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Converting Waste Paper into Functional Advanced Carbon Materials for the Circular Economy: A Systematic Review and Bibliometric Analysis

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Every year, a large amount of waste paper is discarded which causes environmental pollution. Therefore, how to convert this waste paper into a useful products using low-cost and effective techniques has become a challenging work if there are no comprehensive or systematic studies available on research trends especially to observe changes in research development over the year. The present systematic review aims to examine research trend from 2001 to April 2026 on the conversion of waste paper into functional carbon materials for various applications. The conversion of waste paper into high-value carbon materials has increased significant attention in recent year particularly in carbon dioxide capture and utilisation as well as energy storage applications. Data was generated by searching for the proper keywords in Scopus database. Then the resulting data were then filtered according to the PRISMA guidelines. About 116 documents were used to study research trends using VOSviewer and Bibliometrix RStudio. The results showed that the most frequently used keywords were waste paper, activated carbon, carbon, adsorption, aerogel and graphene. The highest number of publications in this field is from China. Based on Bibliometric analysis using RStudio, data generated from Sopus can be used to observe the relationship between keyword, authors publication, countries and publication sources. The results can clearly identify the most important topics, current applications in use, potential research collaborations and topics or areas that have not been clearly explored.

Keywords: Waste paper, paper waste, Carbon-based materials, systematic review, bibliometric analysis

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Paper products have been used in various applications around the world such as for packaging, shipping, writing, printing, personal care, arts, crafts, building and construction, and others [1]. The pulp and paper industry is one of the largest industries in the world with over 400 million metric tons of paper and cardboard produced worldwide each year and expected to increase to 900 million tons by 2050 [2, 3]. Due to large consumption, waste paper produces approximately 40–50 kg of solid waste of which 70% is primary sludge. This sludge contains rich useful fiber and cellulose that is suitable for recycling into the papermaking process and can be reused for high value-added products and materials [4]. Disposing of large amounts of waste paper in landfills will damage the environment and increase processing costs. Alternative methods need to be developed to reduce, reuse and reproduce the waste paper. Converting large amounts of waste paper into high-value products can provide significant benefits to the economy and the environment. Recent research has shown the potential of waste paper as a precursor to the development of high-value products [5, 6]. Waste paper contains a sustainable cellulose source that can be mixed with other materials to produce high-performance carbon materials. Carbon materials derived from paper by products exhibit high surface area, high porosity and thermal stability make these materials suitable for various applications including energy storage, wastewater removal, catalysis, carbon dioxide (CO_2) capture and others [7]. The conversion of waste paper into carbon materials involves a heat treatment or carbonisation process, with or without chemical activation. Commonly used treatment methods include pyrolysis, hydrothermal carbonisation, and chemical activation followed by carbonisation using an activating agent [8, 9].

New and fast techniques, such as microwave-assisted carbonisation using green activating agents, are becoming a trend and hot topic that aim to reduce energy consumption and save processing costs. For example, Sheng et al. [10] studied a microwave carbonisation technique to produce a carbon electrode derived from waste paper. The carbon materials were produced within 10 seconds using a graphene

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microreactor [10]. In another study, Ma et al. [11] developed carbon aerogel using pre-oxidation, carbonisation and activation technique from waste paper for the removal of antibiotics from water. The results showed that a high surface area of 654.58 m^2/g was produced and the highest adsorption capacity of 384.6 mg/g was achieved [11]. The growing demand for sustainable and high-performance carbon materials has led to more research shifts to advanced materials science for a variety of applications. The transformation of paper residues into value-added products is in line with global efforts toward circular economy principles, waste valorisation, and the goal of net-zero greenhouse gas emission by 2050.

This systematic review investigates research trend from 2001 to April 2026 on the conversion of waste paper products into functional carbon materials for various applications. This review includes research articles published between 2001 and 2026, comprising 116 documents from 90 publication sources (journals) and 573 authors who contributed to publications on this topic (Figure 1). The upward trend from 2001 to 2025 from 1 publication to 111 publications in 2025, reflecting the increasing research publications on sustainable materials, advanced materials, waste management and innovative technologies. In this systematic review, a combination of VOSviewer and bibliometric analysis using RStudio was applied to examine research trends in a more comprehensive analysis of progress, gaps, and future prospects in this research area.

