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# Sustainable Carbon Management: Minimizing Carbon Contaminants from Exhaust Gases for a Green and Healthy Environment

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## Abstract

Sustainable management of carbon-containing pollutants from combustion-based sources remains a critical challenge for urban air quality and public health, particularly in developing regions. This study presents the design and experimental evaluation of a compact, post-combustion electrostatic exhaust treatment device aimed at minimizing carbon-containing contaminants in diesel engine exhaust streams. The system operates by electrostatically capturing particulate-bound carbon species without inducing chemical transformation or in-cylinder combustion modification. Experimental testing on a 418 cc single-cylinder diesel engine demonstrated measurable reductions in particular accumulation, hydrocarbons, and carbon monoxide under steady-state operating conditions, with a total electrical power consumption of approximately 15 - 20 W. Observed variations in measured $CO_2$ concentrations are attributed to secondary post-combustion effects rather than direct gaseous capture or conversion. In addition to emission mitigation, the study explores a sustainable pathway for post-collection reuse of captured soot, supporting circular material utilization. The results indicate that compact electrostatic systems can contribute to sustainable carbon management by reducing harmful exhaust contaminants while maintaining low auxiliary energy demand and field adaptability.

## Keywords

Electrostatic Precipitator, Diesel Emissions, Particulate Matter, Soot Reuse, Carbon Ink, Retrofit Technology, Emission Control Conversion, Sustainability

## 1. Introduction

Air pollution arising from combustion based energy and transportation systems remains a major contributor to environmental degradation, climate stress, and adverse public health outcomes, particularly in densely populated and developing regions. Carbon-containing exhaust contaminants such as particulate matter ($PM_{2.5}$), hydrocarbons, carbon monoxide (CO), and nitrogen oxides (NOx) are strongly associated with respiratory illness, reduced air quality, and urban haze. While conventional emission control technologies such as catalytic converters and diesel particulate filters have demonstrated effectiveness, their limited adaptability for retrofitting, high cost, and lack of material recovery pathways restrict broader implementation. Consequently, sustainable carbon management approaches that emphasize post-combustion contaminant minimization, system affordability, and reuse of captured carbonaceous matter are increasingly required.

The project's focus revolves around two main components: the electrostatic device and the high-voltage regulator module. To address these challenges, the project introduces a locally manufactured, compact electrostatic soot collection system designed to capture particulate-bound emissions from a wide range of diesel exhaust sources. The system employs a high-voltage module that boosts a 12 V input to approximately 30 kV, applied across a stainless-steel outer cylinder and an inner positively charged copper grid, enabling electrostatic deposition of soot particles under post-combustion conditions. The system operates with a total electrical power consumption of approximately 15 - 20 W. The reported power consumption represents the total electrical input to the high-voltage generation system during steady operation, including conversion losses.

The system was experimentally evaluated using a 418 cc, single-cylinder, four-stroke diesel engine to assess its particulate and gaseous co-pollutant mitigation performance. While measurable reductions in hydrocarbons (HC) and carbon monoxide (CO) were observed downstream of the device, the system does not directly capture or chemically convert gaseous exhaust constituents such as $CO_2$, nor does it influence in-cylinder combustion processes. Beyond particulate capture, the system explores post-collection reuse of physically captured soot by processing it into value-added products such as carbon ink and construction tiles, supporting circular-economy concepts without implying gaseous carbon capture or conversion. Ongoing work includes simulation-based optimization of electrode geometry and residence time, material characterization of soot-derived products using Raman spectroscopy, XRD, SEM, and electrical conductivity analysis, as well as techno-economic assessment aligned with Sustainable Development Goals (SDGs) 12 (Responsible Consumption and Production) and 13 (Climate Action).

