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Review

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Reported Effects of Coprecipitation Synthesis on ZnO/Activated Carbon Nanocomposite Characteristics: A Systematic Review

ZnO/activated carbon (ZnO/AC) nanocomposites are promising functional materials due to the combination of ZnO semiconducting properties and the high surface area and porosity of activated carbon. This study aims to systematically examine the effects of coprecipitation synthesis on the characteristics of ZnO/AC nanocomposites and their implications for various applications. A systematic review was conducted on research articles published between 2016 and 2026, following predefined inclusion and exclusion criteria. Six studies met the eligibility criteria and were included in the final qualitative synthesis, comprising three studies on supercapacitor electrodes, two on water treatment and photocatalytic applications, and one on biomedical applications. The findings indicate that synthesis parameters, including precursor type, ZnO ratio, precipitating agent, pH, calcination temperature, activation method, and post-synthesis treatment, influence morphology, particle size, porosity, functional groups, crystal structure, and optical properties. The reviewed materials predominantly exhibit hexagonal wurtzite ZnO structures, nanoscale dimensions, and porous morphologies, with characteristic functional groups including O–H, C=O, and Zn–O. Recent studies demonstrate increasing interest in multicomponent composites to enhance material functionality. ZnO/AC nanocomposites show promising potential for biomedical, environmental, and energy storage applications. However, the limited number of eligible studies and variations in reported synthesis parameters highlight the need for further systematic experimental validation.

Keywords: ZnO, activated carbon, coprecipitation, nanocomposite, material characteristics, photocatalysis, supercapacitor, semiconducting properties.

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1 Introduction

The development of nanocomposite-based functional materials in the last few decades has shown very rapid progress, especially in responding to various global challenges in the environmental and energy sectors [1]. Increased industrial activity and population growth have led to the accumulation of organic pollutants,

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synthetic dyes, and hazardous waste in aquatic environments, which require effective, efficient, and sustainable treatment technologies [2, 3]. On the other *hand*, the need for alternative energy sources and energy storage devices continues to increase in line with the limitations of fossil fuels. In this context, the development of nanotechnology-based materials is a promising solution due to their properties that can be engineered at the atomic and molecular scale [4, 5]. One of the materials that has received a lot of attention is the nanocomposite of zinc oxide (ZnO) and activated carbon (AC), which is known to have a combination of superior properties in the form of high photocatalytic activity, large surface area, and good adsorption capacity [6].

ZnO is an n-type semiconductor with a wide bandgap of about 3.37 eV and high exciton energy, thus having great potential in photocatalytic applications, sensors, and optoelectronic devices. The main advantages of ZnO include good chemical stability, non-toxic properties, abundant availability, and relatively low synthesis costs compared to other semiconductor materials [7, 8]. In photocatalytic applications, ZnO is able to produce electron–hole pairs when exposed to light with sufficient energy, which can then form reactive species such as hydroxyl radicals (-OH) and superoxide radicals ($-O^{2-}$) to degrade harmful organic compounds [9, 10]. However, the performance of ZnO is often limited by two main weaknesses, namely the high rate of electron–hole pair recombination which reduces the efficiency of the photocatalytic reaction, and the limited light absorption which is only effective in the ultraviolet region, which is a small fraction of the sunlight spectrum [11].

To overcome these limitations, various strategies have been developed, one of which is the combination of ZnO with activated carbon. Activated carbon is a carbon-based material with a porous structure and a very high specific surface area, as well as containing various active functional groups such as hydroxyl (–OH), carboxyl (–COOH), and carbonyl (C=O). These properties enable activated carbon to act as an effective adsorbent to capture and concentrate pollutants around the surface of the material [12, 13]. When combined with ZnO, activated carbon not only increases the adsorption capacity but also functions as a conductive medium that can facilitate electron transfer and inhibit the recombination of electron-hole pairs. Thus, the synergy between ZnO and AC can increase the efficiency of the photocatalytic process through the adsorption-photocatalysis coupling mechanism, where pollutants are first adsorbed on the surface of activated carbon before being degraded by ZnO [14, 15].

In addition, the integration of ZnO with activated carbon also provides advantages in terms of material stability and particle distribution [16]. Activated carbon can function as a supporting matrix that prevents the agglomeration of ZnO particles, thereby maintaining particle size on a nano scale and increasing the active surface area [17]. This is crucial because smaller particle size correlates with an increased number of active sites and reaction efficiency. Furthermore, the pore structure of activated carbon, particularly mesoporous, allows for more efficient molecular diffusion, thus enhancing the interaction between pollutants and the ZnO active sites [18, 19]. Therefore, ZnO/AC nanocomposites are not only superior in photocatalytic applications, but also show potential in other fields such as supercapacitor electrodes, sensors, and biomedical applications [20, 21].

The success of forming ZnO/AC nanocomposites is greatly influenced by the synthesis method used. Among the various methods that have been developed, the coprecipitation method is one of the most commonly used approaches due to the simplicity of the process, the relatively low cost, and its ability to produce materials with a homogeneous particle distribution [22, 23]. This method involves the reaction between a metal ion precursor, such as Zn^{2+}, with a precipitating agent (usually a base such as NaOH) to form a precipitate of $Zn(OH)_2$ which is then calcined to form ZnO [24]. In composite systems, this process can be carried out in-situ, where ZnO is formed directly on the surface of activated carbon, or ex-situ, where ZnO and AC are synthesized separately before being mixed [25]. The synthesis parameters in the coprecipitation method play a very important role in determining the final characteristics of the material. Factors such as solution pH, precursor concentration, reaction temperature, stirring speed, and the rate of addition of the precipitating agent can affect the nucleation process and growth of ZnO crystals [26, 27]. Too high a pH can lead to uncontrolled particle growth and agglomeration, while too low a pH can inhibit optimal ZnO formation. Similarly, high calcination temperatures can increase ZnO crystallinity, but can potentially damage the pore structure of activated carbon [28, 29]. Therefore, optimization of synthesis parameters is key in producing nanocomposites with desired properties.

Variations in conditions in the coprecipitation method also result in significant differences in the structural properties of the material, such as crystal size, crystal phase, and degree of crystallinity. In addition, morphological properties such as particle shape, size distribution, and porosity characteristics are also greatly influenced by synthesis conditions. These differences will ultimately impact the optical and electronic

properties of the material, including the band gap value and charge separation efficiency. In the context of photocatalysis, lowering the band gap allows the material to absorb light in the visible region, thereby increasing the efficiency of solar energy use [30]. Meanwhile, in electrochemical applications, the pore structure and conductivity of the material are important factors that determine the energy storage performance [31].

Although many studies have reported the synthesis and applications of ZnO/AC nanocomposites, most studies still focus on certain aspects separately, such as synthesis, characterization, or applications. Studies that systematically integrate all these aspects, particularly those that highlight the relationship between coprecipitation method parameters and the resulting material characteristics, are still relatively limited. Yet, a comprehensive understanding of this relationship is crucial for designing materials with optimal performance.

While previous reviews have broadly discussed ZnO-based nanocomposites in terms of synthesis methods, material properties, and applications, this review specifically focuses on ZnO/AC nanocomposites synthesized through the coprecipitation method. It systematically examines the relationships between synthesis parameters, including precursor selection, composition ratio, precipitation conditions, and thermal treatment, and the resulting structural, morphological, optical, and functional properties. Furthermore, this review critically compares findings across selected studies, identifies inconsistencies in experimental reporting, and highlights research gaps that may guide the optimization of ZnO/AC nanocomposites for various applications. Therefore, this systematic review aims to analyze in depth the effect of coprecipitation methods on the structural, morphological, optical, and functional performance of ZnO/AC nanocomposites. By integrating various previous research results, this study is expected to reveal the relationship between synthesis strategies and material performance, as well as identify key parameters that play a role in improving application efficiency. In addition, the results of this study are also expected to provide a strong scientific basis for the development of more effective, efficient, and sustainable ZnO/AC nanocomposites in the future, especially in waste treatment and energy storage applications.

2 Review Methodology

2.1 Research Design

This study uses a systematic review approach to identify, select, and analyze scientific articles that discuss the effect of the coprecipitation synthesis method on the characteristics of the ZnO/AC composite material formed. This approach was chosen because it allows researchers to examine the results of previous research in a systematic, structured, and transparent manner, so that a more comprehensive picture can be obtained regarding the relationship between synthesis methods, physicochemical characteristics of materials, and their potential applications. The reporting and preparation process for this systematic review refers to the PRISMA 2020 guidelines (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) so that the stages of identification, screening, assessment of eligibility, and inclusion of articles are carried out clearly and can be traced back [32].

