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ADOPTION OF BIO–BASED ADSORBENTS FOR EMISSION CONTROL IN DIESEL ENGINES: A COMPREHENSIVE REVIEW

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Abstract: Diesel engines are a dominant source of power in transport, agriculture and industry, but their emissions like nitrogen oxide (NO_x), particulate (PM), sulphur oxide (SO_x) and carbon monoxide (CO) show a detrimental effect on the environment and overall public health. Traditional treatment systems such as diesel oxidation catalysts, particle filters and selective catalysts have obtained remarkable emissions; however, their high costs, dependence on significant raw materials and complex maintenance are major limitations for long–term sustainability. This review examines the potential of biobased adsorbents as an alternative or supplementary solution for severe diesel emission control. They are mainly derived from agricultural residues, forestry by–products and plant–based sources, and they are cost–effective, renewable and environmentally benign. They also demonstrate high porosity, large surface areas and functional groups that increase pollutant adsorption rate, while contributing to circular economy principles by valorising waste streams. The reviews synthesise conclusions from laboratory experiments, pilot–scale studies and hybrid systems, and highlight both opportunities and challenges. Important problems identified include standardisation for thermal stability, durability, regeneration, mass production and regulatory compliance.
Keywords: Air pollution control, Bio–based adsorbents, Diesel emissions, Circular economy and Sustainable materials

1. INTRODUCTION

Diesel engines are very important in transportation, agriculture, construction, industrial processes and the supply of backup electricity power all over the globe (Berge and Devermani, 2024). Nevertheless, their combustion process is naturally less clean than what gasoline engines produce and causes the generation of plentiful pollution of oxides of nitrogen (NOx), particulate matter (PM), carbon monoxide (CO), hydrocarbons (HC), oxides of sulfur (SOx), and Carbon dioxide (CO_2). The effects of such emissions are global in nature in terms of air quality, human health, ecosystems, and climate. Long-term contact with diesel smoke has been linked to respiratory conditions, heart diseases, impaired lung capability, and some malignancies, which the International Agency for Research on Cancer (IARC) has considered detrimental to human life and existence (Ghosh and Sinha, 20250. In environmental terms, diesel contributes to atmospheric heating, acidic rain, pollution of soil and water and global loss of biodiversity. They do not affect only a single industry but affect the life of the population, create adverse climatic conditions in agriculture, destroy infrastructure through corrosion, downgrade the economy because of health expenses and remediation of the environment.

The reduction of emissions from diesel engines has thus been on the list of priorities of policymakers, engineers and environmental activists in recent times (Shahzad *et al.*, 2024). Traditional measures include enhancement in engine design and configuration, adoption of low-sulfur fuels, combustion efficiency optimisation and installation of post-treatment devices like diesel oxidation catalysts (DOC), diesel particulate filters (DPF), and selective catalytic reduction (SCR) devices. Although the methods seem effective, they tend to be costly, involve highly complex maintenance, and, in certain instances, produce secondary environmental challenges like the disposal of the spent catalyst products. Also, emission control catalysts or sorbents prepared using fossil sources might be based on rare or toxic metals and give rise to challenges regarding long-term sustainability (Ali *et al.*, 2025). This has led to a rising demand for a cleaner, low-cost and environmentally friendly substitute that can be locally generated and easily regenerated without any damage to the ecology.

Plant materials and agricultural wastes have been the most recent sources to gain superiority in terms of bio-based adsorbents to control diesel emissions within the past few years (El-Fawal *et al.*, 2025). Raw materials like coconut shell-based activated carbon, rice husk ash-based,

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corncobs, sawdust-based biochar, and other ligno-cellulosic residues have shown phenomenal ability in high uptake of gaseous pollutants and capture of fine particulates. They have porous materials, large surface area, and reactive functional groups, which make the bio-based materials more efficient in binding toxic molecules. Moreover, they are renewable, biodegradable, and they are in most cases by-products of industrial processes, which makes them sustainably cheap. Bio-based adsorbents could also play a role in waste valorisation and circular economy concepts by redirecting agricultural wastes that traditionally were to be burned in the open or sent to landfill to useful environmental methods (Thakur *et al.*, 2025).

