisciplinary collaborations, gaining deeper insights into scientific community dynamics, and facilitating the assessment of journal quality, research reputation, and discipline, among other factors. Bibliometric analysis also provides evidence-based insights that assist policymakers and funding agencies in resource allocation, promoting multidisciplinary research, and supporting strategic objectives [44].

Institutions can use bibliometric analysis to evaluate research initiatives, assess research productivity, benchmark against peers, impact, and global visibility, and monitor overall research performance. Despite extensive investigations into AC-based materials and dedicated sections on $CO_2$ commercialization, environmental pollution, remediation, and energy, there remains a significant gap in comprehensive records focusing on research trends, the productivity of active institutions and authors over time, and specific contributions of AC-based materials to $CO_2$ methanation. This gap highlights the need for a unified framework that integrates bibliometric trends to evaluate commercialization potential and outline the environmental impacts of incorporating AC-based materials into $CO_2$ methanation. This paper aims to fill this void by conducting a meticulous analysis that not only evaluates individual components but also integrates them into a cohesive narrative. One objective is to provide a comprehensive and up-to-date understanding of the broader context surrounding AC-based materials. This compilation addresses existing research gaps and lays the groundwork for identifying future research and application opportunities. The methodology employed in this study utilizes VOSviewer and OpenRefine software for data analysis, highlighting emerging research areas. Ultimately, this evaluation serves as a guiding marker, synthesizing scholarly inputs to illustrate progress, challenges, and forthcoming pathways in the production of $CH_4$ using porous AC catalysts.

## 1.1 Review gap

Despite extensive studies of AC-based materials and their role in $CO_2$ commercialization, pollution control, environmental remediation, and energy production, there is a surprising lack of comprehensive records tracing research trends, the productivity of leading authors and institutions over time, and the specific contributions of AC-based materials in $CO_2$ methanation, including their applications in energy and fuel production and environmental remediation. This gap highlights the need for a coherent framework that integrates bibliometric trends to assess the commercialization prospects and outline the environmental impact of the use of AC-based materials in $CO_2$ methanation. This research aims to fill this gap by providing a comprehensive analysis that not only examines each component separately but also integrates them into a coherent narrative and provides an up-to-date understanding of the broader context around AC-based materials. This synthesis fills gaps in current knowledge and lays the foundation for future research directions and applications.

Table 1 provides a detailed overview of relevant research on porous AC materials for environmental remediation, greenhouse gas (GHG) mitigation, and $CO_2$ and $CH_4$ utilization. VOSviewer and OpenRefine were used in the analysis to highlight key research areas. This evaluation serves as a roadmap that integrates academic contributions to highlight progress, challenges and future directions in the production of synthetic fuels using porous AC catalysts.

## 1.2 Utility and properties of AC

### 1.2.1 *AC as catalyst*

Acids catalyze many reactions in fine chemical synthesis. Traditionally, these reactions are carried out in a homogeneous phase and the presence of strong inorganic acids. Acids such as sulfuric acid ($H_2SO_4$), nitric acid ($HNO_3$), or hydrochloric acid (HCl) often exhibit poor selectivity despite their fast kinetics and high conversion rates, which poses numerous challenges to the process. These substances also place high demands on the equipment as they are corrosive and aggressive. They also require post-treatment, which can be time-consuming, difficult, and potentially harmful to the environment. AC is a very cost-efficient and environmentally friendly replacement for the various heterogeneous catalysts that have been developed and used as acid catalysts in fine chemical synthesis [54].

Building on this shift towards more sustainable catalytic processes, Swalus *et al.* [55] studied the low-temperature methanation of $CO_2$ using a Rh/γ-$Al_2O_3$ catalyst, with hydrogen supplied *in situ* by a Ni/AC catalyst. The methanation process was significantly enhanced by the combined mechanical properties of the Rh/γ-$Al_2O_3$ and Ni/AC catalysts, with the effect being particularly pronounced at a Ni content of 1 wt%. Compared to the performance of the individual catalysts, the mixed catalyst exhibited superior $CH_4$ production, a result attributed to the synergistic interaction between the two catalysts during methanation. Specifically, the 1 wt% Rh/γ-$Al_2O_3$ catalyst efficiently adsorbed $CO_2$, while the 1 wt% Ni/AC catalyst demonstrated a high capacity for hydrogen adsorption and minimal $CO_2$ adsorption. This complementary behavior of the two catalysts, when combined, led to an enhanced conversion of $CO_2$ and increased $CH_4$ formation, with $CH_4$ being the sole product in all cases. The improved catalytic performance was likely driven by the migration of activated hydrogen species from the Ni/AC catalyst to the Rh/γ-$Al_2O_3$ catalyst, where the hydrogen reacted with adsorbed $CO_2$ species to produce $CH_4$. Additionally, this transfer of hydrogen helped maintain the rhodium particles in a reduced state, which is crucial for efficient $CO_2$ hydrogenation.

These findings highlight the importance of the production and modification methods of AC itself in determining its catalytic effectiveness. The two primary methods for producing AC, physical and chemical activation, each significantly impacts the final material's surface properties depending on the activation conditions and chemical agents used [56]. Physical activation involves two steps: First, the raw material is carbonized in the absence of oxygen in a process called pyrolysis, which is usually carried out at temperatures between 400°C and 850°C. The carbon resulting from the carbonization is then activated with oxidizing gases such as steam or $CO_2$ at temperatures between 600°C and 1000°C [57, 58]. Chemical activation is a one- or two-step process that starts with the impregnation of the precursor (biomass or the char resulting from the first carbonization step) with the chemical agent (oxidizing agent and dehydrating agent). The mixture is then heated at temperatures between 400°C and 800°C in an inert atmosphere [57, 58]. The simultaneous use of chemical and physical activation is also possible. The type of precursor or feedstock used in the production of biomass-derived ACs has a major impact on the characteristics and properties of the final carbon [59]. ACs are incredibly adaptable materials with fascinatingly tunable properties that can be used to tailor surface chemistry and porous structure. Modification processes can be used to create materials with very different properties so that the physicochemical properties can be fine-tuned to achieve the desired catalytic performance. The presence of functional groups on the surface of AC is a key feature that is particularly important for these specialized catalytic processes. Since certain of these groups can act as active sites, their use as acid catalysts depends on their nature, type, and concentration [49].

In this context, the chemical properties of ACs are largely determined by the surface's chemical heterogeneity, which is influenced by the presence of heteroatoms. Heteroatoms are atoms in the carbon structure that are not carbon, such as phosphorus, sulfur, hydrogen, nitrogen, and oxygen, which are not carbon

Table 1. An overview of published articles relevant to porous AC materials.

| Title of article | Highlights | Year | Ref. |
|---|---|---|---|
| Recent progress in the synthesis of porous carbon materials | The study explored advancements in porous carbon synthesis, covering methods like templating, activation, and green synthesis, while highlighting their applications in energy storage, remediation, and catalysis. | 2006 | [45] |
| Last decade of research on activated carbons as catalytic support in chemical processes | The study addresses recent advances in the use of AC as a catalyst support, highlighting its tailored properties to improve catalyst performance and stability in applications such as hydrogenation, oxidation, and coupling. It explored novel design strategies that address challenges such as catalyst deactivation and cost efficiency and highlighted the potential of AC-supported catalysts for sustainable and efficient chemical processes. | 2010 | [46] |
| Porous carbon-supported catalysts for energy and environmental applications: a short review | The study investigated porous carbon-based catalysts and emphasized their high surface area, chemical stability, and adaptable properties for applications in energy storage, environmental remediation, and chemical synthesis. It also highlights the challenges and future research opportunities in this area and emphasizes the potential of these catalysts to tackle global energy and environmental problems. | 2011 | [47] |
| $CO_2$ methanation over heterogeneous catalysts: recent progress and future prospects | The article reviews recent advances in heterogeneous catalysts for $CO_2$ methanation, focusing on various materials such as nickel-based catalysts with promoters, transition metal carbides, nitrides, borides, and structured catalysts for improved performance. Challenges such as catalyst deactivation, energy efficiency, and cost-effectiveness were highlighted and the need for further research and development in this area was emphasized. | 2015 | [48] |
| Porous carbon: a versatile material for catalysis | The study stressed porous carbon materials' unique properties, such as high surface area and tunable porosity, and their applications in energy conversion, remediation, and chemical synthesis, highlighting their potential as efficient, sustainable catalysts. | 2017 | [49] |
| Recent progresses in constructing the highly efficient Ni based catalysts with advanced low-temperature activity toward $CO_2$ methanation | The study reviews recent progress in the development of efficient Ni-based catalysts for $CO_2$ methanation, focusing on the use of promoters, support materials, and innovative design strategies such as hierarchical structures, core-shell architectures, and monatomic catalysts. It also highlighted challenges such as catalyst deactivation, energy efficiency, and cost-effectiveness and emphasized the need for further research and development in this area. | 2020 | [50] |
| Promising catalytic systems for $CO_2$ hydrogenation into $CH_4$: a review of recent studies | The review provided an overview of recent advances in catalytic systems for the hydrogenation of $CO_2$ to $CH_4$, focusing on nickel-based catalysts with promoters, various support materials and innovative designs such as hierarchical structures, core-shell architectures, and monatomic catalysts. Challenges such as catalyst deactivation, energy efficiency, and cost-effectiveness were also discussed, emphasizing the need for further research and development. | 2020 | [51] |
| A review of recent catalyst advances in $CO_2$ methanation processes | The review examined advancements in $CO_2$ methanation catalysts, highlighting nickel-based catalysts and emerging materials such as metal carbides, nitrides, and borides. | 2020 | [52] |
| Recent trends in developments of active metals and heterogeneous materials for catalytic $CO_2$ hydrogenation to renewable methane: a review | The study examined recent trends in catalysts for the hydrogenation of $CO_2$ to $CH_4$, focusing on nickel-based, transition metal and heterogeneous materials such as zeolites and metal–organic frameworks. It highlighted challenges such as deactivation, efficiency, and cost and emphasized the need for further research. | 2021 | [53] |
| *$CO_2$ methanation: a bibliometric analysis and review of activated carbon-based materials (2014–24)* | *The study examines the use of porous AC in $CO_2$ methanation to convert $CO_2$ and $H_2$ into $CH_4$. It explores AC's role in carbon capture, environmental remediation, and sustainable energy, while conducting a bibliometric analysis of research trends and identifying commercialization challenges and prospects.* | 2024 | *Current study* |

[60, 61]. The composition and quantity of these elements are influenced by the characteristics of the starting material and the conditions under which they are introduced during the activation process. The acidic or basic properties of the AC surface are influenced by the delocalized electrons within the carbon structure and the surface functional groups formed by the presence of heteroatoms [62].

#### 1.2.1.1 Acidic surfaces

The acidic nature of AC surfaces is closely associated with oxygen-containing surface groups [63–65]. These groups, primarily located on the outer surface or at the edges of the basal planes, significantly influence the chemical properties of the carbon. The oxygen concentration on the surface significantly influences the adsorption capacity of the carbon, as these peripheral sites occupy the largest part of the adsorption surface [66, 67]. Examples of oxygen-containing functionalities identified on the carbon surface are quinone, chromene, pyrone, carbonyl, phenol, lactone, carboxyl, and ether groups (Fig. 1). Carboxylic anhydride is another example of a carboxylic group [69, 70]. The chemical properties of surface oxygen functional groups can be classified into three categories: acidic, basic, and neutral. Surface acidity is primarily attributed to functional groups such as carboxylic anhydrides, carboxylic acids, lactones, and phenolic hydroxyl groups [71, 72].

