Research Square

Preprints are preliminary reports that have not undergone peer review.
They should not be considered conclusive, used to inform clinical practice,
or referenced by the media as validated information.

Bioremediation of Gasoline Engine Exhaust Pollutants using Fixed-bed Biofiltration system

Haroon Tariq[1]

haroon.22313018@mic.qau.edu.pk

Quaid-i-Azam University

Qazi Tabish Bin Tanveer

Quaid-i-Azam University

Muhammad Uzair Nawaz[1]

Quaid-i-Azam University

Muhammad Armaghan Khalid[2]

National University of Medical Sciences

Research Article

Keywords: Biofiltration, Biochar, Volatile organic compounds, Air pollution, Fixed-bed column, Microbial consortium

Posted Date: November 11th, 2026

DOI: https://doi.org/10.21203/rs.3.rs-11073279/v1

License: This work is licensed under a Creative Commons Attribution 4.0 International License.
Read Full License

Additional Declarations: No competing interests reported.

Bioremediation of Gasoline Engine Exhaust Pollutants using Fixed-bed Biofiltration system

Haroon Tariq[1]* (0009-0006-3379-9922) haroon.22313018@mic.qau.edu.pk

Qazi Tabish Bin Tanveer[1] (0009-0003-4187-3916) qtabish.22313013@mic.qau.edu.pk

Muhammad Uzair Nawaz[1] itsuzairnawaz@gmail.com

Muhammad Armaghan Khalid[2] armaghankhalid45@gmail.com

[1]Department of Microbiology, Quaid-i-Azam University, Islamabad, Pakistan

[2]Department of Biological Sciences, National University of Medical Sciences, Rawalpindi, Pakistan

*Corresponding author

Corresponding author email: haroon.22313018@mic.qau.edu.pk

Authors' Contributions

Haroon Tariq conducted the experimental work, data analysis, and manuscript preparation. Qazi Tabish Bin Tanveer, Muhammad Uzair Nawaz and Muhammad Armaghan Khalid contributed to laboratory assistance, data collection, and manuscript review. All authors read and approved the final manuscript.

Acknowledgements

The authors acknowledge the Department of Microbiology, Quaid-i-Azam University, Islamabad, Pakistan, for providing laboratory facilities and technical support to carry out this research.

Abstract

The exhaust produced by gasoline engines is a significant source of air pollution and a severe hazard to human health and the environment because it releases volatile organic compounds (VOC), nitrogen oxides (NO_x), carbon monoxide (CO) and particulate matter (PM), and polycyclic aromatic hydrocarbons (PAHs). Traditional methods of control like catalytic converters, chemical scrubbers and adsorption systems are sometimes expensive, require a lot of maintenance, and they also produce secondary pollutants, therefore there is a need to find a sustainable solution. This paper describes a hybrid biofiltration system, which uses activated wood-chip biochar in KOH, and a synergistic bacterial consortium of *Bacillus subtilis* and *Pseudomonas aeruginosa* to treat the gasoline engine exhaust. The porous biochar structure allows gaseous pollutants to adsorb effectively and at the same time allows the growth of microbes and their biodegradation potential. The proximate analysis, pH, electrical conductivity, and Fourier transform infrared spectrophotometer (FTIR) were used to characterize the biochar. A seven-day closed-loop operation of a laboratory-scale fixed-bed column with gasoline exhaust was conducted. Gas chromatography–mass spectrometry (GC-MS) analyzed the inlet and outlet gases to determine the removal of the pollutants. The developed system of adsorption-biodegradation was able to reduce exhaust pollutants with low operational cost and low levels of secondary waste. These results indicate that biochar-microbe biofiltration has a great potential as a scalable and sustainable technology in gasoline exhaust treatment.

Keywords:

Biofiltration, Biochar, Volatile organic compounds, Air pollution, Fixed-bed column, Microbial consortium

1 Introduction

The gasoline powered vehicles continue to be one of the gravest environmental and public health problems across the world, especially in the rapidly urbanizing and industrializing areas (Debelu et al., 2024). Gasoline combustion involves emission of a complex of dangerous pollutants, such as volatile organic compounds (VOCs), nitrogen oxides (NO), carbon monoxide (CO), particulate matter (PM), benzene compounds, and polycyclic aromatic hydrocarbons (PAHs) (Sapate & Tikekar, 2008; Colbeck et al., 2010; Khan et al., 2019). These are long-lasting, poisonous, and long-range pollutants that can spread across the air. An expanding epidemiological literature suggests that long term exposures to such pollutants are associated with higher risks of respiratory and cardiovascular illnesses, endocrine system malfunction, and cancer, making vehicular emissions one of the largest sources of disease on the planet (Song & Hao, 2024). The effects are also especially high in developing nations, where the number of vehicles is increasing at a rapid pace and the implementation of regulations is inadequate or even insufficient, which further worsens the quality of urban air (Anjum et al., 2021; Yaqoob et al., 2021; Rasheed et al., 2015).

BTEX compounds of particular concern due to their carcinogenic, mutagenic, and cytotoxic potential include benzene, toluene, ethylbenzene, and xylenes and PAHs, which are among the gasoline related pollutants (Yu et al., 2022). The BTEX species are also implicated in the development of photochemical smog and the PAHs like naphthalene, phenanthrene, and pyrene are oxidized in the atmosphere to form secondary organic aerosols that worsen the quality of the air further (Mansha et al., 2011; Nakhjirgan et al., 2024). The chemical complexity of such emissions is another reason to insist on the necessity of the control technologies which will be able to cover a wide spectrum of pollutants at once. Traditional methods of emission control like catalytic converters, mechanical filters, activated carbon adsorption, and chemical scrubbers have resulted in major reduction of some of the pollutants (Agarwal & Mustafi, 2020). Specifically, catalytic converters are very efficient in oxidizing carbon monoxide, nitrogen oxides, and hydrocarbons that are not burned (Sharif et al., 2021; Costa et al., 2023). In spite of these developments, several physical and chemical treatment systems continue to have challenges such as adsorption capacity saturation, high cost of operation and secondary waste streams which have to be further handled and disposed (Usman et al., 2023). These restrictions highlight the necessity of more sustainable, biologically-based options that are able to actively degrade pollutants and not just capture them. Biofiltration has therefore become a promising technology in the treatment of volatile organic compounds and other gaseous contaminants in this regard. It has the benefits of low operating cost,

low secondary wastes produced, and biologically mineralizing pollutants (Wu et al., 2023; Sheoran et al., 2022). Biofilters operate on the principle of immobilizing microorganisms in a type of packing media, in which incoming contaminants are first absorbed and then biodegraded (Sheoran et al., 2022). A packing material is a design issue that is very crucial. It should help to sustain strong microbial colonization, maintain substantial moisture, and have a high mass transfer area, and should have a stable structure over long periods of operation (Hendrych et al., 2021).

Recently, biochar has gained a lot of interest as an advanced biofilter medium due to its high porosity, large specific surface area, and high level of chemical stability (Beesley et al., 2010; Zhao et al., 2017). Activated by KOH, biochar forms a clear network of micro and mesopores and obtains oxygen containing functional groups that include hydroxyl, carboxyl, and carbonyl groups improving the adsorption of aromatic hydrocarbons and electron transfer during microbial respiration (Liu et al., 2019; Dong et al., 2022; Deng et al., 2025). These properties render activated biochar a very appealing dual functional material. It does not only serve as an effective adsorbent but also a supporting structure of pollutant degrading microorganisms (Pachaiappan et al., 2022). *Pseudomonas aeruginosa* and *Bacillus subtilis* are microbial communities that are instrumental in the oxidation of VOCs and BTEX compounds as well as the mineralization of PAHs by enzyme-mediated oxidation, aromatic ring breakdown and complete mineralization pathways (Abo-State & El-Kelani, 2020). Immobilized as consortia on porous biochar matrices, these microorganisms tend to exhibit better degradation rates, wider substrate coverage, and increased resistance to changes in pollutant loading (Fang et al., 2024; Xue et al., 2020; Niu et al., 2024). Moreover, biochar due to its porous structure provide resistance against desiccation and toxic shocks, which helps to preserve stable and active biofilms during long-term operation (Edeh et al., 2023).

Irrespective of these benefits, there are still great gaps in knowledge with respect to the use of activated biochar microbe systems in the treatment of gasoline engine exhaust. Most previous studies have focused on individual VOCs or synthetic gas mixtures under controlled laboratory conditions, which do not reflect the chemical variability and complexity of actual exhaust streams. Furthermore, limited research evaluates KOH-activated biochar as a combined adsorbent–biological support for simultaneous removal of BTEX and PAHs from real exhaust streams (David, 2023; Díaz-Maroto & Mašek, 2023; Zhou & Shi, 2022). The long-term structural stability of microbial biofilms on activated biochar under continuous, moisture-variable, heated exhaust exposure also remains poorly understood (Zhao et al., 2022).