This review is motivated by the dual challenge of reducing diesel emissions and advancing the need for sustainable materials science. Despite some research showing potential of using bio-based adsorbents at a laboratory and pilot scale, the literature is fragmented, and no overall understanding of their properties in terms of adsorption mechanism, performance under the real-engine environment, regeneration possibility and techno-economic feasibility exists. The synthesis of available data, identification of gaps, and a strategic plan should be developed with a comprehensive review of the current situation which is the main aim of this review. This review is also necessary to bridge the gaps in knowledge between environmental engineering, material science, and policy structures to enable the development of effective and socially equitable solutions to emissions control to help decision and policy-makers.

Gautam *et al*. (2025) reported that the usage of bio-based adsorbents for control of emissions from diesel engines has a direct relationship with various United Nations Sustainable Development Goals (SDGs). It also helps to achieve SDG 3 (Good Health and Well-being) by minimising air-pollution related sicknesses, SDG 7 (Affordable and Clean Energy), bolstering energy system sustainability and SDG 9 (Industry, Innovation and Infrastructure) through the promotion of eco-innovative industrial technologies. It can also support SDG 11 (Sustainable Cities and Communities) by enhancing the quality of the urban air, SDG 12 (Responsible Consumption and Production) through valorisation of waste to resources, and SDG 13 (Climate Action) by reducing greenhouse emissions. Indirectly, it is a part of SDG 15 (Life on Land) by preventing the degradation of the ecosystem through emissions and deposits. Hence, the utilisation of the bio-based adsorbents in diesel emission control management is not only a technological breakthrough but an interdimensional avenue to sustainable development and environmental justice.

2. OVERVIEW OF DIESEL ENGINE EMISSIONS

Types of Pollutants

A diesel engine is a complex mixture of gas-shaped and particle-shaped pollutants with significant environmental and public health. Each component is caused by specific combustion processes and has unique chemical properties that affect the atmosphere and its behavior in its biological effects. From nitrogen oxides running smog formation for particles capable of entering the lungs deep, emissions from diesel engines contribute to a series of air quality problems, climate change and acute and chronic diseases (Bharti *et al*, 2025). Understanding the species, sources and effects of these pollutants is necessary to develop effective strategies to reduce harmful footprints on society and ecosystems. These pollutants emphasise how diesel combustion affect both air quality and public health in different domains. The common pollutants are presented in Table 1.

Table 1: Impacts and Description of Various Pollutants

Pollutant	Description & Impact
NO_x (Nitrogen Oxides)	Primarily NO and NO_2, formed under high–temperature combustion. They contribute to smog, acid rain, and are precursors to ground–level ozone and secondary particulate matter. Long–term exposure may increase respiratory diseases, cardiovascular issues, and mortality
PM (Particulate Matter)	Composed of soot, carbon, ash, PAHs, metallic particles, sulfates, and silicates. Diesel PM is typically respirable (<10 μm) and often ultrafine (<1 μm), leading to deep lung penetration and serious health risks including lung inflammation and cardiovascular disease
SO_x (Sulfur Oxides)	Emitted from sulfur content in fuel; contribute to acid rain and respiratory irritation. Low–sulfur diesel fuels have significantly reduced these emissions.
CO (Carbon Monoxide)	Generated by incomplete combustion. It binds to hemoglobin, impeding oxygen delivery; particularly dangerous in enclosed or poorly ventilated areas.
HC (Hydrocarbons)	Unburned or partially oxidized hydrocarbons. Serve as precursors to ozone and photochemical smog, particularly potent in diesel emissions.
CO_2 (Carbon Dioxide)	A byproduct of carbon–containing fuel combustion. Major greenhouse gas contributing to climate change.
Aldehydes and Ketones	Volatile organic compounds formed during combustion, irritating to the eyes and respiratory tract.
PAHs (Polycyclic Aromatic Hydrocarbons)	Often associated with PM. Known carcinogens that pose both long–term cancer risk and environmental persistence.