2.2 Data Sources and Literature Search Strategy

The literature search was conducted using five scientific literature sources: Scopus, ScienceDirect, PubMed, Springer, and Google Scholar. These five sources were selected to provide broad coverage of relevant scientific publications on ZnO/AC nanocomposites synthesized through the coprecipitation method. The search was limited to articles published between 2016 and 2026, with a focus on original research articles. In addition, the search focused on articles that discussed the characteristics of the synthesized materials, such as crystal structure, morphology, functional groups, surface area, porosity, and band gap, and, if available, their relationship to application performance such as photocatalysis. The keywords used in the search were grouped into several aspects, namely materials, synthesis methods, characterization, and applications. In the materials aspect, terms such as ZnO, zinc oxide, activated carbon, and active carbon were used. In the synthesis method aspect, the terms coprecipitation and co-precipitation are used. Furthermore, in the characterization and application aspects, terms such as composite, nanocomposite, surface area, porosity, band gap, functional group, photocatalytic degradation, organic pollutant, dye, and microplastic are used. The reference search strategy can be seen in Table 1.

Table 1

Boolean strategy for literature search in each database

Database	Search strategy
Google Scholar	("ZnO" OR "zinc oxide") AND ("activated carbon" OR "active carbon") AND ("coprecipitation" OR "co-precipitation") AND ("composite" OR "nanocomposite")
Scopus and PubMed	TITLE-ABS-KEY (("ZnO" OR "zinc oxide") AND ("activated carbon" OR "active carbon") AND ("coprecipitation" OR "co-precipitation") AND ("composite" OR "nanocomposite")) AND PUBYEAR > 2015 AND PUBYEAR < 2027
ScienceDirect and Springer	("ZnO" OR "zinc oxide") AND ("activated carbon" OR "active carbon") AND ("coprecipitation" OR "co-precipitation") AND ("composite" OR "nanocomposite")

2.3 Inclusion and Exclusion Criteria

To ensure that the selected articles truly align with the study's objectives, this study established inclusion and exclusion criteria from the beginning of the review process. Inclusion criteria were used to determine which articles were eligible for analysis, while exclusion criteria were used to filter out articles that were irrelevant or did not provide sufficient information. Establishing these criteria is crucial in a systematic review because it maintains consistency in the selection process and enhances the validity of the study's results [33]. Articles included in this review are original research articles that discuss the synthesis of ZnO/AC composites or other equivalent terms, using the coprecipitation method, and presenting adequate material characterization data.

Studies combining coprecipitation with additional processing techniques, such as direct mixing, solid-state processing, or post-synthesis treatments, were considered eligible provided that coprecipitation was employed during ZnO or ZnO/AC synthesis. Studies relying exclusively on physical mixing or solid-state processing without a coprecipitation step were excluded. The intended characterization techniques include X-ray diffraction (XRD), Fourier-transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM), Brunauer–Emmett–Teller (BET) surface area analysis, ultraviolet–visible spectroscopy (UV–Vis), diffuse reflectance spectroscopy (DRS), and other relevant techniques to elucidate the physicochemical properties of the material. Furthermore, articles must be available in full text and published between 2016 and 2026. Conversely, articles in the form of reviews, systematic reviews, editorials, proceedings, or book chapters were not included in this review. Articles were also excluded if they did not discuss ZnO and activated carbon simultaneously, did not clearly explain the use of the coprecipitation method, or did not provide sufficient material characterization data for analysis. The criteria for this study can be seen in Table 2.

Table 2

Article inclusion and exclusion criteria

Aspect	Inclusion criteria	Exclusion criteria
Type of article	Original research article	Review, systematic review, editorial, proceedings, book chapter
Material topics	Discussing ZnO/AC composites or equivalent terms	Only discuss ZnO or activated carbon separately
Synthesis method	Using the coprecipitation method	Did not use coprecipitation or the method was not clearly explained.
Characterization data	Presenting material characterization data, such as XRD, FTIR, SEM, UV-Vis	Does not provide adequate characterization data
Access the article	Full text available	Full text not available
Year of publication	2016–2026	Outside the 2016–2026 range

2.4 Study Selection Procedure

The study selection procedure in this research was carried out in stages with reference to the PRISMA 2020 flow, which includes the identification, screening, eligibility, and final inclusion stages [32]. In the identification stage, all articles obtained from five literature sources, namely Scopus, ScienceDirect, PubMed, Springer, and Google Scholar, were collected and documented (see Table 3).

Table 3

Study selection stages based on the 2020 PRISMA flow

Stage	Process description
Identification	Collecting all articles from Scopus, ScienceDirect, PubMed, Springer, and Google Scholar
De-duplication	Deleting articles detected as the same in more than one database
Screening	Selecting articles based on title and abstract
Eligibility	Assessing the suitability of articles by reading the full text
Inclusion	Determine the final articles that meet all criteria for analysis

Afterward, a review was conducted to remove duplicate articles that appeared more than once in different databases. However, no duplicate records were identified across the five literature sources; therefore, no records were removed during the deduplication stage. The next stage is screening, which is based on the title and abstract. At this stage, articles that are irrelevant to the research focus, such as those that do not discuss ZnO/AC composites or those that are not related to coprecipitation synthesis, are eliminated from the selection process. Articles that pass the screening stage then proceed to the eligibility stage, namely a full text review to ensure that the article truly meets all inclusion criteria and is not included in the exclusion criteria. At this stage, articles are assessed in more depth for topic suitability, clarity of synthesis methods, and completeness of reported material characterization data. Articles that meet all requirements are then submitted to the final inclusion stage and analyzed in the next section.

2.5 Data Extraction

Articles that pass the inclusion stage are then analyzed through a systematic data extraction process. Data extraction is carried out to gather important information from each article in a structured manner, thus facilitating comparisons between publications. The information collected includes the article's identity, the starting materials used, the coprecipitation synthesis conditions, the characterization techniques used, and the reported material characterization results. Furthermore, if the article also discusses material applications, data related to material performance, such as pollutant degradation efficiency, pollutant type, and test conditions, are also recorded. The primary focus of data extraction in this study was the characteristics of the materials formed by the coprecipitation method in the ZnO/AC system. Therefore, parameters such as crystal structure, functional groups, morphology, surface area, porosity, and band gap were the main components recorded in each study. Systematic data extraction enabled researchers to identify general patterns and variations in results that emerged across previous studies.

Table 4

Data components extracted from selected articles

Data components	Description
Article identity	Author, year of publication, article title, journal
Materials and synthesis	ZnO precursor, activated carbon type, coprecipitation conditions, post-synthesis treatment
Structural characterization	XRD data, crystallite size, crystal phase
Characterization of functional groups	FTIR data and functional group identification
Morphological characterization	SEM/TEM data, particle shape, particle distribution
Surface properties	Specific surface area, porosity, pore volume
Optical properties	UV-Vis data, band gap value
Material application	Pollutant type, test conditions, degradation efficiency, photocatalytic performance

2.6 Data Synthesis and Analysis

The extracted data were then analyzed using a descriptive-qualitative approach. The analysis was conducted by comparing the results of previous studies to observe the trend of the influence of the coprecipitation synthesis method on the characteristics of the resulting ZnO/AC composite. Recurring patterns were identified by systematically comparing synthesis parameters, including precursor type, composition ratio, precipitation conditions, and thermal treatment, with the reported physicochemical characteristics across the included studies. Conflicting findings were interpreted by considering differences in material composition, experimental conditions, and characterization methods, while inconsistent or insufficiently reported data were treated

cautiously to avoid unsupported generalizations. The discussion focuses on the relationship between synthesis parameters and material properties, such as changes in crystal structure, development of surface morphology, increase in surface area, changes in porosity, and shifts in band gap values. Where available, the relationship between these characteristics and application performance, particularly in photocatalytic processes, is also analyzed. The methodological reliability of the included studies was considered qualitatively based on the completeness of synthesis parameters, characterization methods, and reported experimental results. However, inconsistencies in methodological reporting and the absence of a formal risk-of-bias assessment limit the certainty of the synthesized findings, requiring cautious interpretation of the identified trends.

2.7 Characteristics of Included Studies

The article selection process in this study followed the PRISMA 2020 framework, which was carried out systematically through several stages. During the identification stage, 1,505 articles were obtained from various databases, namely Scopus (19), Google Scholar (88), ScienceDirect (54), PubMed (1), and Springer (1,343). Subsequently, inappropriate publication types were removed, namely 434 book chapters and 487 review articles, leaving a number of articles for the screening stage. During the screening stage, 584 articles were selected based on their titles and abstracts, with 314 articles eliminated for being irrelevant to the research topic. Afterward, 270 articles entered the full-text retrieval stage, but 256 articles were inaccessible, either due to limited access or not meeting the specified publication timeframe (2016–2026). Next, in the eligibility stage, 14 articles were fully analyzed to assess their suitability for inclusion criteria. Of these, eight articles were eliminated because they only discussed ZnO or activated carbon separately, were irrelevant to the topic of ZnO/AC, and did not include important characterizations such as XRD, SEM, FTIR, and UV-Vis. Finally, six articles were found that met all criteria, and then the articles obtained were further analyzed.