The present study addresses these gaps by developing and evaluating a hybrid biofiltration system composed of KOH-activated wood-chip biochar and a microbial consortium of *Pseudomonas aeruginosa* and *Bacillus subtilis*. The objectives are to: (i) synthesise and characterise activated biochar using proximate analysis, pH, electrical conductivity, and FTIR; (ii) immobilise microbial strains onto the biochar matrix; and (iii) assess the system's performance in removing pollutants from real gasoline engine exhaust in a fixed-bed, closed-loop setup. This work offers a cost effective and sustainable approach for mitigating hazardous vehicular emissions and contributes novel insights into the design of advanced biochar-microbe systems for air pollution control.

2 Materials and Methods

2.1 Study Design

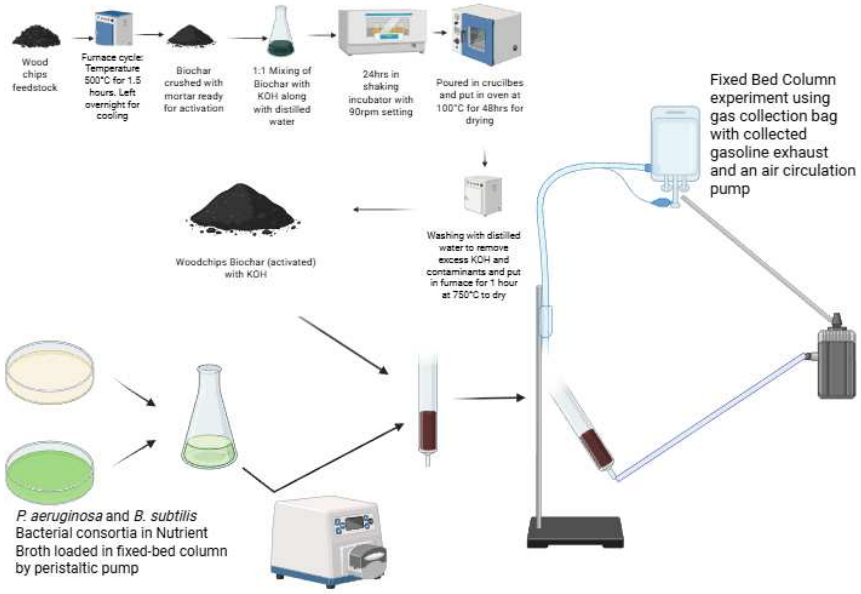


Fig. 1 *Graphical Abstract of the study*

The aim of conducting this study was to investigate the effectiveness of KOH-activated woodchip biochar inoculated with a bacterial consortium of *Bacillus subtilis* and *Pseudomonas aeruginosa* in the treatment of gasoline engine exhaust. The biochar was made by the pyrolysis of woodchips under controlled conditions and at 500 C and then

chemically activated by the ratio of biochar-KOH 1:1 to enhance its porosity, surface area and total adsorption capacity. The activated biochar was placed into a column and fixed, and flushed with distilled water. To guarantee uniform colonization of the bacterial cultures grown in nutrient broth, a mixed culture was introduced in the column. The exhaust of gasoline engines was pumped into gas-tight, sampling bags, and pumped into the column with the help of a gas compressor, the flow rate was controlled to ensure that the gas stream had enough time to mix with the biofilm. The system was left in the lab and ran throughout seven days. During the experiment, regular checks were done in order to have the operating conditions kept constant, and the gas composition, microbial activity, and structural characteristics of the biochar were assessed at the start and end of the seven-day trial. The activated biochar was cooled down and then washed by deionised water followed by 0.1 M HCl in the sequence until the pH reached neutral. It was then dried at 105°C and placed in airtight containers to be subsequently characterized and assembled into biofilters. Overall, the study design enables systematic evaluation of the combined adsorptive and biodegradative performance of KOH-activated biochar and hydrocarbon-degrading bacterial consortia for mitigating pollutants in engine exhaust emissions.

2.2 Biochar Preparation

Wood-chip biomass was collected from Quaid-i-Azam University's Central Workshop in Islamabad, Pakistan. The feedstock was initially washed to get rid of any loose debris, and then it was oven-dried for four hours at 120 °C to get rid of any moisture. Dried biomass was then exposed to slow pyrolysis at 500 °C for 90 min under oxygen-limited conditions in a muffle furnace to obtain raw biochar. Biochar yield was calculated as:

$$\text{Yield (\%)} = \frac{W_2}{W_1} \times 100$$

where W_1 is the dry feedstock mass and W_2 is the biochar mass after pyrolysis.

To obtain a uniform particle size appropriate for chemical activation and packing, the biochar was thoroughly crushed with pestle and mortar and then sieved. Chemical activation was carried out using analytical-grade potassium hydroxide (KOH). A 1:1 (w/w) biochar–KOH impregnation ratio was prepared and mixed for 1 h, followed by 24 h impregnation in a shaking incubator to achieve uniform diffusion of the activating agent. The impregnated material was dried at 100 °C for 48 h, then thermally activated at 750 °C for 1 h in a closed lid ceramic crucible.

Upon cooling, the activated biochar was sequentially cleaned with deionised water and 0.1 M HCl until the pH was neutral. It was then dried at 105 °C and kept in airtight containers for subsequent characterization and biofilter assembly.

2.3 Biochar Characterization

In order to determine the appropriateness of the activated biochar as an adsorptive and physiologically favorable medium, a comprehensive physicochemical characterization was conducted.

2.3.1 Proximate and Chemical Properties

Proximate analysis was conducted according to the ASTM D1762-84 (2007) standards, in order to establish the quantity of moisture, volatile matter, ash, and fixed carbon. EC measurements were recorded following a 24-hour equilibration of a 1:5 (w/v) biochar-water suspension, whereas the pH of biochar was measured by using a 1:10 (w/v) suspension. Collectively, these properties reveal information about acidity, ionic strength as well as carbon structure-parameters which are important in microbial colonisation and effective pollutant adsorption.

2.3.2 Fourier Transform Infrared Spectroscopy (FTIR)

The FTIR spectra were taken on a PerkinElmer system at the wavelength range of 400-4000 cm^{-1}. In order to analyze the chemical changes that pyrolysis and further activation by KOH caused, some of the key functional groups, such as hydroxyl (OH), carbonyl (C=O), aromatic C=C, and carboxyl groups, were analyzed. The reactive surface sites that help in adsorbing VOCs and biocatalytic interactions were determined through the variation in the peak intensity and changes in the band position.

2.4 Microbial Consortium

Bacillus subtilis and *Pseudomonas aeruginosa*, the hydrocarbon-degrading bacterial strains, were chosen due to their favourable metabolic abilities regarding the degradation of VOCs.

Pure cultures were streaked on nutrient agar and incubated for 24 h at 37 °C. Isolated colonies were inoculated separately into 50 mL nutrient broth and cultivated at 150–200 rpm for 18–24 h until reaching OD_{600} = 0.6–0.8 (~10^8 CFU/mL). Equal volumes of both cultures were then mixed and co-incubated for 18–24 h to form a stable microbial consortium. Gram staining, microscopic inspection, and biochemical tests such as catalase, citrate utilization, urease,

indole, and lactose fermentation tests, assisted by API identification kit, were used to validate the identity and viability of the strains. The validated consortium was used for immobilization in the biofilter column.

2.5 Fixed-bed Column Setup

The fixed-bed biofilter was built using a cylindrical glass column with an internal diameter of 2.5 cm and a length of 15 cm. After being cleaned with 70% ethanol and washed with sterile water, the column was autoclaved for 15 minutes at 121 °C.

The filter bed was prepared by evenly packing 30 g of sterilized activated biochar. A peristaltic pump was used to flow 500 mL of sterile distilled water through the column in order to eliminate particulates and guarantee uniform settling. During the biofiltration process, permeability and adequate void fraction were made certain to allow uniform gas distribution.

2.6 Exhaust Generation and Delivery

A 125 cc motorcycle engine was used as the source of gasoline exhaust and operated at a steady idle speed of approximately 1,400–1,600 RPM to keep the exhaust composition consistent. Before collecting samples, the engine was run for 10 minutes to reach stable operating conditions, since emissions during cold start are known to fluctuate and can strongly affect VOC, BTEX, CO, and NO_x levels. Once the engine reached thermal equilibrium, exhaust gases were sampled directly from the tailpipe. To maintain the original chemical makeup of the exhaust, including volatile organic compounds (VOCs), BTEX species, carbon monoxide (CO), nitrogen oxides (NO_x), and other combustion-related pollutants, the exhaust was collected in 2 L Teflon gas-tight sampling bags. The bags were then directly attached to the biofilter inlet with airtight Teflon tubing, reducing the chances of leakage, dilution or contamination by ambient air.