Sources within the Diesel Combustion Cycle

The generation of pollutants from diesel engines is mainly rooted in the physical and chemical combustion processes that occur during the combustion of fuels. The combustion of diesel is a high-temperature, high-pressure process that depends on proper atomization and mixing of fuel with air and subsequent ignition and oxidation (Khedr *et al.*, 2025). Nevertheless, inconsistency in fuel properties, engine working conditions and design specifications usually facilitates incomplete or inefficient combustion, leading to the release of harmful by-products. Unlike spark ignition engines, diesel engines run on excess air and at increased compression ratios, and as a consequence, they are more efficient and also likely to form some pollutants, especially nitrogen oxides (NOx) and particulate matter (PM).

One of the major emission sources is incomplete combustion, which occurs when the combustion process is incomplete and poorly oxidised because of poor spray atomization, unequal air-fuel mixing and poor injection timing. Such a process releases carbon monoxide (CO), unburned hydrocarbons (HC), and particulate matter (PM) that includes soot and organic carbon fractions. Such products from incomplete oxidation are more detrimental to the health of the human population as well as the environment.

Another very important factor is the high-temperature areas in the combustion chamber. At a combustion temperature above about 1,500°C, the nitrogen present in the atmosphere reacts with oxygen to form NO_x (Alaskaree and Khudhair, 2025). Such compounds cause photochemical smog, acid rain and ozone formation. The issue is further escalated in peak-load operations at the time of the highest temperatures and pressures.

The quality of fuel also contributes considerably in the formation of pollutants. Diesel fuel with a high amount of sulfur results in sulfur oxides (SO_x) emissions and secondary sulfate particulates that contribute to acid rain. Fuel that is fragrant can lead to more soaked and polycyclic aromatic hydrocarbon (PAH), most of which are cancer. In addition, fuel viscosity and instability also affect the patterns and speeds for steaming sprays, which otherwise affects the combustion and completion of PM and HC emissions. Therapeutic strategies, such as optimizing the ratio of air and fuel, processing the injection system and turning on cleaner fuel (eg Ultra-low sulfur diesel or biodiesel mixture), can significantly reduce these environmental toxins, which can significantly improve the engine performance and environmental results.

Global and Local Emission Trends

Global and local emission trends from diesel-controlled transportation reveal both the magnitude of the issue and progress achieved through policy intervention and technological innovations. A large consumer of fossil fuels emanating from transportation contributes immensely to Greenhouse Gas Emissions (GHG), with diesel engines being central to freight, public transit and off-road machinery (Mofolasyo, 2023). While the global GHG emissions continue to increase from all regions mainly due to fossil fuels combustion, some regions like Europe have attained notable decreases in the main pollutants like NO_x, SO_2, CO, and Non-Methane Volatile Organic Compounds (NMVOC) through emissions standards and cleaner fuel adoption. In countries such as the United States and the United Kingdom, however, transport is one of the largest contributors in air pollution and climate change. The discovery and understanding of these trends is important for assessing the effect of mushing strategies, identifying political intervals and guiding the future of permanent technologies such as bio-based adsorbents. Emissions from the transport sector are presented in the pattern and insight in Table 2.

