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Biomass-derived adsorbents for diesel engine emission control: a systematic review of synthesis, performance, and mechanistic insights

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Abstract

Agricultural and forestry residues are a potential source for producing biomass-derived adsorbents to control diesel engine emissions. This study critically reviews experimental research on biomass-derived materials for removing carbon dioxide (CO_2), nitrogen oxides (NO_x), hydrocarbons (HC), and particulate matter (PM) from diesel exhaust. Literature searches were conducted according to the PRISMA guidelines and applying the PICO framework. We evaluated included studies and collected data on the feedstock used, preparation process, operating conditions, and pollutant-removal efficiency. The CO_2 removal efficiency of coconut shell-derived activated carbon was reported as 40–64%, similar to values for rice husk- and eucalyptus wood-derived activated carbons. The biochar-AC removed 58% NO_x under the reported conditions. After soot-cake formation, the biomorphic silicon carbide filter exceeded 95% particulate filtration efficiency, and calcium-alginate-encapsulated Moringa oleifera pod powder had adsorption capacities of 14.45 mg/g for HC and 123.51 mg/g for NO_x. The preparation process, pore structure, feedstock, operating conditions, and regeneration process influenced performance. Similarly, inconsistencies in reporting and different experimental setups made direct comparison and material ranking difficult. Biomass-derived materials have shown potential for treating diesel exhaust, but industrial feasibility remains unproven. Standardized testing, realistic engine validation, long-term cyclic stability, life cycle assessment, and techno-economic analysis should be future research priorities to determine the practicality and sustainability of these materials.

Keywords: Biomass-derived adsorbents, Diesel engine emissions, CO_2 capture, NO_x removal, Particulate matter

1. Introduction

Transportation has significant anthropogenic emissions of carbon dioxide (CO_2), nitrogen oxides (NO_x), hydrocarbons (HC), and particulate matter (PM). As a consequence, diesel engines are well suited to a variety of applications, including heavy-duty vehicles, marine and off-road machinery, but exhaust emissions are an environmental and air-quality concern [1]. These pollutants affect climate change, air quality, and human health, and a growing number of regulatory regimes globally regulate them [1]. For instance, the Euro VI and the U.S. Environmental Protection Agency (EPA) Tier 4 emission standards are very strict for pollutants emitted from diesel engines. Emission-control technologies include diesel particulate filters (DPFs) that remove particulate matter, selective catalytic reduction (SCR) systems that reduce NO_x, and diesel oxidation catalysts (DOCs) that oxidize certain gaseous pollutants and hydrocarbons [2]. These technologies work, but they rely on expensive metal catalysts, consume large amounts of heat, and produce secondary waste streams that raise sustainability and economic concerns [3].

Meanwhile, the climate change mitigation requirement has also resulted in greater research into carbon capture and utilization (CCU) technologies [4]. Various methods of post-combustion CO_2 capture from stationary sources (power plants, industrial plants, etc.) have been extensively studied such as amine scrubbing, membrane separation, and solid sorbents [5]. The application of these technologies in mobile applications like diesel engines is, however, challenging because of the different exhaust-gas parameters (variable exhaust-gas temperature, the different pollutants influencing the exhaust-gas capture process, etc.) [6]. Thus, multifunctional adsorbents to remove CO_2, NO_x, HC and PM from the diesel exhaust under realistic operation conditions are being investigated [7].

Agricultural and forestry wastes like coconut shell, rice husk and wood chip are used to make the adsorbents which are termed as biomass-derived adsorbents. Corn stover, etc., are a new class of material that have emerged as a suitable option for emission-control applications [8]. The materials have some advantages over conventional adsorbents: they are cheap, renewable and have a good supply

of feedstock; and they can be produced as a carbon-negative resource with bioenergy with carbon capture and storage (BECCS) [9]. Biochar production by combining pyrolysis or hydrothermal carbonization (HTC) and physical or chemical activation, has been studied as a method for producing biomass-based adsorbents. Biochar production by combining pyrolysis or HTC and physical or chemical activation is an approach studied for producing biomass based adsorbents [10]. They can have high specific surface area, tunable pore size distribution and different surface chemistries and can be used to adsorb a wide variety of gaseous and particulate pollutants [11].

While the use of biomass-based adsorbents for the removal of pollutants has been used in diesel emissions, there are still research gaps to be addressed. Second, the evidence base is disjointed: research has been conducted with a variety of feedstocks, activation methods, test conditions and performance measures, which makes it hard to draw general conclusions from research findings regarding the effectiveness of these materials [12]. Secondly, the mechanism of the adsorption of pollutants on biomass carbons, particularly when pollutant adsorption takes place in the presence of other pollutants (i.e. multi-pollutant environment of diesel exhaust), is not fully understood [13]. Third, there are no systematic studies that investigated the stability and regenerability of these adsorbents in the engine operating conditions involving high temperature, moisture and sulfur compounds [14]. Fourthly, the economic and environmental life cycle impact of the production and use of the biomass-based adsorbents for the purpose of diesel emission control is less talked about [15].

This prompted the present systematic review, which critically analyses and summarizes the existing experimental data of biomass-based CO_2, NO_x, HC and PM adsorption from diesel engine exhaust. The three key contributions of this review are to provide a comprehensive, organized summary of the state of knowledge, identifying trends, approaches, and levels of performance for each feedstock and test condition; and to identify key gaps in the state of knowledge. Second, we critically review the quality and comparability of the studies included, as well as their methodological strengths and weaknesses, and give suggestions for future research. Third, we combine mechanistic knowledge of adsorption processes, by linking material properties (such as pore structure, surface chemistry, etc.) to performance, and identify the most promising adsorbent-pollutant couples to investigate. This research is relevant because it could provide researchers and practitioners with scientific information to develop more efficient and sustainable emission-control strategies and to incorporate biomass-derived materials into the circular bioeconomy.