A low-flow air compressor was then used to feed the exhaust at a maintained flow rate of 2.0 L min -1 in the fixed-bed biofilter column. This flow rate ensured constant and even load of pollutants without causing too much pressure drop or channeling in the biofilter bed. Based on the column dimensions (2.5 cm internal diameter × 15 cm length), the internal column volume was approximately 0.074 L, giving an empty bed residence time (EBRT = V/Q) of approximately 2.2 s, which is adequate to permit effective gas–biofilm contact and microbial degradation.

2.7 Biofilm Formation and Operation

The microbial consortium was prepared and the 250 mL of it was added to the biochar packed column in six hours. In order to ensure even attachment of the microbes in the bed, up-flow and down-flow cycles alternated. The system was left undisturbed two to four hours after inoculation so that the microorganisms could settle on the biochar surface and start to form an introductory biofilm layer. A nutrient medium was then added to the flow of 0.75 mL/min to support the growth of biofilms under nonstress conditions and induce the microbial metabolism prior to exposure to exhaust pollutants after 48 hours.

The compressor, fixed-bed column, and exhaust sampling bag were then connected together, creating a recirculating biofiltration system made in a closed-loop. Seven days of continuous feeding of gasoline exhaust into the column at room temperature was carried out. The microbial activity in this stage was ensured through a steady flow rate and internal hydraulic pressure, avoiding desiccation, biofilm detachment by shear forces, and oxygen limitation. The performance of the biofilter after some time was analyzed by collecting samples of the exhaust gases before and after the biofiltration.

2.8 Analytical Evaluation

2.8.1 Gas Chromatography–Mass Spectrometry (GC-MS)

The Gas Chromatography-Mass Spectrometry (GC-MS) is a type of chromatography that is equipped with a mass spectrometer (MS) at its end. All samples of exhaust (treated and untreated) were extracted with dichloromethane (DCM) solvent and had to undergo GCMS to measure VOCs, BTEX compounds, and other hydrocarbons. Separating the compounds upon injection was done in split/splitless mode in a capillary column with optimized temperature program in light aromatics and aliphatics. The compounds were identified using the NIST mass spectral library matching and typical fragmentation patterns. Chromatographic peak areal extents were used as a basis of quantitative evaluation and inlet-outlet concentration differentials were used to calculate removal efficiencies.

2.8.2 FTIR Analysis of Biochar Before and After Treatment

FTIR (4000-400 cm^{-1}) was used to assess the alteration in surface functional groups of the biochar samples before exposure to gasoline exhaust pollutants and after exposure. The disparity will be taken as a pointer of removal performance of the biofilter.

3 Results

3.1 Physical Characteristics of Biochar:

The biochar generated during the pyrolysis process of the woodchips at 500°C in 90 minutes had a matte, dark black solid, an indicator which sufficiently revealed that the biomass was completely carbonized. The end product was a biochar of 36.9% or slightly more than a third of the starting mass of the woodchip turned to solid carbon. This yield represent an efficient thermal conversion at the selected conditions and is quite close to the range of values generally cited with lignocellulosic materials subjected to these temperatures.

3.2 Proximate Analysis of Biochar:

The proximate analysis indicates that the properties of the woodchips biochar have changed significantly once they have been activated with KOH. The untreated biochar contained some traces of moisture (0.75%), and the activated material was totally dry, which means that more bound water was removed. The percentage loss in volatile matter was also found to be considerably high, going down to 20.5% on activation compared to 37.5% of the inactivated biochar, which indicates an increase in thermal stability, and an enhanced carbon structure. Meanwhile, the amount of ash rose to 15.1% as opposed to 10.07% in the initial sample, which is probably caused by inorganic residues that were deposited during the activation process. Such modifications were also followed by an increment in fixed carbon, which rose from 52.4% in the untreated sample to 58.5% in the KOH-activated biochar. By and large, the findings propose the notion that chemical activation increased carbon enrichment and a more stabilized and adsorptive material that can be applied in the environment.

3.3 Chemical Characterization of Biochar:

The biochar of woodchips had a pH of 7.0 which implies that it is neither an acid nor basic and can be widely applied. Its electrical conductivity (EC) was between 2.2-5.0 μS cm^{-1} indicating a low concentration of soluble salts and indicating that it is chemically stable. These properties advocate the use of the biochar in adsorption and remediation of the environment.

3.4 Microscopy of Bacterial strains:

Both strains used in the biofiltration column set up were examined using microscopy. They are depicted in below:

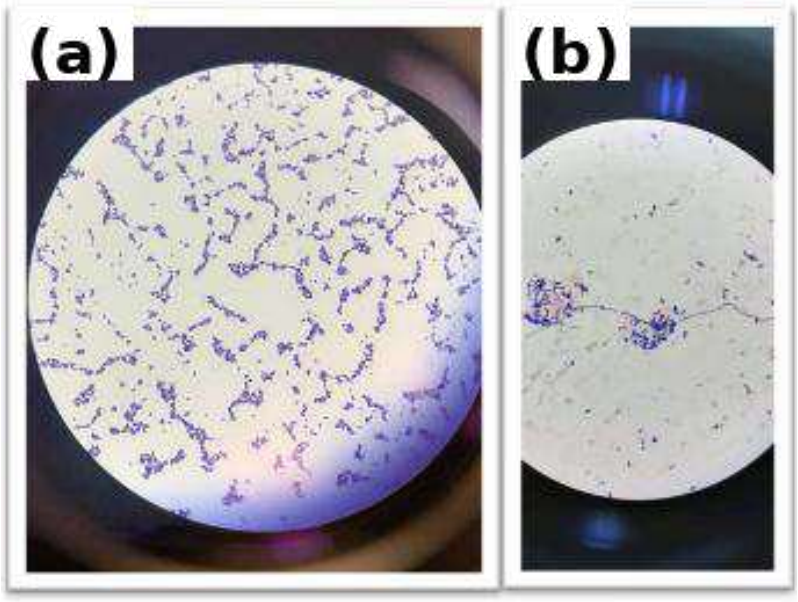


Fig. 2 *Gram-stained Bacillus subtilis: (a) low-magnification field showing purple-stained, rod-shaped cells arranged in long chains typical of Gram-positive bacilli; (b) higher-magnification view of a chained cluster showing the characteristic rod morphology*

Figure 2 shows microscopy of *Bacillus subtilis* after a Gram stain. The cells stain purple, which tells us they are Gram-positive, and they have the classic rod shape expected for this species. Many of the bacteria form long chains, while others are seen on their own or in small clusters, a pattern that reflects how the cells divide and often stay connected. The rods are fairly consistent in size and shape, giving the slide a neat, organized look. Altogether, the staining and arrangement are typical of *B. subtilis* and help set it apart from round bacteria or Gram-negative organisms.