The research questions guiding this study are as follows:

RQ1. How have research trends and developments on conversion of waste paper into functional carbon materials for various applications evolved over time?

RQ2. What topics and applications are trending?

RQ3. What are the main keywords or topics?

To answer this question, this systemic review aims to perform a bibliometric analysis in the Scopus database from 2001 to April 2026 and used RStudio and VOSviewer to interpret key patterns in keyword co-occurrence, and citation dynamics. From 2001 to 2012, only a slow increase was observed in publication trend. However, an increasing trend in the publication of research articles started to appear after 2021 to 2026. In 2021, the number of publications was 52, while in 2025 number of publications increased to 111 documents. The reason for this stable increase might be due to increasing global efforts by researchers on reduce solid waste, tackling waste management, to produce carbon materials derived from waste paper as an alternative method to reduce solid waste. Currently most researchers are striving to produce research that can impact society and industry as well as achieve targets that are in line with the United Nations Sustainable Development Goals (SDGs). The goal is to provide researchers with up-to-date overview of the most prominent research topics and publication trends, as well as future directions for better improvement of the current technologies. The structure of this systematic review is as follows: Section 2 presents the methodology of this review including details the data collection process and the bibliometric methodology employed. Section 3 presents the results and discussion of the bibliometric analysis. Finally, Section 4 concludes the study.

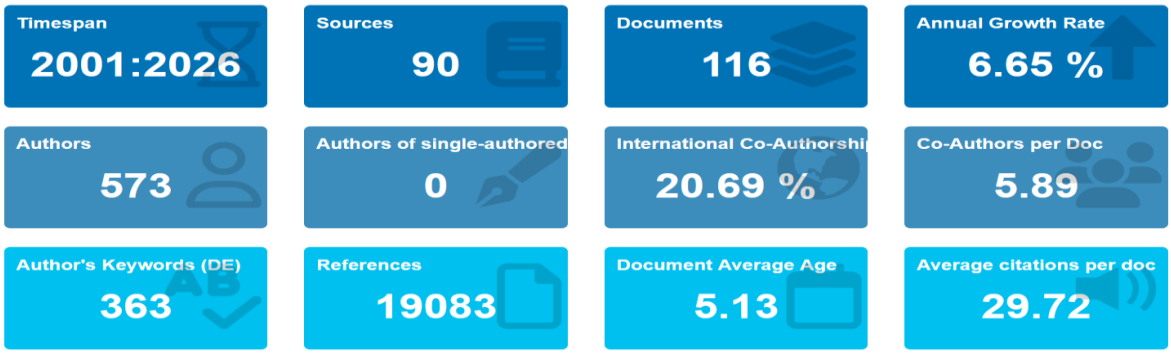

Figure 1. Scientific output based on Scopus database and generated from bibliometrix analysis.

METHODOLOGY

Research Strategy and Data Collection

This study followed the step-by-step review procedure by Preferred Reporting Items for Systematic Reviews and Meta (PRISMA 2020) flow diagram (Figure 2). In the first step, the Scopus database was used to conduct keyword search. The keyword string used in this study is ("paper waste" OR "waste paper" OR "cardboard waste" OR "corrugated paperboard waste" OR "paper and pulp industry waste" OR "paper and pulp industry by product*") AND ("porous carbon"

OR "activated carbon" OR "carbon material*" OR "graphene oxide" OR "graphene" OR "cellulose-graphene oxide" OR "carbon aerogel"). The screening process was carried out by setting the language to English only, the year between 2001 and April 2026, the document type to journal articles and only documents with access to download will be counted. After irrelevant items were eliminated, the number of documents to be used for further analysis was 116 documents. In this study, open source bibliometrix RStudio (biblioshiny) package and VOSviewer tools were used to conduct comprehensive bibliometric analyses [12, 13]. The analysis focuses on the trending topics, keyword patterns over time, relationship between keywords, authors, countries and publication sources.