2. Materials and methods

2.1 Review protocol

This systematic review followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [16]. The research question was constructed using the PICO (Population, Intervention, Comparison, Outcome) framework, in which the population was diesel engine exhaust emissions, the intervention was the use of biomass-derived adsorbents, the comparison was with conventional exhaust gas treatment technologies or untreated exhaust gas, and the outcome was quantitative adsorption performance such as removal efficiency, adsorption capacity, breakthrough time, etc.

A comprehensive literature search was carried out in the Web of Science, Scopus, ScienceDirect, and SpringerLink databases and additionally in Google Scholar as a grey literature search tool for conference proceedings. Using multiple databases allows broad coverage of the engineering, environmental science, materials science, and chemical engineering literature and reduces the chance of missing pertinent studies [17]. We chose Web of Science because it covers top journals in engineering and environmental science. Scopus was also selected because it is an interdisciplinary search engine with strong citation analysis. We included ScienceDirect largely because it offers many full-text articles in science and chemical engineering. We selected this new service because SpringerLink provides many environmental and energy research publications. Finally, we searched Google Scholar for studies not included in the other databases, especially regional journals or non-English-language journals with English abstracts.

We conducted a systematic search to identify studies on the use of biomass-based adsorbents to control emissions from diesel engines. A structured search was conducted to identify studies on the use of biomass-based adsorbents to control emissions from diesel engines. We searched Web of Science, Scopus, ScienceDirect, and SpringerLink for articles, and used Google Scholar as a supplementary database. The main search term used was: (biomass OR biochar OR “agricultural waste” OR “activated carbon” OR exhaust OR diesel OR “diesel engine” OR adsorbent OR adsorption OR emission OR NO_x OR SO_x OR particulate OR CO_2). We conducted the initial search in March 2025 and the updated search in March 2026. We used the following search terms: Topic in Web of Science, TITLE-ABS-KEY in Scopus, and title, abstract, and keyword fields in ScienceDirect and SpringerLink (only available for databases without a Topic field). We searched Google Scholar with no field restrictions and reviewed the first 200 results for relevance. Records from both searches were merged together, duplicates were then eliminated and the remaining records were screened for certain eligibility requirements. The search logs in the supplementary log will contain the exact search strings, search dates, search fields and search record counts, which will facilitate independent replication. A PRISMA flow chart was created to illustrate the identified, deduplicated, and selected studies.

2.2 Analytical Taxonomy for study classification.

This reviews biomass-derived materials, performances, and mechanisms of pollutant removals from diesel-engine emissions with emphasis on the preparation of materials, and their effectiveness and mechanism of pollutant removal. Because they employed different processes, studies were grouped by the pollutant removed, the material properties studied, and the predominant removal mechanism. Adsorption is the retention of gaseous species on or in the material that occurs due to surface interactions [18], and particulate filtration is the removal of suspended particles from the exhaust gas stream. This distinction is significant because there is no correlation between the filtration efficiencies and the ability to adsorb gaseous contaminants. For this use, the study related to biomorphic silicon carbide was maintained as further evidence of the evolution of biomass-templated materials for emission control and only the particulate filtration properties were analyzed. Therefore, the studies that addressed adsorption capacity and the adsorption mechanism included the claims regarding adsorption capacity and removal of gaseous pollutants, as well as adsorption mechanism, while the others did not. This classification preserves the overall relevance of biomass-based materials, and not leave space for confusion if there is difference in results due to different mechanisms.

2.3 Inclusion and exclusion criteria.

Screening followed an agreed standard procedure for systematic reviews [19], and clear inclusion/exclusion criteria were set before screening to ensure the selected studies were relevant and methodologically consistent. Studies were eligible for inclusion if they investigated biomass-derived adsorbents produced from agricultural, forestry, algal, or other biomass resources for diesel engine emission control. Eligible studies had to report the material preparation or activation method, investigate the removal of relevant exhaust pollutants, and provide quantitative performance data or sufficient experimental information to evaluate adsorption performance and mechanisms. We considered peer-reviewed journal articles published in English. Studies focused exclusively on non-adsorption applications, unrelated emission sources, non-biomass-derived materials, or applications without relevant pollutant-removal performance data were excluded. We identified any complementary filtration study retained in the review separately and did not treat it as evidence of adsorption performance.

However, we excluded review articles, meta-analyses, book chapters, conference abstracts, editorials, and opinion articles. Studies limited to the synthesis or characterization of biomass-derived materials, but not tested for adsorption against diesel engine emissions, were not included. Studies that did not involve biomass-based adsorbents, such as synthetic zeolites, metal-organic frameworks, and commercial activated carbons from non-renewable sources, were excluded. Investigations that tested adsorbents only for non-gas emission sources, such as coal combustion flue gas, indoor air purification, or water treatment, were also excluded. In addition, studies that used biomass-based materials only as a catalyst support or fuel additive were excluded, as they did not involve using the material as an adsorbent. Finally, studies that were missing too much detail in their experiments to evaluate the methodology, such as those lacking the adsorbent preparation conditions, test gas composition, or flow rates, and duplicate publications and studies with comparable data sets were excluded.

2.4 Study selection process

We identified, screened, evaluated eligibility, and included studies following PRISMA 2020 guidelines [20]. The search identified 425 records; 138 were duplicates, and 287 were screened by title and abstract. Two reviewers screened all 287 records independently and excluded 245 because they were clearly outside the review scope, such as review articles, studies of sources other than diesel engines, or studies lacking quantitative performance results relevant to this review. Forty-two reports were sought for retrieval; 36 full-text reports were retrieved and evaluated for eligibility, and six reports were not retrieved. Two reviewers assessed each paper independently and resolved discrepancies through discussion and consensus. We selected studies based on their relevance to diesel-engine emission control, biomass source and adsorbent preparation, experimental design and operating conditions, quantitative performance data, and the completeness of the reported methodology and conclusions. Experimental data were missing for assessing methodological validity in 12 reports and for quantitative performance data in 9 reports, and the material was not biomass-derived in 9 reports. Thus, we included six studies in this review. After noting that the research was published and eligible for the revised evidence synthesis, we excluded retracted studies. To reflect these decisions, we updated the number of included studies and the study tables, and revised the PRISMA flow diagram. The PRISMA flowchart (Figure 1) shows the full selection process.