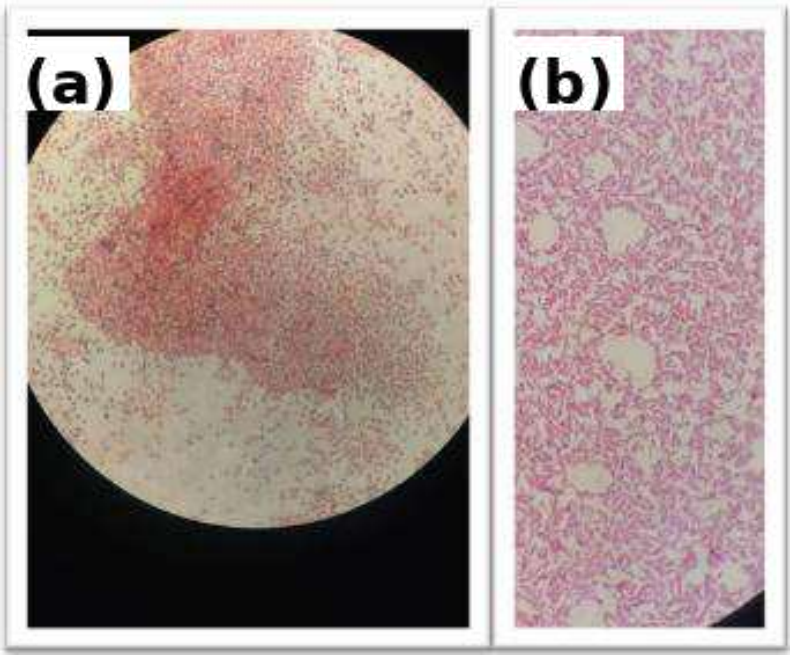


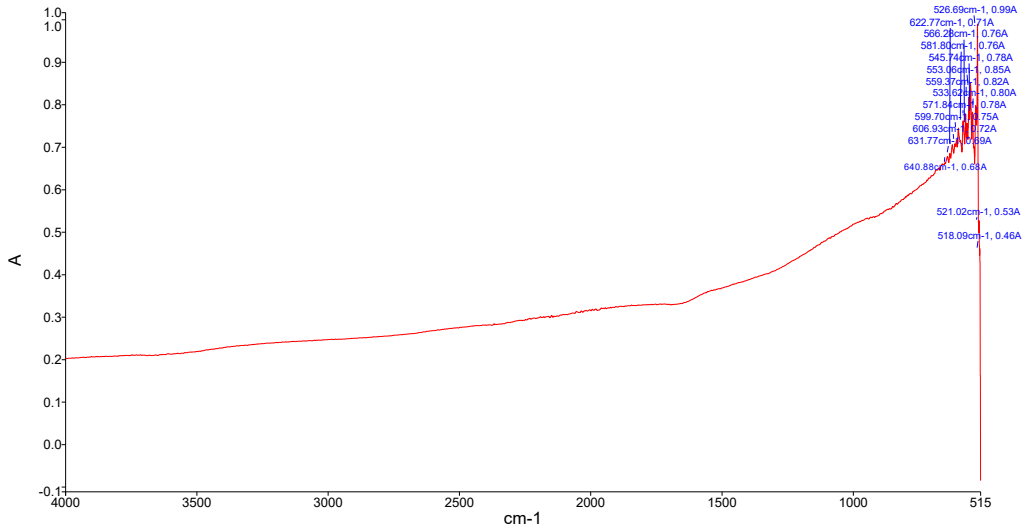
Fig. 3 *Gram-stained Pseudomonas aeruginosa: (a) low-magnification field showing pink to red, slender, straight-to-slightly-curved rod-shaped cells characteristic of Gram-negative bacilli; (b) higher-magnification view of the rod-shaped cell morphology*

Figure 3 gives the image of *P. aeruginosa* Under the microscope, which appears as slender, straight to slightly curved rod-shaped cells, typically arranged singly or in short, loose groupings. In Gram-stained preparations, the cells take on a pink to red color, confirming their Gram-negative nature. The rods are fairly uniform in size, giving the field a fine, evenly distributed texture, although denser clusters can sometimes be seen where cells have accumulated. Overall, the morphology is clean and well defined, with smooth cell outlines and a characteristic bacillary form that reflects a healthy, actively growing population.

3.5 FTIR Results

Figure 4 provides FTIR spectrum of woodchips biochar before the activation of KOH (NAB1).

261



262 ***Fig. 4*** *Non-activated Biochar FTIR spectrum (NAB1)*

263 *Table 1 FTIR absorption peaks and functional groups identified in NAB1 sample*

Wavenumber (cm^{-1})	Functional Group	Interpretation
627–631 cm^{-1}	Aromatic C–H out-of-plane bending	Indicates residual aromatic ring structures from lignin or other plant materials.
580–620 cm^{-1}	C–Br / C–Cl stretching	Possible trace halogens, may arise from process residues.
520–565 cm^{-1}	Metal–O or Si–O bending/stretching	Suggests the presence of inorganic minerals (e.g., silicates, oxides from ash).
< 520 cm^{-1}	Lattice vibrations or Fe–O/Mg–O types	Can also indicate heavy metal residues or crystalline ash components.

264

In the FTIR spectrum interpretation shown in Table 1, there are multiple structural and inorganic remnants of the sample. The band at 627-631 cm^{-1} indicates leftover aromatic rings, which is probably the result of lignin-based materials. Absorptions at 580-620 cm^{-1} indicates the presence of trace inorganic halogen-containing groups, and the such 520-565 cm^{-1} indicates the presence of an inorganic mineral phase like metal oxygen or silicate compounds. Peaks less than 520 cm^{-1} also contribute towards the existence of lattice vibrations that would relate to the existence of heavy-metal oxides or crystalline ash materials.

Figure 5 shows the spectrum of KOH activated woodchips biochar (BT1) before exposure to pollutants of the gasoline engine in the biofilter.

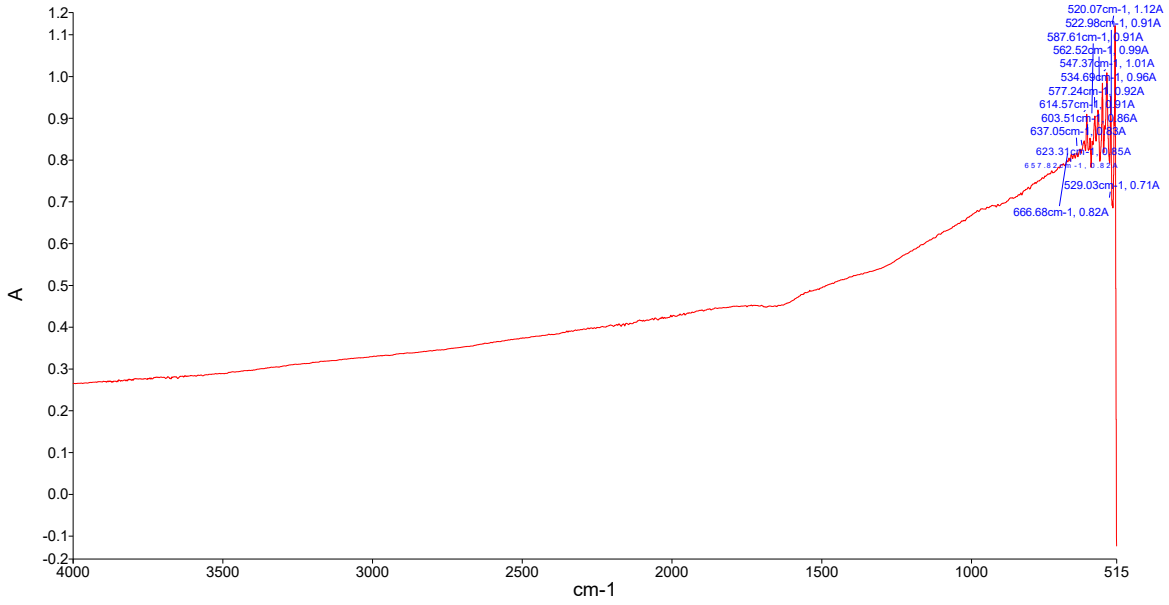


Fig. 5 *FTIR spectrum of KOH activated Biochar before treatment in biofilter (BT1)*

Table 2 FTIR absorption peaks and functional groups identified in BT1 sample

Wavenumber (cm^{-1})	**Functional Group**	**Interpretation**
665–675 cm^{-1}	Aromatic C–H out-of-plane bending	Stronger than in NAB1, suggesting more developed aromatic ring structures

615–625 cm^{-1}	C–Cl / C–Br or metal–O stretching	May indicate residual potassium compounds (e.g., KCl, KBr, or metal-oxygen bonds)
540–580 cm^{-1}	Si–O or metal–O stretching	Likely from ash or reaction products of KOH with silica or other minerals
520 cm^{-1}	Strong metal–O or K–O bonding	Indicates potassium residues from KOH activation

As shown in Table 2, A greater aromatic C–H out-of-plane bending band of higher intensity at 665-675 cm^{-1} can be observed in the FTIR spectrum, which shows that the aromatic ring structure is more developed in the BT1 sample than in the NAB1 sample. The characteristics of absorption in the range of 615-625cm^{-1} indicate the existence of the remaining potassium-related substance, including KCl, KBr, or additional metal-oxygen complexes. The presence of bands at 540-580 cm^{-1} would indicate silicate or metal groups, which are probably due to the presence of ash content or the result of an activation reaction in activating KOH. Furthermore, a strong band at 520 cm^{-1} also indicates strong metal-oxygen or K-O bonding, and it is confirmed that potassium residues remain in the activated biochar matrix.

3.5.1 Comparison of BT1 and NAB1:

The most striking comparison is between the KOH-activated biochar (BT1) and non-activated sample in that the former has a considerably higher peak intensity in the range that spans 500-700 cm^{-1} indicating a more well-developed structural framework. BT1 also has more functional diversity, as it has several other inorganic and aromatic bands which are mostly missing in the non-activated biochar (NAB1). Specifically, all the peaks related to metal and oxygen and potassium (including K-O or potassium oxide and carbonate species) can be observed vividly in BT1 yet are weak or not present in NAB1. This verifies the chemical modifications that have been made by activating KOH.