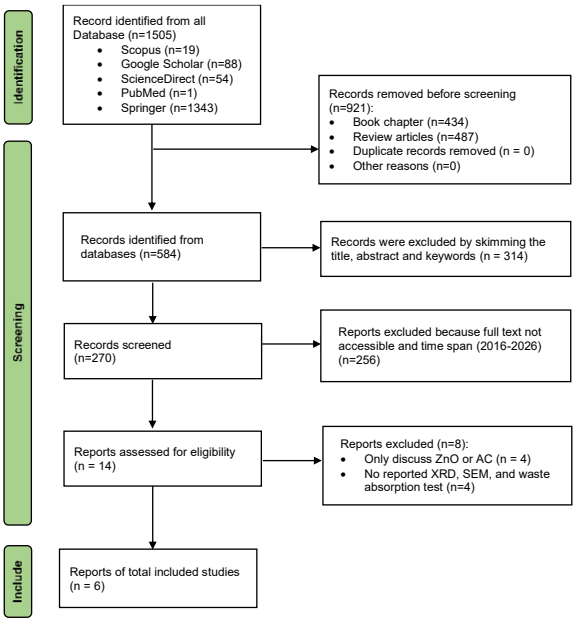


Figure 1. PRISMA 2020 Flow Diagram

3 Research Development Trends of ZnO/AC Nanocomposites

Research on ZnO/AC nanocomposites has shown significant progress in recent years, both in terms of material complexity and application. This trend reflects a shift in focus from fundamental studies to more specific applications, particularly in the environmental and energy sectors. The research developments are shown in Table 5. Based on Table 5, the characteristics of the selected articles show variations in terms of publication year, country of origin, journal, publisher, keywords, and number of citations, which generally illustrate the development of ZnO/AC composite research in the 2018–2025 period. Temporally, the reviewed articles were concentrated in 2018 with three articles, followed by one article in 2020, and two articles in 2025. This pattern shows that research on ZnO/AC-based materials has grown in recent years and remains a relevant topic up to the latest publication period. From a geographical perspective, articles come from India, Saudi Arabia, Pakistan, and Indonesia, with research from India dominating at three articles. These findings indicate

that the development of ZnO/AC materials is quite widespread in developing countries, likely related to the need for relatively economical and applicable functional materials, both in the energy and environmental sectors. Furthermore, the presence of articles from Indonesia, Pakistan, and Saudi Arabia demonstrates that interest in the development of these composites is also widespread across Asia.

Table 5

Characteristics of articles based on article identity

Country	Journal name	Publisher	Keywords	Cit.	Year	Ref
Indonesia	International Journal of Biological Macromolecules	Elsevier	Bamboo STEM; Porous Activated Carbon; BSPAC/CS/ZnO	6	2025	[34]
Pakistan	Journal of Alloys and Compounds	Elsevier	Quaternary Composite; Lemon Yellow (LY) additive; Photocatalytic Detoxification; Photoluminescence	1		[35]
Arab Saudi	Molecules	MDPI	Nanocomposite; Green Synthesis; Activated Carbon; Antibacterial; Catalytic Activity; Neem Leaf Extract	92	2020	[36]
India	Materials research Express	IOP	Nanocomposite, Nanoparticles, SXRD, SEM, Supercapacitor	41	2018	[37]
India	Journal of Materials Science: Materials in Electronics	Springer	Supercapacitor Electrodes; Activated Carbon; Zinc Oxide Synthesis; Fourier Transform Infrared Spectroscopy; Energy Storage; Carbon Electrodes	113		[38]
India	Ionics	Springer	Nanoparticles; Nanocomposite; XRD; SEM; TEM; XPES; Supercapacitor	45		[39]

Note – Citation counts were retrieved in April 2026; BSPAC = bamboo stem porous activated carbon.

When reviewed based on research focus, the 2018 articles, all written by Yadav et al., tend to emphasize synthesis, material characterization, and electrochemical applications, particularly for supercapacitors. This is evident from keywords such as supercapacitor, carbon electrodes, nanoparticles, XRD, SEM, TEM, and energy storage. Meanwhile, more recent articles show a more diverse research direction. Study Taha et al. [36] associates composites with green synthesis, antibacterial activity, and catalytic activity, while studies Cinnathambi Subramani et al. and Rizvi et al. [34, 35] began to show a focus on photocatalytic, multicomponent composites, and the use of biomass-based materials such as bamboo stem porous activated carbon. This indicates a shift in focus from basic characterization and energy storage to broader applications, including environmental fields and functional materials based on renewable resources.

In terms of publication quality, all articles were published in international journals managed by reputable publishers, namely Elsevier, Springer, MDPI, and IOP Publishing. This indicates that the topic of ZnO/AC has strong scientific appeal and has been featured in reputable international publications. The number of citations in the reviewed articles also varied, ranging from 1 to 113. Articles from 2018 had a relatively higher number of citations, particularly the article in the Journal of Materials Science: Materials in Electronics with 113 citations, while articles from 2025 still had a low number of citations. This variation is understandable because the number of citations is strongly influenced by the publication date, so older articles have a greater chance of being cited than more recently published articles. Based on the keywords used, it is apparent that research in this field is no longer limited to the synthesis of ZnO/AC as a simple binary composite, but is beginning to develop towards more complex and applicable systems. The emergence of terms such as quaternary composite, photocatalytic detoxification, photoluminescence, green synthesis, and bamboo stem porous activated carbon indicates an expansion of research approaches, both in terms of material composition and application.

4 Synthesis Strategy of ZnO/AC Nanocomposites Based on Coprecipitation Method

The synthesis strategy is a crucial factor in determining the success of the formation of ZnO/AC nanocomposites, especially in controlling interfacial interactions, particle distribution, and the functional properties of the material. The coprecipitation method is widely used due to its ability to produce materials with a homogeneous structure and relatively simple and easily controlled synthesis conditions. The various synthesis strategies for ZnO/AC nanocomposites based on the coprecipitation method can be seen in Table 6.

Table 6

Overview of ZnO/AC nanocomposite synthesis based on coprecipitation method: process parameters and material treatment

Ref.	Treatment	AC Raw Mater.	ZnO prec.	ZnO:AC (w/w)	Other Comp.	Precip. Agent	Calcin. Temp. (°C)	pH	rpm	Activation Method	Drying Conditions	Activa-tion Comp.
[34]	Chemical activation of AC (K_2CO_3); acid washing (HCl); ultrasonication for dispersion; annealing for enhancement of ZnO–AC interaction	Bamboo Sembilang	$Zn(CH_3COO)_2.2H_2O$	2.2:1	-	NaOH	700	AC:7 ZnO: (9-10)	10,000	Chemical activati-on	Dried in a hot air oven at a temperature of 100°C	K_2CO_3
[35]	Ultrasonication; ethanol washing; sur-face modification via green synthesis; solid-state mixing for AC–ZnO integra-tion	NR	$(Zn(NO_3)_2{\cdot}6H_2O)$	1:1	-	NaOH	500	NR	1,500	NR	60 °C for 7 hours	Orange Peel Extract
[36]	Biomass-based surface activation (neem extract); ZnO impregnation on AC; in-situ formation of ZnO on AC matrix	NR	$AgNO_3$ dan $Zn(NO_3)_2$	NR	0.05 M (100 mL Zn) and 5 g AC	NaOH	NR	8	NR	NR	room temperature	Neem leaves
[37]	Repeated washing for purification; grinding for homogenization of ZnO–AC; composite formation by direct mix-ing	Activated Charcoal	$ZnCl_2$	NR	45:45 (elec-trode form.)	NaOH	600	NR	NR	NA	Vacuum drying, 110 °C (overnight, for elec-trodes)	NA
[38]	Washing to remove residue; grinding; mixing ZnO–AC in solvent media to im-prove homogeneity	Activated Charcoal	$(Zn(NO_3)_2{\cdot}6H_2O)$	1:1; 1:2		NaOH	400, 500, 600	NR	NR	NR	100 °C (2 hours, ZnO), and 80 °C (overnight, electrode)	NA
[39]	Washing; grinding; variation of ZnO–AC composition for optimization of in-teractions and phase distribution	Activated Charcoal	$ZnCl_2$	1:1; 1:2; 1:3		NaOH	400, 500, 600	NR	NR	NA		NA

Note – NR = not reported. ZnO:AC ratios are expressed as mass ratios (w/w) where available. Precursor concentrations and electrode formulations are reported separately. AC activation methods are distinguished from composite preparation and modification treatments.