DISCUSSION

Citations

Table 1 summarises the top 10 articles that received highly cited articles. The findings show that the most cited article out of 230 citations was on the topic of supercapacitors followed by 157 citations on sensor applications and 142 and 135 citations were published on wastewater treatment. A highly cited articles from 2009 highlights the early development of carbon materials derived from paper waste for energy storage applications. However, from 2017 onwards the conversion of paper waste into carbon materials has been studied in many other applications such as adsorption, wastewater, energy storage, catalysis, electrocatalysis, composite materials and advanced functional materials.

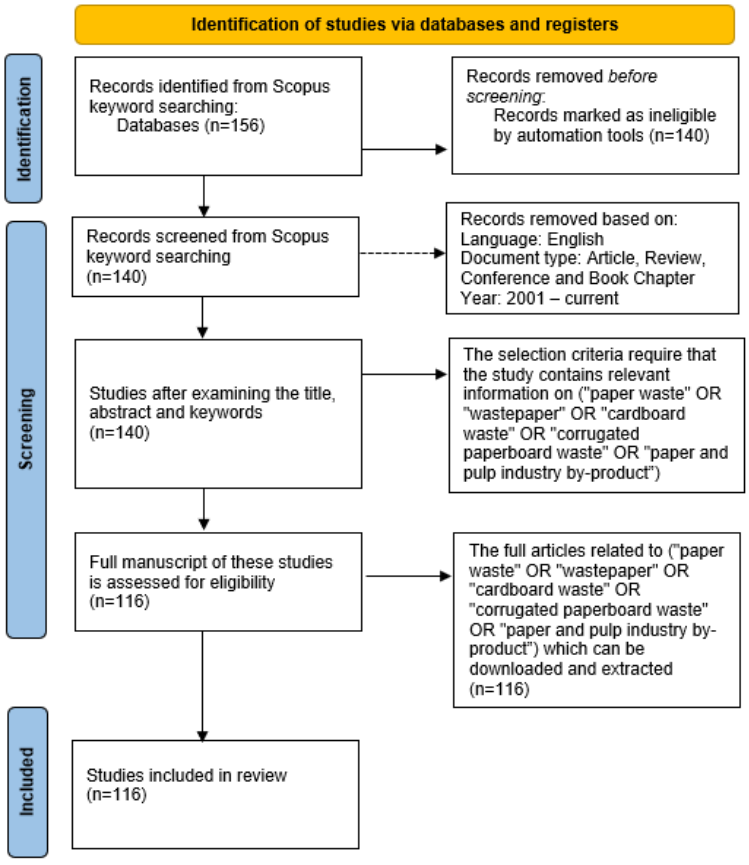

Figure 2. Prisma flow chart adapted from PRISMA 2020 flow diagram for systematic review **[14]**.

Table 1. The top 10 highly cited articles.

Keywords/Topics	Year	Applications	Cited by	References
Activated carbon, Newspaper, Supercapacitor, Potassium hydroxide activation, Surface area, Paper waste	2009	Supercapacitors	230	[15]
Aerogels, Carbonization, Waste Papers	2017	Sensors and electronic devices	157	[16]
Cork-based activated carbon, wastewater, dye adsorption, paper waste	2018	Removal of dyes from wastewaters	142	[17]
Solar evaporation, aerogel Cellulose, paper waste	2020	Seawater and complex wastewater	135	[18]
Biomethane, Granular activated carbon, paper waste	2017	Food waste anaerobic digestion, Biomethane	102	[19]
Magnetic biochar, Paper Waste, Tetracycline Fruit preservation	2023	Tetracycline removal and fruit preservation	83	[20]
Cellulose, Semiconductor quantum dots, Waste paper	2015	Semiconductor quantum dots	75	[21]
Bioenergy, bioethanol, biofuel, cellulose nanofibers, hydrogen, paper waste	2019	Bioethanol, hydrogen, biofuel	62	[22]
Activated carbon, adsorption, energy storage, tissue paper	2019	Organic pollutant and heavy metals	60	[23]
Graphene oxide sheets, office waste paper, supercapacitor	2017	Energy storage devices	58	[24]