291 Figure 6 shows the FTIR spectrum of KOH-activated biochar in the end of the biofiltration experiment (AT1).

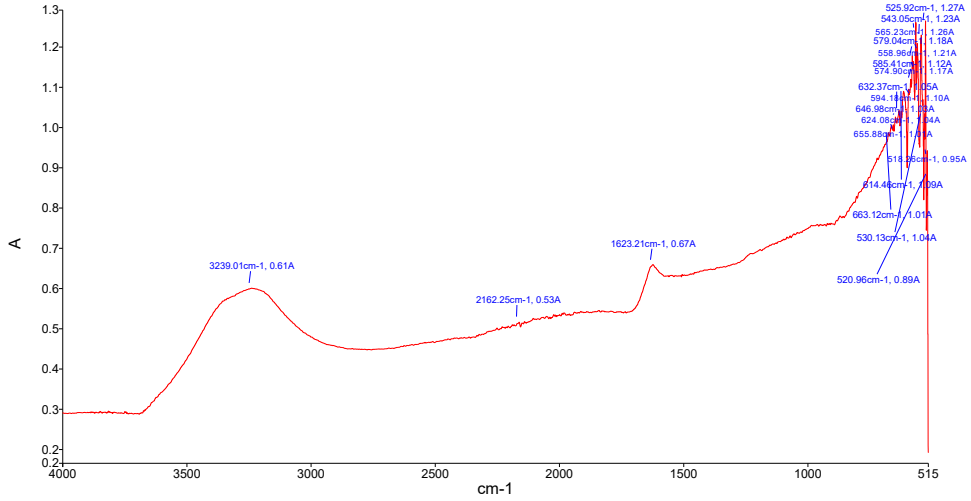


Fig. 6 *FTIR spectrum of KOH activated Biochar after treatment in biofilter (AT1)*

292

293

294 *Table 3 FTIR absorption peaks and functional groups identified in AT1 sample*

Wavenumber (cm^{-1})	**Functional Group / Vibration**	**Interpretation**
3299 cm^{-1}	O–H or N–H stretch (broad)	Indicative of hydroxyl or amine groups; likely from microbial metabolites, proteins, or EPS (extracellular polymeric substances).
2162 cm^{-1}	C≡C or C≡N stretch (alkyne or nitrile)	Could originate from hydrocarbon breakdown products (exhaust gas or microbial degradation of gasoline components).
1623 cm^{-1}	C=O (amide I), C=C, or aromatic ring	Stronger than in BT1 — suggests protein binding, aromatic

		structures, or carbonyl groups introduced by microbes.
550–650 cm^{-1}	Aromatic C–H bend / Metal–O / P–O	Enhanced, suggesting metal interaction, phosphate groups, or increased ash/mineral content from biofilm or gas exposure.
520–530 cm^{-1}	K–O or Si–O stretch	Still visible from original KOH activation, but more overlapped with biological residues.

As interpreted in Table 3, the spectrum of the biologically treated sample shows a number of different characteristics that indicate the presence of microbial activity, as well as the intrinsic properties of the activated biochar. A wide band at 3299 cm^{-1} implies O -H or N -H vibrations, which reveals the existence of hydroxyl- or amine-containing biomolecules including microbial metabolites, proteins, or extracellular polymeric substances (EPS). At 2162 cm^{-1}, attributed to C -C or C -N stretching, there is a peak that is presumably the result of hydrocarbon transformation products formed in the breakdown of gasoline-derived exhaust products by microbes. This high absorption at 1623 cm^{-1} compared to BT1 indicates a greater contribution of amide I (C=O) structure, aromatic C=C structure or conjugated carbonyl structures associated with microbial colonisation as well as metabolic by-products. The presence of improved signals at 550-650 cm^{-1} reflects interactions with aromatic C-H bending, or metal-oxygen coordination or phosphate-containing groups, which is indicative of increased mineral residues or biofilm-associated material. The rest of the band at 520-530 cm^{-1} is K -O or Si -O stretching remnant of the initial KOH activation, but is partially covered by the biological residues that form during treatment.

Comparative analysis of the FTIR spectra of the sample before and after biological treatment indicates clearly that the activated biochar was chemically modified. A clear band is observed in the treated sample at approximately 3300 cm^{-1}, in O-H or N-H stretching, which was missing or with low intensity in BT1. This feature is an indicator of the presence of hydroxyl- or amine-containing species that are related to microbial biomass, enzymes or moisture. Furthermore, the 1600-1700 cm^{-1} region is characterized by a strong positive shift in carbonyl absorption, which

corresponds to the microbial metabolite, enzyme proteins, or newly developed functional groups. The 2100 -2200 cm^{-1} range further indicates the presence of a new peak attributed to C=C or C=N, which is an indication of an interaction with the hydrocarbons derived by the exhausts or the transformation products of microbial degradation. Though the region of 500-700 cm^{-1} still reflects metal-oxygen and ash related vibrations, the fact that the intensity of this region is higher in AT1 could be due to more interactions of minerals, which can be caused by bacterial attachment, phosphate additions, or alterations in the surface chemistry after treatment.

3.6 GC-MS Results:

Figure 7 and Figure 8 respectively provides the untreated exhaust gas sample and treated exhaust gas sample in the technique of chromatography prepared and analyzed in analytical grade Di-cholormethane (DCM) solvent.

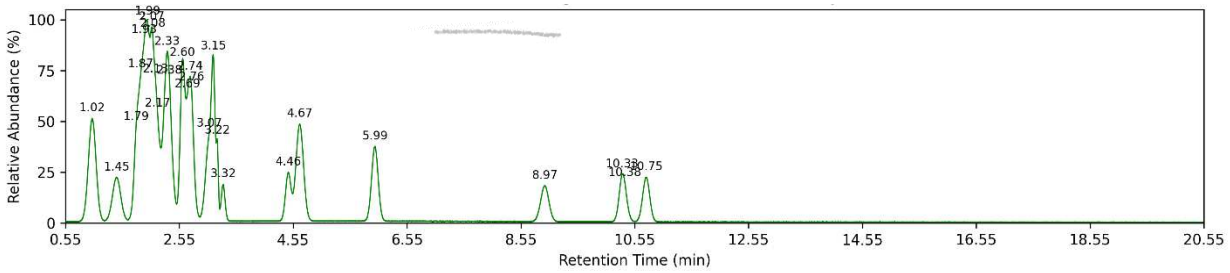


Fig. 7 *Chromatogram of Untreated Exhaust Gas sample prepared in Di-Chloromethane (DCM)*

The chromatogram indicates that there is a rich chemical mixture that is spread in the large range of retention time, where majority of the compounds eluted in the initial stages between 1.0 and 3.5 minutes. It is a high density area with sharp and well resolved peaks implying a high concentration of light hydrocarbons and oxygenated volatiles that travel rapidly through the column under the conditions applied. This part has clear indications at 1.02, 1.45, 1.79, 2.17, 2.33, 2.60, and 3.02 minutes that represent a high-density concentration of low-molecular-weight aromatics, aliphatics and small aldehydes or alcohols. In addition to this initial window, there are clear peaks at approximately 4.46, 4.67 and 5.99 minutes indicating the existence of compounds of moderate weight. Some subsequent-eluting components can be observed close to 8.97, 10.38 and 10.75 minutes, which may be considered the heavier aromatics and species of the ester type. Collectively, the profile is a representation of the very complex nature of the exhaust-derived sample, where the separation of the various peaks is excellent, and the baseline is stable to allow the identification and quantification of the various compounds with confidence.

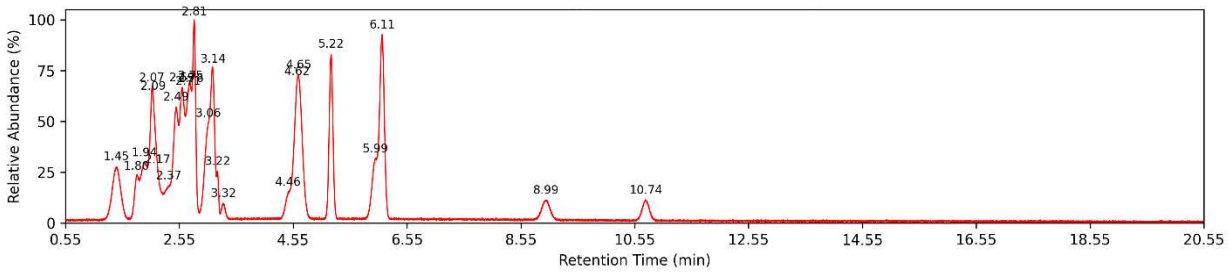


Fig. 8 *Chromatogram of Treated Exhaust Gas sample prepared in DCM*

The change in the chemical composition of the treated exhaust sample is evident in the chromatogram and this shows the effects of the treatment process. Just as in the untreated sample, the majority of compounds continue to be eluted early, roughly between 1.0 and 3.5 minutes in general, although the overall distribution is significantly cleaner with less overlap between peaks and even more defined and distinct signals. Strong responses at around 2.01, 3.14, 4.65, 5.22, and 6.11 minutes stand out, suggesting that only a limited number of compounds dominate after treatment. A few mid-range peaks near 4.46 and 5.99 minutes remain visible, while just two late-eluting components appear around 8.99 and 10.74 minutes. Compared to the untreated exhaust, the later part of the chromatogram is far less crowded, reflecting a clear shift in composition as a result of the treatment.