Based on Table 6, the synthesis of ZnO/AC nanocomposites based on the coprecipitation method shows that the material formation process is not carried out simply as a single precipitation, but is generally accompanied by various additional treatments to improve the quality of the resulting composite. These treatments include chemical activation of activated carbon, acid washing, ultrasonication, impregnation, grinding, repeated washing, direct mixing, and annealing. Specifically, coprecipitation was employed to synthesize ZnO, CuO, and WO_3 before solid-state composite formation in [35], to prepare Ag–ZnO/AC through a distinct coprecipitation route in [36], and to synthesize ZnO nanoparticles before their incorporation into activated carbon in [37]. Thus, solid-state processing, impregnation, and direct mixing represent additional or alternative preparation steps rather than necessarily replacing the coprecipitation process. In terms of the raw materials for activated carbon, the studies summarized in the table use quite diverse sources, such as Sembilang bamboo, activated charcoal, and several studies that do not report in detail the origin of the activated carbon materials. On the other hand, the ZnO precursors used also vary, namely zinc acetate dihydrate [$Zn(CH_3COO)_2.2H_2O$], zinc nitrate [$Zn(NO_3)_2$ or $Zn(NO_3)_2.6H_2O$], and zinc chloride ($ZnCl_2$).

These precursor variations indicate that the synthesis of ZnO/AC via coprecipitation does not yet have a standard formulation, but rather still adjusts to the research objectives, types of supporting materials, and synthesis treatments chosen in each study. From the composition aspect, the ZnO:AC ratio used also shows quite wide variations, ranging from 2.2:1, 1:1, 1:2, 1:3, up to a composition of 45:45 in electrode applications. One study even reported the composition in the form of 0.05 M x 100 mL : 5 g, which indicates that the reporting of ratios between studies is not completely uniform. This variation indicates that the ratio of ZnO and activated carbon is a very flexible parameter and is most likely adjusted to the target function of the material, whether it is more directed at increasing the role of the ZnO phase or at the contribution of activated carbon as a support and adsorbent.

In terms of precipitating agents, most studies used NaOH, while one study did not report the precipitating agent clearly. The dominant use of NaOH in this table shows that this strong base is the most commonly used precipitating agent in coprecipitation-based ZnO/AC synthesis. However, information related to process pH is not always fully reported. Of the six studies summarized, only a small fraction included pH, namely around pH 7, pH 8, and pH 9–10. This situation indicates that one of the reporting weaknesses in the reviewed literature is the inconsistent inclusion of important operational parameters, even though pH is a very determining factor in the ZnO precipitation process. Other process parameters, such as stirring speed (rpm), are also not reported uniformly. Only two studies listed rpm values, namely 10,000 rpm and 1,500 rpm, while the remaining studies did not provide this information. This confirms that standards for reporting synthesis conditions between articles still vary considerably. In fact, stirring speed can affect the level of mixture homogeneity, the rate of particle formation, and the distribution of ZnO on the surface of activated carbon.

In terms of thermal treatment, the calcination temperatures in these studies ranged from 400ºC — 700ºC, with some studies using a single temperature, while others applied a variety of temperature variations such as 400 ºC, 500 ºC, and 600 ºC. Furthermore, the drying conditions also varied, ranging from room temperature drying, 60ºC for 7 hours, 100ºC for 2 hours, to vacuum drying at 110ºC overnight. These variations in calcination temperature and drying conditions indicate that thermal treatment is an important part of ZnO/AC synthesis, but there is no uniformity in the parameters used across all studies. Thus, the calcination and drying temperatures appear to be optimized specifically according to the material design and its intended application. Regarding activation methods, the table shows the use of various approaches, namely chemical activation, physical combinations, impregnation, and several studies that did not report specific activation methods. The activation compounds or materials used also varied, such as K_2CO_3, orange peel extract, and neem leaves, while several studies did not use or did not report activation compounds.

The presence of natural ingredients such as orange peel extract and neem leaves shows that some research is starting to move towards a more environmentally friendly approach through the use of biomass-based materials or biological agents in the material surface modification process. The numerous NR entries in Tables 6 and 8 indicate incomplete reporting of synthesis conditions and characterization results, rather than necessarily indicating the absence of specific processes or material properties. Missing information on pH, stirring speed, activation conditions, lattice parameters, and FTIR characteristics limits experimental reproducibility and reduces the reliability of comparisons between synthesis parameters and material properties. Consequently, the identified synthesis–property relationships should be interpreted as descriptive trends rather than quantitatively established or causal relationships.

5 Performance and Applications of ZnO/AC Nanocomposites

The performance and applications of ZnO/AC nanocomposites are strongly influenced by the combination of ZnO semiconducting properties and the pore characteristics and surface area of activated carbon, which allows these materials to be used in a wide range of fields. The development of composites with varying structures and compositions also plays a crucial role in improving performance efficiency, both in photocatalytic, biomedical, and energy storage applications. A summary of the performance and applications of ZnO/AC nanocomposites can be seen in Table 7.

Table 7

Summary of synthesis study of ZnO/AC nanocomposites based on coprecipitation method and their performance in various applications

Ref.	Material	Objective	Application	Conclusion
[34]	BSPAC/CS /ZnO	Synthesized and characterized BSPAC/CS/ZnO ternary nanocomposites via one-pot coprecipitation method.	Antibacterial and anticancer agents for biomedical applications.	The BSPAC/CS/ZnO ternary nanocomposites synthesized by coprecipitation exhibit spherical morphology measuring 3–10 nm, high surface area, and good antibacterial and anticancer activities, thus having potential for biomedical applications.
[35]	AC@ZnO/ CuO/WO_3	Synthesize $ZnO/CuO/WO_3$ and $AC@ZnO/CuO/WO_3$ composites by a simple method, then evaluate their performance in detoxification and photocatalytic degradation of Lemon Yellow.	Photocatalysts for water treatment and degradation of organic pollutants.	The quaternary composite $AC@ZnO/CuO/WO_3$ exhibited very high photocatalytic performance, with a Lemon Yellow detoxification efficiency of 98.4 % and a Total Organic Carbon (TOC) mineralization of 96.13 %, which was supported by a decrease in the band gap, an increase in the surface area, and a reduction in charge recombination.
[36]	Ag-ZnO/AC	Developing Ag–ZnO/AC nanocomposites through green synthesis, then evaluating their structural properties, antibacterial activity, and photocatalytic performance for water treatment applications.	Water treatment: pollutant degradation and antibacterial.	Green synthesis of AgNPs and ZnO/AC nanocomposites based on neem leaf extract successfully produced materials with good catalytic and antibacterial activities, thus having potential for water treatment applications.
[37]	ZnO–AC	Synthesize ZnO–AC nanocomposites through coprecipitation method and evaluate their performance as supercapacitor electrode materials through structural, morphological, and electrochemical characterization.	Supercapacitor electrodes for energy storage.	ZnO–AC nanocomposites exhibit good electrochemical performance with high capacitance, thus having potential as supercapacitor electrodes for energy storage applications.
[38]	ZnO–AC	Synthesize ZnO nanoparticles through coprecipitation method and develop ZnO–AC nanocomposites with varying composition ratios, and evaluate their performance as supercapacitor electrodes through structural characterization and electrochemical properties.	Supercapacitor electrodes for energy storage.	ZnO–AC nanocomposites at a ratio of 1:1 exhibited the highest supercapacitor performance among the compositions investigated under the reported experimental conditions.
[39]	ZnO–AC	Synthesize ZnO nanoparticles through coprecipitation method and develop ZnO–AC nanocomposites with variations in composition and calcination conditions, and evaluate their performance as supercapacitor electrodes through structural characterization and electrochemical properties.	Supercapacitor electrodes for energy storage.	ZnO–AC nanocomposite at a ratio of 1:1 exhibited the highest supercapacitor performance among the compositions investigated under the respective experimental conditions with high capacitance, power density, energy density, and coulombic efficiency, thus it has the potential to be a stable and reversible supercapacitor electrode.

Based on Table 7, ZnO/AC nanocomposites synthesized by the coprecipitation method have a wide range of applications, including biomedicine, water treatment, and energy storage. This diversity confirms that the

combination of ZnO and activated carbon is capable of forming functional materials with characteristics that can be directed according to application needs. In addition to the ZnO–AC binary system, material development has also included ternary and quaternary systems, which indicates efforts to improve material function through composition modification [34–39]. In the biomedical field, BSPAC/CS/ZnO materials exhibit spherical morphology measuring 3–10 nm, high surface area, and good antibacterial and anticancer activity. These characteristics suggest that the addition of components such as chitosan to the ZnO/AC system could expand the material's functionality toward biomedical applications [34].