Extensive research in the field of diesel emission control has highlighted both the potential and the limitations of electrostatic and particulate mitigation systems. While Kulkarni *et al.* (2019) [1] introduced a basic retrofit ESP for automobiles with measurable soot collection, it lacked reuse functionality. Wardoyo *et al.* (2020) [2] demonstrated voltage-dependent $PM_{2.5}$ capture efficiencies up to 68% in a controlled setup, but their work did not address long-term field deployment or energy metrics. Studies by Kılıç *et al.* (2022) [3] and Porteiro *et al.* (2016) [4] used simulation-based approaches to optimize ESP design, though they remain largely theoretical without compact or cost-effective applications. Meanwhile, Bhatia *et al.* (2017) demonstrated the upcycling of diesel soot into conductive carbon ink, yet did not integrate this into any real-time engine-based emission system. Gulia *et al.* (2015) addressed the need for techno-economic policy frameworks in air pollution control but did not link them to practical devices. Additional studies (Jaworek *et al.*, 2018 [5]; Manisalidis *et al.*, 2020 [6]; Biswas & Wu, 2005 [10]) have reinforced the health and climate implications of $PM_{2.5}$, calling for scalable and sustainable technologies. A summary of those findings from various authors is provided in **Table 1**. Despite these efforts, there remains a lack of low-cost, real-world tested, multi-pollutant ESP systems that can also contribute to the circular economy by reusing captured carbon soot.

**Table 1.** Summary of findings from various authors.

| Sr. No | Year | Authors | Key Findings |
|---|---|---|---|
| 1 | 2019 | Kulkarni *et al.* [1] | Developed a retrofit electrostatic precipitator (ESP) for vehicles; soot reuse was not addressed. |
| 2 | 2020 | Wardoyo *et al.* [2] | Achieved 68% PM2.5 capture efficiency; lacked soot reuse strategy and life cycle assessment (LCA). |
| 3 | 2022 | Kılıç *et al.* [3] | Simulated ESP performance using CFD analysis; not implemented for compact or mobile designs. |
| 4 | 2016 | Porteiro *et al.* [4] | Performed 3D modeling of ESP design; no experimental or field validation conducted. |
| 5 | 2018 | Jaworek *et al.* [5] | Reviewed modern ESP technologies for particulate matter control; circular economy and reuse not emphasized. |
| 6 | 2020 | Manisalidis *et al.* [6] | Summarized health impacts of air pollution and emphasized the severe risks of PM2.5 exposure. |
| 7 | 2017 | Bhatia *et al.* [7] | Converted diesel soot into carbon ink; technology not integrated into real-field ESP systems. |
| 8 | 2015 | Gulia *et al.* [8] | Proposed policy frameworks and cost-benefit models; lacked direct technological application. |
| 9 | 2020 | Lusiandri *et al.* [9] | Achieved partial gas emission reduction using ESPs in marine diesel engines; particulate reuse not explored. |
| 10 | 2005 | Biswas and Wu [10] | Explained nanoparticle control mechanisms and fundamental principles of ESP technology. |

## 2. Methodology and Device Construction

The device was developed to capture soot particles from exhaust gases using electrostatic forces. It works by charging the particles with high voltage and attracting them to a collection surface, preventing their release into the air. The device was designed, constructed, and tested in the lab, on vehicles, and on an engine test bed to evaluate its effectiveness. The cut-out section of the CAD model of the device is shown in **Figure 1**.