Oxygen-containing functional groups are formed when the carbon surface is oxidized. The most commonly employed methods for incorporating these acidic groups involve oxidation

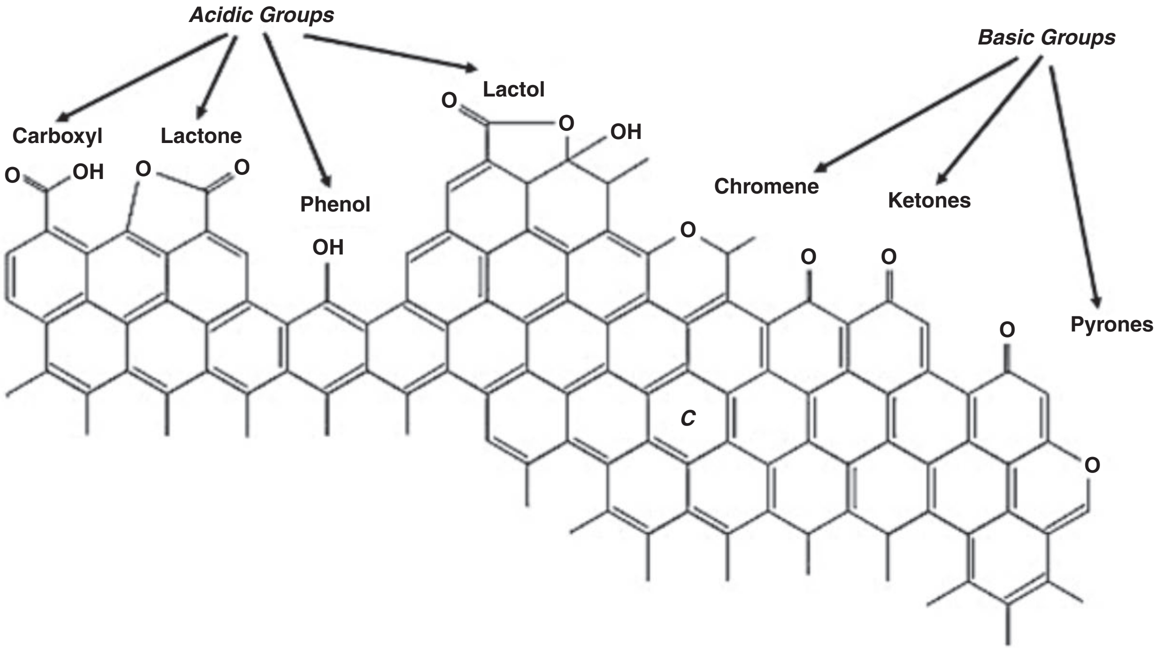

**Figure 1.** Surface functionalities of acidic and basic groups on a basal plane of carbon. Adapted from Montes-Morán *et al.* [68].

using gases or aqueous oxidants [73, 74]. In the gas-phase treatment, oxidants such as steam, $CO_2$, air, and oxygen can be used. Low-temperature gas-phase oxidations typically generate strong acidic groups, such as carboxylic groups, while high-temperature oxidations tend to produce a higher concentration of weaker acidic groups, like phenolic groups [75, 76]. As opposed to gas-phase treatments, liquid-phase oxidations can contribute a greater quantity of oxygen to the carbon surface at a much lower temperature [77]. $HNO_3$, or $H_2SO_4$–$H_2SO_4$ acid mixture, are particularly effective oxidizing agents, introducing a significant number of oxygenated acidic functionalities, such as phenolic hydroxyl, carboxylic, and lactone groups, onto the carbon surface [74, 78]. Studies have shown that gas-phase oxidation of AC primarily increases the concentration of hydroxyl and carbonyl surface groups. In contrast, liquid-phase oxidation, even at lower temperatures, can incorporate a greater amount of oxygen in the form of phenolic hydroxyl and carboxylic groups [75, 79].

### 1.2.1.2 Basic surfaces

The basicity of AC can be attributed to two main factors: (i) the resonating π-electrons in the aromatic carbon rings, which attract protons, and (ii) basic surface functionalities, such as nitrogen-containing groups, which can bind to protons [80–82]. It has been hypothesized that the basicity of carbon can be influenced by certain oxygen-containing surface functionalities, including pyrones [83], ketones [84], and chromenes [77] (Fig. 2). The fundamental properties of ACs are primarily attributed to the delocalized π-electrons within the graphene layers [68, 86]. Research has demonstrated that these π-electrons can function as Lewis bases [87, 88]. Several studies have explored how the basal planes contribute to the basicity of carbon [87, 89]. For instance, Leon y Leon *et al.* [90] examined the surface basicity of two series of carbons and found that oxygen-free carbon sites can effectively adsorb protons from a solution. These sites are situated in regions abundant with π-electrons on the basal plane of the carbon crystallites. Consequently, the carbon structure itself is associated with Lewis-type basic sites [91].

It has been demonstrated that introducing nitrogen functional groups onto the carbon surface can significantly enhance the ability of AC to adsorb $CO_2$ [92–94]. Nitrogen-containing functionalities can be incorporated either by reacting with nitrogen-rich reagents (such as $NH_3$, $HNO_3$, or R-$NH_2$) or by activating the carbon with nitrogen-containing precursors [81, 95]. Figure 2 illustrates the potential structures of these nitrogen functionalities, which include amide, imide, lactam, pyrrolic, and pyridinic groups [96, 97]. These nitrogen-containing groups typically exhibit properties that enhance interactions between acidic molecules and the carbon surface, such as covalent bonding, hydrogen bonding, and dipole–dipole interactions [81].

Several treatments can be carried out to obtain an oxidized carbon surface. The best known are the liquid-phase treatments with acids (usually $H_2SO_4$, $HNO_3$, or a combination of both) and the gas-phase treatments with hydrogen peroxide ($H_2O_2$), $N_2$ doped with $O_2$, air, or even $NH_3$ and $N_2O$, where additional heteroatoms can be added. Studies using X-ray photoelectron spectroscopy (XPS) and temperature-programmed desorption mass spectrometry (TPD/MS) can be used to identify and quantify surface functional groups and their relationship to catalytic activity.

Moreover, Matos *et al.* [98] investigated the methoxylation of α-pinene using three $HNO_3$-oxidized carbon materials: a commercial microporous carbon (NoritN), a xerogel carbon, carbon mesoporous nanoparticles (CMN), and a meso-microporous AC from olive stones, along with carbon-based nanoparticles (CBN) as acid catalysts to generate α-terminal methyl ether as the main product of the reaction. The results showed that the surface chemistry of these catalysts was their most important component, although some influence of their textural properties was evident (Fig. 3). As phosphate groups were added during the synthesis of the carbon, the olive stone-based carbon prepared by chemical activation with phosphoric acid ($H_3PO_4$) produced a biomass catalyst with improved properties for the reaction studied. The catalytic activity increased in the following order: NoritN < CMN < CBN, showing that the textural properties also

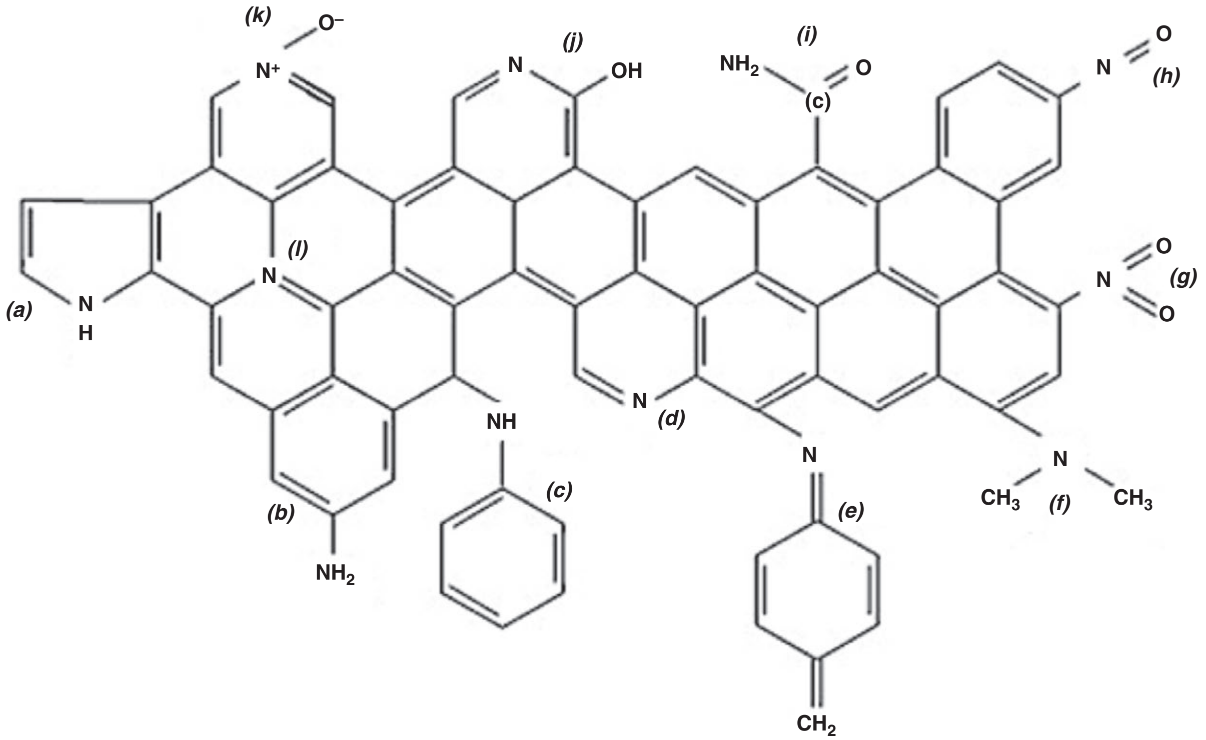

**Figure 2.** Various nitrogen-containing surface functional groups: (a) pyrrole, (b) primary amine, (c) secondary amine, (d) pyridine, (e) imine, (f) tertiary amine, (g) nitro, (h) nitroso, (i) amide, (j) pyridone, (k) pyridine-N-oxide, and (l) quaternary nitrogen [85].

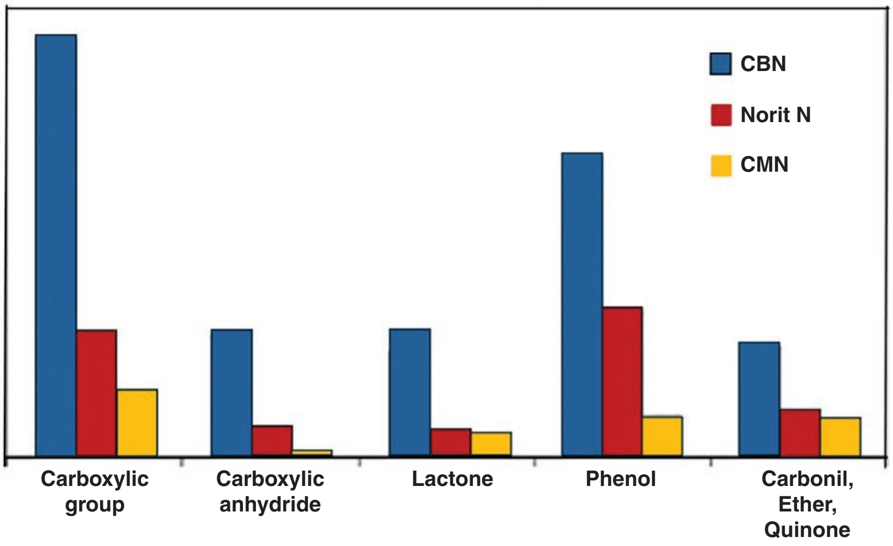

**Figure 3.** Comparative surface group oxygen content for CBN, NoritN, and CMN as determined by TPD. Adapted from Matos *et al.* [98].

have some influence. All catalysts showed good selectivity towards the α-terminal methyl ether.

Palm kernel shells, a low-grade byproduct of the palm oil industry, were used as a raw material to produce another biomass-based carbon. After carbonization, the solid acid catalyst was produced by an intensive $H_2SO_4$ treatment. It was found that the produced solid acid was very active in cellobiose hydrolysis processes. The results showed a correlation between the catalytic activity and the amount of sulfonic groups on the surface. Higher turnover numbers are the consequence of a mechanism of preferential sulfonation position on the surface, which was hypothesized and validated by quantitative XPS. Lower concentrations of sulfonic groups are located at sites with better access to the reactants. When carbons were used instead of resins with higher sulfur content, better results were obtained. The importance of additional functional groups present on the carbon surface in a synergistic effect can, therefore, be deduced from this result [99].

The most acidic microporous carbon materials with sulfonic groups on the surface proved to be effective catalysts in the Friedlander reaction and a cost-effective substitute to produce quinolines with moderate selectivity and high conversions.

**Table 2.** Catalytic performance of unpromoted and promoted Ni catalysts over AC-based supports for various $CO_2$ methanation processes.

| Catalysts | Ni (wt%) | Promoter | Synthesis method | Conditions/performance | | | | Ref. |
|---|---|---|---|---|---|---|---|---|
| | | | | Pressure (bar) | Temperature (°C) | $X_{CO2}$ (%) | $S_{CH4}$ (%) | |
| Ni–Ca/AC | 15 | Ca | IWI | 1 | 360 | 76 | 100 | [101] |
| Rh/γ-$Al_2O_3$ + Ni/AC | 1 | Rh | IWI | 2 | 125 | 50 | 100 | [55] |
| Ni–Ce/$AC_N$ | 15 | Ce | IWI | 1 | 360 | 70 | 99 | [102] |
| Ni–Mo/AC | 13 | Mo | IWI | 1 | 350 | 80 | 92 | [27] |
| Ni–Re/C | 50 | Re | CPM | 1 | 325 | 72 | 96 | [103] |
| Ni–Mo/C | 50 | Mo | CPM | 1 | 325 | 70 | 98 | [103] |
| Ni/C | 50 | | CPM | 1 | 330 | 83 | 99.7 | [103] |
| Ni/ACR–$CeO_2$ | 15 | $CeO_2$ | CPM | 1 | 370 | 87.4 | 100 | [104] |
| Ni–ACR | 15 | | CPM | 1 | 450 | 76 | 97 | [104] |
| Ni/AC–$ZrO_2$ | 15 | $ZrO_2$ | IWI | 1 | 430 | 76.4 | 98.5 | [105] |
| Ni/AC550 | 10 | | IWI | 1 | 330 | 75 | 97 | [106] |
| Ni–$Mg_{0.26}$/CSC | | Mg | CI | 1 | 450 | 90.1 | 99.22 | [107] |
| Ni/CSC | | | CI | 1 | 450 | 77.06 | 98.5 | [107] |
| Ni/CeZrAC | 7 | CeZr | IWI | 1 | 350 | 85 | 100 | [108] |

$AC_N$, AC from natural cork waste; ACR, reduced activated carbon; CI, co-impregnation; CPM, carbon porous nanoparticles; CSC, coconut shell carbon catalyst; IWI, incipient wetness impregnation; $SCH_4$, $CH_4$ selectivity; $XCO_2$, $CO_2$ conversion.