Keywords

Word Cloud

Figure 3 shows a word cloud of the most frequently used keywords in the field of research on the valorisation of paper and pulp by-products into carbon materials. Based on the figure, the size of each word reflects its frequency of occurrence, allowing for rapid identification of dominant keyword and areas of emphasis in the literature. Keywords such as activated carbon, adsorption, carbon, waste paper, carbonization, aerogels and porous materials emerged significantly as the largest keywords. This indicates that these topics are most frequently studied until 2026, and this suggests that these topics are still hot topic and new research in this field particularly in limited or new applications are needed. Supporting this observation, Figure 4 shows the number of publications and percentage data for each keyword based on the word cloud. Data extracted from word cloud shows that activated carbon had the highest occurrence, with 64 counts (8%), followed by adsorption with 62 counts (7%), carbon with 57 counts (7%) and waste paper with 39 counts (5%). This data shows that carbon materials have unique properties such as high porosity and high surface area and provide unique textural and physical properties that are flexible to be modified for various applications. In addition, keywords such as surface area, porosity, and adsorption capacity also have significantly occurrence, reflecting the importance of textural properties in determining material performance.

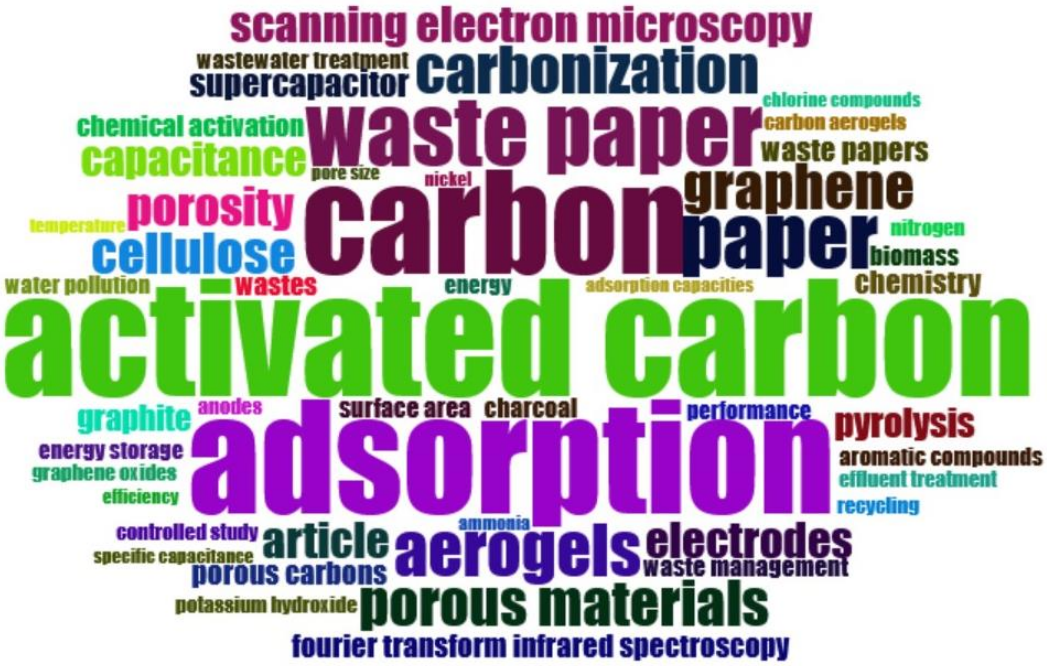

Figure 3. Word cloud produced from bibliometric R-Studio.