In the field of water treatment, increasing composition complexity is accompanied by increasing functional performance. The AC@ZnO/CuO/WO_3 material exhibited very high photocatalytic performance, with a Lemon Yellow detoxification efficiency of 98.4 % and a TOC mineralization efficiency of 96.13 %. This performance was supported by a decrease in the band gap, an increase in the surface area, and a reduction in charge recombination [35]. In antibacterial applications, the coprecipitated Ag–ZnO/AC nanocomposite exhibited inhibition zones of up to 12 mm against *Pseudomonas aeruginosa*, demonstrating its potential antibacterial activity under the reported experimental conditions [36]. In the field of energy storage, especially as a supercapacitor electrode, ZnO–AC material shows good electrochemical performance. High capacitance, power density, energy density, and good coulombic efficiency are obtained especially at a composition ratio of 1:1, which indicates that the compositional balance of ZnO and activated carbon plays an important role in improving supercapacitor performance [37–39]. However, the evidence supporting these electrochemical performance trends is largely derived from three studies [37–39] sharing the same first author (Yadav), indicating limited independent corroboration across different research groups. Nevertheless, the superior performance of the 1:1 ZnO composition was reported in only two studies [38,39] under specific experimental conditions and should not be considered a universally optimal composition without further experimental validation. Quantitatively, the BSPAC/CS/ZnO nanocomposite exhibited an IC_{50} value of 50.28 μg/mL against MDA-MB-231 breast cancer cells [34]. In antibacterial applications, ZnO/AC demonstrated an inhibition zone of up to 12 mm against *E. coli* [36]. For energy storage, ZnO–AC electrodes achieved specific capacitances of 342.6 F g^{-1} in 6 M KOH and 326.1 F g^{-1} in 1 M NaOH [38]. These findings provide quantitative support for the reported material performance, although differences in experimental conditions limit direct comparisons across studies.

6 Morphology and Porosity Analysis of ZnO/AC Nanocomposites

Morphology and porosity analysis are important aspects in und[36–38]erstanding the performance of ZnO/AC nanocomposites, especially in determining the surface area, particle distribution, and interaction efficiency with pollutants. Variations in morphological structure and pore type resulting from the synthesis process will significantly affect the adsorption capacity and photocatalytic activity of the material. The morphological and porosity characteristics of the ZnO/AC nanocomposites can be seen in Table 8. Morphologically, reported shapes include fragmented honeycombs, hexagonal rods, spheres, nanorods, and elongated spindle-like shapes [34–39]. This diversity indicates that the formation of ZnO on an activated carbon matrix can produce different microarchitectures. The hexagonal rod and nanorod morphologies indicate a tendency for more directional crystal growth, while the spherical, spongy, and hollow structures indicate a more complex and heterogeneous particle arrangement. The presence of porous and cavities in some samples also demonstrates the contribution of activated carbon in shaping the surface texture of the material.

The reported particle sizes are in the range of 9.1–64.2 nm, which confirms that the obtained material remains at the nanoscale [34–39]. The smallest particle sizes were recorded in materials with fragmented honeycomb morphology, while larger sizes appeared in hexagonal rod systems. In some samples, particle sizes were in a relatively close range, namely around 25–35 nm, which indicates that coprecipitation is quite effective in producing nano-sized ZnO/AC particles, although the size distribution is not completely uniform between studies. Nevertheless, variations in particle-size reporting, including single values and size ranges, as well as differences in porosity characterization, limit direct quantitative comparisons across studies and require cautious interpretation of synthesis–property relationships. From the porosity aspect, the most obvious trend is the emergence of mesopores, especially in materials explicitly classified as type IV [34, 35, 39]. In addition, several studies reported the presence of voids, porous microstructures, and rough and heterogeneous surfaces. These findings indicate that activated carbon plays a significant role in forming the pore network and surface texture of the composite.

Table 8

Characteristics of ZnO/AC material

Ref.	Morphology	Particle Size (nm)	Pore Type	Functional Group	Wave Number (cm^{-1})	Crystal Structure	Lattice Parameters (Å)	Crystallite Size (nm)	Database
[34]	Fragmented honeycomb	9.1	Mesoporous (Type IV)	O–H and C–H; –OH and –NH_2; Zn–O	3389 and 3006; 555 and 1364; 1012 and 485	Hexagonal wurtzite	NR	2-67	ICDD 891397
[35]	Hexagonal rod	25 — 64.2	Mesoporous (Type IV)	NA	NA	ZnO (hexagonal), CuO & WO_3 (monoclinic)	ZnO: a=b= 3.22; c=5.2; CuO: a=4.68; b=3.42; c=5.12; AC: a=b=2.456; c=20.08	25.9-36.7	JCPDS 01-075-1526
[36]	Round, nanorod, sponge	35	Rough and heterogeneous surface	–OH and N–H; –OH; C=O (–COOH)	3239; 3433; 1636	FCC (Ag) & hexagonal ZnO	NR	Ag: 6.4; ZnO: 7.5	ICDD 893722 JCPDS No. 79-0207
[37]	Rod-shaped ZnO aggregates distributed on the activated carbon surface	NR	Voids	NA	NA	Hexagonal wurtzite	a = 3.253; c = 5.2107	25.5 ± 0.5	JCPDS No. 79-0207
[38]	Round with hollow spindle	25.15	Porous microstructure	Zn–O; C=O; O–H	468.70 and 1020.34; 1400-1500 and 2368.59; 1651.07 and 3674.39	Hexagonal wurtzite	a = 3.2491; c = 5.2074 (c/a = 1.6027)	25.15	JCPDS No. 79-0207
[39]	Elongated like a spindle interspersed with cavities	32.30	Mesoporous	Zn–O; C=O; O–H	443.63 and 1020.34; 1400–1500 and 2362.79; 1622.13 and 3614.60	Hexagonal wurtzite	a = 3.2447; c = 5.2069 (c/a = 1.6047)	32.30	JCPDS No. 00-036-1451

Note – Particle size refers to particle dimensions determined by morphological characterization, whereas crystallite size represents the coherent crystalline domain estimated from XRD analysis. All values are expressed in nm and retained as reported in the original studies. These parameters should not be considered equivalent; and NR = Not reported

The presence of mesopores and voids indicates that the material not only contains the active ZnO phase but also has a surface structure that supports broader interactions with the surrounding environment. FTIR characterization shows that the most frequently appearing functional groups are O–H, C=O, and Zn–O, accompanied by several additional groups such as N–H and $–NH_2$ in certain systems [34, 36, 38, 39]. The absorption band in the range of 3200–3600 cm^{-1} is generally associated with hydroxyl groups, while the band in the range of 1400 cm^{-1} — 1700 cm^{-1} indicates the presence of carbonyl groups or oxygen groups on the surface of activated carbon. Meanwhile, the band in the low wavenumber region, around 443 cm^{-1} — 555 cm^{-1}, confirms the presence of Zn–O bonds as an indicator of the formation of the ZnO phase [34, 38, 39]. The presence of these groups indicates that the material surface contains a combination of metal oxide components and activated carbon that still retains its surface functional groups. In terms of crystal structure, the most dominant phase is ZnO with a hexagonal wurtzite structure, which appears in almost all studies [34, 35, 37–39]. In several multicomponent materials, additional phases were also identified, such as Ag with an FCC structure and CuO and WO_3 with a monoclinic structure, which indicates the formation of a more complex composite system [35, 36]. These data show that the basic ZnO structure remains dominant, but may be accompanied by other phases depending on the composition of the material used. The reported lattice parameters of hexagonal wurtzite ZnO are approximately around a = 3.22–3.25 Å and c = 5.20–5.21 Å [35, 38, 39]. This consistency indicates that the resulting ZnO crystal structure still conforms to the typical characteristics of the wurtzite phase. The reported ZnO crystallite sizes range from approximately 7.5 to 36.7 nm, with most values concentrated around 25–32 nm [35–39]. Notably, the crystallite size of 6.4 nm reported in [36] corresponds to the Ag phase rather than ZnO. In addition, phase identification is carried out by referring to standard databases such as ICDD and JCPDS, which strengthens the validity of crystal structure determination in the studied materials [34–39].