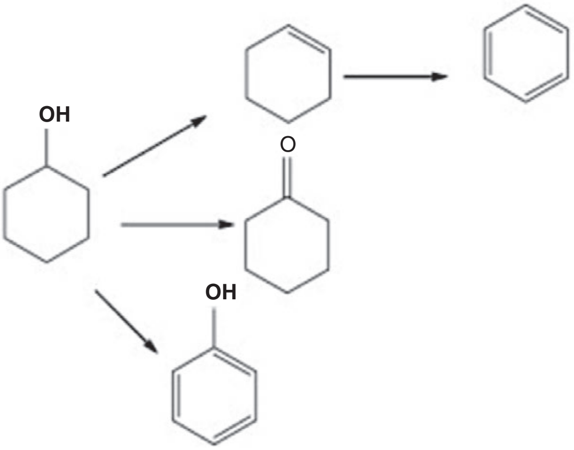

**Figure 4.** Schematic diagram depicting the reaction pathway for converting cyclohexanol using carbon catalysts, as developed by Silva *et al.* [109].

Theoretical calculations also support the importance of the functional acid group. According to the calculation results, the intermediate product that is formed after binding to the surface is less flexible. The porosity and the specific surface area of the carbon materials are also important factors in these studies that probably contribute to selectivity [100]. The results given in Table 2 highlight the importance of understanding the effects of nickel loading, $CO_2$ methanation, promoter influence, and particle size on AC nanoparticles (ACNPs).

Surface functional groups are crucial for both the conversion and the selectivity in the gas-phase reaction of cyclohexanol, in which benzene phenol cyclohexanone and cyclohexene can be formed (Fig. 4). The oxidation process used for the same starting carbon was varied to produce different catalysts. The resulting materials were characterized to determine the amount and type of surface groups originating from the different oxidation processes. After $HNO_3$ treatment, it was found that the dehydration of cyclohexanol occurs mainly in the carboxylic acid groups. The highest concentration of phenolic groups and the best selectivity to cyclohexanone were found for carbons produced with oxygen or peroxide. A high phenol selectivity was achieved by treating the carbon with $N_2O$, but in this case, the involvement of the nitro groups in the reaction process should be taken into account [109].

Various commercially available AC products have also proven suitable as catalysts. Specifically, ACs produced using $H_2SO_4$ and $HNO_3$ have been identified as highly efficient and selective catalysts for *N*-heterocycle alkylation [110]. The ionic liquid imidazolium, a high-value product with increasing demand, can be produced using this process (Fig. 5). The most important property of carbon was its acidity, and the improved results of the reaction without solvent further emphasized the environmental friendliness of the catalyst.

The sol-gel method is the most widely used of the various processes for producing synthetic carbon. Using a basic catalyst, resorcinol is polycondensed with formaldehyde in a simple process, which is then dried and pyrolyzed in an inert atmosphere. A xerogel is produced by evaporating the solvent under normal, non-supercritical conditions [111]. In addition to adjusting the synthesis conditions, surfactants can be used to fine-tune the distribution of porosity, which is one way to control the resulting nanostructure [112]. It is also possible to modify the mesoporous carbons produced by this method and use them as catalysts [113]. In the ring-opening reaction of epoxides by alcohols, mesoporous ACs showed high conversion and selectivity, which makes them effective catalysts (Fig. 6). In addition, the catalyst can be regenerated to regain its original activity [114].

### 1.2.2 *AC as support*

In addition, metals, organocatalysts, and organometallic catalysts can be supported by AC in a variety of processes [115, 116]. The ongoing effort to combine the advantages of solid supports and homogeneous catalysts with known active sites has led to the heterogenization of homogeneous active species,

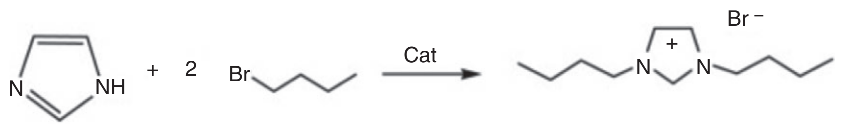

**Figure 5.** Reaction scheme illustrating the synthesis of *N*,*N*-di-*n*-butyl-imidazolium bromide. Adapted from Durán-Valle *et al.* [110].

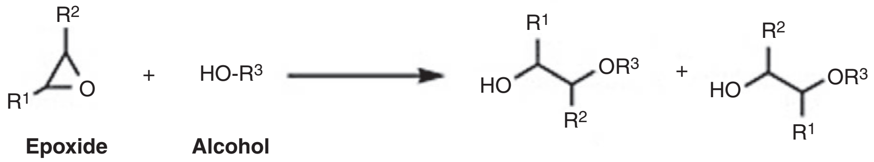

**Figure 6.** Epoxide and alcoholic reactions. Adapted from Matos *et al.* [114].

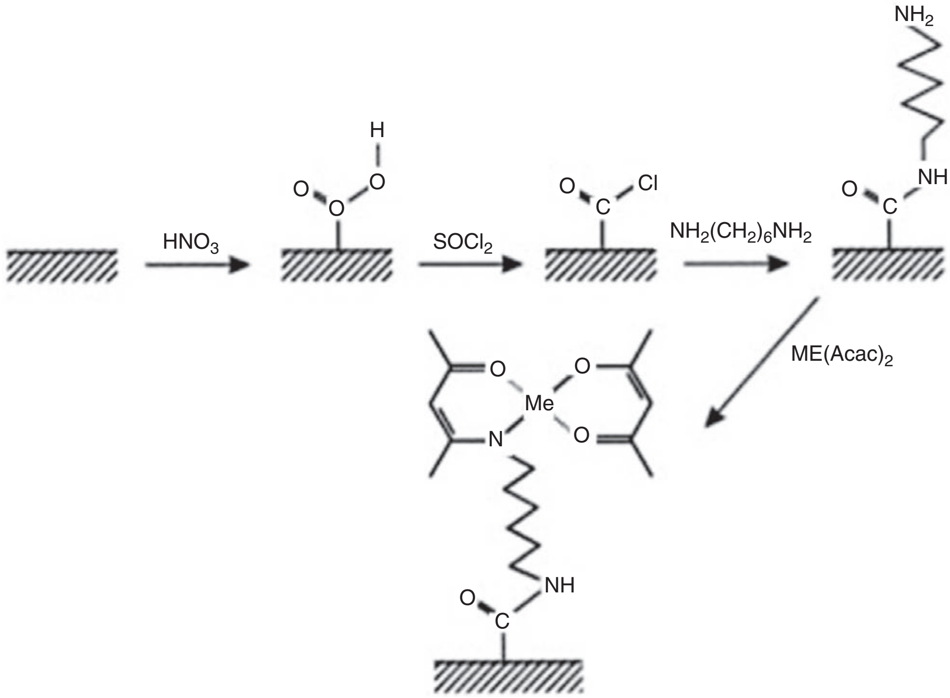

**Figure 7.** A schematic depiction of the acetylacetonate complex heterogenization process. Adapted from Valente *et al.* [120].

potentially improving selectivity even further. When Pd catalysts are present, hydrogenation reactions can take place [117, 118]. Zea *et al.* [119] synthesized and characterized PdAg/C and Pd/C catalysts using plasma torch technology. According to the authors, the metal catalysts obtained were extremely highly dispersed, in some cases with a dispersion of over 50%. The high activity of these catalysts was demonstrated in two hydrogenation processes. When the Pd/C catalysts were compared with those prepared by conventional methods, they showed comparable or superior activity and selectivity for the isomerization of 1-butene. The hydrogenation of acetylene by the PdAg/carbon-supported catalysts was more selective than that of the PdAg/$Al_2O_3$, indicating the importance of the support in these systems.

Similarly, studies conducted on AC with Ni have also demonstrated its effectiveness as a support for catalysts, particularly in $CO_2$ methanation. A high surface area and improved dispersion of the metal particles on the support were key factors noted in various articles [101, 104] and [106] using AC. For instance, according to Feng *et al.* [101], AC provided a high surface area (940 $m^2/g$) and a pore volume of 0.51 $cm^3/g$ when used as a support for Ni, resulting in significant catalytic performance. At 360°C, with 68% $CO_2$ conversion and 65% $CH_4$ production, the catalyst Ni/AC synthesized by impregnation and containing 15 wt% of Ni was able to exhibit the maximum catalytic activity [101]. Goncalves *et al.* [104] also reported a Ni/AC catalyst with 15 wt% Ni that achieved 95% $CH_4$ selectivity and 72% $CO_2$ conversion at 425°C. Additionally, Wang *et al.* [106] investigated Ni catalysts supported on AC and prepared by impregnation of 10 wt% Ni and found that the catalyst provided 96% $CH_4$ selectivity and 69% $CO_2$ conversion at 340°C [106].

Building upon the versatility of AC as a support material, Valente *et al.* [120] investigated the oxidation of pinane with switch metal-acetylacetonate complexes immobilized on modified AC. The surface of the functionalized AC was effectively chemically anchored by copper and cobalt acetylacetonate complexes. Through *in situ* Schiff condensation between the complexes and the amine groups added to the carbon surface, a method for covalent binding of these organometallic complexes to AC supports was demonstrated in this work (Fig. 7). The results showed that Schiff condensation could be performed well, giving these catalytic materials more durability against complicated leaching and yielding materials that would be very valuable for liquid-phase oxidations. In the oxidation of pinane at ambient temperature and atmospheric pressure, these catalysts were extremely selective and active towards 2-pinane hydroperoxide.

In another work, iron phthalocyanines, a homogeneous catalyst, were supported on AC to create heterogeneous catalysts [121]. The surface of commercially available Norit carbon was modified by a series of chemical and thermal processes, including oxidation in the liquid and gas phases. At atmospheric pressure and room temperature, various catalysts were investigated for the oxidation of cis-pinane using *tert*-butyl hydroperoxide. The primary reaction product obtained was 2-pinane hydroperoxide, with a selectivity of 77% at 91% conversion. Additionally, minor products such as verbanol, pinocampheol, and 2-pinanol were also identified. An intriguing finding related to the carbon surface chemistry emerged: catalyst supports with either very high or very low oxygen content exhibited minimal activity, whereas supports with moderate oxygen content demonstrated a strong correlation between the presence of lactones and phenols and catalytic activity.

Heteropoly acids (HPAs) are renowned for their strong Brönsted acidity and are frequently employed as acid catalysts [122]. However, HPAs typically have a low specific surface area (1–10 $m^2/g$). To overcome this limitation, AC supports have been utilized to immobilize HPAs, thereby increasing their specific surface area and the number of accessible acid sites. In a recent study, glycerol was acetylated using dodecatungstophosphoric acid (PW) supported on AC [123]. Catalysts were prepared by impregnation and heat treatment at 403°C. The catalytic esterification of glycerol with acetic acid (3.5–6.5 wt%) was evaluated over various loadings of PW immobilized on AC, with the catalyst containing 4.9 wt% PW exhibiting the highest activity. Increasing the loading of HPA on the AC resulted in decreased catalytic activity, attributed to pore blockage within the porous AC framework. The main reaction products observed were triacetin, diacetin, and monoacetin (Fig. 8), with good selectivity towards diacetin achieved across all catalysts tested. Furthermore, the catalytic stability of the most active catalyst was assessed through successive batch runs, revealing a stabilization of catalytic performance after the third batch.

## 2. Methods

Bibliometric analysis generates networks of citation links between authors, journals, and countries and includes analyses of co-authorship among authors and co-occurrence of keywords. This method utilizes the outputs of academic literature to map and understand the relationships and trends within a specific scientific research area [28].