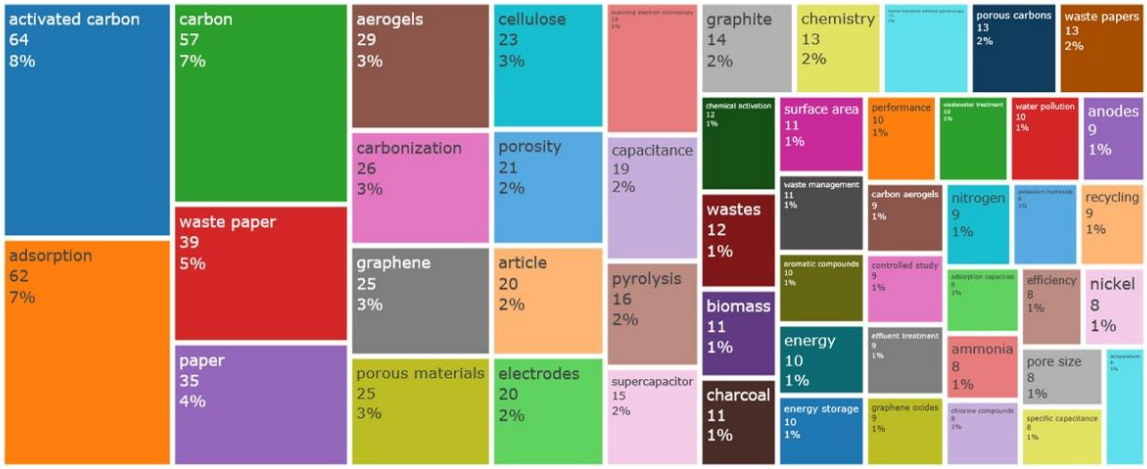

Figure 4. Tree map produced from bibliometric R-Studio.

Evolution of Keywords Over Time

Trending topics provide important insights into how research on paper and pulp by-products as carbon materials for various applications have evolved over time. Figure 5 shows that the development of the field can be broadly categorised into five distinct phases which are 2001–2009, 2012–2021, 2022–2023, 2024, and 2025–2026, each reflecting changes in research priorities and technological maturity. In the early stage (2001–2009), research activities were quite limited and mainly focused on two main scopes of research topic. The dominant keywords are activated carbon and adsorption, with published articles focusing on supercapacitor and organic contaminants. This phase can be characterised as the feasibility and proof-of-concept stage, with minimal focus on advanced material performance or specific applications. The total number of publications in 2001 to 2009 was 6 articles. A significant development in research activity is observed in the medium term (2012–2021), where publications continue to increase annually until 2021. During this phase, the research and keyword shift towards the development of new carbon materials derived from paper waste or waste paper and target applications. Topics such as activated carbon, carbon, aerogels, pyrolysis and waste management became increasingly prominent. This reflects the rapid

transition to the engineering of materials with improved functional properties and innovative technologies. In addition, environmental applications, particularly pollutant removal, are receiving considerable attention. The number of publications in 2012 to 2021 was 46 articles.

In the recent phase (2022–2023), the trend topics show a noticeable shift towards advanced material design and functionalisation. Keywords related to sodium hydroxide, potassium hydroxide, graphene started to appear more strongly. This suggests that research is no longer limited to improving surface area and adsorption capacity but is increasingly focused on material modification. The research scope leaned more towards interdisciplinary research combining materials science, chemistry, environmental and engineering technology to develop high-performance materials. Similar trend is observed with the keywords in 2024, which focused more on the functional and material modification using carbonization method. The most recent period (2025–2026) highlights a trend of topic towards innovation, and industrial applications. Research is more focused on developing materials that are more environmentally friendly, low-cost and highly efficient. Keywords such as energy and performance appear in this phase. Based on thematic evolution, keywords trend by year represents the growth of research from lab-scale to industrial-scale or industrial implementation, including considerations of scalability, cost-effectiveness, environmental impact and lifecycle performance.