Several limitations in the study selection process warrant acknowledgment. First, we searched only English-language publications, which could have introduced language bias and excluded relevant studies published in other languages. Language restrictions can affect systematic review results by limiting access to potentially relevant evidence [21]. Second, the fact that conference abstracts and other grey literature were not included may have produced a publication bias–studies with positive or statistically significant results may be more likely to be published in full journal articles [22].

Third, because the search algorithms and keywords were database-specific, this may have led to the exclusion of studies using alternative terminology or indexed in databases not searched. Therefore, search strategy design is an important determinant of the comprehensiveness of systematic literature searches [23]. Fourth, the quality assessment relied on information provided in published papers, and studies with poor method descriptions may have been hard to assess consistently. Nevertheless, the review used systematic methods and transparency to build a structured synthesis of what is available on biomass-based adsorbents for controlling emissions.

3. Results

3.1 Research trends

The temporal distribution of the six studies included in this work shows that, although this is a new research area, it is gradually developing in the field of biomass-derived adsorbents for controlling emissions in diesel engines. Figure 2 shows that during the year 2017 and 2018, two research publications on misconceptions took place, one in each year, suggesting that research into misconceptions was still in its early stages during these years. This preliminary research was probably a precursor to methodologies and proof-of-concept demonstrations of the use of agricultural residues as adsorbent precursors. There was also a considerable gap in publication from 2019 to 2023, in which no studies were identified that fulfilled our inclusion criteria. This could be due to methodological consolidation, changes in research focus to other emission-control technologies, strict inclusion criteria, and/or limited database coverage.

There has been a renewed interest in research in 2024 following on the two studies published in 2024, and the one in 2025 and 2026. The rising interest could be linked to the growing regulations on emissions worldwide and the interest in sustainable materials. The field is a relatively new one and the number of publications has been increasing over the past few years, while a number of feedstocks and activation technologies are being explored. However, the number of studies is quite limited ($n = 6$) and this still is a very niche area of biomass valorization and emission control. This indicates that the research community is not yet at critical mass as the number of publications has not increased consistently from year to year, and a large number of combinations need to be studied systematically, especially the ones that are not being explored, as regards to the pollutants and the adsorbents. Apart from that, the geographical distribution of these studies (not analyzed in our data) is likely to reflect priorities in biomass waste management and the use of diesels, since countries with a big agricultural output, and a fleet of heavy-duty diesels are the ones that lead on this literature.

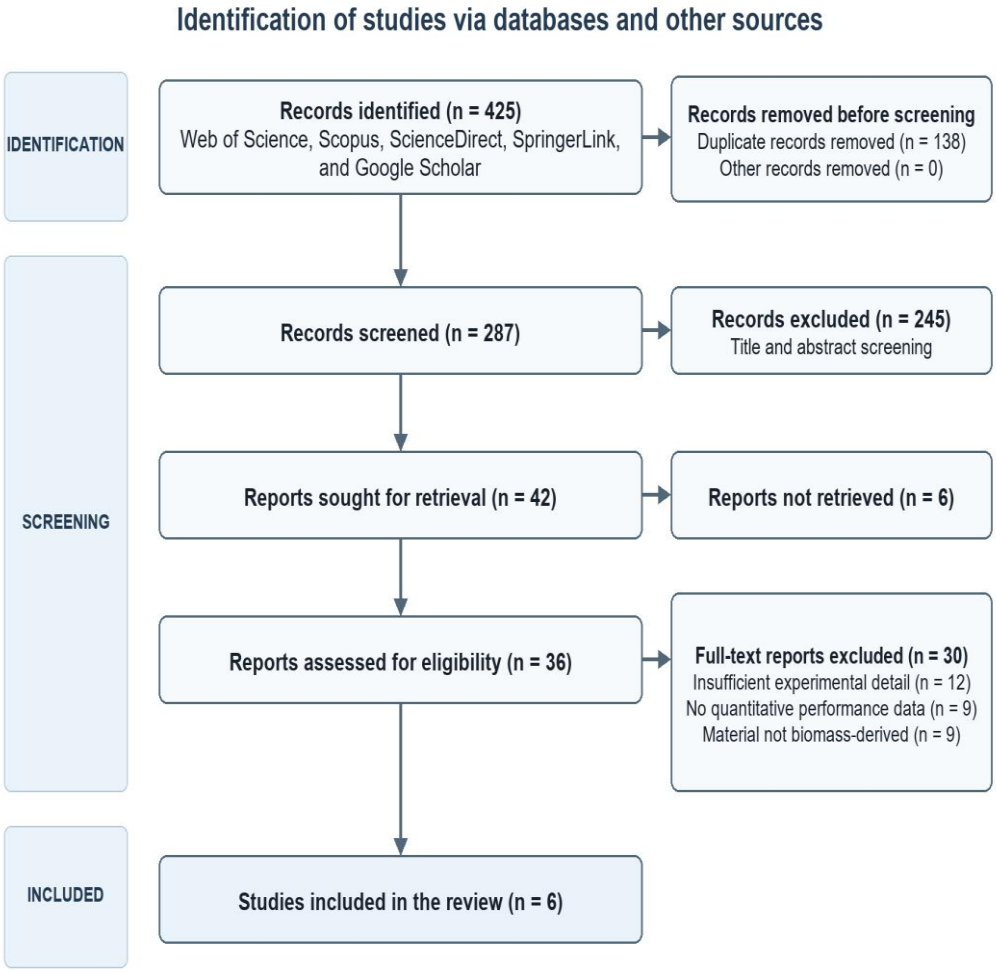


Figure 1 PRISMA flowchart of the study selection process for the systematic review on biomass-derived adsorbents for diesel engine emission control