### 2.1 Data sourcing strategy

The schematic flowchart in Fig. 9 outlines the procedures used to complete the systematic review and bibliometric analysis for this study. The Web of Science (WOS) database was searched, and all articles published between 2014 and July 2024 were retrieved. The WOS is a renowned citation database that provides a current and retrospective index of journals, books and proceedings of multidisciplinary publications. Numerous studies have shown that WOS is suitable for bibliometric analysis [124]. Therefore, the data for this study were restricted to articles published in WOS. The title, abstract, and keyword fields in WOS were searched with specific keywords related to $CO_2$ methanation and $CO_2$ hydrogenation. The query string utilized was (Porous activated carbon) OR (Activated carbon-based porous materials) OR (Porous AC)

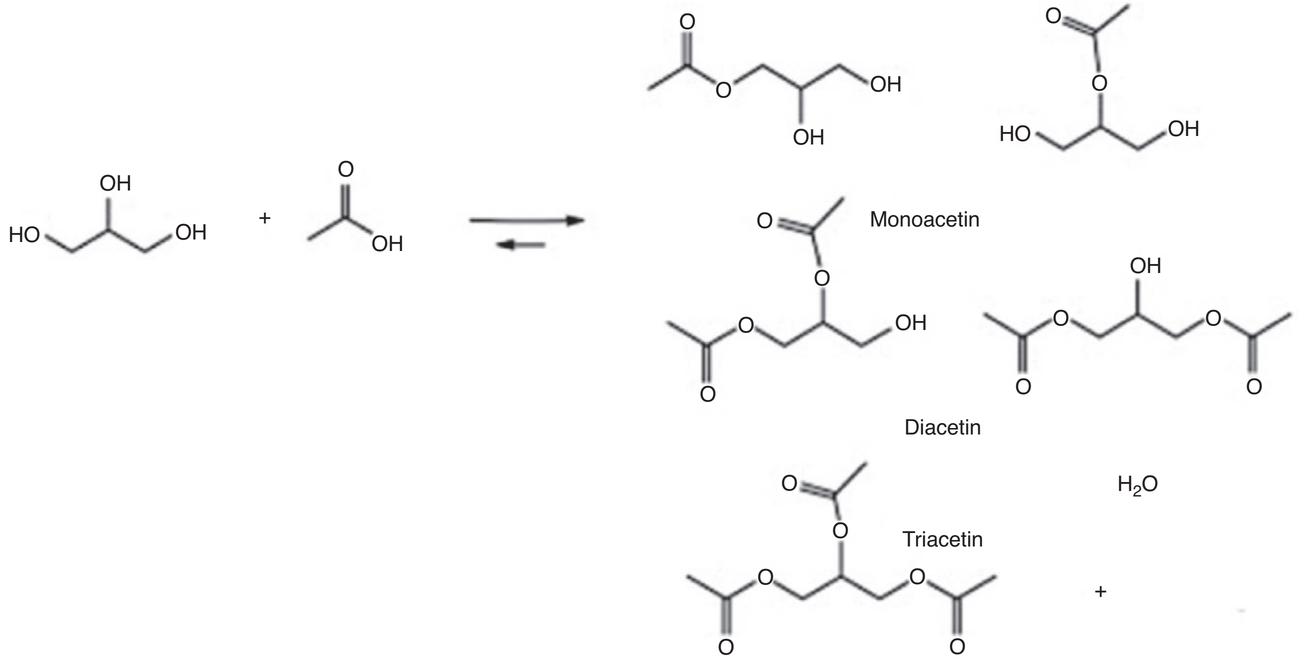

**Figure 8.** Glycerol esterification with acetic acid. Adapted from Ferreira *et al.* [123].

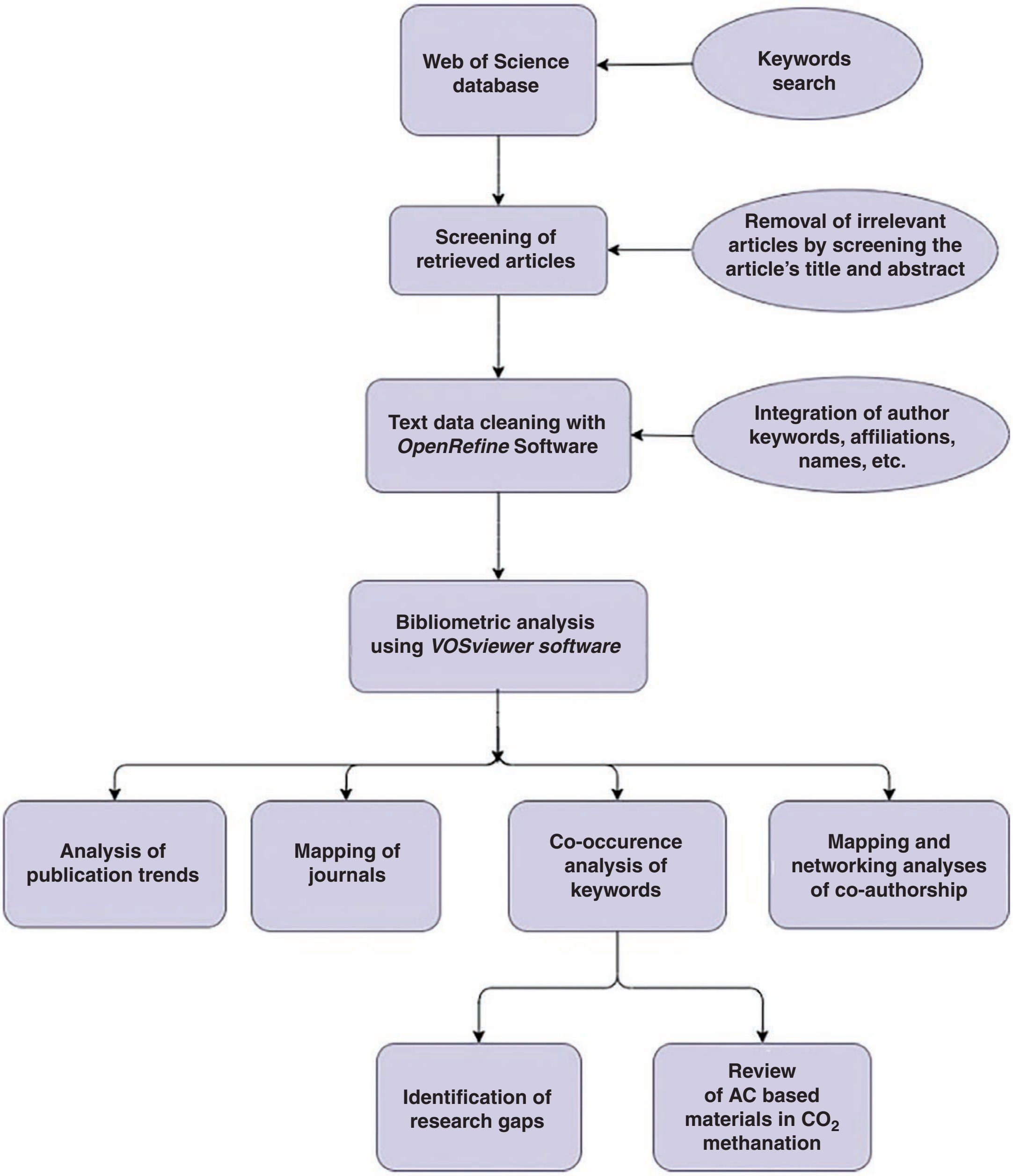

**Figure 9.** Flowchart depicting the process of bibliometric analysis.

OR (AC-based fibers) OR (activated carbon porous catalyst) OR (activated carbon-supported catalysts) OR (activated carbon mesoporous porous material) OR (mesoporous AC) OR (Activated carbon supported catalysts) OR (Activated carbon-based catalytic materials) OR (Activated carbon fiber catalyst systems) OR (Activated carbon fiber-supported heterogenous catalysts) OR (Nanoscale activated carbon catalyst) OR (Nanostructured activated carbon fibers) OR (Nanofibrous activated carbon composites) OR (Activated carbon nanocomposites) OR ($CO_2$ valorization) OR ($CO_2$ methanation) OR ($CO_2$-$CH_4$ utilization) OR ($CO_2$ utilization) OR (greenhouse gas valorization) OR (sustainable energy) OR (synthesis gas generation) OR (synthesis gas production) OR (hydrogenation of $CO_2$ to $CH_4$) OR (carbon dioxide methanation) OR ($CO_2$ hydrogenation to methane) OR (methanation of $CO_2$) OR (methanation of carbon dioxide) OR ($CO_2$ recycling) OR (Carbon–neutral technologies) OR (Eco-friendly catalysts) OR (Renewable syngas production) OR (Clean energy generation) OR (Sustainable catalysis) OR (Greenhouse gas conversion) OR (Carbon–neutral energy) (Topic) and Early Access (Document Types) and English (Languages) and Article (Document Types) and English (Languages). A total of 4196 articles matching the search term were extracted from the database. The metadata for the selected literature was retrieved as of 10 July 2024. These search terms encompassed various aspects pertinent to $CO_2$ methanation, renewable energy, GHG conversion, and the utilization of porous AC catalysts in $CH_4$ and $CO_2$ applications. The comprehensive search approach was designed to ensure all relevant research publications were included.

## 2.2 Data reconciliation and text cleaning

The titles, keywords, and abstracts of the 4196 retrieved articles were screened to identify and exclude any that were clearly unrelated. Since no irrelevant articles were found, all 4196 articles underwent further text cleansing and bibliometric analysis.

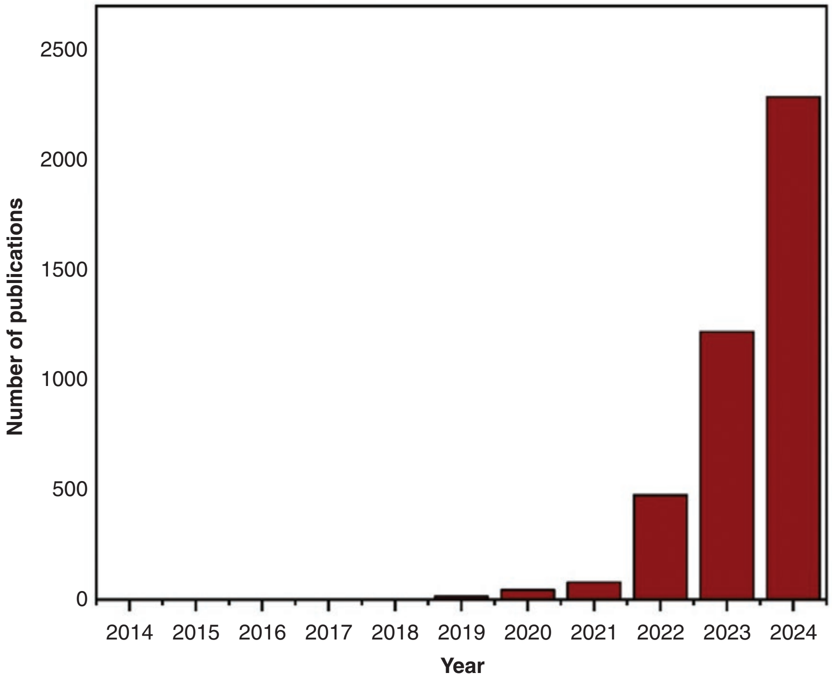

**Figure 10.** Annual scientific outputs on porous AC-related $CO_2$ methanation.

The text cleansing process involved standardizing various author keywords to ensure consistency. For instance, keywords like “Ni-catalysts” and “nickel catalyst” were combined and treated as *ni catalyst*. Likewise, “bi-functional catalysts” and “Bifunctional catalysts” were combined as *bifunctional catalyst*. Additionally, author keywords such as “power to gas” and “Power-to-Gas” were grouped as *power-to-gas*. Text cleaning was performed using the open-source software OpenRefine, version 3.4.1 [125].

## 2.3 Bibliometric analyses

Following data cleaning, the articles underwent analysis to determine the publication growth trend over time. Additionally, bibliometric analyses were conducted to scrutinize the co-occurrence of article keywords (i.e. author keywords), co-citations among articles and scientific journals, and co-authorship among countries. These analyses aimed to unveil primary research interests and directions, citation patterns, influential platforms for scientific papers, and scientific collaborations among institutions and countries. VOSviewer 1.6.17, an open-source, free science mapping software, was utilized for these analyses [126]. VOSviewer employs a distance-based map, where the relationship between items is depicted by the length of the distance between them; a shorter distance signifies a stronger relationship. This visual representation facilitates the identification of clusters of related items [126]. Each facet of the analyses (e.g. journal, country, author) is denoted by a node (e.g. circle or rectangle), with the size of the node indicating its influence and significance. For instance, the importance of an article can be assessed based on metrics such as the number of documents, citations, and average citations. Items sharing the same color belong to the same cluster, suggesting they are frequently cited together in research on porous AC-related $CO_2$ methanation studies. Density visualization maps, such as those for journals, elucidate which journals have received a high number of citations or have published a larger number of articles [126].

# 3. Analysis and discussion of bibliometric findings regarding literature on porous AC-related $CO_2$ methanation (2014–24)

## 3.1 Scientific publication trend

Figure 10 illustrates the annual scientific publication trends for $CO_2$ methanation based on porous AC. According to the publication trend, significant research attention on porous AC-related $CO_2$ methanation began to gain traction in 2019, with 15 articles published. In 2020, 46 articles were published, which is twice the total publications from 2019. From 2021 to 2024, a cumulative total of 4135 publications were indexed in the WOS database, indicating significant growth in this research area. As of May 2024, approximately 2329 articles have been published. This trend suggests that the number of publications will continue to rise as more researchers focus on porous AC-related $CO_2$ methanation, as evidenced by the increased output in 2024.

## 3.2 Top journals for publishing porous AC-related $CO_2$ methanation

Identifying the most reputable journals for publishing research on porous AC-related $CO_2$ methanation is crucial for both funders and researchers. Reputable journals ensure that information sources are reliable and current while also serving as vital channels for disseminating novel concepts and receiving recognition for their work. Publishing in a reputable journal has been demonstrated to boost article citation rates significantly [127, 128]. Figure 11 illustrates the article network map for porous AC-related $CO_2$ methanation studies within the top 20 research journals. The map was created by setting the minimum number of articles per journal to 5 and the minimum number of citations per journal to 10. It is important to note that there are no standardized criteria for creating this type of network map in the bibliometric literature. Nevertheless, we selected these criteria to facilitate the study of 151 distinct scientific journals.