7 Discussion

The development of coprecipitation-based ZnO/AC nanocomposite research shows a clear shift from studies focused on fundamental characterization to material design directed at specific applications. In the reviewed articles, the initial phase of development is still dominated by the evaluation of crystal structure, morphology, and basic electrochemical performance, as seen in a series of studies Yadav, et al. [37–39]. In more recent periods, the research focus has shifted towards more complex systems, such as ternary and quaternary composites for biomedical and water treatment applications, for example in [34–36]. This shift is in line with the general development of ZnO-based materials, which are essentially promising for environmental and energy applications, but are still limited by a relatively wide band gap and fast electron–hole pair recombination, thus requiring modification through the formation of composites, heterostructures, or integration with carbon matrices [40].

From the synthesis side, the results in the reviewed tables show that coprecipitation is not just a procedure for ZnO formation, but serves as a synthesis platform that is almost always combined with chemical activation, ultrasonication, impregnation, controlled washing, and thermal treatment. This indicates that the final quality of ZnO/AC is largely determined by the interface engineering between the ZnO and activated carbon phases, rather than solely by the formation of ZnO itself. More broadly, this pattern is consistent with analogous activated carbon-based materials and other semiconductors. Feng et al. [41] showing that the addition of activated carbon to the g-C3N4 system broadens visible light absorption, enhances electron transfer, and suppresses charge recombination. A similar pattern was reported by Yue et al. [42] on the TiO_2/AC system, where the composite shows a clear synergy between adsorption and photocatalysis. Recent literature reviews also confirm that the combination of adsorption and photocatalysis mechanisms in composite materials generally increases the effective surface area, charge separation efficiency, and material regeneration opportunities, thus becoming an increasingly important approach in modern water treatment [43].

The material characteristics in Table 8 confirm that coprecipitation is capable of producing highly adaptive micro and nano architectures, as indicated by the morphology in the form of fragmented honeycombs, hexagonal rods, nanorods, sponge structures, and elongated shapes resembling spindles. The particle size in the nanometer range and the dominance of mesopores or hollow surfaces indicate that the ZnO/AC system offers a combination of high surface area, pore accessibility, and a large number of active sites. In the structure–function framework, this combination is very important because porosity accelerates the diffusion of target ions or molecules, while the nanocrystal size increases the active interfacial area. Such a pattern has also been a central theme in the literature on supercapacitors based on metal oxide/porous carbon composites, where the capacitance enhancement and stability generally stem from a balance between the pseudocapacitance contributions of the metal oxide and the conductive porous carbon network [44, 45]. Thus, the morphology

and porosity of ZnO/AC cannot be viewed as a by-product of synthesis, but as a key design parameter that determines the material's response in the final application.

From the crystallinity aspect, the dominance of the hexagonal wurtzite ZnO phase in most studies indicates that the integration of ZnO with activated carbon or with additional components does not eliminate the basic crystal framework of ZnO. This finding is important because performance improvements in semiconductor composite systems generally do not depend on a complete change in the crystal phase, but rather on the formation of an interface architecture that supports charge separation and migration. In multicomponent systems, such as materials containing Ag, CuO, or WO_3, the presence of additional phases is more accurately read as a heterojunction formation strategy to extend electron migration trajectories, suppress recombination, and broaden the spectral response of the material. Recent ZnO literature emphasizes that approaches such as heterostructuring, hybridization, and surface engineering are the main routes to overcome the limitations of pure ZnO, especially in photocatalytic applications under visible light [40]. Thus, the stability of the wurtzite phase in ZnO/AC is actually an advantage, because performance improvements can be achieved without sacrificing the stable basic ZnO structure.

Characterization of functional groups and optical properties further clarifies that the role of activated carbon in these systems goes beyond its function as a passive support. The presence of –OH, C=O, Zn–O, and in some systems nitrogen-based groups indicates that the composite surfaces contain active chemical sites relevant for adsorption, particle growth, and redox reactions. At the same time, the decrease in the band gap in the composite system compared to pure ZnO indicates a modification in the electronic environment of the material. This pattern is in line with the findings Feng et al. [41], which shows that activated carbon in g-C_3N_4/AC composites expands the light absorption region and increases electron transfer efficiency. In the same framework, literature reviews on ZnO state that band gap reduction and charge recombination suppression are the two most important indicators of successful ZnO modification for environmental applications [40]. Therefore, the success of ZnO/AC lies not only in the stability of the structure, but also in the ability of this composite system to engineer the optical and chemical properties of the surface simultaneously.

In biomedical applications, the results obtained for the BSPAC/CS/ZnO system demonstrate that the integration of ZnO/AC with chitosan expands the functionality of the material from a mere adsorptive or catalytic system to a relevant platform for antibacterial and anticancer activities. This trend is consistent with the broader literature on chitosan-based materials. Mawazi et al. [46] shows that chitosan and its derivatives are widely used in antibacterial, anticancer, wound healing, and tissue engineering applications due to their biocompatible, biodegradable, and mucoadhesive properties. At a more specific level, [47] also demonstrated that ZnO/chitosan composites can be developed as antimicrobial and biofilm inhibitor delivery platforms. Thus, the BSPAC/CS/ZnO system can be understood as a logical extension of the ZnO/chitosan platform, with the addition of activated carbon providing the advantages of higher pore texture, surface area, and interaction capacity.

In water treatment applications, increasing the complexity of composites from binary to ternary and quaternary systems correlates with more measurable improvements in material functionality. Composites such as AC@ZnO/CuO/WO_3 and Ag–ZnO/AC not only utilize activated carbon for initial adsorption, but also utilize heterostructures and additional components to improve charge separation and broaden the optical response. This pattern is highly consistent with the hybrid adsorption–photocatalysis paradigm, which according to [43] offers a more robust middle ground than using either adsorption or photocatalysis alone. As well as, Yue et al. [42] showed that the TiO_2/AC composite can achieve very high degradation efficiency while maintaining stability over multiple cycles, whereas Feng et al. [41] showed similar functional enhancement in g-C_3N_4/AC. Therefore, the results on ZnO/AC and its derivatives should be read as part of a broader trend in environmental materials engineering, namely combining pollutant capture and photocatalytic degradation capacities in a single platform.

In energy storage applications, a series of ZnO–AC studies have shown that this composite works through a combination of the conductivity and surface area of activated carbon and the pseudocapacitance of ZnO. Optimal performance often occurs at specific composition ratios, particularly around 1:1, suggesting that supercapacitor performance is highly sensitive to the balance between the oxide phase and the carbon network. A recent literature review supports this interpretation. Ngidi et al. [44] asserted that the integration of metal oxides into porous carbon structures tends to enhance capacitance, charge storage, and cycling stability because carbon provides efficient ion diffusion pathways and surface area. Tundwal et al. [45] also showed that metal oxide and carbon based composite materials are one of the most promising strategies to improve the performance of supercapacitor electrodes. Thus, the behavior of ZnO–AC in the corpus of this article is

consistent with the general theory that high performance in composite supercapacitors arises from the synergy of electric double-layer capacitance and pseudocapacitance.

Critically, two major weaknesses remain in the reviewed research landscape. First, standardization of synthesis parameters remains weak, particularly in the reporting of pH, stirring speed, holding time, and activation and washing details. Second, the relationship between synthesis parameters–interface structure–charge transfer mechanism–final performance has not always been established quantitatively. Comparative literature in the field of hybrid photocatalysis and supercapacitors also shows that the main challenge today lies not only in improving instantaneous performance, but also in reusability, long-term stability, technological readiness, and scalability of synthesis [43, 45]. Therefore, future research directions should not only increase compositional complexity, but also emphasize more precise synthesis control, more complete parameter reporting, and more rigorous mechanistic evaluation and long-term application. Although calcination temperatures and particle sizes are reported in several studies, the limited availability of comparable numerical band-gap values prevents reliable cross-study correlation analysis, as differences in material composition and characterization conditions may introduce additional uncertainties.

8 Conclusions

The six included studies report the use of coprecipitation synthesis to produce ZnO/AC nanocomposites exhibiting diverse structural, morphological, and functional characteristics. Variations in synthesis parameters, including ZnO precursor type, ZnO ratio, precipitating agent, pH, calcination temperature, activation method, and post-synthesis treatment, are associated with differences in morphology, particle size, porosity, functional groups, crystal structure, and optical properties. In general, the resulting material is dominated by the hexagonal wurtzite ZnO phase, nano-sized, and has a pore character that tends to be mesoporous with the main functional groups O–H, C=O, and Zn–O. The results of the study also show that the integration of ZnO with activated carbon not only increases the surface area and pore accessibility, but also supports the formation of interfaces that play an important role in improving material performance. In biomedical applications, ternary composites exhibit good antibacterial and anticancer activities. In water treatment applications, ternary and quaternary systems exhibit significant photocatalytic efficiency enhancement, primarily through band gap reduction, surface area increase, and charge recombination suppression. Meanwhile, in energy storage applications, ZnO–AC composites show promising electrochemical performance as supercapacitor electrodes, especially at balanced composition ratios. Nevertheless, the inclusion of only six eligible studies, together with variations in synthesis conditions and characterization methods, limits the generalizability of the findings. Therefore, the identified relationships should be interpreted as descriptive trends requiring further experimental validation.