Table 2: Global and Local Emission Patterns from Transportation Sector

Region/Level	Trends & Insights
Global Transport CO_2 Emissions	Transport accounted for about 15% of global greenhouse gas emissions and around 23% of energy–related CO_2 emissions as of 2019 (Kopecek and Libal, 2021; Jaramilo *et al.*, 2022).
Global GHG Trends	Global anthropogenic greenhouse gases continued to rise, hitting an estimated 59 ± 6.6 Gt CO_2–eq in 2019, with fossil fuel combustion accounting for roughly 38 Gt CO_2 (Bholouchos *et al.*, 2021; Dhakal *et al.*, 2022)
U.S. Transportation	In 2022, transportation represented 29% of total U.S. greenhouse gas emissions, with direct combustion making it the largest contributing sector (US EPA, 2025)
EU Air Pollutants Trends (1990–2022)	Transport emissions in EU–27 substantially declined: NO_x down by 51%, SO_2 by 82%, CO by 90%, and NMVOCs by 76–91% (EEA, 2025)
UK Transport Emissions	Transport contributes roughly 32% of NO_x and 14% of $PM_{2.5}$ emissions locally (Gov–UK, 2025)
On–Road Global Energy Use	Approximately 1.3 billion vehicles consume 79 quadrillion BTU, releasing 5.7 Gt CO_2 annually (Frey, 2018; Kelly *et al.*, 2023)

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Health and Environmental Impacts

Diesel engine emissions create major threats to human health, interfering with the ecosystem and the world's economy, as mentioned below:

- The effects of short-term risk, especially in cities and workplaces where diseases are widespread, are quite worrying. Airborne exposure to these pollutants can cause intense manifestations, including eye and neck irritation, constant cough, headache, dizziness, nausea and asthma, which can exacerbate respiratory problems. Employees, especially in industries that deal with heavy machines, transit hubs and shipping, are very high risk due to their long risk in the work area.
- Long-term and old effects are worse. Diesel exhaust due to the use of diesel engines are classified by the International Agency for Research on Cancer (IARC) as a group 1 carcinogenic substance, which has a direct correlation between long exposure and risk of lungs and lungs and bladder cancer (Barul *et al*, 2025). There is also long -term risk associated with heart disease, vascular insufficiency, neuroinflammation and developmental poisoning among children. These health threats are due to proper and ultrafine particulate matter (PM) and the toxic components of diesel exhaust that can go deep into the lungs and move to the blood.
- Another problem of extreme significance is common risk. Nitric oxide (NOx), particulate matter and carbon dioxide (CO_2) can interact to increase oxidative stress with sub-eating respiratory and heart damage. This continuous toxicity means that even the moderate environmental toxins can cause high amounts of damage when combined.
- Both agriculture and environmental implications are also scary. The emission of NOx and hydrocarbon (HC) contributes to grassroots ozone affecting the crop yield (reduction in food safety) and plant growth. Sulfur oxide (SO_x) is also a factor of acidic rain where the earth's poor condition and the water in the water is sour and the forest's ecosystem is destroyed.
- Social and economic values are enormous. A 2025 study estimated that without mitigation, a global deficiency alone in life-inspired by the diesel car number 856 population, 307,000 early deaths, 217,000 pediatric examples, lost 120 million working days and financial losses between 2021 and 2040 can lead to the peak of $ 1.4 in financial losses (CREA, 2025).

3. DIESEL EMISSIONS AND CONTROL TECHNOLOGIES

Diesel engines are widely used in transport, power generation and industrial applications due to their high efficiency and durability. However, they are also prominent contributors to air pollution such as nitric oxide (NO), particulate matter (PM), carbon monoxide (CO) and unbalanced hydrocarbons (HC). To reduce these emissions, significant advances have been made in the engine's design and subsequent treatment systems, although many restrictions remain.

An approach improves engine design. Technologies such as general injection of railways allow accurate control of fuel distribution, improve combustion efficiency and reduce soot formation. Turbocades increase the air intake, ensuring a better mixture of fuel and air, causing more complete combustion. In addition, exhaust reserving (EGR) helps in low combustion temperature, which reduces no emissions. While being effective, these techniques often involve a trade-off between reducing and increasing the other, for example, now, but reducing high particle emissions with EGR.