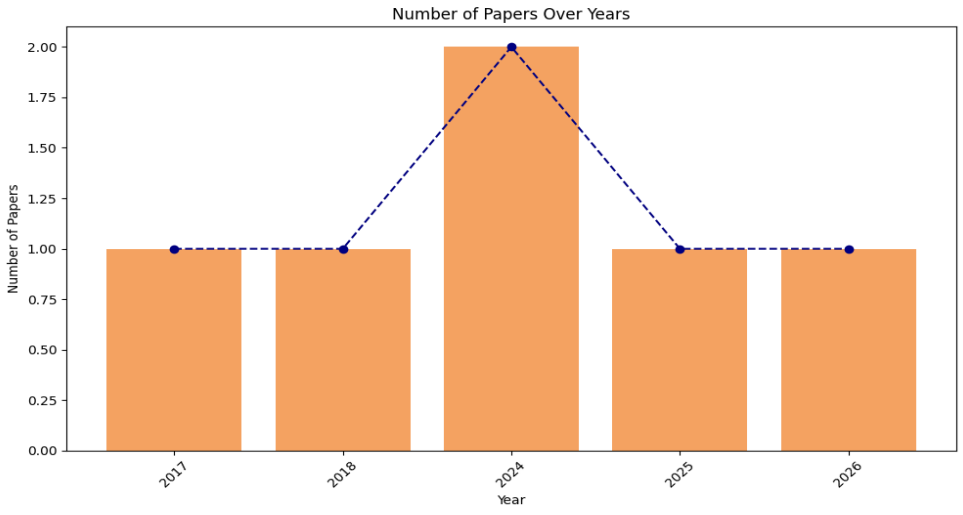


Figure 2 Research trends in the domain of biomass-derived adsorbents for diesel engine emission control

3.2 Summary of included studies

Table 1 shows the key features of the included studies. The studies included information on study identification, biomass feedstock, adsorbent type, target pollutant, and engine type (if applicable). The studies included in this paper varied across biomass feedstocks, adsorbent types, target pollutants, and other factors. These differences matter for interpreting the review's results and identifying potential sources of heterogeneity across the evidence base. The characteristics table summarizes the included studies and will form the basis for the subsequent narrative or quantitative synthesis.

Table 1 Characteristics of the included studies

Study Id	Biomass feedstock	Adsorbent/material	Target pollutant	Test system
[24]	Coconut shell, rice husk and eucalyptus wood	Activated carbon, biochar	CO_2	Single-cylinder, four-stroke diesel engine
[25]	Wood	Biomorphic silicon carbide	Particulate matter	Diesel boiler
[26]	Moringa oleifera pod powder	Encapsulated Moringa oleifera beads (EMBs) cross-linked with calcium alginate	HC (unburned hydrocarbons) and NO_x	Single-cylinder diesel engine
[27]	Coconut shell, rice husk, eucalyptus wood	Biomass-based activated carbon	Carbon dioxide (CO_2)	Single-cylinder, four-stroke, air-cooled, naturally-aspirated, direct-injection (DI) CI engine
[28]	Coconut shell, rice husk, eucalyptus wood	Activated carbon	CO_2 and NO	Diesel generator
[29]	Palm shell, barley straw and corn cob	Agro-based capture material	CO_2	CI engine

3.3 Adsorbents for capturing Carbon Dioxide from diesel exhaust

The first four studies listed in Table 1 were related to the capture of CO_2 [24 ,27-29]. These studies evaluated the use of carbonaceous materials derived from biomass as CO_2 capture materials from the exhaust gas of diesel engines. However, there is methodological heterogeneity, particularly with regard to the methods of adsorbent preparation, the engine configuration, the regeneration methods, the operating conditions, and the performance measures, which makes it difficult to make direct comparisons and assign differences in reported performance to the adsorbent composition alone. Therefore, the results are compared and not used to draw conclusions about a clear ranking of performance of the investigated adsorbents. One of the important aspects of these investigations will be to compare systematically under the same test conditions, so that the most promising biomass feedstocks for CO_2 capture can be identified. In two studies without any feedstock retrofitting, it was reported that CO_2 capture from exhaust gases of the diesel engine was possible with the biomass-based carbonaceous material, but no direct comparison of the superiority of the different feedstocks. [24, 27]. In addition to the feedstock mass, there are various parameters that do not depend on the feedstock and can cause performance variations such as biomass composition, carbonization and activation conditions, surface chemistry and pore structure, engine configuration, exhaust-gas composition, and adsorption operating parameters. This means that it is not possible to say that any one of the coconut shell, rice husk, eucalyptus wood derived adsorbents is superior to the others because of its suitability related to the biomass precursor. This limitation is important because the composition of the precursors is not the only variable that can affect the adsorption capacity; the preparation method of the adsorbent and the way that this is used in the process can also have a significant influence on the adsorption capacity. Thus, a defensible ranking of these feedstocks would necessitate a study done under comparable preparation, characterization and adsorption conditions.

Thermodynamic and kinetic studies in [28] also helped clarify the adsorption mechanisms of CO_2 on these biomass-derived carbons. This study found that the isosteric heat of adsorption for all three adsorbent samples (coconut shell, rice husk, and eucalyptus wood activated carbons) was below 40 kJ/mol, typical of exothermic physisorption rather than chemisorption. This is crucial because it suggests the adsorption is reversible and relatively low energy; thus, the adsorbent can be 'regenerated' through mild temperature changes without the risk of chemical degradation or the formation of secondary pollutants. Furthermore, the authors found that both CO_2 and NO decreased by ~40-64% and ~38-58%, respectively, with the post-combustion carbon capture unit, showing the multifunctional pollutant-removal capacity of these materials.