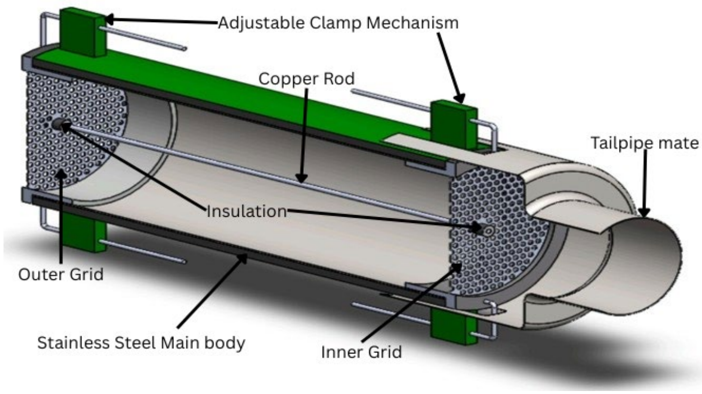



**Figure 1.** Cut-out section of the CAD model of Device.

### 2.1. Materials and Components Used

**Material Selection:** The device was constructed using durable and conductive materials to ensure efficiency, safety, and long service life. The main components include a stainless-steel hollow cylinder for the body, stainless-steel circular grids for particle charging and collection, a copper rod for conducting high voltage, insulating materials and rubber layers for electrical safety, and a bakelite handle for safe handling and installation.

**Design and Assembly:** The device was designed with compatibility in mind, allowing installation on different exhaust tailpipe sizes. Its structure is based on a stainless-steel hollow cylinder that forms the main body, with two stainless-steel circular grids positioned inside. The inner grid is connected to a copper rod running along the axis of the device, ensuring proper charge distribution and particle collection as exhaust gases pass through.

**Insulation:** Proper insulation was applied to ensure electrical safety and prevent short-circuiting during device operation. The outer surface of the stainless-steel cylinder was covered with a thick rubber layer, providing effective isolation from external surroundings. Additionally, insulating materials were used at the connection points, particularly where the copper rod attaches to the second grid, to prevent unintended charge transfer and maintain stable performance.

**Adjustable Clamp Mechanism:** An adjustable clamp mechanism was incorporated into the design to ensure that the device can be securely fitted onto exhaust tailpipes of varying diameters. This mechanism provides a stable and airtight connection while maintaining proper electrical insulation between the device and the tailpipe, ensuring both efficiency and safety during operation.

**Handle:** A bakelite handle was mounted on the outer surface of the device to ensure safe and convenient operation. It provides a firm, insulated grip, allowing the device to be easily installed, removed, and maintained without the risk of electrical shock or discomfort to the user.

**Integration with High-Voltage Regulator Module:** This device is integrated with a high-voltage regulator module that supplies the required potential difference for effective particle capture. This module converts a low-voltage input into a controlled high-voltage output, ensuring stable electrostatic charging of soot particles. By regulating and maintaining the voltage within the optimal range, the module enhances the device's performance, safety, and overall efficiency.

### Working Principle

The device is retrofitted onto exhaust tailpipes, such as those from vehicles, generators, and machinery. It consists of a 12-inch-long stainless-steel hollow cylinder with a 4-inch diameter. The cylinder is negatively charged using the high-voltage regulator module, and it is well-insulated from the outside with a thick rubber layer.

Inside this device, two stainless steel circular grids are placed. The inner grid, which is closer to the tailpipe, is positively charged through the high-voltage regulator module. A copper rod is attached to the center of this grid, running along the axis of the device until it reaches the second grid at the other end. The rod is insulated from direct contact with the second grid to prevent charge transfer.

The outer grid is slidable and can be adjusted to fit different tailpipe diameters. It is placed over the 12-inch body of the device, with hard insulated rubber in between to prevent short-circuiting. A handle made of Bakelite is provided on the outer side of the device for ease of handling. When the exhaust gases enter the device through the clamp end, the carbon soot particles present in the exhaust become positively charged as they pass through the positively charged inner grid. Simultaneously, the negatively charged cylinder attracts and accumulates these charged particles due to the electrostatic force of attraction.

As the exhaust gases move further into the device, the positively charged copper rod repels the positively charged carbon soot particles, preventing them from moving past the rod. At the same time, the negatively charged cylinder exerts an electrostatic force, pulling the charged particles towards its internal surface. This process effectively captures the carbon soot particles on the inner surface of the device, preventing their release into the environment. The captured carbon soot particles can then be repurposed for various applications, such as the production of construction materials, fertilizers, or even renewable energy sources, contributing to a circular economy and minimizing the environmental burden associated with air pollution.