Beyond the engine modifications, the treatment system plays a central role. Diesel oxidation catalyst (DOC) oxidizes CO and HC in less harmful carbon dioxide and water vapor (Hunag *et al.*, 2025). Diesel particle filter (DPF) burns network and soot particles and achieves high removal capacity. To target no_x, selective catalyst reduction (SCR) uses Urea-based reagents to convert no_x to no_x to nitrogen and water, while lean no_x mesh (LNTS) adsorber and reduces periodic NO_x emissions during engine operation. Together, these systems have enabled modern diesel engines to meet strict global emission standards.

Despite this progress, there are boundaries and challenges. Later treatment systems increase costs and require regular maintenance, such as DPF regeneration. Catalytic performance may be low over time due to thermal stress or toxicity (Jin *et al.*, 2025). In addition, many systems depend on rare or expensive metals such as platinum, increasing the concerns of stability. In some cases, secondary pollutants may also be under treatment procedures. These challenges emphasise the need for alternative solutions, including biobased adsorbents to complement or replace traditional approaches. Table 3 shows the Diesel After-Treatment Systems, Benefits, and Limitations.

Table 3: Conventional Diesel After–Treatment Systems, Benefits, and Limitations

Technology	Main Function	Key Pollutants Targeted	Advantages	Limitations & Challenges
Diesel Oxidation Catalyst (DOC)	Catalytic oxidation of CO, HC, and soluble organic fractions in PM	CO, HC, some PM components	– Simple, robust design – Effective in reducing CO and HC by 80–90% – Passive system requiring minimal intervention	– Ineffective for NO_x reduction – Requires high exhaust temperatures to function efficiently – Catalyst poisoning (e.g., from sulfur in fuel) reduces performance – Relies on precious metals (Pt, Pd) that are costly and scarce
Diesel Particulate Filter (DPF)	Physically traps and oxidizes particulate matter (soot)	PM (solid carbon particles, ash)	– High removal efficiency (>90%) – Reduces visible smoke – Essential for meeting Euro VI/US EPA standards	– Requires periodic regeneration (active/passive) – Risk of clogging leading to engine backpressure – High maintenance cost – Durability issues under low–temperature driving cycles – Secondary emissions during regeneration (e.g., NO_2, ash)
Selective Catalytic Reduction (SCR)	Converts NO_x into N_2 and H_2O using a urea–based reductant (AdBlue/DEF)	NO_x	– High NO_x reduction efficiency (70–95%) – Effective across wide operating conditions – Can improve fuel efficiency by enabling engine–out NO_x trade–off	– Requires continuous urea/DEF supply and refilling – Ammonia slip (secondary pollution) if dosing is not controlled – Complex system with higher installation costs – Catalyst deactivation over time due to thermal stress or sulfur poisoning – Relies on expensive metals like vanadium, platinum, or zeolites
Lean NO_x Trap (LNT)	Adsorbs NO_x under lean conditions and reduces it under rich conditions	NO_x	– Effective at low–load, low–temperature operations (urban driving) – Compact system compared to SCR – Does not require urea infrastructure	– Limited NO_x storage capacity – Requires frequent regeneration with rich fuel operation → increases fuel consumption – Thermal degradation reduces long–term efficiency – Sensitive to sulfur contamination – High reliance on precious metals (Pt, Rh, Ba–based materials)

4.BIO-BASED ADSORBENTS: SOURCES, PROPERTIES, AND MECHANISMS

In response to increasing environmental considerations related to diesel emissions, biobased adsorbents have emerged as promising, low-cost and permanent alternatives for traditional control technologies. These adsorbents were revealed by renewable resources such as agricultural residues, forestry by -products and ingredients based on plants, and are quickly studied for their efficiency in capturing particle fabric and gaseous pollutants. Unlike synthetic adsorbents, biobased alternatives provide the benefits of extensive availability, biodegradation and low organic footprints, while at the same time producing materials for valuable products. Their physical and chemical properties, which include scams, surface area and functional group structure, play an important role in the efficiency of environmental toxins. In addition, progress in preparation and activation methods, such as carbonisation, chemical modifications and bio-production, has increased greatly. This section examines the sources of the underlying mechanisms that control bio-based adsorbents, their structural and chemical properties, preparation techniques and their polluting absorption ability.