**Figure 11.** Network map highlighting key journals for publishing porous AC-related CO$_2$ methanation.

Figure 11 shows the 46 journals that meet these criteria. Table 3 lists the top 20 journals ranked by overall link strength, citations, and the number of articles published. The overall link strength is a key metric that measures the strength of connections between an item (e.g. journal, country) and other items being analyzed [34].

Figure 12 shows nine clusters of journals, each marked by a different color: red denotes Cluster 1 (11 journals), green Cluster 2 (8 journals), blue Cluster 3 (5 journals), yellow Cluster 4 (6 journals), purple Cluster 5 (5 journals), cyan Cluster 6 (3 journals), orange Cluster 7 (2 journals), brown Cluster 8 (2 Journals), and pink Cluster 9 (2 journals). Journals within the same cluster exhibit higher citation rates compared to those outside the cluster. The number of publications or citations a journal has is indicative of its influence, with this influence visually represented by the size of the node assigned to it. The strength of the link between the two journals is indicated by the length of the line connecting them, with shorter lines representing stronger links [126]. *Environment Development and Sustainability* emerges as the most influential journal, boasting the highest total link strength (60), number of published articles (274), and number of citations (458). It publishes more articles than *Biomass Conversion and Biorefinery*, which ranks second with 259 articles and 579 citations. The next three leading journals are *Environment Science and Pollution*, *Advanced Functional Materials*, and the *Journal of Small*. These five journals combined account for 53.4% of all papers on porous AC-related CO$_2$ methanation. While these journals are the most prolific in terms of the number of papers published, *Energy & Fuels* and *Clean Technologies & Environment* have each published 40 papers, together accumulating a total of 199 citations. Additionally, both *Economic Research – Ekonomska Istrazivanja* and *Advanced Energy Materials* have published 30 papers, together amassing 155 citations. The *Angewandte Chemie International* has fewer published articles compared to *ChemSusChem*, the *Advanced Materials*, *Industrial & Engineering Chemistry*, *ACS Omega*, and the *Journal of the Knowledge Economy*. *Energy Sources Part A – Recovery Utilization Journal* and *ACS Applied Materials & Interfaces* have fewer articles but more citations than *Energy and Environment* and *Natural Resource Forum*. This strongly suggests that the research published in these journals is of high quality. Factors such as the novelty of the research, the reputation of the publishing journal, and the journal's publication model (subscription-based or open access) also contribute significantly to high citation counts [127–129].

**Table 3.** Top 20 bibliometrically analyzed research journals.

| Journal | Cluster | Number of articles | Citations | Total link strength |
|---|---|---|---|---|
| *Environment Development and Sustainability* | 5 | 274 | 458 | 60 |
| *Biomass Conversion and Biorefinery* | 5 | 259 | 579 | 11 |
| *Environment Science and Pollution* | 7 | 159 | 637 | 52 |
| *Advanced Functional Materials* | 2 | 92 | 42 | 9 |
| *Small* | 3 | 90 | 54 | 5 |
| *Energy and Environment* | 4 | 82 | 261 | 34 |
| *ACS Applied Materials & Interfaces* | 1 | 80 | 872 | 6 |
| *Natural Resource Forum* | 4 | 79 | 62 | 61 |
| *Energy Sources Part A – Recovery Utilization* | 6 | 70 | 776 | 10 |
| *Journal of the Knowledge Economy* | 4 | 64 | 95 | 12 |
| *ACS Omega* | 3 | 48 | 253 | 4 |
| *Industrial & Engineering Chemistry* | 1 | 47 | 165 | 1 |
| *Advanced Materials* | 2 | 44 | 58 | 8 |
| *ChemSusChem* | 3 | 41 | 97 | 2 |
| *Energy & Fuels* | 4 | 40 | 183 | 16 |
| *Clean Technologies & Environment* | 6 | 40 | 16 | 10 |
| *Angewandte Chemie International* | 1 | 37 | 95 | 2 |
| *Economic Research – Ekonomska Istrazivanja* | 8 | 30 | 312 | 23 |
| *Advanced Energy Materials* | 1 | 30 | 116 | 4 |
| *Nano Research* | 1 | 29 | 39 | 4 |

## 3.3 Scientific collaboration networks

### 3.3.1 *Co-authorship analysis of researchers*

Scientific cooperation among researchers facilitates access to costly and specialized research facilities, knowledge exchange, and technology transfer [40, 130]. Furthermore, it serves as a critical metric for evaluating universities [34, 40]. Using the criteria "minimum number of documents of an author = 3" and "minimum number of citations of an author = 6," a co-authorship cluster density map of authors is generated in VOSviewer. This map, illustrated in Fig. 12, includes 71 authors out of the 19 239 researchers in the database. Table 2 displays the top 10 authors based on *total link strength* and other ranking attributes, while Fig. 12 shows the co-authorship cluster density map of the top 71 connected researchers. These researchers are organized into 10 clusters, denoted by different colors: red (*Cluster* 1; 11 researchers), green (*Cluster* 2; 10 researchers), blue (*Cluster* 3; 8 researchers), yellow (*Cluster* 4; 8 researchers), purple (*Cluster* 5; 8 researchers), cyan (*Cluster* 6; 7 researchers), orange (*Cluster* 7; 7 researchers), brown (*Cluster* 8; 4 researchers), pink (*Cluster* 9; 4

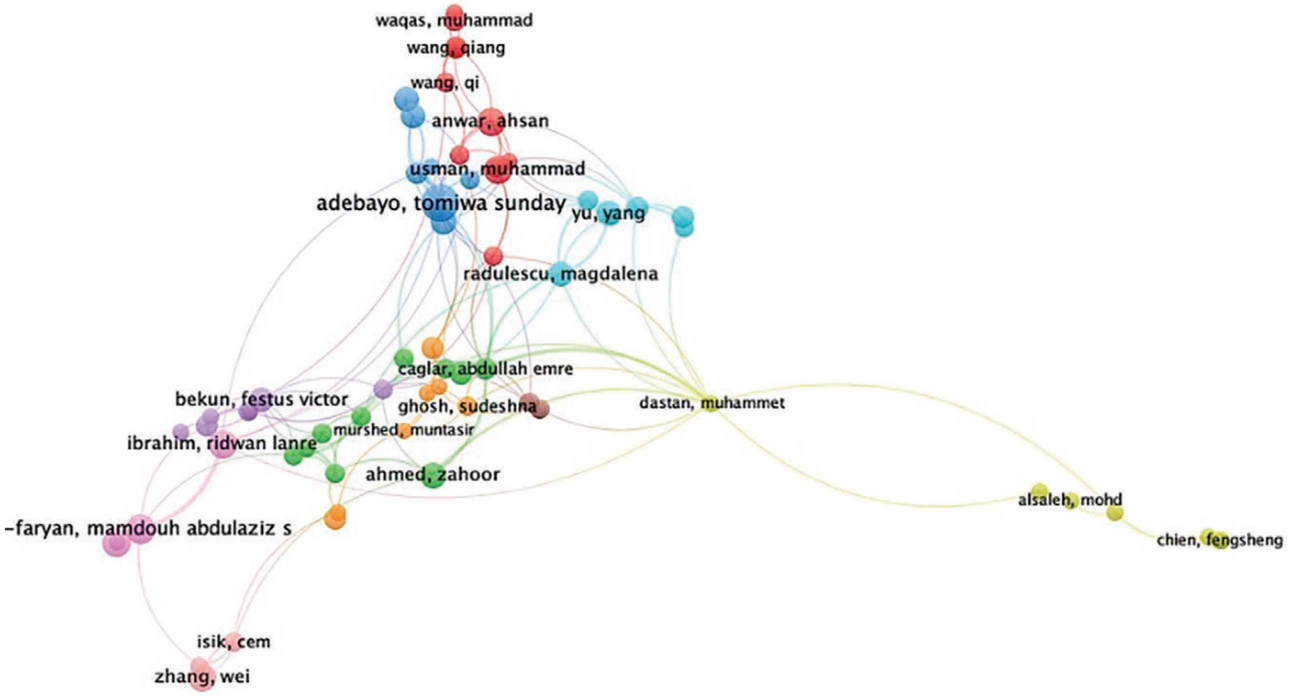

**Figure 12.** Co-authorship cluster map of authors based on publication volume.

researchers), and light pink (*Cluster 10*; 4 researchers). Each cluster represents a collaborative group of scientists. A brighter node linked to a researcher indicates a stronger and more collaborative network. Apparently, the most influential researchers in each of these clusters are Tomiwa Sunday Adebayo (red; 14 articles; 13 collaborators), Al-faryan Abdulaziz Mamdouh (green; 9 articles; 6 collaborators), Ibrahim Lanre Ridwan (blue; 8 articles; 6 collaborators), Anwar Ahsan (yellow; 8 articles; 10 collaborators), Usman Mohammad (purple; 8 articles; 5 collaborators), Wang Ying (cyan; 8 articles; 1 collaborator), Ugur Korkut Pata (orange; 7 articles; 11 collaborators), Ahmed Zahoor (brown; 7 articles; 5 collaborators), Festus Victor Bekun (pink; 6 articles; 9 collaborators), and Magdalena Radulescu (peach; 6 articles; 7 collaborators). Among all these clusters, Tomiwa Sunday Adebayo emerges as the most prominent author, with research collaborators situated in *red*, *pink*, *green*, *brown*, and *orange* clusters. The diversity of research collaboration could be influenced by various factors, including the presence of numerous foreign postgraduate students and visiting scholars, as well as substantial research funds [40].

The collaborative network of the top 10 most prolific authors is detailed in Table 4. Tomiwa Sunday Adebayo (14 articles), Al-faryan Abdulaziz Mamdouh (9 articles), Ibrahim Lanre Ridwan (8 articles), Anwar Ahsan (8 articles), and Usman Mohammad (8 articles) emerge as the five most prolific authors. However, when considering citation counts, the rankings of these authors exhibit fluctuations. The top five authors by citation count are: Anwar Ahsan (118 citations), Wang Ying (55 citations), Tomiwa Sunday Adebayo (51 citations), Al-faryan, Abdulaziz Mamdouh (37 citations), andMagdalena Radulescu (37 citations). This new ranking emphasizes that the number of articles published by an author does not necessarily correlate with increased citation counts. Instead, high citation counts are more likely attributed to factors such as the quality of research work, novelty, the reputation of the publishing journal, and access type (subscription-based or open access) [127, 128].

### *3.3.2 Analyses of international and institutional co-authorship*

Table 5 illustrates the analysis of institutional co-authorship, generated by setting the "minimum number of documents of an institution" and "minimum number of citations of an institution" to three and six, respectively. Only the top 10 institutions are listed in Table 3, while 584 out of 4707 institutions meet these criteria. Additionally, only 332 of the 4707 institutions have collaborative relationships with other institutions, indicating a low level of inter-institutional collaboration. The Chinese Academy of Sciences (CAS) in China leads with the highest number of articles (135) and citations (472). The Lebanese American University (LAU), China, closely follows in terms of publication quantity. Despite LAU publishing more papers than University of Chinese Academy of Sciences (UCAS), UCAS's citation count is over 79% higher. This suggests that UCAS's articles are likely of superior quality and published in highly regarded journals compared to those of LAU.

The significantly higher number of citations for UCAS compared to LAU, even though UCAS published fewer articles, can be attributed to several key factors. Firstly, UCAS probably publishes in higher-impact journals that have a wider readership and are more influential in the academic community. These high-impact journals tend to attract more citations due to their high profile. Secondly, UCAS could focus on research areas of greater global interest, such as cutting-edge fields like technology, environmental science, or biomedical research, which tend to generate more citations due to their relevance and popularity. In addition, while LAU has a higher total link strength, indicating more collaborations, UCAS' association with the prestigious CAS gives it an advantage in terms of academic reputation and visibility. Research from prestigious institutions tends to be cited more frequently as these institutions are trusted, and their publications carry more weight. In addition, UCAS citations could also benefit from stronger

**Table 4.** Analysis of co-authorship of authors.

| Author | Cluster | Citations | Number of articles | Institution/country |
|---|---|---|---|---|
| Adebayo, Tomiwa Sunday | 3 | 51 | 14 | Cyprus International University, Nicosia, Cyprus |
| Al-faryan, Mamdouh Abdulaziz | 9 | 37 | 9 | University of Portsmouth Faculty of Business and Law, Portsmouth, England |
| Ibrahim, Ridwan Lanre | 9 | 25 | 8 | University of Lagos, Lagos, Nigeria |
| Anwar, Ahsan | 1 | 118 | 8 | Materials Science and Chemical Engineering Department, State University of New York, NY, USA |
| Usman, Mohammad | 1 | 11 | 8 | King Fahd University of Petroleum & Minerals (KFUPM), Dhahran, Saudi Arabia |
| Wang, Ying | 9 | 55 | 8 | Department of Physics, Harbin Institute of Technology, Harbin, China |
| Pata, Ugur Korkut | 3 | 30 | 7 | Faculty of Economics and Administrative Sciences, Department of Economics, Osmaniye Korkut Ata University, Osmaniye, Turkey |
| Ahmed, Zahoor | 2 | 22 | 7 | Max Planck Institute for Dynamics of Complex Technical Systems, Magdeburg, Germany |
| Bekun, Festus Victor | 5 | 10 | 6 | Istanbul Gelişim University, Istanbul, Türkiye |
| Radulescu, Magdalena | 6 | 37 | 6 | POLITEHNICA Bucharest National University of Science and Technology, Bucharest, Romania |

**Table 5.** Analyses of institutional co-authorship.

| Institution | Country | Number of published articles | Total link strength | Citations |
|---|---|---|---|---|
| CAS | China | 135 | 48 | 472 |
| LAU | Lebanon | 58 | 192 | 144 |
| King Saudi University | Saudi Arabia | 57 | 34 | 99 |
| UCAS | China | 46 | 17 | 258 |
| Xi'an Jiaotong University | China | 45 | 32 | 107 |
| Beijing Institute Technology | China | 38 | 42 | 137 |
| Tsinghua University | China | 35 | 13 | 142 |
| University of Science & Technology | China | 35 | 8 | 176 |
| Zhejiang University | China | 33 | 12 | 102 |
| Sichuan University | China | 32 | 9 | 122 |

international collaborative networks, as co-authored papers with prestigious institutions increase the likelihood of being cited more frequently. Language and accessibility could also play a role. If UCAS publishes more frequently in widely accessible languages such as English, its research could reach a wider global audience, which would further increase its citations. Finally, cultural differences in citation practices between different academic communities could also play a role. For example, UCAS research may be embedded in an academic environment where higher citation rates are important. Taken together, these factors suggest that the higher citation rate of UCAS is likely due to the higher quality, greater visibility, and wider accessibility of its research compared to LAU rather than the mere quantity of publications.