De et al. [9] investigated the high-performance carbon materials derived from waste paper for energy storage applications. They developed a new electrode consisting of cobalt and cobalt oxide nanoparticles embedded in waste paper-derived porous carbon. The results show that specific capacitance is high, and the device maintains excellent cycle stability, keeping 82.86 % of its capacitance after 10,000 charge-discharge cycles [9]. In another study, for catalyst fabrication, Zhao et al. [21] fabricated microfibrous catalyst with superior durability up to 25 cycles. They synthesised the catalyst by mixing graphene oxide and cellulose solution from waste paper sheets to form composite microfibers [21]. In energy storage applications, Zhang et al. [22] developed a new method by converting discarded cloth and paper waste into high-efficience composite anodes for sodium-ion batteries by producing a high capacity of 813.5 at 0.5 mA cm^{-2} [22]. Sheng et al. [10] introduced a rapid carbonisation method for electrode catalysts to produce graphene carbon anodes using microwave carbonisation by rapidly carbonising waste paper in 10 seconds using a graphene microreactor. The carbon materials are used for energy storage applications. The results show that the electrode material can be reused and achieves a high stability of 97.2% after 1000 cycles due to its strong structural stability, resulting in excellent long-term stability and high-performance capabilities [10]. Dermawan et al. [23] developed high-performance modified composite carbon by synthesising it from pulp waste and sugarcane bagasse waste for heavy metal removal. The results show that the modified carbon composite adsorbent produced highly porous carbon and high removal efficiency reaching 96.7 % for the first 30 min. The material can be reused for more than three cycles [23]. Jerome et al. [24] have studied the potential of converting paper waste (cellulose) into composite material for CO_2 capture applications. They developed a new material consisting of a cellulose-graphene oxide composite aerogel adsorbent to increase CO_2 adsorption capacity. The results showed that the CO_2 adsorption capacity of composite material was 2.5 mmol/g at 1 bar [24].

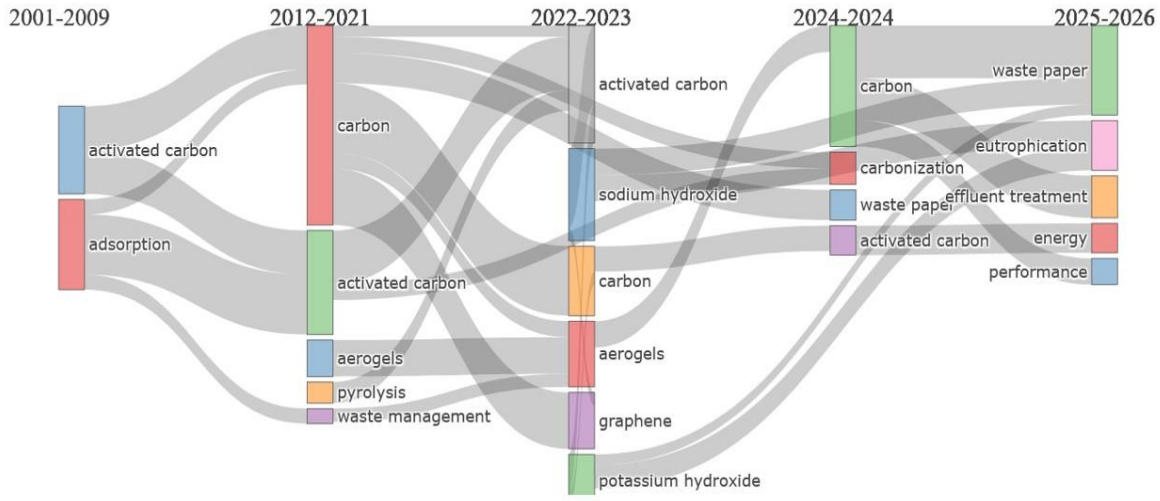

Figure 5. Thematic evolution between 2001 and 2026. Produced from bibliometric R-Studio.