3.6.1 Mass Spectrometry

Table 4 Compounds identification in Untreated Gas Sample

Retention Time (min)	Compound	Relative Area %	Match Quality
1.02	Benzene	0.96	96
1.449	Nonane	3	95
1.789	Octane	1.27	96
1.87	m-Xylene	7.44	94
1.933	Styrene	5.6	92
1.991	Hexane	5.54	91
2.068	Benzaldehyde	0.7	87
2.082	Acetic acid	3.13	97
2.132	Acetaldehyde	4.88	97
2.169	Cresol	2.67	86
2.335	Propanoic acid	6.85	86
2.378	o-Xylene	3.67	89
2.599	Ethanol	4.71	89

2.69	Acetone	5.32	97
2.741	Decane	2.92	84
2.764	Toluene	1.78	82
3.073	Benzoic acid	5.38	89
3.149	Butanol	4.38	84
3.219	Isopropanol	1.07	87
3.319	Phenol	1.15	93
4.464	Ethylbenzene	2.23	93
4.665	Formaldehyde	6.86	86
5.986	Heptane	4	90
8.97	Ethyl acetate	2.72	90
10.326	Methanol	1.79	92
10.752	Naphthalene	7.35	91

347

348 *Table 5 Compounds identification in Bio-filter treated Sample*

Retention Time (min)	Compound	Relative Area %	Match Quality
1.446	Nonane	4.52	95
1.796	Octane	1.56	96
1.936	Styrene	5.96	92
2.067	Benzaldehyde	1.12	87
2.092	Acetic acid	4.63	97
2.172	Cresol	3	86
2.366	o-Xylene	3.15	89
2.494	2-Hydroxybenzaldehyde	5.95	82
2.594	Ethanol	4.95	89
2.707	Acetone	7.66	97
2.748	Decane	2.19	84
2.756	Toluene	1.26	82
3.058	Benzoic acid	7.77	89
3.141	Butanol	4.93	84
3.223	Isopropanol	0.86	87
3.324	Phenol	0.61	93
4.46	Ethylbenzene	1.28	93
4.617	Catechol	2.75	86
4.646	Formaldehyde	10.18	86
5.216	Acetaldehyde	6.14	89
5.993	Heptane	4	90
6.113	Propanoic acid	8.13	88
8.989	Ethyl acetate	1.89	90
10.744	Naphthalene	1.67	91

The standard formula for removal efficiency (RE) is:

$$\left(\frac{C_{\%area\ before} - C_{\%area\ after}}{C_{\%area\ before}}\right) \text{x } 100$$

According to this, the removal efficiency for each targeting BTEX compounds and PAH (Naphthalene) was calculated individually along with removal efficiency of all of them combined. This is shown in Table 6.

Table 6 Removal Efficiency calculation

Compound	Area Before (%)	Area After (%)	Reduction Efficiency (%)
Benzene	**0.96**	**0**	**100**
Toluene	**1.78**	**1.26**	**29.21**
Ethylbenzene	**2.23**	**1.28**	**42.6**
o-Xylene	**3.67**	**3.15**	**14.17**
m-Xylene	**7.44**	**0**	**100**
Naphthalene	**7.35**	**1.67**	**77.28**
TOTAL (BTEX+Naphthalene)	**23.43**	**7.36**	**68.59%**

Because these values are expressed as relative peak area rather than absolute concentration, apparent increases in individual compounds may partly reflect renormalization to the total peak area rather than true production; formaldehyde and acetaldehyde, for example, both increased in relative abundance after treatment despite not being among the compounds targeted for removal. Removal efficiencies reported here should therefore be interpreted as semi-quantitative rather than absolute.

4 Discussion

Biochar has gained a lot of attention in the environmental remediation area because of its porous nature, high surface area and chemically reactive carbon network as well as its sustainability and low cost. It offers a two-fold advantage of eliminating pollutants as well as sequestration of carbon. Its hydrocarbon, particulate matter, and volatile organic compounds (VOC) adsorbing properties are determined by pore fillers, π-π electron donor acceptor interactions, and

electrostatic forces. Specifically, biochar prepared by woodchips followed by its activation with potassium hydroxide (KOH) demonstrates an improved porosity and surface chemistry, rich in minerals, which is why it could be a promising solution to the gasoline engine exhaust treatment (Díaz-Maroto & Mašek, 2023).

When applied to Pakistan, biochar and sustainable environmental technologies research is gaining traction, however, most of the existing research has been conducted in the areas of soil improvement and agricultural uses, but not in air pollution mitigation. Agricultural residues production into biochar (as a measure to mitigate open-field burning and smog) has been tested as pilot projects because biochar production offers national sustainable agriculture and climate benefits (biochar pilots under COP29 goals) as well. The importance of these initiatives is especially explained by the fact that Pakistan is one of the countries with the poorest air quality in the world, and high rates of PM2.5 emissions associated with automobile traffic and other factors are highly dangerous to human health. Although the necessity to find a solution to air pollution is acute, there is an evident deficit in studies on the topic that specifically focuses on the use of biochar in addressing vehicle pollution, which makes the current research relevant and innovative in terms of developing air pollution regulation practices that can be applied to address the Pakistan's environmental issues.

Even though biochar alone is also an effective physical and chemical adsorbent, by combining it with microbial consortia like *Bacillus subtilis* and *Pseudomonas aeruginosa*, it is possible to have a synergistic biofiltration system that would be capable of capturing and degrading gaseous pollutants. These microbes have various metabolic pathways on oxidation of hydrocarbons, and the biochar immobilization offers a protective microenvironment and availability of adsorbed pollutants. It is a combination of adsorption and biodegradation processes that not only increases the life of filters by biologically replacing the lost adsorption sites, but also provides an alternative to conventional adsorption only filters (Chaudhary, 2023; Zhao et al., 2022).

Proximate analysis ensured that there was significant physicochemical enrichment of woodchip biochar after activation of KOH. The activated material had lower moisture and volatile matter, higher ash content and higher fixed carbon compared to non activated biochar, showing better carbonization, aromaticity and thermal stability. Lima et al. (2015) also described similar activation trends; nevertheless, their procedure involved more severe activation conditions and increased chemical loading. Conversely, the current study produced significant structural enhancement under the moderate pyrolysis conditions (500 °C, 1.5 h) showing better energy efficiency and scalability.

This increment in ash level following activation correlates with base catalyzed mineral changes and remnants of potassium compounds, which were earlier documented (Lima et al., 2015). Biochar yield (36.9%), near-neutral pH (7.0), and EC values (2.2–5.0 μS cm^{-1}) were in agreement with values at wood-based biochar that Beesley et al. (2010) reported and thus indicated suitability to use in environmental practices. As compared to previous works, this research also develops wood-derived biochar in the context of practical air pollution control systems, rather than relying on agronomic applications. In addition, Consortium based method offers greater metabolic diversity and system stability over mono culture biofilters, boosts tolerance to changing exhausts compositions and broadens hydrocarbon-degradation pathways.

The FTIR analysis showed that the non-activated and KOH-activated biochar had significant structural and mineralogical changes especially in the low-wavenumber region (below 700 cm^{-1}) that is associated with aromatic skeletal vibrations, inorganic ash components, and metal-oxygen bonding. The absorption band at 627-631 cm^{-1} is associated with the out-of-plane bending of aromatic C -H in non-activated biochar, which proves the existence of condensed aromatic structures formation through the use of lignin-rich biomass, which is consistent with Keiluweit et al. (2010) and Zhao et al. (2017). Other bands present at 580-620 cm^{-1} are due to C -Cl/ C -Br vibration which is probably because of the presence of trace halogens introduced in the growth or processing of biomass (Beesley et al., 2010). Bands that are lower than 565 cm^{-1} denote metal oxide and silicate lattice vibrations due to its ash fraction (Lima et al., 2015).

After the addition of KOH, aromatic skeletal vibrations of 665-675 cm^{-1} were enhanced, as a result of enhanced aromatic condensation and carbon reorganization. This is consistent with the results of Zhao et al. (2017) and Corro et al. (2024), who found an improvement in the graphitic domain formation when KOH is activated. The presence of strong potassium-oxygen and metal-oxygen bands at 615-625 cm^{-1} and 520-521 cm^{-1} proves the integration of mineral phases with potassium to the carbon structure (Lima et al., 2015; David, 2023; Sadegh et al., 2024). These are mineral carbon hybrid structures that increase the π-π interaction between aromatic hydrocarbons and provide sites of catalysis, enabling the activated biochar to be utilized as an adsorbent and catalytic support. The analysis of the FTIR spectrums before and after the biological treatment showed that the biochar was definitely chemically altered. The main band at about 3300 cm^{-1} in the treated sample is an indication of O-H or N-H stretching, which is a species with hydroxyl or amine molecules associated with microbial biomass, enzymes or moisture. The 1600-1700 cm^{-1} zone was also

positively changed by carbonyl absorption to indicate microbial metabolites, enzyme proteins or functional groups formed. The appearance of a new peak in the 2100-2200 cm^{-1} range implies the interactions with hydrocarbons or with products of microbial transformation. The 500-700 cm^{-1} range also highlights the presence of metaloxygen and ash vibrations though the greater strength in the treated biochar indicates higher mineral interactions either by attaching bacteria or reacting with surface chemistry.