Regenerating exhausted adsorbents is an important practical issue for the economic feasibility of all adsorption-based emission control systems. Two studies in this paper explicitly addressed this question by using temperature swing adsorption (TSA) regeneration protocols [27, 29]. In [27], the researchers used TSA to regenerate the original CO_2-saturated coconut shell, rice husk, and eucalyptus wood adsorbents. They captured desorbed CO_2 in a gas bag and analyzed the collected CO_2 by gas chromatography-mass spectrometry (GC-MS) during the heating phase. GC-MS analysis of the captured CO_2 verified the purity obtained from the TSA process, showing that the material regeneration and product recovery process was effective. Likewise [29] prepared palm shell, barley straw and corn cob based adsorbents by TSA after a few adsorption-desorption cycles to assess the cyclic stability and capacity retention. Authors did not report rates of capacity degradation after each cycle. However, they did run through a number of cycles without any catastrophic failure, suggesting that these natural materials are strong enough to be usable. Additionally, GC-MS analysis identified gas desorption and further verified the ability of the adsorbents to selectively adsorb CO_2 from the complex exhaust gas matrix.

Based on the three non-rejected studies focused on CO_2 capture, Table 2 summarizes the findings and considers the biomass feedstock, adsorbent characteristics, regeneration method, reported CO_2-reduction performance, and methods used to characterize the adsorbents. However, studies vary considerably in how they report and measure removal effectiveness. No single effect size can be calculated across studies because performance measures, experimental conditions, and reporting formats differ, and ranking studies by performance measures is subject to methodological bias. The evidence is therefore evaluated qualitatively and comparatively; more attention is paid to the role of adsorbent properties and operating conditions than to individual capacity values.

Of the five studies that addressed CO_2 capture, only two explicitly reported a numerical reduction efficiency [24, 28], and the other three either did not report efficiency or did not report a single efficiency value [27, 29]. Reporting standards vary widely, which is a major barrier to meta-analytic synthesis and calls for more consistent performance measures in future studies. However, analysis of the available data indicates that biomass-derived activated carbon and biochar can have CO_2 removal efficiencies of ~ 40-64 % from diesel exhaust, with even higher removal efficiency with a multi-stage adsorption configuration or optimized combination of adsorbents.

Data from the study in [24] and [28] give information on CO_2 removal performance under various engine operating conditions. These results apply to evaluating biomass-derived activated carbon materials for treating diesel exhaust and to how operating conditions affect the reported removal efficiency. Comparisons with other studies, however, should take into consideration that there might be variations in the experimental configuration, properties of the adsorbents used, and the methods employed for measuring the parameters. Without any adsorption system, CO_2 emissions at baseline were proportional to the engine load up to 13.5% at full load. The reduction of CO_2 emission with the help of biochar and activated carbon filters was significant, and the results indicated that the activated carbon filter was more effective at low load, whereas the biochar filter was more effective at high load. This load dependent

behaviour means that the adsorption process depends on exhaust gas temperature and flow rate, which increase in proportion to engine load. CO_2 adsorption is not thermodynamically preferred at higher temperature as physisorption of CO_2 is exothermic; however, biochar seems to be more capable of adsorption than activated carbon. This phenomenon could be attributed to the composition of the pore-size distribution and surface chemistry of the two materials; perhaps biochar contains more mesopores or oxygen containing functional groups on its surface, which are more likely to be bound by CO_2 at high temperatures.

Table 2 Summary of CO_2 adsorption performance and key experimental parameters for biomass-derived adsorbents included in the systematic review

Study Id	Biomass feedstock	Adsorbent type	Regeneration method	Co_2 Reduction efficiency	Characterization techniques
[24]	Coconut shell, rice husk, eucalyptus wood	Activated carbon, biochar	Not reported	Up to 48% reduction with single chamber; additional 16% reduction with second chamber; from 6.2% to 0.4% at maximum load with optimal configuration	Not reported
[27]	Coconut shell, rice husk, eucalyptus wood	Biomass-based activated carbon	Temperature swing adsorption (TSA)	Not explicitly quantified	Gas chromatography-mass spectroscopy (GC-MS)
[28]	coconut shell, rice husk, eucalyptus wood	activated carbon	Not reported	40-64% for CO_2; 38-58% for NO	Proximate and ultimate analyses
[29]	Palm shell, barley straw, corn cob	Agro-based capture material	Temperature swing adsorption (TSA)	Not explicitly quantified	Gas chromatography-mass spectroscopy (GC-MS)

3.4 Adsorbents for beyond CO_2 and particulates: hydrocarbon and NO_x capture

Literature has been mostly dedicated to the capture of CO_2 and to the filtration of particles. However, two studies were mentioned for direct regulation of gaseous pollutants due to their effects on air quality and human health: unburned hydrocarbons (HC) and nitrogen oxides (NO_x). The investigations extend the use of biomass-based adsorbents beyond greenhouse gas mitigation and hold promise for multi-functional materials for addressing multiple emission components. These studies are summarized below, and the different forms of adsorbents are seen, as well as the significance of the operational parameters for the adsorption performance.

A fixed-bed column was used in the study of the ability of calcium-alginate-encapsulated Moringa oleifera pod powder to remove hydrocarbons (HCs) and NO_x from diesel exhaust. The Thomas model [26] was used to estimate the maximum adsorption capacity (q_o) from fixed-bed adsorption data. The capacities of the encapsulated Moringa oleifera beads were 14.45 mg/g of hydrocarbons and 123.51 mg/g of NO_x. These values were determined using a double-stage fixed-bed column with a bed height of 30 cm, a feed flow rate of 8 kg/h, and an operating temperature of 80-90 °C [26]. The reported NO_x capacity is significantly greater than that for hydrocarbons, but this does not necessarily mean a greater intrinsic affinity for NO_x, as it depends on pollutant composition, inlet concentrations, gas-phase interactions, mass-transfer behavior, and the modeling approach used to estimate capacity. Thus, it remains unclear whether the increased NO_x uptake is due to surface functional groups unless surface characterization data or direct evidence of interaction between the adsorbate and the surface is provided.