Plant and Agricultural Waste-Derived Adsorbents

Plant and agricultural waste has emerged as durable, affordable sources, which are affordable sources for producing diesel emissions and other environmental toxins to produce biobased adsorbents. Materials such as coconut shells, bamboo, palm nucleus, rice peel and sugar tube fault are widely available in tropical and subtropical regions, offering abundant raw material (Aman *et al.*, 2022). Their lignocellulosic composition - rich in cellulose, hemicellulose and lignin provides a favourable precursor to carbonaceous adsorbents due to high carbon content and structural stability. For example, coconut shells and palm cores are characterised by dense microstructure that provides biochars with excellent holes and stiffness after carbonisation. Similarly, rice shells contain silica, which increases thermal resistance and surface reaction (Hamidu *et al.*, 2025). This waste-specific content reduces the dependence on synthetic sorbents, while transforming agricultural residues into functional products and addressing the targets for waste management and the circular economy (Aliyu *et al.*, 2025). In addition, mining and environmental prints are compared to adsorbents as a source of local biomass, zeolite or active carbon derived from fossil fuels. The renewable character of this biomass feed ensures scalability in areas facing both problems with waste management and high pollution burden. Overall, cruel bio-based adsorbents from agricultural waste not only provide an environmentally friendly alternative, but also, according to permanent development principles, provide double benefits of pollution control and waste conversion.

Physical and Chemical Properties

The effectiveness of bio-based adsorbents is mainly determined by their physical and chemical properties, which directly affect the contamination capacity. The main parameters include holes, surface area, hole size distribution, functional group and thermal stability. High surface area and micro-porosity that enable gaseous pollutants (NO_x, SO, CO) and fine particle -shaped substances. For example, coconut shell rituals provide active carbon, which often exceeds 1000 square meters/grams in the surface with sufficiently active gas phase calls. Stretch structure (micro, meso- and macro-pores) plays an extra role, where micro-pore improves molecular exploitative, while mesopores facilitate spreading and storage (Shen *et al.*, 2024). Chemical properties are just as important: Functional groups such as hydroxyl (-OH), carboxyl (-COOH) and carbonill (-C = O) surface polarity, electron donations and acid-base interactions, which are essential to catching reactive gases such as NOx (Chen *et al.*, 2025). In addition, thermal stability determines the durability of the specific high-temperature exhaust of the diesel engine. Adsorbents of agricultural waste usually show stability up to 400–700 ° C, depending on the source and treatment method. The presence of inorganic components, such as potassium in silica or baggase in rice shells, changes the catalyst and absorbent properties, sometimes increases the reaction, but also introduces the risk of ash formation. Thus, balancing these physical and chemical properties through controlled processing is important for adapting absorbent performance in real-world applications.

Preparation and Activation Methods

The transformation of raw agricultural residues into adsorbents requires systematic preparation and activation procedures. The most common process begins with carbonisation, where biomass is heated under oxygen-limited conditions (300–700°C), so that carbon-rich biochar can remain after removal of volatiles. This process increases structural hardness and introduces basic holes. To improve the ability to absorb, activation methods are used either physically (using steam, CO_2 or air) or chemically (using activation that activates agents such as KOH, H_3PO_4, or $ZnCl_2$).
Chemical activation usually provides high surface areas and well-developed microposity, but it may be necessary to wash completely to remove residual chemicals (Zafar *et al.*, 2025). Biochar production from slow or rapid pyrolysis provides another route, where procedural parameters such as heating rates, residence time, and temperature determine surface morphology and pore properties. Metal oxide (eg Fe, Cu, MN) or activity with amines can further increase selectivity for NO_x and SO_x gases by promoting chemistry, including impregnation, chemistry (Vanshpati and Timari, 2025). It is important that preparation methods should balance performance with cost efficiency, especially for mass applications in emission control. Energy requirements, chemical use and need for finishing of finishing often determine economic viability. Therefore, adaptation to the state of activation is important for producing high-quality biobased adsorbents suitable for medium temperatures and environmentally friendly agent-diesel emission control.