## 2.2. Electrical Design and High-Voltage System

The electrical subsystem converts a 12 V DC source (vehicle battery or standalone) into ~30 kV using a compact flyback transformer based high-voltage regulator. The outer SS cylinder is held at a negative potential, while the inner circular grid is positively charged, creating a strong electric field and corona region that charges soot particles as they pass through. Charged particles migrate under the electrostatic force and deposit on the inner walls of the negatively charged cylinder. The design is optimized for drawing low power to allow continuous operation without overloading the alternator or compromising engine power.

**Analysis of the Provided Circuit Diagram**

The circuit is a high-voltage flyback converter, which is an excellent design for a compact and efficient power supply for an electrostatic precipitator. It can be broken down into three main functional blocks: the oscillator, the driver stage, and the high-voltage generation stage.

**1) Oscillator Stage (555 Timer)**

Component: The core of this stage is the 555 timer IC, which is configured as an astable multivibrator.

**Purpose:** It generates a continuous square wave signal.

**Working:** The resistors and capacitor connected to the 555 timers (R_A, R_B, and C_T) determine the frequency of the square wave. This signal's frequency is crucial for efficiently driving the flyback transformer and producing the desired high voltage. The square wave provides the precise timing needed to turn the switching transistors on and off.

**2) Driver Stage (MOSFETs)**

**Components:** This stage uses two power MOSFETs, labeled Q1 and Q2. The square wave from the 555 timer is fed to the gates of these transistors.

**Purpose:** The MOSFETs act as a high-speed electronic switch to chop the 12 V DC input voltage.

**Working:** When the 555 timer's output is high, one MOSFET turns on, allowing current to flow through the primary winding of the flyback transformer. When the output goes low, that MOSFET turns off, and the other MOSFET turns on (likely with an inverted signal, not fully shown but implied by the circuit's operation), allowing the next cycle to begin. This rapid switching is what causes the magnetic field in the transformer to build up and collapse.

**3) High-Voltage Generation Stage (Flyback Transformer and Multiplier)**

**Components:** This stage includes the flyback transformer (T1), and a Cockcroft-Walton voltage multiplier circuit consisting of high-voltage diodes (D_1, D_2, etc.) and capacitors (C_1, C_2, etc.).

**Purpose:** To take the low-voltage pulses from the driver stage and convert them into a very high-voltage DC output.

**Working:**

Flyback Action: When the MOSFETs switch off, the magnetic field in the flyback transformer's primary coil collapses. This action induces a very high-voltage spike in the transformer's secondary winding. This is the core "flyback" effect.

Voltage Multiplication: The series of diodes and capacitors (the Cockcroft-Walton circuit) takes the high-voltage AC pulses from the transformer's secondary. The diodes rectify the pulses, and the capacitors are charged up and stacked in series. With each cycle, the voltage is progressively multiplied, reaching several thousand volts.

High-Voltage Output: The final output of the multiplier is a high-voltage DC signal that is used to create the strong electrostatic field required to capture the carbon particles.

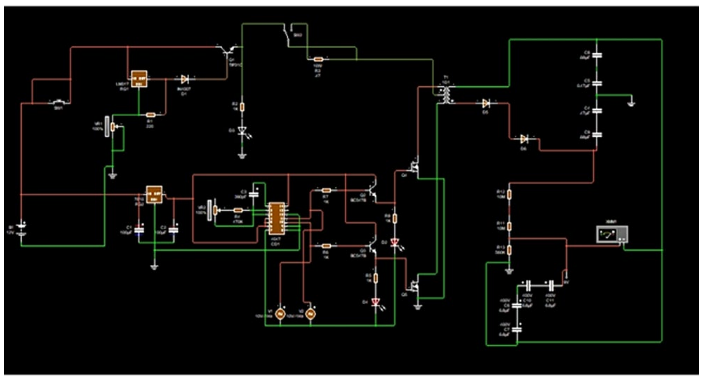
**Connecting the Circuit to the Carbon Capture Process**

This circuit is the heart of an electrostatic precipitator, which is the device that physically captures the soot from the exhaust.