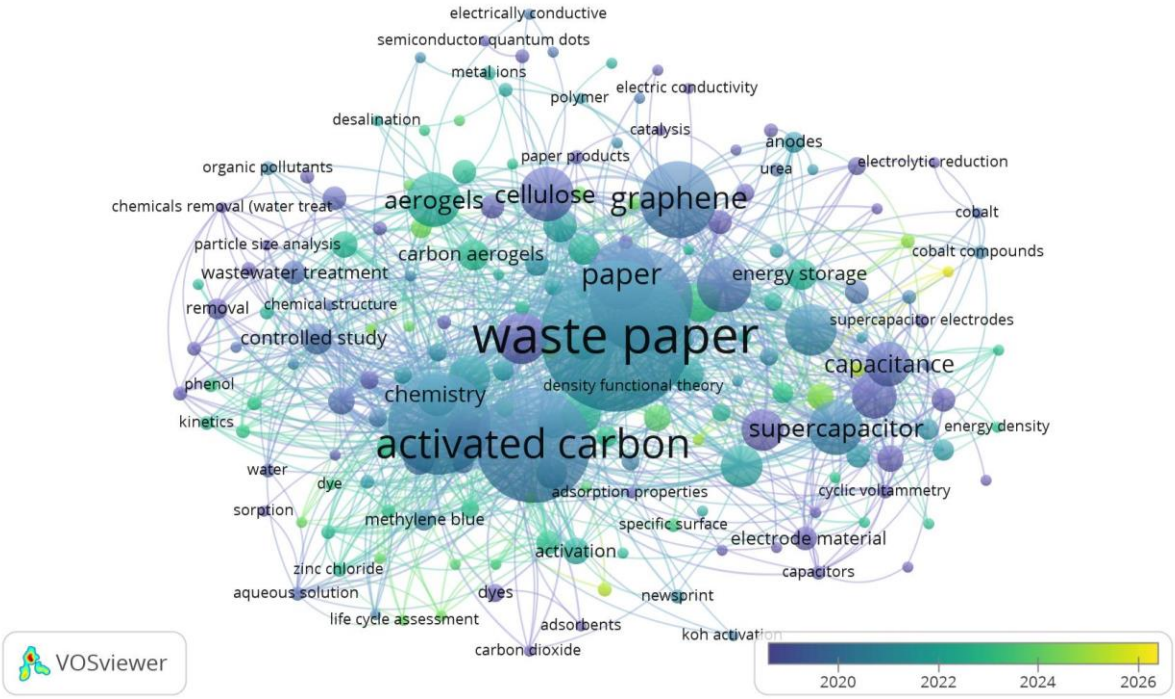

Figure 6. Overlay visualisation of co-occurrence over time. Produced from VOSviewer software.

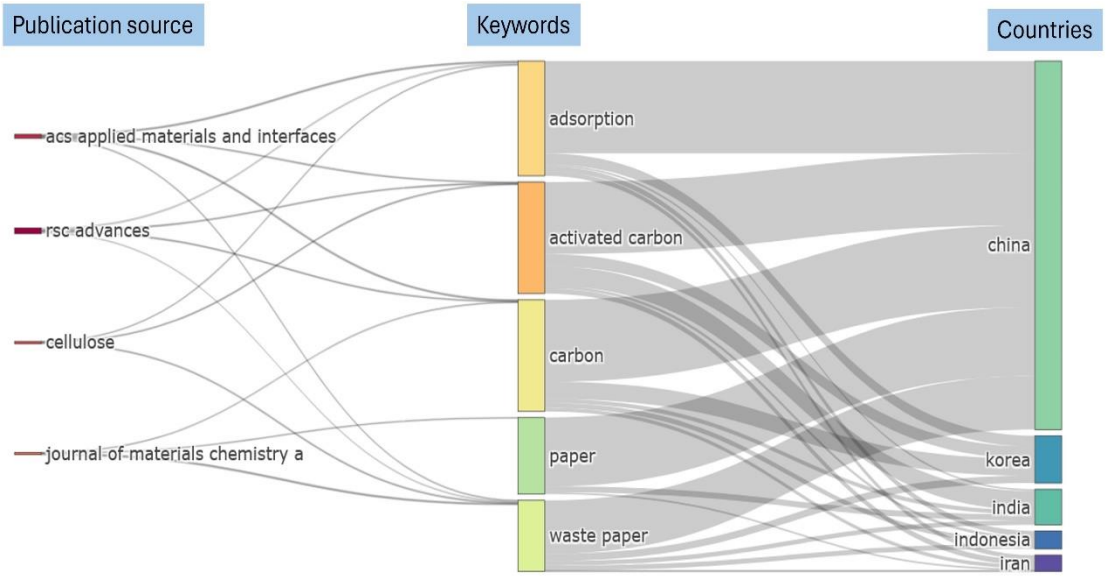

Figure 7. Three-field plot analysis. Produced from bibliometric R-Studio.