The direct evidence of the effectiveness of the developed biofiltration system to treat the gasoline engine exhaust is provided by the GCMS analysis. The untreated exhaust chromatogram had high-intensity peaks of BTEX compounds and other hydrocarbons, which are similar to those observed by Allahabady and Yousefi (2022). Peak number and intensity were significantly low after treatment, which showed efficient removal of pollutants. The selective oxidation of alkyl side chains by the microbial consortium is in agreement with Mukherjee & Bordoloi (2012) and Wu & Xiu (2023) and indicates that mitigation oxidized m-xylene and ethylbenzene over the alkyl side chains. Further evidence of the high affinity of the activated biochar to lipophilic PAHs and their microbial degradation is high sorption of naphthalene (77.3%), which is mentioned by Zhou & Shi (2022).

The post-treatment appearance of catechol (2.75%) and 2-hydroxybenzaldehyde (5.95%), both absent from the untreated chromatogram, is consistent with ring-hydroxylation and ring-cleavage activity typical of monooxygenase- and dioxygenase-mediated aromatic biodegradation pathways (Seo & Keum, 2009). Although earlier studies have investigated biochar as a microbial support medium (El-Naas & Acio, 2014; Jayawardhana & Keerthanan, 2021), the current research contributes to the development of this idea by showing continuous treatment of gasoline exhaust in a fixed-bed setup. In line with the research of Niu et al. (2024), biochar increased the efficiency of the mass transfer and biofilm growth and facilitated the gas-phase remediation compared to laboratory aqueous systems.

Overall, this paper substantiates that KOH-activated woodchip biochar immobilized by a consortium of *Bacillus subtilis* and *Pseudomonas aeruginosa* is capable of capturing gasoline engine exhaust pollutants in a synergistic adsorption-biodegradation mechanism. It should be noted that these findings are based on a single experimental run rather than replicate trials, so the reported removal efficiencies represent a preliminary indication of feasibility rather than a statistically validated result; replicate runs would be needed to establish the reproducibility of these findings. Even though substantial decreases in hazardous hydrocarbons and VOCs were confirmed under controlled laboratory conditions, this system is not yet tested in terms of long-term stability of microbes, safety of biochar, and its

functioning during the changing compositions of exhausts. Future directions in this would be therefore towards continuous flow and field scale validation, long term operational stability and investigation of alternative biomass feedstocks or microbial consortia to expand degradation pathways. Addressing these aspects in future research might further validate the biofilter's biodegradation potential.

5 Conclusion

In this paper, it has been shown that KOH-activated biochar on woodchips is an effective media in the removal of gasoline engine exhausts. FTIR, proximate, and pH/EC analysis revealed that the biochar had high porosity, structural stability, and a large number of functional groups, which offered an ideal surface on which microbes could be colonized. An effective consortium of *Bacillus subtilis* and *Pseudomonas aeruginosa* was effectively immobilized on biochar, which increased the biodegradation and formed a synergistic system that was able to remove volatile organic compounds and other dangerous contaminants. The analysis, GC-MS and FTIR, reflected that there was a significant reduction in harmful emissions, which indicates the feasibility of the method. Experiments were, however, done in controlled laboratory conditions and may not fully represent real-world exhaust streams. The long-term microbial stability, the biochar durability and the performance under variable exhaust compositions are not tested. Future studies should concentrate on continuous-flow and field-scale applications, long term operation evaluations and exploration of alternative biomass feeds and microbial consortia to widen the degradation routes. With more optimization, this biologically active biochar platform can be a cheaper solution to the control of vehicular emissions, specifically in industrial and urban areas of Pakistan.

Statements and Declarations

Ethical Approval

This study did not involve human participants, human biological samples, animals, or clinical trials. All experiments were conducted using biochar and bacterial cultures under standard laboratory conditions. Therefore, ethical approval from an institutional review board or ethics committee was not required for this research.

Consent to Participate

Not applicable.

Consent for Publication

Not applicable.

Availability of Data and Materials

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors. The work was conducted as part of the author's academic research under laboratory supervision at Quaid-i-Azam University.

References

Abo-State, M. A. M., & El-Kelani, T. A. (2020). Bacterial biodegradation pathways of low and high molecular weight polycyclic aromatic hydrocarbons (PAHs). *Archives of Petroleum & Environmental Biotechnology, 5*, 158. https://doi.org/10.29011/2574-7614.100058

Agarwal, A. K., & Mustafi, N. N. (2020). Real-world automotive emissions: Monitoring methodologies, and control measures. *Renewable and Sustainable Energy Reviews, 137*, 110624. https://doi.org/10.1016/j.rser.2020.110624

Allahabady, A., Yousefi, Z., Mohammadpour Tahamtan, R. A., & Payandeh Sharif, Z. (2022). Measurement of BTEX (benzene, toluene, ethylbenzene and xylene) concentration at gas stations. *Environmental Health Engineering and Management Journal, 9*(1), 23–31. https://doi.org/10.34172/EHEM.2022.04

Anjum, M. S., Ali, S. M., Imad-ud-din, M., Subhani, M. A., Anwar, M. N., Nizami, A. S., Ashraf, U., & Khokhar, M. F. (2021). An emerged challenge of air pollution and ever-increasing particulate matter in Pakistan: A

critical review. *Journal of Hazardous Materials, 402*, 123943. https://doi.org/10.1016/j.jhazmat.2020.123943

Beesley, L., Moreno-Jiménez, E., & Gomez-Eyles, J. L. (2010). Effects of biochar and greenwaste compost amendments on mobility, bioavailability and toxicity of inorganic and organic contaminants in a multi-element polluted soil. *Environmental Pollution, 158*(6), 2282–2287. https://doi.org/10.1016/j.envpol.2010.02.003

Chaudhary, D. K., Park, J.-H., Kim, P.-G., Ok, Y. S., & Hong, Y. (2023). Enrichment cultivation of VOC-degrading bacteria using diffusion bioreactor and development of bacterial-immobilized biochar for VOC bioremediation. *Environmental Pollution, 320*, Article 121089. https://doi.org/10.1016/j.envpol.2023.121089

Colbeck, I., Nasir, Z. A., & Ali, Z. (2010). The state of ambient air quality in Pakistan—A review. *Environmental Science and Pollution Research, 17*(1), 49–63. https://doi.org/10.1007/s11356-009-0217-2

Corro, E., Antxustegi, M., Murua Berrio, J., & Gonzalez Alriols, M. (2024). Residual lignocellulosic biomass-based activated biochar: Comparison between single and two-step thermochemical and activation processes. *Chemical Engineering Transactions, 109*, 217–222. https://doi.org/10.3303/CET24109037

Costa, M. A. M., da Silva, B. M., de Almeida, S. G. C., Felizardo, M. P., Costa, A. F. M., Cardoso, A. A., & Dussán, K. J. (2023). Evaluation of the efficiency of a Venturi scrubber in particulate matter collection smaller than 2.5 μm emitted by biomass burning. *Environmental Science and Pollution Research, 30*(4), 8835–8852. https://doi.org/10.1007/s11356-022-22786-3

David, E. (2023). Production of activated biochar derived from residual biomass for adsorption of volatile organic compounds. *Materials, 16*(1), 389. https://doi.org/10.3390/ma16010389

Debelu, D., Mengistu, D. A., Aschalew, A., Mengistie, B., & Deriba, W. (2024). Global public health implications of traffic-related air pollution: Systematic review. *Environmental Health Insights, 18*, 11786302241272403. https://doi.org/10.1177/11786302241272403

Deng, L., Xia, W., Yang, Z., Zhang, W., Feng, D., Sun, S., & Zhao, Y. (2025). Research on biochar prepared by trace KOH catalyzed CO_2 activation vs KOH activation as advanced candidate for carbon capture. *Journal of Fuel Chemistry and Technology, 53*(9), 1330–1341.