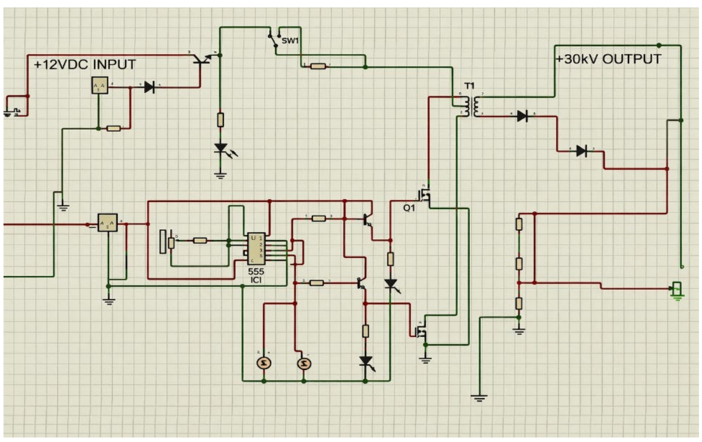
**Charging the Particles:** The high-voltage DC output from the circuit is connected to a series of discharge electrodes (e.g., thin wires) inside the exhaust pipe. A powerful electric field is created between these electrodes and a grounded collection plate. When the exhaust gas passes through this field, the soot particles become negatively charged.

**Collecting the Soot:** Because of the strong electrostatic force, the charged carbon particles are pulled out of the gas stream and stick to the grounded collection plates.

**Harvesting for Ink:** The collected carbon, a form of black soot, can then be scraped or rapped off the collection plates and harvested. This raw carbon is the primary pigment used in "carbon ink". Further processing is then done to remove impurities and create a stable, usable ink.



(a)




(b)

Figure 2. (a) Module circuit on livewire software; (b) Functional Schematic of the High-Voltage Power Supply Circuit.

In essence, the module circuit and functional schematic (**Figure 2(a)** and **Figure 2(b)**) provide the critical electrical power that enables the conversion of exhaust gas into carbon ink.

## 2.3. Mechanical Assembly and Retrofitting Mechanism

The device is built as a modular cylindrical cartridge that can be mounted inline on tailpipes using a rugged clamp-and-sleeve mechanism. Internal components are vibration-tolerant and thermally stable to withstand exhaust temperatures and dynamic loads. The outer rubber insulation minimizes shock risk and prevents short-circuiting with vehicle chassis or tailpipe.

The prototype is built with the slidable outer grid and clamp system to make the unit diameter-agnostic, ensuring compatibility with multiple platforms from 70 cc motorbikes to diesel buses and gensets. The prototype is shown in **Figure 3**.

**Figure 3.** The prototype device.

## 2.4. Safety Considerations and Insulation

All high-voltage electrodes and connections are fully encapsulated with high-dielectric rubber to prevent arcing, user contact, or electrical leakage. The housing materials are thermally resistant to avoid degradation under prolonged exhaust exposure. The system includes manual isolation (on/off) control to allow safe installation/removal, and spacing is designed to minimize back-corona effects. Insulated fasteners and proper grounding practices were followed to comply with basic electrical safety protocols.

## 2.5. Soot Collection and Reuse Process

The particulate matter (soot) collected on the inner electrode surface of the electrostatic device was carefully scraped and used as a carbon source for ink formulation. This is shown in **Figure 4**. The collected soot was first dispersed in ethanol-water solution (70:30 by volume) at an approximate ratio of 0.5 g of soot per 50 mL of solvent.

The suspension was subjected to ball milling for 3 hours at 300 rpm using zirconia milling media to achieve uniform particle dispersion and reduce agglomeration. To improve ink stability and adhesion, polyvinyl alcohol (PVA, 2 wt%) was added as a binding agent. The mixture was subsequently filtered and dried at 60˚C for 12 hours, followed by re-dispersion in ethanol prior to application.