Furthermore, as noted in Table 5, all the listed institutes exhibit relatively low *total link strengths*, meaning that while institutions like LAU may have more collaborative efforts, these collaborations do not always translate into higher citation counts. UCAS, though with lower collaboration rates, capitalizes on its prestigious affiliations and research impact. Notably, China hosts more than half of the top institutions listed, highlighting the growing dominance of Chinese institutions in publishing high-impact research. This emphasizes the need for enhanced inter-institutional and global collaboration, as strengthening such networks can further advance knowledge and increase citation visibility.

In addition to inter-institutional collaboration, international research collaborations are another crucial avenue for enhancing technology transfer and information sharing. Figure 13 displays the density map of countries with the most publications. To produce this figure in VOSviewer, the "minimum number of documents of a country" is set to three, while the "minimum number of citations of a country" is set to six. From the data retrieved from the WOS database, it is evident that all porous AC-related $CO_2$ methanation articles are associated with 124 countries. However, only 71 countries meet this threshold, as depicted in Fig. 13. Notably, Palestine (*Link 1*, *Research Articles 4*; *citations 8*) and New Zealand (*Link 1*, *Research Articles 13*; *citations 72*) have the least number of co-authorships with other nations. The most prominent nodes are attributed to China (1462 articles), followed by India (802 articles), and then the USA (354 articles). The brightness of a node corresponds to the density or number of articles published by the respective country.

This international collaboration is well established and emphasizes the interconnectivity of all countries in research. Table 6 further summarizes the statistics regarding the 10 most prolific countries, highlighting their contributions to global scientific output and reinforcing the importance of continued cross-border partnerships.

China leads with the highest number of publications (1462) and citation counts (4316). During the reviewed period, China's publication output exceeded that of the next four countries in the rankings: India, the USA, Turkey, and Pakistan, demonstrating

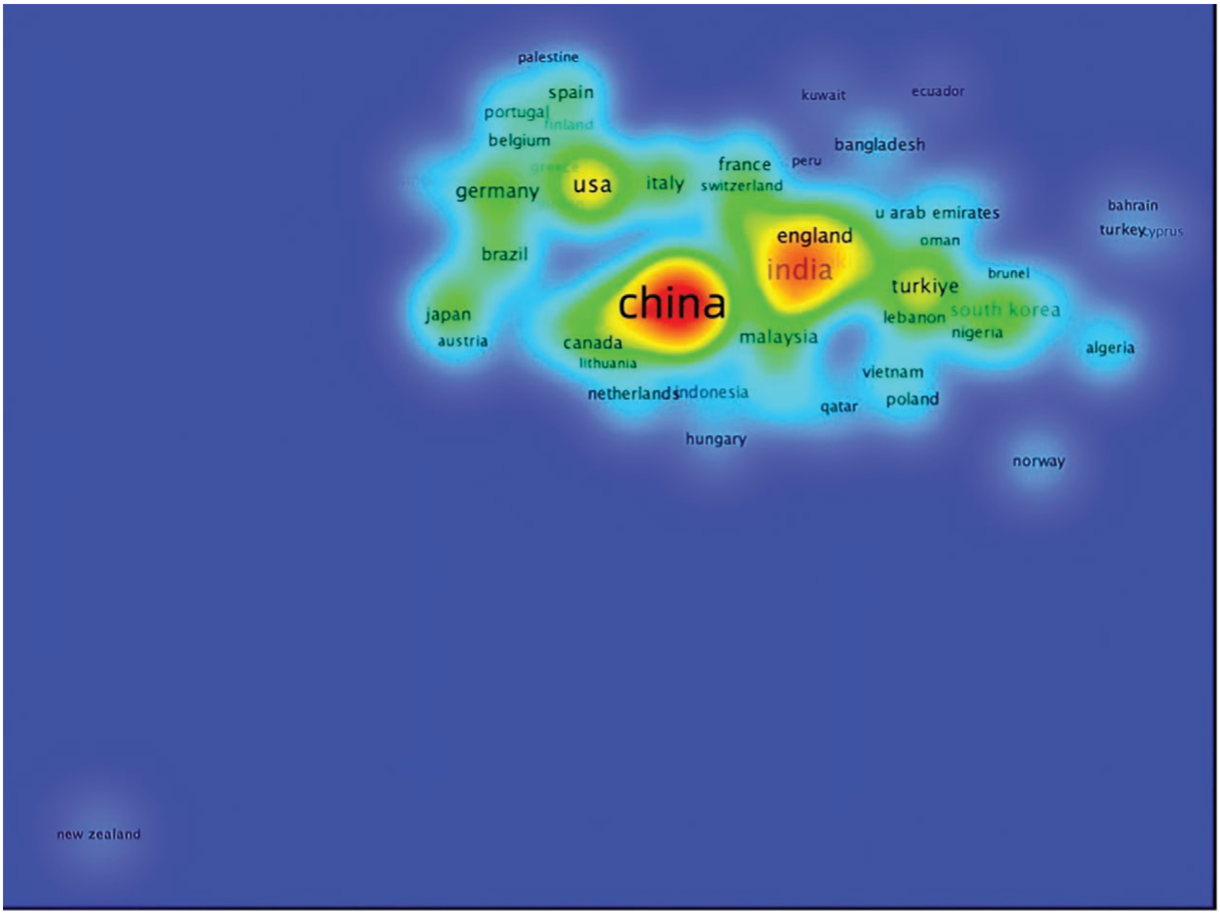

**Figure 13.** Co-authorship density map of countries based on scientific publications.

the country's dominance in porous AC-related $CO_2$ methanation research.

## 3.4 Analysis of citations for influential articles on porous AC-related $CO_2$ methanation

Figure 14 illustrates the citation analysis of the most influential articles on porous AC-related $CO_2$ methanation, highlighting the outcomes of examining the most influential publications in this field. Out of the 19 239 articles, 183 meet the minimum criterion of 6 citations per document. However, Fig. 14 focuses solely on the top 71. Notably, while the initial articles in this field were published before 2020 [131, 132], the top five most frequently cited articles emerged after 2021 [133–137]. This deviation from the norm is somewhat unusual; typically, pioneering research articles boast the highest citation counts as they continue to be referenced by newer articles. The most frequently cited articles in the expansive field of porous AC-related $CO_2$ methanation studies are those authored by Anwar *et al.* [133] and Adebayo *et al.* [134], regarded as pioneering publications on this subject. Together, these two articles amass over 169 citations.

The most cited article in the subfield of porous AC-related $CO_2$ methanation is Anwar *et al.* [133], boasting 118 citations. Following closely are Adebayo and Kirikkaleli [134], with 51 citations and Balsalobre-Lorente *et al.* [138], with 49 citations. The top five most cited articles are rounded out by Shah *et al.* [136] with 41 citations and Al-faryan and Dockery [137] with 37 citations. Table 7 contains additional details regarding these highly cited articles and the publication outlets.

## 3.5 Co-occurrence network analysis of author keywords

A co-occurrence network serves as a valuable tool for identifying significant research areas and potential future research directions [37]. The co-occurrence network map of author keywords was created in VOSviewer by setting the minimal number of occurrences of a keyword to 20. Out of a total of 12 597 keywords, 55 meet this criterion. In Fig. 15, every circular node symbolizes a keyword, and the node's size correlates directly with the frequency of appearance of the keyword across articles. The relatedness of any two keywords is quantified by their distance; closer distances indicate stronger links. Additionally, keywords within the same cluster share the same color, suggesting that they are more likely to occur together than those in separate clusters [39].

All 55 keywords are organized into four clusters. *Cluster 1*, highlighted in red and comprising 25 keywords, is the largest. The most prominent keywords in this cluster are *adsorption* and *biomass*, each occurring 63 times. Additionally, *adsorption* is linked 9 times, while *biomass* is linked 14 times with other keywords. Other keywords in this cluster include *anaerobic digestion*, *biochar*, *biodiesel*, *graphene*, *carbon dioxide*, etc. *Cluster 2*, depicted in green and containing 16 keywords, is notable for the prevalence of *Renewable energy* (162 occurrences, with 30 links). This suggests that there is a gradual shift from fossil fuels to renewable energy. Hence, other keywords co-occurring in this cluster with *Renewable energy* include *energy transition*, *energy efficiency*, *green innovation*, *clean energy*, *carbon emission*, *environmental quality*, *energy consumption*, *$CO_2$ emissions*, *climate change*, *sustainable energy*, etc. All these keywords share a strong correlation with "$CO_2$ methanation." For example, $CO_2$ methanation, depending on the catalyst employed, is an exothermic catalytic reaction typically conducted within the temperature range of 150°C–550°C [52]. Moreover, $CO_2$ methanation plays a crucial role in the context of renewable energy integration, energy efficiency improvement, carbon emission reduction, and overall sustainability, making it a significant area of research and development in the field of clean and sustainable energy technologies.

*Cluster* 3, depicted in blue, encompasses 8 keywords. Notable among these are *sustainability* (176 occurrences, 32 links), *circular economy* (46 occurrences, 14 links), *energy* (46 occurrences, 23 links), *environment* (22 occurrences, 16 links), *life cycle assessment* (36 occurrences, 14 links), *machine learning* (30 occurrences, 6 links), *recycling* (21 occurrences, 11 links), and *sustainable development goals* (45 occurrences, 17 links).

**Table 6.** Top 10 countries leading research in porous AC-related $CO_2$ methanation.

| Country | Number of articles | Citations |
|---|---|---|
| China | 1462 | 4316 |
| India | 802 | 2223 |
| USA | 354 | 1152 |
| Turkey | 224 | 324 |
| Pakistan | 223 | 981 |
| England | 213 | 705 |
| Saudi Arabia | 199 | 577 |
| Germany | 165 | 505 |
| Iran | 152 | 426 |
| Australia | 145 | 734 |

*Cluster* 4, represented in yellow, consists of 6 keywords, including *carbon emissions*, *economic growth*, *institutional quality*, *renewable energy consumption*, *ecological footprint*, and *technological innovation*. *Economic growth* stands out as the most frequently used keyword, with 78 mentions and 22 links. These keywords reflect the ongoing discourse on the economic and environmental impact of renewable energy, with a focus on how sustainable development is influenced by factors such as carbon emissions and institutional quality. This group emphasizes research that examines the relationship between environmental sustainability and economic development.