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The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript. CRediT: **Kormil Saputra:** Conceptualization, Validation, Investigation, Resources, Data Curation, Writing — Review & Editing, Supervision, Project Administration; **Muhammad Rifaan Ramdani:** Conceptualization, Methodology, Formal Analysis, Investigation, Writing — Original Draft, Writing — Review & Editing; **Dian Wjaya Kurniawidi:** Software, Validation, Formal Analysis, Data Curation, Visualization, Writing — Review & Editing, Supervision.

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Conflicts of Interest

The authors declare no conflict of interest.

References

1 Kausar, A., Ahmad, I., Zhao, T., Aldaghri, O., Ibnaouf, K. H., & Eisa, M. H. (2023). Graphene Nanocomposites as Innovative Materials for Energy Storage and Conversion—Design and Headways. *International Journal of Molecular Sciences*, *24*(14), 11593. https://doi.org/10.3390/ijms241411593

2 Hanafi, M. F., & Sapawe, N. (2020). A review on the current techniques and technologies of organic pollutants removal from water/wastewater. *Materials Today: Proceedings, 4th International Conference on Green Chemical Engineering and Technology: Materials Science*, *31*, A158–A165. https://doi.org/10.1016/j.matpr.2021.01.265

3 Periyasamy, A. P. (2024). Recent Advances in the Remediation of Textile-Dye-Containing Wastewater: Prioritizing Human Health and Sustainable Wastewater Treatment. *Sustainability*, *16*(2), 495. https://doi.org/10.3390/su16020495

4 Ong, W. -J., Zheng, N., & Antonietti, M. (2021). Advanced nanomaterials for energy conversion and storage: Current status and future opportunities. *Nanoscale*, *13*(22), 9904–9907. https://doi.org/10.1039/D1NR90103F

5 Seok, D., Jeong, Y., Han, K., Yoon, D. Y., & Sohn, H. (2019). Recent Progress of Electrochemical Energy Devices: Metal Oxide–Carbon Nanocomposites as Materials for Next-Generation Chemical Storage for Renewable Energy. *Sustainability*, *11*(13), 3694. https://doi.org/10.3390/su11133694

6 Termoul, M., Attouti, S., Benallou, M. B., Zerhouni, A., Uğur, T., Tuna, M., Benderdouche, N., & Bestani, B. (2024). Synthesis and characterization of ZnO/activated carbon nanocomposite for the removal of cationic dye from aqueous solutions. *Studies In Engineering And Exact Sciences*, *5*(1), 3462–3483. https://doi.org/10.54021/seesv5n1-172

7 Raha, S., & Ahmaruzzaman, M. (2022). ZnO nanostructured materials and their potential applications: Progress, challenges and perspectives. *Nanoscale Advances*, *4*(8), 1868–1925. https://doi.org/10.1039/D1NA00880C

8 Güell, F., Galdámez-Martínez, A., R. Martínez-Alanis, P., C. Catto, A., Silva, L. F. da, R. Mastelaro, V., Santana, G., & Dutt, A. (2023). ZnO-based nanomaterials approach for photocatalytic and sensing applications: Recent progress and trends. *Materials Advances*, *4*(17), 3685–3707. https://doi.org/10.1039/D3MA00227F

9 Alwash, A. (2025). Green fabrication of p-n CuO/ZnO heterojunctions for efficient photocatalytic degradation of dyes. *South African Journal of Chemical Engineering*, *54*, 441–450. https://doi.org/10.1016/j.sajce.2025.09.007

10 Mahajan, M., Kumar, S., Gaur, J., Kaushal, S., Somvanshi, A., Kaur, H., Singh, G., Hatshan, M. R., Kumar, S., & Lotey, G. S. (2025). Role of cellulose, phenolic compounds, and water-soluble proteins in ZnO nanoparticle synthesis using *Mangifera indica* leaf extract for photocatalytic and antioxidant investigations. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, *720*, 137066. https://doi.org/10.1016/j.colsurfa.2025.137066

11 Zhu, X., Wang, J., Yang, D., Liu, J., He, L., Tang, M., Feng, W., & Wu, X. (2021). Fabrication, characterization and high photocatalytic activity of Ag–ZnO heterojunctions under UV-visible light. *RSC Advances*, *11*(44), 27257–27266. https://doi.org/10.1039/D1RA05060E

12 Ahmed, A. S., Alsultan, M., Sabah, A. A., & Swiegers, G. F. (2023). Carbon Dioxide Adsorption by a High-Surface-Area Activated Charcoal. *Journal of Composites Science*, *7*(5), 179. https://doi.org/10.3390/jcs7050179

13 Hu, M., Wu, W., Lin, D., & Yang, K. (2022). Adsorption of fulvic acid on mesopore-rich activated carbon with high surface area. *Science of The Total Environment*, *838*, 155918. https://doi.org/10.1016/j.scitotenv.2022.155918

14 Adeoye, J. B., Lau, S. Y., Tan, Y. H., Tan, Y. Y., Chiong, T., Mubarak, N. M., Khalid, M., & Ng, J. T. W. (2025). Efficient dye removal from aqueous solution using a hybrid GA@ZnO-AC nanocomposite. *Scientific Reports*, *15*(1), 31754. https://doi.org/10.1038/s41598-025-17464-6

15 Ayadi, A., Jellouli Ennigrou, D., Proietto, F., Hamzaoui, A. H., & Jaouadi, M. (2023). Electrochemical Degradation of Phenol in Aqueous Solutions Using Activated Carbon-ZnO Composite. *Environmental Engineering Science*, *40*(9), 349–361. https://doi.org/10.1089/ees.2023.0016

16 Luo, S., Liu, C., Zhou, S., Li, W., Ma, C., Liu, S., Yin, W., Heeres, H. J., Zheng, W., Seshan, K., & He, S. (2020). ZnO nanorod arrays assembled on activated carbon fibers for photocatalytic degradation: Characteristics and synergistic effects. *Chemosphere*, *261*, 127731. https://doi.org/10.1016/j.chemosphere.2020.127731

17 Rajendran, R., Rojviroon, O., Arumugam, P., Ramasamy, G., Paramasivam, S., & Rojviroon, T. (2025). Synergistic effects of activated Carbon-Supported TiO2/ZnO nanocomposites for photocatalytic dye degradation and antibacterial activity. *Journal of Molecular Liquids*, *433*, 127792. https://doi.org/10.1016/j.molliq.2025.127792

18 Li, N., Jiao, F., Pan, X., Ding, Y., Feng, J., & Bao, X. (2019). Size Effects of ZnO Nanoparticles in Bifunctional Catalysts for Selective Syngas Conversion. *ACS Catalysis*, *9*(2), 960–966. https://doi.org/10.1021/acscatal.8b04105

19 Vijayalakhmi, K. A., & Deepa, R. (2025). Electrochemical Performance of Supercapacitors Based on ZnO/NiO@ Coconut Shell Activated Carbon Composite. *Journal of The Electrochemical Society*, *172*(7), 073504. https://doi.org/10.1149/1945-7111/adeb35

20 Islam, M. U., Iqbal, M., & Kossar, S. (2025). Synthesis and characterization of ZnO-graphite binary nanocomposite for supercapacitor and photocatalyst application. *The European Physical Journal Plus*, *140*(12), 1241. https://doi.org/10.1140/epjp/s13360-025-07082-6

21 Aslam, M., Raman, A. P. S., Sharma, U., Nand, B., Ebenso, E. E., Pandey, G., Singh, P., & Kumari, K. (2026). Carbon nanocomposites in electrochemical sensing of pesticides: Trends, materials, and applications. *Chemistry & Biodiversity, 23*(2), e02490. https://doi.org/10.1002/cbdv.202502490

22 Soualmi, S., Henni, M., Djahnit, L., & Hamdani, H. (2024). Sol-gel Synthesized ZnO–$SrMn_2O_4$ Nanocomposite and Its Antibacterial Properties. *Eurasian Journal of Chemistry*, 29(4 (116)), 71–81. https://doi.org/10.31489/2959-0663/4-24-12

23 Ramadhani, F. A. F., Taufiq, A., Mufti, N., Kurniawan, R., Hidayat, A., & Subadra, S. U. I. (2025). Synthesis and characterization of cobalt ferrite/zinc oxide nanocomposite combined with activated carbon for Cu removal application. *AIP Conference Proceedings*, *3197*(1). https://doi.org/10.1063/5.0241030