The significant difference between the adsorption capacity of HC and NO_x is an interesting result that needs mechanistic interpretation. This may be because EMBs have a higher affinity for NO_x, which can be attributed to the chemical composition of Moringa oleifera pod powder, which contains functional groups such as hydroxyl, carboxyl, and amine groups that can interact with acidic NO_x molecules through acid-base interactions. The binding of unburned hydrocarbons, most of which are un- or weakly polar aliphatic and aromatic compounds, is probably mediated mainly by weaker van der Waals forces and hydrophobic interactions, with a lower overall capacity. Moreover, the experimental breakthrough data obtained in the present work were regressed to well-known mathematical models such as the Thomas model, Yoon-Nelson model, and Wang model to characterize adsorption dynamics and predict column performance under various operating conditions. Scaling up the fixed-bed adsorption process from lab to pilot/industrial scale is very important, and these model fits are necessary to determine the adsorption rate constant and the bed's saturation capacity. Besides, the use of the mass transfer models, namely the Weber–Morris intraparticle diffusion model and the Boyd film diffusion model, enabled the authors to identify the rate-controlling step of the overall adsorption process. The results showed that mass transfer resistance in both external film diffusion and intraparticle diffusion was important for the overall process, with the relative resistance of each step depending on the adsorbate used and other operating conditions. This insight can be used to design adsorbent columns to avoid or minimize mass transfer limitations, such as decreasing bead size to reduce the diffusion path length within the beads, or increasing superficial velocity to increase the external mass transfer coefficient.

The second study in this theme was related to the filtration of particulate matter from the diesel exhaust using a totally new class of biomorphic material, known as biomorphic Silicon Carbide (bioSiC) [25]. Natural wood, which contains silicon, is used, and the silicon is reacted to SiC, creating the original wood's structure of cells with a directionality. The porous ceramic obtained exhibits high mechanical strength, thermal stability and resistance to chemical attack, rendering it suitable for use in a diesel particulate filter (DPF) substrate. In this research, [25] tested different samples of bioSiC having different microstructures, which were prepared from different wood precursors and different cutting directions, using a specially designed test facility in a controlled environment, by filtering a portion of the exhaust of a diesel boiler. The results indicated a close correlation between the initial filtration efficiency and the cutting direction and thus the wood precursor microstructure. The bioSiC sample fabricated from the radially cut wood exhibited high initial efficiency of > 95% due to having a honeycomb-like pore structure and the channel alignment was good. The initial efficiency of samples from axially cut wood ranged between 70-90%, depending on the pore size and permeability of the wood [25]. The generation of macropores in some axially cut samples was recognized as a major factor affecting efficiency, since particles could pass through these large pores without capture.

However, one important result of this study was that during continuous operation, particles accumulated in the porous bioSiC media and formed a soot cake layer on the filter surface. This soot cake served as a secondary filter medium and captured incoming particles, significantly increasing overall capture efficiency. According to [25], the tested biomorphic ceramic samples showed filtration

efficiencies above 95% with few operating cycles. This performance enhancement was attributed to secondary particle capture by the soot-cake layer that formed over the underlying porous structure. However, the increased filter efficiency should not be assumed to indicate filter regeneration, as soot indicates particle retention, not necessarily contaminant removal from the filter. This behavior was not observed for the extra-large-pore sample because the pore structure could not form an effective soot-cake layer. This difference suggests that pore structure is important in defining filter performance and shows that how a particle layer forms and its stability are important in defining filter performance. However, efficiency alone does not prove the long-term performance of these ceramics; other factors must be considered, including pressure-drop evolution, soot-loading capacity, thermal stability, and regeneration needs. Under the experimental conditions, the initial filtration efficiency of the radially cut wood precursors was higher than that of the axially cut wood precursors. These differences can be linked to differences in pore structure and flow pathways, but should be considered alongside the characterization data provided in the original study. After forming a soot-cake layer, the filtration efficiency of all tested samples increased or remained unchanged, indicating that particles deposited during operation contributed to filtration efficiency. To provide a brief overview of the key parameters and results from these two studies, we summarize the adsorbent material, the precursor, the target pollutant, the performance metric, and the reported performance value of the studies in Table 3.

Table 3 Summary of biomass-derived materials and reported performance metrics for hydrocarbon and NO_x adsorption and particulate matter filtration

Study ID	Precursor material	Material form	Performance metric	Performance value
[25]	Wood	Biomorphic Silicon Carbide (bioSiC) samples	Initial filtration efficiency	>95% for radially cut wood; 70-90% for axially cut wood depending on pore size and permeability
[26]	*Moringa oleifera* pod powder	Encapsulated *Moringa oleifera* beads (EMBs) cross-linked with calcium alginate	Maximum adsorption capacity (q_o)	14.45 mg/g for HC and 123.51 mg/g for NO_x

The two studies outlined in Table 3 differ in their basic strategies for using biomass-derived materials to control diesel emissions. The bioSiC approach [25] is a structural/engineering solution in which biomass is sacrificed during the process to produce a high-performance ceramic filter with good mechanical and thermal characteristics that can withstand the harsh conditions of the exhaust stream. The main pollutant-removal mechanism is physical sieving, in which particles larger than the pore are sieved out. By contrast, the EMB approach [26] is a chemical or surface approach in which biomass is consumed as an active sorbent that interacts with gaseous pollutants via physisorption and/or chemisorption. Molecular adsorption is the main removal mechanism and occurs on the internal and external surfaces of the sorbent. These methods are not mutually exclusive and can be used in a multi-stage emission control system, with a bioSiC filter removing particulate matter followed by an EMB or other adsorbent bed to remove gaseous pollutants such as HC and NO_x. Differences like biomass-derived materials and their mechanisms of action highlight the versatility of this class of materials and the need to tailor adsorbent properties to the pollutant and operating conditions.