Pollutant Removal Mechanisms

The ability to remove environmental toxins of biobased adsorbents occurs from a combination of physical filtration, chemical abscess and catalytic surface interactions. For particulate matter (PM), the porous structure of biobased adsorbents and fibrous morphology enables mechanical adhesion of mechanical and fine particles (Shi *et al.*, 2025). For gaseous pollutants such as No_x, Sox and CO, micropores and chemical in reactive functional locations are removed through materiality. Oxygen-rich groups (-OH, -COOH, -C = O) increase the affinity against polar molecules, while alkaline soil metals (ca, k, mg) are naturally present in some biomass, forever present in some biomass, catalysed with so_x and no. Surface chemistry also plays a role in redox interaction, where carbonaceous surfaces facilitate partial reduction of NO under certain conditions (Wang *et al.*, 2025). In addition, the tensile structure that absorbs the adsorption canion is the narrow micropores in favor of the selective gas that absorbs, while the mesopores allow rapid spreading and storing of pollutants. Factors such as gas concentration, temperature, humidity and competitive species can significantly affect efficiency. For example, high humidity can block the absorption sites at water vapor, which can reduce gas absorption. At the same time, the elevated temperature increases desorption and limits performance in hot exhaust currents. Thus, the efficiency depends on the removal of environmental toxins of adsorbent properties and careful adjustment of operating conditions. In summary, bio-based adsorbents removed contaminated materials through continuous physical and chemical mechanisms, making them a promising alternative for traditional emission control technologies.

5. APPLICATIONS, PERFORMANCE, AND CHALLENGES

The use of biobased adsorbents for diesel emission controls has attracted attention as a permanent alternative for traditional catalyst converters and particle-shaped filters. These adsorbents, derived from agricultural residues and plant-based materials such as coconut shells, rice husks, sugarcane bagasse, and corncobs, present an eco-friendly and cost-effective option for mitigating particulate matter (PM), nitrogen oxides (NOx), sulfur oxides (SOx), and carbon monoxide (CO) emissions from diesel exhaust. Their practical applications, performance in various experimental setups and related challenges are discussed in subsequent sub-sections.

Laboratory, Pilot-Scale and On-Road Studies

The laboratory investigations provided considerable insight into the absorption prospects of biobased materials under controlled conditions. The study of batch and fixed-bed adsorption suggests that biochar and activated carbons from biomass consist of high surface areas and functional groups that increase the capture of particulate substances and gaseous environmental toxins (Verma and Devi, 2025). For example, coconut shells and bamboo biochar demonstrate strong absorption of NOx due to the presence of functional groups containing oxygen, while rice husk shells and groundnut shells have shown high affinity to remove SOx.

Pilot scale performances have improved laboratory findings by testing small diesel generator sets and absorbing beds and coated filters in stable engines. These studies suggest that bio-based adsorbents can reduce PM emissions 40–70% and NOx by 15–30% based on operating conditions and material activation techniques (Weidemann *et al.*, 2016). Although limited, integrating the bio-based filter in exit systems reduces visible smoke opacity and fine particulates which informs applications in real-world.

Comparative Performance with Conventional Catalysts

When compared with conventional diesel oxidation catalysts (DOCs), diesel particulate filters (DPFs), and selective catalytic reduction (SCR) systems, biobased adsorbents usually show low removal capacity, especially for NOx reduction (Rehnlund *et al.*, 2007). However, they provide different benefits when it comes to affordability, accessibility and environmental sustainability. For example, while platinum-based catalysts can achieve more than 90% removal of polluting substances, their high costs and dependence on rare metals is a major barrier in their mass adoption in low-income areas. In contrast, bio-based adsorbents can be produced locally from agricultural residues, aiding waste valorisation and reducing the dependence on imported technologies.