24 Rahmadani, F. N. A., Fadlilah, I., & Rahayu, T. E. P. S. (2024). Sintesis Material Fotokatalis Seng Oksida –Silika Abu Tongkol Jagung (ZnO-SiO2) dengan Metode Kopresipitasi dan Karakterisasinya. *JC-T (Journal Cis-Trans) : Jurnal Kimia Dan Terapannya*, *8*(1), 34–43. https://doi.org/10.17977/um0260v8i12024p033

25 Haraki, R. E., Arie, A. A., Susanti, R. F., Oktaviano, H. S., & Nugroho, A. (2023). Synthesis and Electrochemical Properties of ZnO/ Activated Carbon from Vetiver Distillation Waste. *Engineering Chemistry*, *2*, 35–41. https://doi.org/10.4028/p-1z7h01

26 Ardiansyah, F. F., Ma'arif, M. S., Riska, A. M., Fadlilah, F., Alfan, M. W. N., & Rohmawati, L. (2025). Fabrication of ZnO/MgO nanocomposites from natural materials by coprecipitation method. *AIP Conference Proceedings*, *3166*(1). https://doi.org/10.1063/5.0240562

27 Hareeshanaik, S., Prabhakara, M. C., Bhojya Naik, H. S., Vishnu, G., Viswanath, R., & Adarshgowda, N. (2024). Multifunctional Applications of Gd-Doped ZnO Nanoparticles Prepared Easily by the Coprecipitation Method. *ChemistrySelect*, *9*(43), e202403303. https://doi.org/10.1002/slct.202403303

28 Tao, H., & Song, S. (2023). Study on the effect of high temperature heat treatment of H_2 on the pore structure of activated carbon. *Journal of Physics: Conference Series*, *2539*(1), 012003. https://doi.org/10.1088/1742-6596/2539/1/012003

29 Ejsmont, A., & Goscianska, J. (2023). Hydrothermal Synthesis of ZnO Superstructures with Controlled Morphology via Temperature and pH Optimization. *Materials*, *16*(4), 1641. https://doi.org/10.3390/ma16041641

30 Peymanfar, R., Yektaei, M., Javanshir, S., & Selseleh-Zakerin, E. (2020). Regulating the energy band-gap, UV–Vis light absorption, electrical conductivity, microwave absorption, and electromagnetic shielding effectiveness by modulating doping agent. *Polymer*, *209*, 122981. https://doi.org/10.1016/j.polymer.2020.122981

31 Zhang, K., Sun, J., E, L., Ma, C., Luo, S., Wu, Z., Li, W., & Liu, S. (2022). Effects of the Pore Structure of Commercial Activated Carbon on the Electrochemical Performance of Supercapacitors. *Journal of Energy Storage*, *45*, 103457. https://doi.org/10.1016/j.est.2021.103457

32 Page, M. J., Moher, D., Bossuyt, P. M., Boutron, I., Hoffmann, T. C., Mulrow, C. D., Shamseer, L., Tetzlaff, J. M., Akl, E. A., Brennan, S. E., Chou, R., Glanville, J., Grimshaw, J. M., Hróbjartsson, A., Lalu, M. M., Li, T., Loder, E. W., Mayo-Wilson, E., McDonald, S., … McKenzie, J. E. (2021). PRISMA 2020 explanation and elaboration: Updated guidance and exemplars for reporting systematic reviews. *BMJ*, *372*, n160. https://doi.org/10.1136/bmj.n160

33 Higgins, J. P. T., & Thompson, S. G. (2002). Quantifying heterogeneity in a meta-analysis. *Statistics in Medicine*, *21*(11), 1539–1558. https://doi.org/10.1002/sim.1186

34 Cinnathambi Subramani, M., Kandasamy, B., Budiman, I., Subyakto, S., Chitraningrum, N., Widyaningrum, B. A., Saputra, N. A., Fauzi, A. A. B., Holilah, H., Hata, T., & Nafiqoh, N. (2025). Synthesis and characterization of bamboo stem porous activated carbon/chitosan/zinc oxide (BSPAC/CS/ZnO) ternary nanocomposite for enhancement of biological activities. *International Journal of Biological Macromolecules*, *305*, 141041. https://doi.org/10.1016/j.ijbiomac.2025.141041

35 Rizvi, H. I., Mushtaq, A., Iqbal, T., Afsheen, S., Ashfaq, Z., Al-Zaqri, N., & Warad, I. (2025). Photocatalytic detoxification of lemon yellow food additive by Novel AC@ZnO/CuO/WO3 quaternary composites via Citrus sinensis and solid-state-reaction method. *Journal of Alloys and Compounds*, *1022*, 179915. https://doi.org/10.1016/j.jallcom.2025.179915

36 Taha, A., Ben Aissa, M., & Da'na, E. (2020). Green Synthesis of an Activated Carbon-Supported Ag and ZnO Nanocomposite for Photocatalytic Degradation and Its Antibacterial Activities. *Molecules*, *25*(7), 1586. https://doi.org/10.3390/molecules25071586

37 Yadav, M. S., Sinha, A. K., & Singh, M. N. (2018). Electrochemical behaviour of ZnO–AC based nanocomposite electrode for supercapacitor. *Materials Research Express*, *5*(8), 085503. https://doi.org/10.1088/2053-1591/aad2c4

38 Yadav, M. S., Singh, N., & Kumar, A. (2018). Synthesis and characterization of zinc oxide nanoparticles and activated charcoal based nanocomposite for supercapacitor electrode application. *Journal of Materials Science: Materials in Electronics*, *29*(8), 6853–6869. https://doi.org/10.1007/s10854-018-8672-5

39 Yadav, M. S., Singh, N., & Bobade, S. M. (2018). Zinc oxide nanoparticles and activated charcoal-based nanocomposite electrode for supercapacitor application. *Ionics*, *24*(11), 3611–3630. https://doi.org/10.1007/s11581-018-2527-1

40 Zhu, C., & Wang, X. (2025). Nanomaterial ZnO synthesis and its photocatalytic applications: A review. *Nanomaterials, 15*(9), 682. https://doi.org/10.3390/nano15090682

41 Feng, P., Cui, K., Hai, Z., Wang, J., & Wang, L. (2023). Facile synthesis of activated carbon loaded g-C_3N_4 composite with enhanced photocatalytic performance under visible light. *Diamond and Related Materials, 136*, 109921. https://doi.org/10.1016/j.diamond.2023.109921

42 Yue, Y., Yue, X., Tang, X., Han, L., Wang, J., Wang, S., & Du, C. (2024). Synergistic adsorption and photocatalysis study of TiO2 and activated carbon composite. *Heliyon*, *10*(10), e30817. https://doi.org/10.1016/j.heliyon.2024.e30817

43 Ahmadi, S., Quimbayo, J. M., Yaah, V. B. K., De Oliveira, S. B., & Ojala, S. (2025). A critical review on combining adsorption and photocatalysis in composite materials for pharmaceutical removal: Pros and cons, scalability, TRL, and sustainability. *Energy Nexus*, *17*, 100396. https://doi.org/10.1016/j.nexus.2025.100396

44 Ngidi, N. P. D., Koekemoer, A. F., & Ndlela, S. S. (2024). Recent advancement in the electrochemical performance of electrochemical capacitors based on biomass-derived porous carbon: A review. *Journal of Energy Storage*, *89*, 111638. https://doi.org/10.1016/j.est.2024.111638

45 Tundwal, A., Kumar, H., J. Binoj, B., Sharma, R., Kumar, G., Kumari, R., Dhayal, A., Yadav, A., Singh, D., & Kumar, P. (2024). Developments in conducting polymer-, metal oxide-, and carbon nanotube-based composite electrode materials for supercapacitors: A review. *RSC Advances*, *14*(14), 9406–9439. https://doi.org/10.1039/D3RA08312H

46 Mawazi, S. M., Kumar, M., Ahmad, N., Ge, Y., & Mahmood, S. (2024). Recent Applications of Chitosan and Its Derivatives in Antibacterial, Anticancer, Wound Healing, and Tissue Engineering Fields. *Polymers*, *16*(10), 1351. https://doi.org/10.3390/polym16101351

47 Rashki, S., Dawi, E. A., Zilaei, M. R., Safardoust-Hojaghan, H., Ghanbari, M., Ryadh, A., Lafta, H. A., Khaledi, A., & Salavati-Niasari, M. (2023). ZnO/chitosan nanocomposites as a new approach for delivery LL37 and evaluation of the inhibitory effects against biofilm-producing *Methicillin-resistant Staphylococcus aureus* isolated from clinical samples. *International Journal of Biological Macromolecules*, *253*, 127583. https://doi.org/10.1016/j.ijbiomac.2023.127583