4. Discussion

The six selected studies form a small, methodologically mixed body of evidence for assessing biomass-based materials as emission controls for diesel engines. This creates a lack of comparability between studies, as experimental setups, target pollutants, and performance metrics vary, as do feedstock composition and carbonization and activation methods. The other findings should therefore be considered suggestive, not conclusive, of the relative merits or widespread use of the biomass feedstocks or preparation methods. This limitation is particularly evident in the CO_2 investigations [24, 27]. Because carbonization and activation conditions, causing differences in the textural and surface-chemical properties of the adsorbents, exhaust gas composition, and engine operating parameters, can be potential confounding factors, differences between the reported adsorption performance and the type of feedstock cannot be distinguished from other influencing factors. In summary, current research provides no evidence that any biomass is a superior CO_2 precursor for capture from diesel engine exhaust gases. Evaluation of the material should instead be based on exhaust conditions, adsorbent stability, regeneration requirements, and physicochemical properties resulting from the preparation route, rather than on surface area and a single reported removal-efficiency value. In general, the limited data and high methodological variation make quantitative comparisons of biomass adsorbents difficult and suggest the need for standardized experimental protocols to enable meaningful comparisons between studies.

Evidence on using biomass-derived materials to control diesel emissions is available. Still, methodological differences and the limited number of studies reduce explanatory power and practical use when comparing materials. Adsorption energetics are important in regeneration, as the energy needed for desorption partly depends on adsorbate-surface interactions and the nature of the adsorption process. The two studies that did not explore the concept of adsorption/desorption (TSA) [27, 29] reported CO_2 recovery; however, they provide no evidence of durable adsorption capacity over long-term adsorption/desorption cycles or effective regeneration of CO_2 over long cycles. Therefore, recovery performance must be interpreted with the understanding that capacity-retention and regeneration data are lacking unless long-term cyclic stability data are reported. Study [24] reported that the biochar performance was better than the activated carbon in the experimental condition and in high engine load. This indicates that the adsorbents might be more or less effective depending on the conditions of the operation; however, it does not indicate that biochar is better than activated carbon overall. Similarly, there is no unambiguous hierarchy of biomass feedstocks according to the fixed-carbon content, specific surface area, or microporosity, as these values are only meaningful in combination with the surface chemistry, preparation and activation process, exhaust composition, and operating conditions. Comparisons between studies are difficult because of the wide range of various experimental designs and performance variables used in the different studies and because the differences in results between studies may not necessarily be due to the material properties. Thus, biomass-based adsorbents are not well-established substitutes for conventional after-treatment materials, but rather are complementary materials for treatment of diesel exhaust to be considered. They must be standardized and compared to some extent, undergo long term cyclic testing under representative exhaust conditions, and be evaluated in terms of pressure drop, regeneration energy, material durability and economics for proof of their practical usefulness.

The conclusions of these results are significant for emission control. Conceptual relationships between the exhaust environment and the resulting pore structure can be built and so can be built relationships between the properties of the biomass substrate and

activation properties and the pore structure. Theoretically, connections between the exhaust environment and the resulting pore structure can be developed as well as connections between the properties of the biomass substrate and the activation properties and the pore structure. In principle, there are conceptual connections between the adsorption properties of an actual exhaust atmosphere, the properties of the biomass substrate and the activation properties, on the one hand, and the resulting pore structure on the other. From a few of these studies [24, 27-28], it is obvious that the selection of feedstock is another important parameter in determining the quality of the activated carbon to be used for gas adsorption applications as a more appropriate feedstock would be one with high fixed carbon content and inherent microporosity. This data may provide guidance on the development of new materials, by identifying feedstocks that are likely to be good adsorbents, thereby reducing the need for trial-and-error experiments during the development process. Up to 64% of CO_2 and 58% of NO_x emissions are reduced by using biomass-based adsorbents as a complementary technology to existing after-treatment technologies like SCR and Diesel Particulate Filter (DPF) [28]. These technologies are not expected to be totally superseded by biomass-based adsorbents in the near future. Nevertheless, they can be cascaded in a multi-stage after-treatment system to further reduce other pollutants, particularly CO_2, which are not removed by conventional after-treatment systems. The cheapness and renewability of the agricultural waste feedstocks also makes this approach practical and consistent with the principles of the circular bioeconomy, and could provide an economic advantage to the agricultural sector by valorising agricultural waste.

The reported NO_x adsorption capacity of the encapsulated beads of Moringa oleifera is 123.51 mg/g under the conditions examined [26]. This value is a quantitative result for the tested system and is not a proof of superiority of this material over zeolites or activated carbon without a comparison under the same experimental conditions. The mechanism of surface functional groups contribution to NO_x retention is proposed, but until it is confirmed by direct characterization or evidence of interaction, the mechanism is a conjecture. The reported breakthrough modelling can inform fixed-bed analysis but will need to be validated when modelled under representative exhaust composition, varying flow, temperature fluctuations and under repeated adsorption/regeneration cycles under industrial conditions. Similarly, biomorphic silicon carbide filters have been demonstrated to perform better than 95% in terms of particulate-filtering efficiency after soot cake formation [25] and hence are a promising alternative to conventional cordierite or silicon carbide filters for sustainable diesel particulate filters (DPFs). An important characteristic and should be maintained, so that the filter efficiency will keep improving with the number of particles it removes, as it does with this. However, efficiency can vary depending on the direction of cutting and wood precursor microstructure [25] and careful material selection and process control is important to ensure the optimum efficiency. Potential methodological limitations and issues that could impact the interpretation and generalizability of the conclusions from this systematic review should be noted. Few such studies (n = 6) were included, reducing the statistical power in conducting any synthesis, and thus reducing robustness. This is a small sample size and will not affect the review methodology but rather the stage of research in this area; the results are limited and should be viewed as provisional. Second, the exclusion of English-language publications might have resulted in language bias and the neglect of relevant studies that were published in other languages, such as Chinese, Portuguese, Spanish, or other widely used languages in the countries where biomass research is significant. Major producers of agricultural residues like China, India, and Brazil also have large fleets of diesel engines, and it is likely that considerable research in this field is published in non-English journals. If studies are not included, this may lead to gaps in or bias in the global evidence base. Third, conference abstracts, book chapters and grey literature were omitted, which might have underestimated the results of preliminary studies or studies with negative outcomes, resulting in potential publication bias. Studies that show poor or no performance can also under represent their results in the literature, potentially leading to overestimation of effectiveness of biomass-based adsorbents. Fourth, only published articles provided information for the quality assessment of the included studies and there was a possibility that some studies that lacked fully reported methods were either misclassified or not included in the quality assessmen. Finally, the diverse test conditions (type of engine, exhaust gas composition, temperature, flow rate and configuration of the packing of the adsorbent) precluded meaningful quantitative meta-analysis, therefore the synthesis was conducted narratively. This level of heterogeneity is common for SRAE, so the precision and certainty of the conclusions is also lowered.