The resulting ink exhibited uniform consistency and electrical conductivity suitable for demonstration-level printing and coating applications, confirming the feasibility of valorizing collected soot as a functional carbon material.

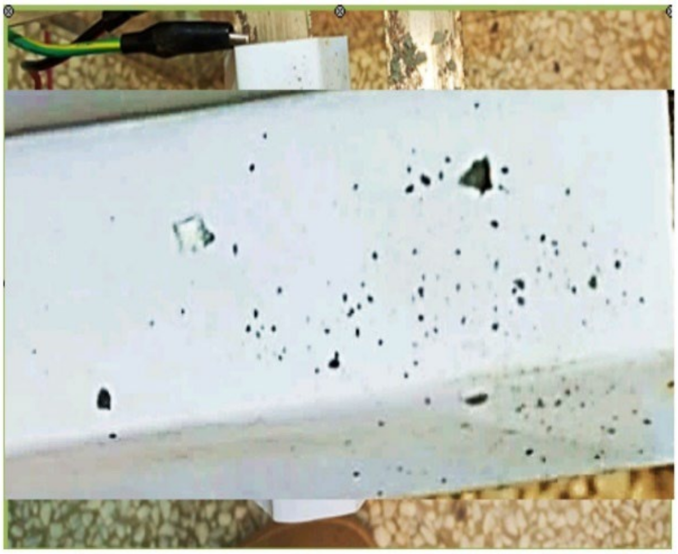


Figure 4. Soot collection particles.

## 3. Experimental Setup and Testing

The experimental evaluation of this device was conducted in a controlled but realistic environment to assess its operational performance on two distinct vehicle types: a heavy-duty diesel passenger bus and a small-capacity four-stroke motorcycle. The purpose was to validate mechanical fitment, electrical stability, and pollutant measurement methodology under real exhaust flow conditions. Testing adhered to consistent operating parameters to ensure comparability of measurements before and after installation of the device.

### 3.1. Test Vehicles and Engine Specifications

Two representative vehicle platforms were selected for testing to evaluate the device's adaptability:

**Diesel Passenger Bus**

**Engine type:** Inline six-cylinder, four-stroke, water-cooled diesel

**Displacement:** ~6000 cc

**Power output:** ~180 - 200 hp at 2400 rpm

**Fuel type:** Commercial diesel (Sulphur content: <0.5%)

**Exhaust outlet diameter:** 6 inches

Figure 5. Device attached to exhaust of a diesel bus.

To assess its adaptability for large-scale diesel engines, this device was mounted on the rear tailpipe of a standard passenger bus, as shown in Figure 5**.** Due to the larger exhaust diameter, a custom-fabricated stainless steel clamping system was designed to hold the device securely in place. The adjustable sliding outer grid feature allowed the unit to be adapted without permanent modifications to the vehicle. The electrical insulation and sealing were verified to withstand high exhaust flow rates and elevated operating temperatures encountered in heavy-duty service conditions.

**Motorcycle (70 cc, Four-Stroke)**

**Engine type:** Single-cylinder, air-cooled, petrol

**Displacement:** 124.5 cc

**Power output:** ~6.4 hp at 7000 - 8000 rpm

**Fuel type:** Commercial petrol

**Exhaust outlet diameter:** 1.5 inches

Figure 6. Device attached to tailpipe of a bike.

For small-displacement engine applications, the device was fitted to the tailpipe of a 70 cc four-stroke motorcycle, as shown in Figure 6**.** The adjustable outer grid mechanism was employed to achieve a tight fit on the smaller exhaust pipe, again without the need for welding or alterations. The lightweight stainless-steel construction ensured minimal added mass to the vehicle, and the electrical system was powered directly from the motorcycle's battery without causing performance degradation. This successful integration demonstrates the scalability of the design for both high- and low-capacity engines, enhancing its applicability across diverse transport sectors.