Co-occurrence (Keyword) Patterns Over Time using Bibliometric Analysis

The VOSviewer software settings were set to "All Keywords" and "Full Counting" as analysis parameter. Based on the overlay visualisation from VOSviewer's analysis, the total keywords are 1802 keywords, categorised into 5 clusters. The main keywords such as waste paper, activated carbon, carbon, adsorption and graphene are similar to keywords determined from bibliometric analysis as presented in Fig 4 and 5. Based on VOSviewer analysis, the dominant keyword is measured based on total link strength. This indicates the total strength of links representing the number of publications. The highest total link strength is waste paper (402), followed by activated carbon (297), carbon (286) and adsorption (255). Based on keyword co-occurrence clustering, current research directions can be divided into five categories: fundamental, synthesis

method, material modification, characterisation and applications. Based on the overlay visualization, purple indicates keywords that appeared relatively early (year <2020), green represents middle phase (2022-2024) and yellow represents recently emerging keywords (2024 -2026). This figure (Figure 6) can be used as a reference to study the current keyword trend and research topic as well as determine research gaps whereby highlighting research areas that have not been explored.

Three-Field Plot Relationship between Publication Source, Keywords, and Countries

Figure 7 shows the three-field plot analysis used to investigate the relationship between publication sources, keyword or research topic and author's countries. The thickness of the connecting line between the publication sources, keyword or research topic and author's countries, indicates the strength of the relationship between elements, representing the number of published documents or papers linking one element to another and the number of experts in that topic from those countries. The top countries include China, Korea, India, Indonesia and Iran which show strong research activity and high number of publications. Among these countries, the analysis clearly shows that China is the most dominant contributing country with the highest number of publications, followed by the Korea and India. The top or frequently used keywords in this research topic are adsorption (gas and liquid), activated carbon, carbon, paper, waste paper. This figure highlights how various countries and authors contribute to a particular area of research. Based on the Scopus database, the highest citated article, with 230 citations in 2009 was about carbon composite electrode obtained from waste newspaper as effective materials for supercapacitors, which was research under collaboration between two countries of South Korea and India [15]. Recent articles published in 2025 and early 2026 focused more on the supercapacitors, wastewater, CO_2 capture, energy storage applications. In the previous year, no articles were published on CO_2 capture applications. This indicates that paper waste or waste paper can be converted into valuable materials for CO_2 capture applications. Overall, the three-field plot demonstrates the interdisciplinary and globally distributed nature of research on the specific research topics where this waste can be converted into valuable materials for a various application, with research focus aligned with the United Nations sustainable development goals and net-zero 2050 emission goal.

CONCLUSION

In conclusion, paper waste or waste paper results in high solid waste generation in landfills if not treated properly. Recycling is a conventional method that has been used to reduce the production of paper waste or waste paper. These wastes contain valuable rich materials that have been potential to be reused as functional carbon materials. To find research gaps and observe research trends on this topic, it is necessary to gain knowledge and understanding of current and cutting-edge technologies. Advances in understanding textural properties, surface chemistry, and synthesis methods are important for developing high performance materials for specific applications. The purpose of this study is to performance a systematic review on the conversion of paper waste or waste paper products into functional carbon materials for various applications. The findings of this review present the results that predict the current research trends and highlighted some gaps particularly in the areas. Based on the findings, the data can be used to examine which areas are most published, which research is specialised and which scopes are unexplored. There are few challenges that need to be addressed such as scalability, and sustainability of the materials or process. Future research should focus on green synthesis techniques, optimizing material properties, comparative case-studies of lab-scale and industrial-scale and proof-of concept studies.

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CONFLICT OF INTEREST STATEMENT

The authors declare that the research was conducted without any commercial or financial relationships that could potentially create a conflict of interest.

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