Maintenance, Regeneration, and End-of-Life Disposal

The long-term success of bio-based emission control systems depends on effective maintenance and regeneration strategies. Unlike traditional DPFs, which require high temperature regeneration, bioadsorbents can be revived at relatively moderate temperatures or through chemical washing, which reduces the operating complexity. However, there are challenges with clogging, pressure drop and frequent regeneration efficiency. At the end of life, tired bio-based filters can be safely re-treated or recently presented, for example as a modification (biochar) in the Earth, the circular economy further contributes to the principles. This end -life advantage makes them more durable than metal -based catalyst systems that cause hazardous waste. Despite their potential, several challenges hinder the widespread adoption of bio-based adsorbents in diesel emission control as shown in Table 4.

Table 4: Key Challenges in the Development and Commercialization of Bio–Based Adsorbents for Diesel Emission Control

Challenges	Analysis
Durability and Thermal Resistance	Diesel exhaust temperatures can exceed 500°C, while most bio–based adsorbents degrade or lose activity at elevated temperatures. Enhancing thermal stability through composite formulations or chemical modification remains a research priority.
Scaling Production	Although agricultural residues are abundant, large–scale, standardized production of high–quality bio–adsorbents requires infrastructure for collection, processing, and activation. Supply chain logistics, particularly in developing countries, remain underdeveloped.
Standardisation and Certification	Unlike established catalytic systems that are regulated under emission standards, bio–based adsorbents lack standardized performance metrics, certification protocols, and regulatory approval, limiting their integration into commercial diesel systems.
Limited Real–World Data	While laboratory studies are abundant, long–term field evaluations under diverse driving conditions remain scarce. Without extensive real–world validation, commercial adoption remains slow, especially for heavy–duty transport and industrial diesel engines.

6. CONCLUSION

Continuous dependence on diesel engines for transport, agriculture, power generation and industrial activities poses serious challenges for air quality, human health and climate change. Traditional treatment systems such as diesel oxidation catalyst, diesel particulate filter and selective catalyst reduction have contributed significantly to emission reduction, but they are still expensive, resource intensive and in some cases depending on rare or toxic metal and complex maintenance. Against this background, bio-based adsorbents have emerged as a permanent, low cost and environmental as a sound option for diesel engines.

This review shows that bio-based adsorbents obtained from agricultural residues, forestry by-products and plant-based materials, possesses high engineering property including high porosity, large surface areas and functional groups sufficient enough for capturing of particulate matter, nitrogen oxide (NO_x), sulphur-oxide (SO_x) and carbon monoxide. The extensive availability, biodegradation and waste volarisation of the bio-based adsorbents makes them better alternatives in the broad structure of circular economy and sustainable development. Laboratory and pilot scale studies highlight continuous capacity, while hybrid systems integrate biobased materials with traditional catalysts, showing synergistic benefits by increasing the ability to remove and reduce costs.

Despite these advances, many major barriers limit wide adoption. Long -term use, regeneration efficiency and long -term stability are still important technical barriers in high temperature applications. More importantly, a standardized performance prevents the absence of matrix and the real world -recognizing integration and commercial distribution.

For future research, it is necessary that they develop a thermally stable bio-based composites, promote low -price activity and regeneration methods and create certification structures that can coordinate these techniques with emission standards. The collaboration between material researchers, car engineers, decision makers and stakeholders in the industry will be required to bridge the current interval. In addition, technical-economic evaluation and life cycle analysis are necessary to determine the viability of mass adoption on a large scale.

Finally, bio-based adsorbents provide more than a technological innovation; they represent a convergence of environmental technology, permanent material science and politically run climate acts. Diesel emission control strategies have the ability to improve public health in their successful integration, reduce environmental decline and accelerate progress in the UN's sustainable development goals.

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