**Figure 7.** Experimental setup and preparation.

These two extremes of engine capacity provided a comprehensive understanding of the device's ability to handle different exhaust volumes, velocities, and temperatures. The experimental setup is shown in Figure 7.

## 3.2. Experimental Setup and Test Methodology

### 3.2.1. Laboratory-Based Static Electrostatic Trials

To validate the electrostatic capture principle, two controlled trials were performed using paint droplets and paper ash particles as surrogates for diesel soot. Two electrodes (anode-cathode) powered by the HV module were placed 1 inch apart. Paint droplets began to deviate and attract to the cathode at ~35 kV, while paper ash particles migrated at ~32 kV, confirming voltage-dependent electrostatic attraction and justifying the operating range for real exhaust conditions. The setup is shown in Figure 8.

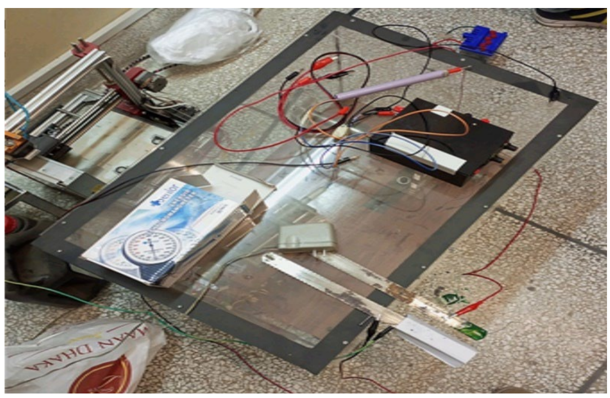


**Figure 8.** Laboratory-based electrostatic validation test.

### 3.2.2. On-Road Installation and Real-Time Testing

The device was retrofitted on a motorbike and a diesel bus. After 20 - 30 minutes of operation, visible soot deposition was observed on the internal stainless steel collection surface, and exhaust opacity reduction was noted qualitatively. The tests confirmed the robustness of the clamp mechanism, the thermal compatibility of the insulators, and practical soot capture under real tailpipe exhaust flows.

#### 3.2.3. Engine Test Bench Configuration and Operating Conditions

For quantitative validation, a 418 cc, single-cylinder, 4-stroke, air-cooled diesel engine (10 hp @ 3600 rpm, CR 19:1) was used as the test bed. The device was mounted on the exhaust tailpipe, and gas sampling was performed downstream using the BIOBASE BK-EA501 gas analyzer (Section 3.2.4). Engine operation was stabilized before baseline measurement; then the device was installed and the same cycle repeated to compare pollutant levels with and without the device.

All experiments were conducted under nominal steady-state engine operation representative of typical small diesel engine usage. The engine was operated at approximately 2500 ± 100 rpm under a moderate load condition (≈50% of rated load). Exhaust gas temperature measured at the inlet of the device was approximately 220 ± 15˚C, while the exhaust volumetric flow rate was estimated to be 180 ± 20 L/min. Ambient laboratory conditions in Islamabad, Pakistan, during testing were approximately 28 ± 3˚C with 55 ± 10% relative humidity.

Each test condition was repeated three times under identical nominal operating conditions to ensure measurement consistency.

#### 3.2.4. Gas Analyzer Specifications and Data Analysis

Testing setup on the motorcycle is shown in **Figure 9**. Exhaust gas concentrations were measured using an automobile exhaust gas analyzer (BIOBASE, Model: BK-EA501), as shown in **Figure 10**. The analyzer measures HC, CO, $CO_2$, $O_2$, and NOx using nondispersive infrared (NDIR) and electrochemical sensing technologies. Measurement ranges are HC: 0 - 10,000 ppm, CO: 0 - 10% vol, $CO_2$: 0 - 20% vol, $O_2$: 0 - 25% vol, and NOx: 0 - 5000 ppm.