The current research trends in the fields of environmental sciences, renewable energies, and sustainability are reflected in the keywords of the four clusters illustrated in Fig. 14. The "red cluster" focuses on the development and application of innovative materials, including AC, graphene, and nanocomposites, for applications such as adsorption, oxygen evolution reactions, photocatalysis, and $CO_2$ reduction. These results point to a research trend that aims to develop advanced materials for renewable energy technologies and environmental remediation. The "blue cluster" includes keywords such as solar energy, hydrogen, and optimization, which indicate a focus on improving the efficiency and sustainability of a variety of energy systems. The "green cluster" is centered on the intersection of renewable energy and sustainable development, which includes topics such as clean energy, climate change, and energy transition. This cluster emphasizes the link between the deployment of renewable energy and the achievement of broader sustainable development goals. The "yellow cluster" includes keywords related to the economic and environmental dimensions of renewable energy, emphasizing economic growth, ecological footprint, and carbon emissions. This group refers to research that examines the relationship between environmental sustainability and economic development. Ultimately, the compilation of these keywords demonstrates a multidisciplinary approach to research that

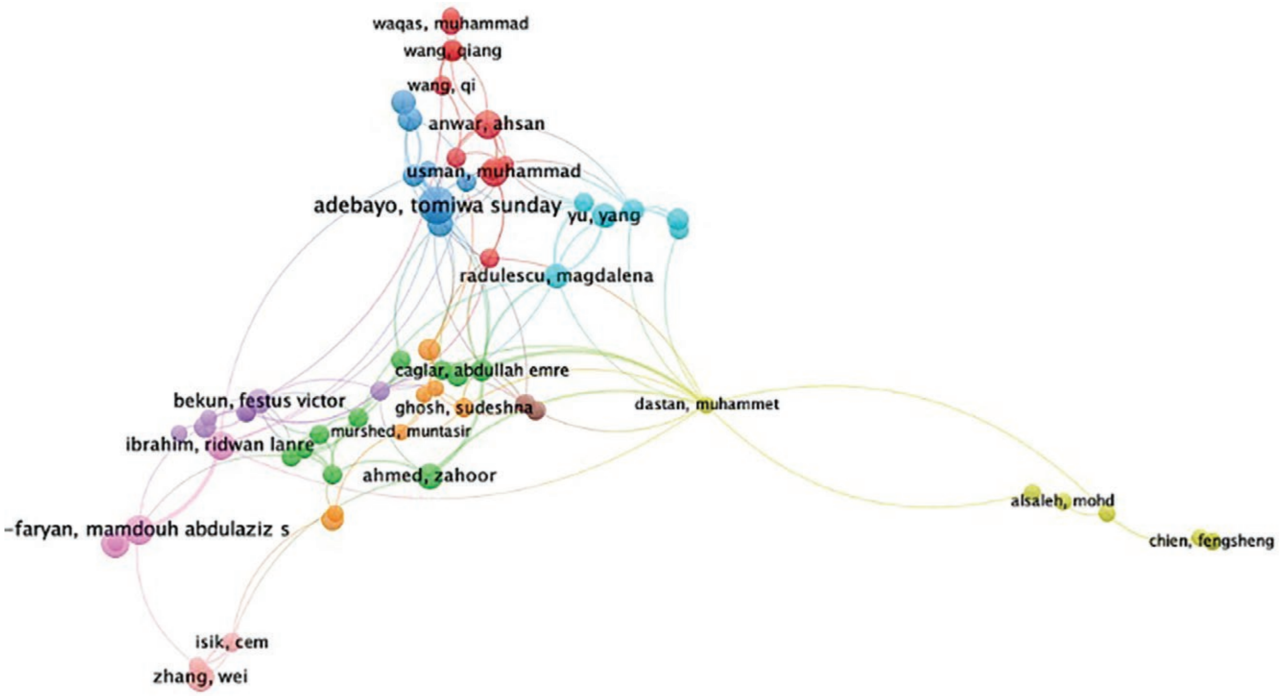

**Figure 14.** Network map of highly cited articles on porous AC-related $CO_2$ methanation.

**Table 7.** Top 20 influential articles on porous AC-related $CO_2$ methanation.

| First author and year | Article title |
|---|---|
| Anwar (2021) [133] | The moderating role of renewable and non-renewable energy in environment-income nexus for ASEAN countries: evidence from method of moments quantile regression |
| Adebayo (2021) [134] | Impact of renewable energy consumption, globalization, and technological innovation on environmental degradation in Japan: application of wavelet tools |
| Balsalobre-Lorente (2022) [135] | Influence of growth and urbanization on $CO_2$ emissions: the moderating effect of foreign direct investment on energy use in BRICS |
| Shah (2024) [136] | Advanced high-energy all-solid-state hybrid supercapacitor with nickel-cobalt-layered double hydroxide nanoflowers supported on jute stick-derived activated carbon nanosheets |
| Al-faryan (2021) [137] | Testing for efficiency in the Saudi stock market: does corporate governance change matter? |
| Ibrahim (2021) [139] | Nonrenewable and renewable energy consumption, trade openness, and environmental quality in G-7 countries: the conditional role of technological progress |
| Zhang (2018) [140] | Coconut-based activated carbon fibers for efficient adsorption of various organic dyes |
| Wang (2012) [141] | Recent advances in the synthesis and application of layered double hydroxide (LDH) nanosheets |
| Pata (2018) [142] | Renewable energy consumption, urbanization, financial development, income and $CO_2$ emissions in Turkey: testing EKC hypothesis with structural breaks |
| Ahmed (2020) [143] | Moving towards a sustainable environment: the dynamic linkage between natural resources, human capital, urbanization, economic growth, and ecological footprint in China |
| Zhang (2022) [144] | A universal nonhalogenated polymer donor for high-performance organic photovoltaic cells |
| Bekun (2019) [145] | Toward a sustainable environment: nexus between $CO_2$ emissions, resource rent, renewable and nonrenewable energy in 16-EU countries |
| Radulescu (2022) [146] | Exploring the impacts of banking development, and renewable energy on ecological footprint in OECD: new evidence from method of moments quantile regression |
| Nassani (2017) [147] | Environmental Kuznets curve among BRICS countries: spot lightening finance, transport, energy and growth factors |
| Yu (2017) [148] | Cerium oxide modified activated carbon as an efficient and effective adsorbent for rapid uptake of arsenate and arsenite: material development and study of performance and mechanisms |
| Liu (2021) [149] | EKC and carbon footprint of cross-border waste transfer: evidence from 134 countries |
| Zaman (2017) [150] | Dynamic linkages between tourism transportation expenditures, carbon dioxide emission, energy consumption and growth factors: evidence from the transition economies |
| Zhang (2017) [151] | Response surface methodology approach for optimization of ciprofloxacin adsorption using activated carbon derived from the residue of desilicated rice husk |
| Çağlar (2017) [152] | Environmental Kuznets Hypothesis and the impact of renewable energy consumption on carbon emissions in Turkey: cointegration with structural breaks approach |
| Eweade (2024) [153] | Japan energy mix and economic growth nexus: focus on natural gas consumption |

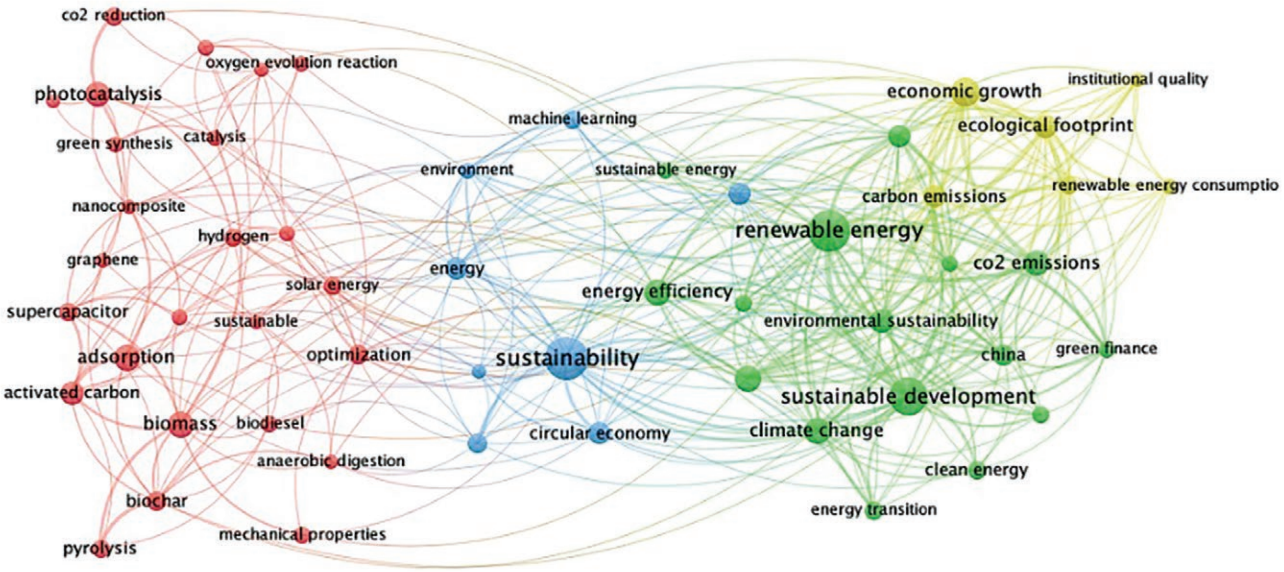

**Figure 15.** Co-occurrence network visualization of author keywords.

**Table 8.** $CO_2$ prospects and existing sector applications. Adapted from Valluri *et al.* [179].

**$CO_2$ utilization techniques**

| Applications | Sector | Impact | Readiness (1–10) |
|---|---|---|---|
| High urea, ammonia, chemicals (oxalic acid and formic acid), and fertilizer production are included. Production of carbonates, processing of biodiesel, and production of olefins and polymers are components of fuels, which include $CH_4$, ethanol, diethyl ether, methanol, and synthesis gas. | Fuels and chemicals | High | 5–6 |
| EOR: $CO_2$ is used for a variety of purposes, including producing acid during well stimulation, removing hydrogen sulfide from natural gas, maintaining pressure in depleted reservoirs, and improving oil flow in gas lift systems. | Oil and gas | High | 10 |
| Operating cycle of fluid (in power): $CO_2$ is used for acid gas removal, dry ice cleaning for equipment maintenance, enhanced oil recovery, carbon capture, fire suppression, and cooling functions in power generation. | Power | Medium | 3–4 |
| Materials/concrete construction and neutralization of bauxite residues (red mud); in addition to material and waste treatment, $CO_2$ is used in the carbonation of minerals for a variety of purposes. It is used for geological sequestration, waste disposal, ocean alkalinity enhancement, carbon storage, and soil improvement. | Mineral carbonation | Medium | 7–8 |
| To reduce emissions from steel production and produce bio-based polymers, $CO_2$ is utilized in iron and steel production, rare earth extraction, dewatering of acid drainage, carbonization of steel, and the implementation of CCS. $CO_2$ is also employed as a raw material in chemical synthesis, helps in metal casting, and used in water treatment to control pH. It is also used in EOR, experimental carbonization of minerals, and other industrial processes. | Materials processing/ chemical industries | Medium | 6–8 |
| The functions of $CO_2$ in food processing are varied. It is used to reduce the acidity of drinks, modify packaging for a longer shelf life, cool food, and act as a leavening agent in baking. In food production, it is also used in extraction, pH control, controlled ripening, and fermentation. In addition, it enables precise temperature control and reduces the growth of microorganisms at certain stages of food processing. | Food | High | 10 |

**Energy requirements for generating $CO_2$-based chemicals**

| Overall equation | Reagent/chemical | Energy (mJ/kg) |
|---|---|---|
| $6CO_2 + 8H_2O \rightarrow 2C_3H_7OH + 9O_2$<br>$3CO_2 + 4H_2O \rightarrow C_3H_7OH + 4.5O_2$ | Propanol | 29.53 |
| $2CO_2 + 2H_2O \rightarrow 2HCOOH + O_2$ | Formic acid | 5.51 |
| $2CO_2 + H_2O \rightarrow 2CO + O_2 + H_2O$ | Carbon monoxide | 9.19 |
| $2CO_2 \rightarrow C_2O_4^{2-}$ | Oxalate | 2.68 |
| $2CO_2 + 3H_2O \rightarrow C_2H_5OH + 3O_2$ | Ethanol | 28.70 |
| $2CO_2 + 2H_2O \rightarrow C_2H_4 + 3O_2$ | Ethylene | 41.29 |
| $2CO_2 + 4H_2O \rightarrow 3O_2 + 2CH_3OH$<br>$CO_2 + 2H_2O \rightarrow 1.5O_2 + CH_3OH$ | Methanol | 21.17 |
| $CO_2 + 2H_2O \rightarrow 2O_2 + CH_4$ | Methane | 51.15 |

CCS, carbon capture and storage; EOR, enhanced oil recovery.

addresses the complex challenges of environmental protection, renewable energy, and sustainability.

In addition to these clusters, $CO_2$ methanation is emerging as an evolving field, as shown by the articles retrieved from the WOS database. Technological innovations such as direct $CO_2$ electrolysis, advanced catalyst developments, and process intensification are complemented by ongoing efforts in digitization and automation, aimed at enhancing the efficiency and reliability of methanation processes. Alongside the technological advances, there is an emerging discourse on institutional quality, which explores how governance structures, regulatory frameworks, and institutional practices influence the adoption and success of $CO_2$ methanation technologies [154–156]. Strengthening institutional quality through improved transparency, accountability, and governance can significantly impact the implementation of $CO_2$ methanation projects, ensuring they are not only economically viable but also socially and environmentally sustainable. This broader perspective highlights the importance of robust institutional frameworks in supporting the transition to cleaner energy technologies and addressing climate change. Hence, the occurrence of keywords such as institutional quality fewer than 20 times suggests they represent potential future research directions.

## 3.6 Study limitations

The study under consideration shares limitations commonly observed in similar reviews and bibliometric analyses. A primary constraint is the reliance on data sourced solely from one database, WOS. This approach inherently excludes articles not indexed in WOS from the scope of the study. While efforts were made to use comprehensive keywords covering a majority of relevant publications, there is a possibility that some articles were missed due to mismatches or variations in search terms. Additionally, the study's data collection was limited to articles published between 2014 and 2024, thereby excluding documents published before or after this timeframe. However, this focused timeframe allows for a detailed analysis within the selected period. Future researchers can mitigate these limitations by considering publications from other citation index databases, such as Dimensions or WOS, provided by Clarivate Analytics. These databases may offer a broader perspective and enhance document retrieval. These limitations are typical in bibliometric research and are not unique to this study. Future studies can improve upon these constraints by utilizing multiple databases and employing a wider array of keywords to achieve more comprehensive document retrieval and analysis.