Díaz-Maroto, C. G., Mašek, O., Pizarro, P., Serrano, D. P., Moreno, I., & Fermoso, J. (2023). Removal of NO at low concentrations from polluted air in semi-closed environments by activated biochars from renewable feedstocks. *Journal of Environmental Management, 341*, Article 118031. https://doi.org/10.1016/j.jenvman.2023.118031

Dong, H., Zhang, L., Shao, L., Wu, Z., Zhan, P., Zhou, X., & Chen, J. (2022). Versatile strategy for the preparation of woody biochar with oxygen-rich groups and enhanced porosity for highly efficient Cr(VI) removal. *ACS Omega, 7*(1), 863–874. https://doi.org/10.1021/acsomega.1c05506

Edeh, I. G., Mašek, O., & Fusseis, F. (2023). 4D structural changes and pore network model of biomass during pyrolysis. *Scientific Reports, 13*(1), 22863. https://doi.org/10.1038/s41598-023-49919-z

El-Naas, M. H., Acio, J. A., & El Telib, A. E. (2014). Aerobic biodegradation of BTEX: Progresses and prospects. *Journal of Environmental Chemical Engineering, 2*(2), 1104–1122. https://doi.org/10.1016/j.jece.2014.04.009

Fang, X., Zhang, M., Zheng, P., Wang, H., Wang, K., Lv, J., & Shi, F. (2024). Biochar–bacteria–plant combined potential for remediation of oil-contaminated soil. *Frontiers in Microbiology, 15*, 1343366. https://doi.org/10.3389/fmicb.2024.1343366

Hendrych, J., Arvajová, A. B., & Špaček, P. (2021). Innovative packing material for waste gas biofiltration. *Environmental Technology & Innovation, 24*, 101837. https://doi.org/10.1016/j.eti.2021.101837

Jayawardhana, Y., Keerthanan, S., Lam, S. S., & Vithanage, M. (2021). Ethylbenzene and toluene interactions with biochar from municipal solid waste in single and dual systems. *Environmental Research, 197*, Article 111102. https://doi.org/10.1016/j.envres.2021.111102

Keiluweit, M., Nico, P. S., Johnson, M. G., & Kleber, M. (2010). Dynamic molecular structure of plant biomass-derived black carbon (biochar). *Environmental Science & Technology, 44*(4), 1247–1253. https://doi.org/10.1021/es9031419

Khan, M. W., Ali, Y., De Felice, F., Salman, A., & Petrillo, A. (2019). Impact of brick kilns industry on environment and human health in Pakistan. *Science of the Total Environment, 678*, 383–389. https://doi.org/10.1016/j.scitotenv.2019.04.369

Lima, I., Ro, K., Reddy, G., Boykin, D., & Klasson, K. (2015). Efficacy of chicken litter and wood biochars and their activated counterparts in heavy metal clean up from wastewater. *Agriculture, 5*(3), 806–825. https://doi.org/10.3390/agriculture5030806

Liu, L., Li, Y., & Fan, S. (2019). Preparation of KOH and H_3PO_4 modified biochar and its application in methylene blue removal from aqueous solution. *Processes, 7*(12), 891. https://doi.org/10.3390/pr7120891

Mansha, M., Saleemi, A. R., & Naqvi, J. H. (2011). Status and spatial visualization of toxic pollutants (BTEX) in urban atmosphere. *Advances in Chemical Engineering and Science, 1*(4), 231–238. https://doi.org/10.4236/aces.2011.14033

Mukherjee, A. K., & Bordoloi, N. K. (2012). Biodegradation of benzene, toluene, and xylene (BTX) in liquid culture and in soil by *Bacillus subtilis* and *Pseudomonas aeruginosa* strains and a formulated bacterial consortium. *Environmental Science and Pollution Research International*. https://doi.org/10.1007/s11356-012-0862-8

Nakhjirgan, P., Fanaei, F., Jafari, A. J., Gholami, M., Shahsavani, A., & Kermani, M. (2024). Extensive investigation of seasonal and spatial fluctuations of BTEX in an industrial city with a health risk assessment. *Scientific Reports, 14*(1), 23662. https://doi.org/10.1038/s41598-024-74901-8

Niu, S., Li, C., Gao, S., Tian, J., Zhang, C., Li, L., Huang, Y., & Lyu, H. (2024). Biochar, microbes, and biochar–microbe synergistic treatment of chlorinated hydrocarbons in groundwater: A review. *Frontiers in Microbiology, 15*, 1443682. https://doi.org/10.3389/fmicb.2024.1443682

Pachaiappan, R., Cornejo-Ponce, L., Rajendran, R., Manavalan, K., Rajan, V. F., & Awad, F. (2022). A review on biofiltration techniques: Recent advancements in the removal of volatile organic compounds and heavy metals in the treatment of polluted water. *Bioengineered, 13*(4), 8432–8477. https://doi.org/10.1080/21655979.2022.2050538

Rasheed, A., Aneja, V. P., Aiyyer, A., & Rafique, U. (2015). Measurement and analysis of fine particulate matter (PM2.5) in urban areas of Pakistan. *Aerosol and Air Quality Research, 15*(2), 426–439. https://doi.org/10.4209/aaqr.2014.10.0269

Sadegh, F., Sadegh, N., Wongniramaikul, W., Apiratikul, R., & Choodum, A. (2024). Adsorption of volatile organic compounds on biochar: A review. *Process Safety and Environmental Protection, 182*, 559–578. https://doi.org/10.1016/j.psep.2023.11.071

Sapate, K. D., & Tikekar, A. N. (2008). Pollution aspects of emissions from small two-stroke automobile engines. *Nature Environment and Pollution Technology, 7*(1), 33–38.

Seo, J.-S., Keum, Y.-S., & Li, Q. X. (2009). Bacterial degradation of aromatic compounds. *International Journal of Environmental Research and Public Health, 6*(1), 278–309. https://doi.org/10.3390/ijerph6010278

Sharif, H. M. A., Mahmood, N., Wang, S., Hussain, I., Hou, Y.-N., Yang, L.-H., Zhao, X., & Yang, B. (2021). Recent advances in hybrid wet scrubbing techniques for NOx and SO_2 removal: State of the art and future research. *Chemosphere, 273*, 129695. https://doi.org/10.1016/j.chemosphere.2021.129695

Sheoran, K., Siwal, S. S., Kapoor, D., Singh, N., Saini, A. K., Alsanie, W. F., & Thakur, V. K. (2022). Air pollutants removal using biofiltration technique: A challenge at the frontiers of sustainable environment. *ACS Engineering Au, 2*(5), 378–396. https://doi.org/10.1021/acsengineeringau.2c00020

Song, X., & Hao, Y. (2024). Emission characteristics and health effects of PM2.5 from vehicles in typical areas. *Frontiers in Public Health, 12*, 1326659. https://doi.org/10.3389/fpubh.2024.1326659

Usman, A., Salisu, L., & Iliyasu, A. L. (2023). Review on technological challenges of vehicle engine emissions control. *International Journal of Engineering Research & Technology, 12*(5), 691.

Wu, B., Xiu, J., Yu, L., Huang, L., Yi, L., & Ma, Y. (2023). Degradation of crude oil in a co-culture system of *Bacillus subtilis* and *Pseudomonas aeruginosa*. *Frontiers in Microbiology, 14*, Article 1132831. https://doi.org/10.3389/fmicb.2023.1132831

Wu, X., Lin, Y., Wang, Y., Wu, S., & Yang, C. (2023). Volatile organic compound removal via biofiltration: Influences, challenges, and strategies. *Chemical Engineering Journal, 471*, 144420. https://doi.org/10.1016/j.cej.2023.144420

Xue, S., Huang, C., Tian, Y., Li, Y., Li, J., & Ma, Y. (2020). Synergistic effect of rhamnolipids and inoculation on the bioremediation of petroleum-contaminated soils by bacterial consortia. *Current Microbiology, 77*(6), 997–1005. https://doi.org/10.1007/s00284-020-01899-3

Yaqoob, H., Teoh, Y. H., Goraya, T. S., Sher, F., Jamil, M. A., Rashid, T., & Yar, K. A. (2021). Energy evaluation and environmental impact assessment of transportation fuels in Pakistan. *Case Studies in Chemical and Environmental Engineering, 3*, 100081. https://doi.org/10.1016/j.cscee.2021.100081

Yu, B., Yuan, Z., Yu, Z., & Feng, X.-S. (2022). BTEX in the environment: An update on sources, fate, distribution, pretreatment, analysis, and removal techniques. *Chemical Engineering Journal, 435*, 134825. https://doi.org/10.1016/j.cej.2022.134825

Zhao, S.-X., Ta, N., & Wang, X.-D. (2017). Effect of temperature on the structural and physicochemical properties of biochar with apple tree branches as feedstock material. *Energies, 10*(9), 1293. https://doi.org/10.3390/en10091293

Zhao, Z., Wang, B., Theng, B. K. G., Lee, X., Zhang, X., Chen, M., & Xu, P. (2022). Removal performance, mechanisms, and influencing factors of biochar for air pollutants: A critical review. *Biochar, 4*(1). https://doi.org/10.1007/s42773-022-00156-z

Zhou, X., Shi, L., Moghaddam, T. B., Chen, M., Wu, S., & Yuan, X. (2022). Adsorption mechanism of polycyclic aromatic hydrocarbons using wood waste-derived biochar. *Journal of Hazardous Materials, 425*, Article 128003. https://doi.org/10.1016/j.jhazmat.2021.128003