The constraints of the review process suggest several key areas for future research to consider to address gaps and inconsistencies in the existing evidence base. Most significantly, a standardized testing procedure and reporting guidelines for biomass-based adsorbents to control diesel emissions should be established. Results from studies are often reported in multiple ways, however, and few reports specifically report reduction efficiency, thus making it difficult to compare results across studies and to make general conclusions, particularly if the study examines CO_2 as the pollutant. Common adsorption parameters like adsorption capacity (mg/g), breakthrough time (minutes) and adsorption efficiency (%). should be used in future studies. It should be reported with other parameters that are important such as temperature, pressure, flow rate, and gas composition as well as these parameters. It would be useful to have a standardized test protocol, similar to existing ASTM or ISO protocols for gas adsorption testing, so that easy comparison between studies could be made and discovery of optimal adsorbent materials could be accelerated. Secondly, the long term cyclic stability of biomass-based adsorbents under the actual operating conditions of engines should be investigated. Two studies showed that the materials could be regenerated by temperature swing adsorption; however, they did not provide quantitative data on capacity degradation over multiple adsorption/desorption cycles [27, 29]. Understanding how the adsorption capacity changes after hundreds or thousands of adsorption/desorption cycles is important for the assessment of the potential of such materials; if they are to be used repeatedly, loss of adsorption capacity over time will result in loss of feedstock cost savings. Third, testing of biomass derived adsorbents in real diesel engines in real operating conditions, instead of steady state lab conditions, is needed. For real world applications, the load on the diesel engine, exhaust temperature, and speed are dynamic and constantly changing, which may lead to performance of the adsorbent that is significantly different from the idealized steady state performance. No transient testing is included in all of the studies in this review [24-29]. Fourth, future studies should measure more than one pollutant, as diesel exhaust is composed of CO_2, NO_x, HC, CO and PM.

The studies included were generally focused on the effects of one pollutant or a limited number of pollutants, and the effects of competitive adsorption (where two pollutants have competition for adsorption) on the reaction are largely unstudied. It is important to understand the competition between pollutants when developing effective multi-pollutant control systems. Fifth, life cycle assessment (LCA) and techno-economic analysis (TEA) of the adsorbents produced from biomass sources would be beneficial for their production and deployment for diesel emissions control. While the biomass feedstocks are cheap and renewable, the energy and chemical requirements for pyrolysis, activation and pelletization may be large, and the overall environmental and competitive effects of the biomass materials, particularly vis-à-vis conventional adsorbents, remain poorly quantified. Further research work should be undertaken to assess the environmental and economic advantages of biomass-based adsorbents such as production costs and disposal costs by performing a cradle to grave LCA and TEA. Last but not least, little attention has been paid to chemical activation agents such as KOH and H_3PO_4 to enhance porosity of algae-based absorbent materials or to the behavior of the adsorbent under high humidity

conditions, as often present in diesel exhaust. The identified gaps provide a roadmap for further research to strengthen and expand the body of evidence and contribute to implementation.

5. Conclusions

The systematic review included experimental data on biomass-derived materials for emission control in diesel engines, covering CO_2 adsorption, hydrocarbon and NO_x removal, and particulate filtration. The reported results show that these materials can remove pollutants under specific experimental conditions, such as adsorbing gaseous pollutants from calcium-alginate-encapsulated Moringa oleifera pod powder and achieving high particulate-removal efficiency with a biomorphic silicon carbide filter. These results are for separate removal processes, though, and cannot be considered comparable measurements of overall emissions-control performance. Thus, the evidence points to the technical viability of biomass-based materials but cannot prove they are superior in pollution reduction, feedstocks, or operating conditions, among other parameters. The small number of eligible studies, significant methodological variation, and different performance measures limit the strength of this conclusion. These limitations prevent reliable cross-study ranking and limit the generalisability of the reported results to practical engine applications. Furthermore, proof of pollutant removal under single test conditions is not sufficient to prove sustained performance in repeated operations and/or industrial viability. Capacity retention, regeneration efficiency, competitive adsorption in multi-component exhaust streams, transient engine loads, pressure-drop evolution, and environmental and economic trade-offs are not yet fully characterized. Standardized testing and reporting would be a priority for future work, as would direct comparisons of candidate materials under similar operating conditions, and repeat adsorption–desorption testing with exhaust gas compositions representative of real exhaust streams. The investigations should also be coupled with life cycle analysis and techno-economic evaluation to determine whether the observed reductions apply to long-term, energy-efficient, economic emission-reduction solutions. Until this evidence is provided, it is sensible to consider biomass-derived materials promising for future development but not proven alternatives to existing diesel exhaust after-treatment materials.

6. Author contributions

Oyelami S: Conceptualization, methodology, investigation, writing–original draft, writing–review and editing, visualization. Azeez NA: Conceptualization, methodology, investigation, writing –original draft, writing –review and editing, visualization. Okedere OB: Conceptualization, supervision, writing–review and editing. Alamu OJ: Methodology, supervision, writing–review and editing. Adedeji WO: Methodology, supervision, writing–review and editing. Oyewo AT: Methodology, supervision, writing–review and editing. Abioye AG: Supervision, writing–review and editing. Both authors read and approved the final manuscript.

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