## 4. The potential of porous AC catalysts for $CO_2$ methanation

Porous AC-based catalysts have emerged as promising options for enhancing the efficiency of $CO_2$ methanation and related energy processes. These catalysts offer distinct advantages, such as improved stability, resistance to carbon deposition, and enhanced catalytic activity [157]. Their large surface area provides numerous active sites for catalytic reactions and efficient adsorption of reactants, thereby boosting catalytic performance and utilization. The porous architecture promotes a high surface-to-volume ratio, facilitating easier access to active sites and enhancing the mass transfer of reactants and products [158]. The interconnected porous network of AC catalysts minimizes diffusion limitations, allowing for faster gas diffusion and ensuring better contact between reactants and active sites. This improves reaction kinetics and overall catalytic efficiency in $CO_2$ methanation [159]. Moreover, the efficient heat dissipation capability of porous AC reduces the risk of catalyst deactivation or sintering, thereby extending catalyst lifespan and enhancing methanation efficiency. Porous AC catalysts also demonstrate improved resistance to coking, a common challenge in $CO_2$ methanation, by inhibiting the accumulation of carbon species and facilitating their desorption [50]. These characteristics preserve catalyst selectivity and effectiveness. Additionally, the regenerability of porous AC catalysts enables effective cleaning of clogged pores, restoring surface access and active sites, which contributes to consistent and sustainable catalytic performance over time [160, 161]. Overall, porous AC catalysts hold significant promise for enhancing $CO_2$ methanation efficiency. Their attributes, including large surface area, thermal stability, improved mass transport, resistance to carbon deposition, and regenerability make them valuable catalysts for improving activity, selectivity, and stability in catalytic processes [46, 157]. Leveraging these benefits, researchers can advance the development of effective and economically feasible methods for sustainable $CH_4$ synthesis and GHG utilization through $CO_2$ methanation.

## 5. Challenges inhibiting AC catalysts

Catalyst deactivation poses a significant challenge in the $CO_2$ methanation process, gradually diminishing catalytic activity through mechanisms such as sintering, poisoning, and carbon deposition. Carbon deposition, resulting from carbon species adhering to the catalyst surface, leads to the formation of coke, which reduces the catalyst's active surface area and hampers reactant access to active sites, thereby impairing $CO_2$ methanation conversion and selectivity [162, 163]. Strategies to mitigate catalyst deactivation include developing coke-resistant catalysts, optimizing reaction conditions, and employing catalyst regeneration methods [164, 165]. During $CO_2$ methanation, high carbon activity and a low hydrogen-to-carbon ratio in the feed gas exacerbate carbon deposition, where reactant gases thermally decompose,

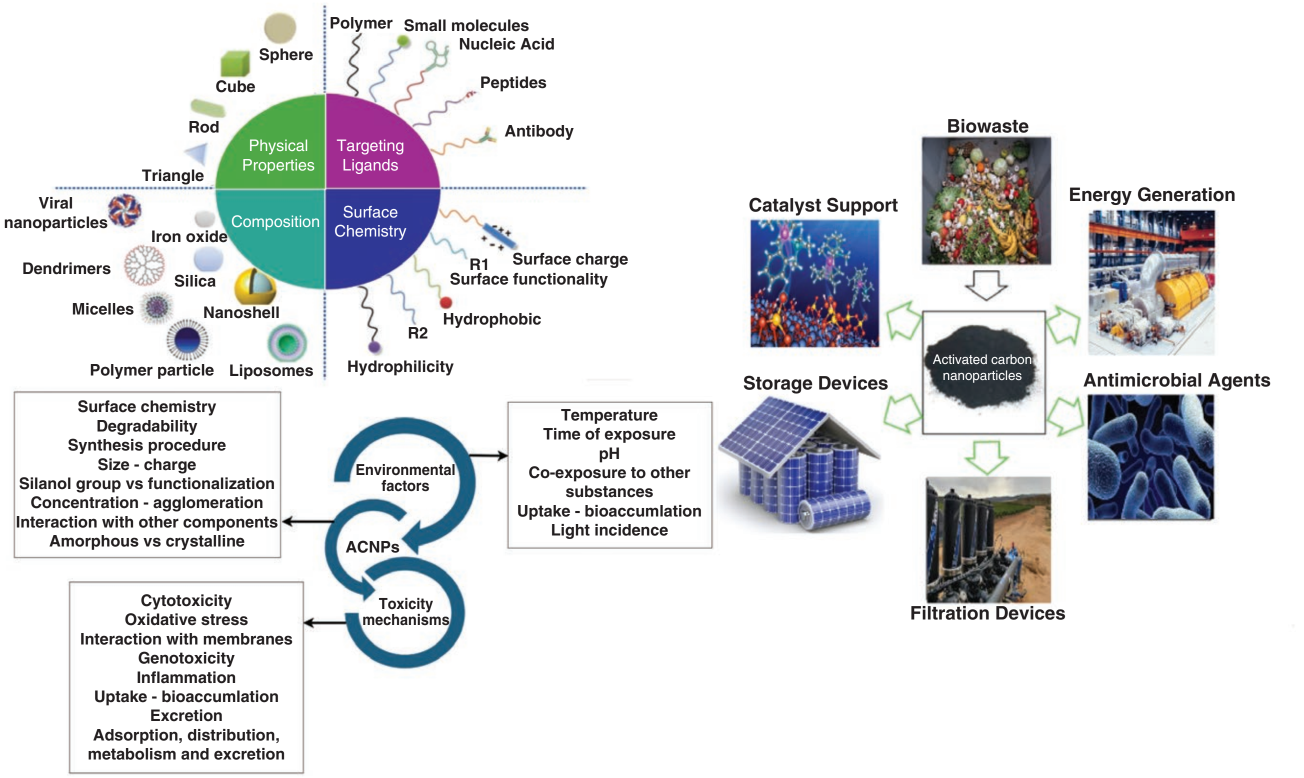

**Figure 16.** Types of ACNPs for delivering active drugs and biological agents (a), main applications of ACNPs (b), and parameters affecting toxicity mechanisms in ACNPs (c). Adapted and modified from [184, 185].

forming amorphous and graphitic carbon species on the catalyst surface [166, 167]. These carbon deposits diminish reactant conversion and product selectivity by altering reaction kinetics and obstructing active sites. Designing catalysts and modifying surfaces to promote the formation of more reactive surface species and prevent coke formation are two strategies to mitigate carbon deposition [168, 169].

Thermal stability is critical in $CO_2$ methanation due to the operation at relatively low temperatures (200°C –400°C), where catalysts may suffer from phase changes, sintering, or agglomeration at higher temperatures (>400°C), resulting in loss of catalytic activity and surface area [52, 170]. Furthermore, thermal cycling during startup and shutdown activities can contribute to catalyst deactivation. Enhancing thermal stability involves developing robust catalyst supports, advanced formulations, and implementing thermal management strategies [171]. Achieving the desired $H_2$-to-$CO_2$ ratio for $CH_4$ production in $CO_2$ methanation requires precise control over reaction conditions, catalyst composition, and operational parameters to optimize selectivity for downstream applications in chemical synthesis and energy production [172, 173]. Balancing methane reforming and reverse water–gas shift processes is crucial for controlling product selectivity. Ongoing research focuses on developing novel catalyst materials, such as metal alloys or bimetallic catalysts, to improve stability, selectivity, and catalytic activity in $CO_2$ methanation.

## 6. Applications and commercialization prospects

$CH_4$ serves as a crucial intermediate in numerous industrial processes and can be sustainably produced through $CO_2$ methanation [174, 175]. This process offers an environmentally and economically viable alternative to traditional fossil fuel-based methods by utilizing $H_2$ and $CO_2$ as feedstocks for $CH_4$ production [176]. By harnessing these feedstocks, the process not only generates energy but also mitigates negative environmental impacts, addressing both financial and ecological concerns simultaneously. Integration with carbon capture and utilization technologies allows $CO_2$ emissions from diverse sources, such as power plants or industrial facilities, to be captured and converted into $CH_4$ [177, 178], thereby contributing to GHG reduction and achieving carbon neutrality.

Table 8 summarizes the applications of $CO_2$ and its potential for industrialization, highlighting the current state of technological readiness. Processes like Fischer–Tropsch synthesis enable the efficient and clean conversion of $CO_2$ into liquid hydrocarbon fuels, which can serve as energy sources for fuel cells, gas turbines, and transportation. Furthermore, coupling $CO_2$ methanation with renewable energy sources like wind or solar power presents opportunities for developing a more sustainable energy ecosystem, prompting further exploration in this field.

The $CO_2$ methanation market shows significant promise. It offers a compelling alternative to traditional carbon-intensive practices and GHG emissions as the demand for sustainable technologies continues to grow.

## 7. Environmental consequences

Catalysts based on porous AC have emerged as transformative materials offering significant environmental benefits. For instance, they play a pivotal role in the catalytic process of $CO_2$ methanation, facilitating the conversion of $CO_2$ and $H_2$ into valuable $CH_4$ [55]. Porous AC materials are recognized for their ability to contribute to climate change mitigation, aligning with global shifts towards cleaner energy. The growth of the Direct Air Capture industry, powered by renewable energy sources, emphasizes the potential of AC catalysts in advancing environmental sustainability through concerted multidimensional efforts. ACNPs find extensive use across various industrial sectors, including engineering, synthesis, manufacturing, and medicine, owing to their perceived low toxicity and versatility. They are often proposed as ideal negative controls in studies evaluating the impacts of exposure to other nanoparticles like fullerenes and polystyrene NPs. However, uncertainties remain regarding the potential adverse effects of ACNPs, with current literature predominantly focusing on their implications for human health [180, 181]. Notably, despite their small size, ACNPs have been shown to penetrate the blood–brain barrier, raising concerns about potential neurotoxicity [182, 183]. Extensive assessments have documented impacts on multiple physiological systems in various cell and animal models, encompassing the heart, skin, lungs, liver, immune system, reproductive system, kidneys, and nervous system [120].

While human health impacts have been extensively studied, less attention has been given to the interactions of ACNPs with biological entities, non-target organisms, and both inorganic and organic substances in the environment. A comprehensive understanding of their toxicity is crucial for expanding research beyond human health concerns to encompass broader environmental interactions and non-target species. Such a holistic approach will enable informed decisions regarding the industrial and medical applications of ACNPs. Figure 16 illustrates various types of ACNPs, including hollow, mesoporous, covalently or non-covalently bound variants, among others [186]. It explores their targets, such as small compounds, peptides, and antibodies, as well as applications spanning biorecognition agents, medical devices, molecular imaging, and textiles. Discussions encompass environmental conditions and mechanisms like concentrations of silanol groups, agglomeration, interactions, degradability, toxicology mechanisms, bioaccumulation, inflammation, cytotoxicity, pH, substance exposure duration, and temperature [186].

## 8. Conclusion and future outlooks

In conclusion, this article offers a comprehensive analysis of AC catalysts, encompassing their applications, environmental considerations, and prospects for commercialization. It presents diverse perspectives on the utilization and advancement of AC materials, drawing from an extensive review of literature spanning 2014–24. The study emphasizes the key role of AC in carbon-neutral energy processes and environmental applications while addressing challenges encountered by porous AC based on a detailed analysis of 4196 published articles. Significantly, the research identifies areas necessitating further collaboration and acknowledges leading contributors in the field, such as the CAS and Anwar Ahsan. Through literature evaluation and keyword co-occurrence analysis, the study elucidates the strengths and limitations of porous AC, highlighting its potential in environmental remediation and energy generation. This investigation lays a foundation for advancing sustainable practices in carbon-neutral technology and energy production, employing advanced data mapping techniques. In summary, the interdisciplinary nature of AC research and its transformative impact on fostering a sustainable and eco-friendly future are elaborated, positioning AC materials at the forefront of innovative solutions for global environmental challenges.

Building on this foundation, the research findings of this study have significant implications for the future of catalytic technologies, particularly in the use of porous AC catalysts for $CO_2$ methanation processes. The findings reinforce previous research by demonstrating that the porous nature of AC enhances catalytic performance through improved reactant adsorption and increased surface area for reactions. Moreover, the study confirms the advantages of AC catalysts in reducing carbon deposition and enhancing the sustainability of methanation processes. However, it also highlights areas where existing findings may be challenged, especially regarding the practical application of these catalysts outside laboratory settings. The study suggests that further exploration of institutional and policy factors is necessary to promote the real-world adoption of these technologies. Therefore, future research should focus on improving the scalability and long-term stability of these catalysts while aligning technical advancements with supportive government policies to enable broader industrial use.

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## Author contributions

Stephen Okiemute Akpasi (Conceptualization [equal], Data curation [equal], Formal analysis [equal], Investigation [equal], Methodology [equal], Software [equal], Writing—original draft [lead], Writing—review & editing [lead]), Yusuf Makarfi Isa (Supervision [supporting]), Thembisile Patience Monama (Supervision [supporting], Writing—review & editing [supporting]), Peterson Thokozani Ngema (Supervision [supporting], Writing—review & editing [supporting]), and Sammy Lewis Kiambi (Supervision [equal], Writing—review & editing [equal])

## Conflict of interest statement

None declared.

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## Data availability

Data will be made available upon request.

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