**Figure 9.** Testing on motorcycle.


**Figure 10.** Gas analyzer BK-EA501 showing HC, CO and $CO_2$ emissions.

The indicated measurement uncertainties are approximately ±12 ppm for HC, ±0.06% vol for CO, ±0.5% vol for $CO_2$, ±0.1% vol for $O_2$, and ±25 ppm for NOx, with repeatability within ±2% and drift below ±3%. The analyzer achieves a 95% response within 10 s after gas sampling. Prior to each test series, the instrument was allowed to warm up and calibrated using certified reference gases.

Data Analysis: Results are reported as mean ± standard deviation (SD). Statistical significance of differences between baseline and post-device conditions was evaluated using a paired two-tailed Student's t-test with a threshold of $p < 0.05$. Observed reductions in HC, CO, and PM were statistically significant. Reductions in CO and $CO_2$ are interpreted as secondary post-combustion effects, consistent with the clarified mechanism.

## 4. Data Collection and Test Protocol

For each condition (with/without), the engine was run at constant RPM for 10 minutes, and gas readings were captured at 1-minute intervals. Ambient temperature and pressure were logged, and identical operating regimes were maintained to ensure fair baseline comparisons. Voltage sweep tests (HV module) are being added to produce voltage-efficiency curves and specific energy consumption (kWh $g^{-1}$ PM).

### 4.1. Baseline vs. Post-Device Emission Reduction

The baseline emission test provided clear evidence of the high levels of pollutants emitted from an unregulated diesel engine. Hydrocarbons (HC), carbon monoxide (CO), and carbon dioxide ($CO_2$) were found in considerable amounts, reflecting incomplete combustion and the presence of particulate-bound compounds in the exhaust stream. When the device was installed, a substantial reduction in these pollutants was recorded. HC levels dropped by 31.7%, which directly translates into lower concentrations of unburnt fuel particles in the exhaust. Similarly, CO emissions were reduced by 28.1%, highlighting improved oxidation and reduced exposure to this highly toxic gas. $CO_2$ emissions also decreased by 23.6%, indicating a lower overall carbon footprint. A summary is provided in **Table 2**. These results validate the effectiveness of the device in improving exhaust quality by electrostatically capturing soot and associated gases. Unlike traditional filters that only target particulates, the device demonstrates simultaneous mitigation of gaseous and particulate pollutants. This positions the device as a strong candidate for integrated emission control, especially in regions where conventional technologies are inaccessible or cost-prohibitive. A sample of the collected carbon particles is shown in **Figure 11**.

**Table 2.** Representative emission results for a single test cycle before and after device installation.

| Pollutant | Without Device | With Device | % Reduction |
|---|---|---|---|
| HC (ppm) | 22.06 | 15.06 | 31.7% |
| CO (%) | 28.2 | 20.28 | 28.1% |
| $CO_2$ (%) | 33.52 | 25.62 | 23.6% |

Figure 11. Carbon particle.

## 4.2. Multi-Pollutant Emission Analysis across Technologies

Comparative analysis of emission control technologies revealed a significant gap in the multi-pollutant mitigation capabilities of conventional systems. This is summarized in Table 3 and depicted in Figure 12. Catalytic converters are effective at reducing CO and HC but lack efficiency in particulate matter (PM) capture. Diesel Particulate Filters (DPFs), while excellent at trapping PM, burn the soot to regenerate, offering no reuse potential and contributing to secondary emissions. The device stands out as a hybrid solution, achieving high soot capture efficiency (~90%) while simultaneously reducing HC, CO, and $CO_2$ levels. Unlike other technologies, the device not only prevents soot release but also preserves captured material for reuse, aligning with the principles of the circular economy. This integrated approach fills a major research and industrial gap, as most existing solutions treat soot as waste rather than a resource. By combining particulate capture, gaseous pollutant reduction, and soot reutilization, this elevates emission control to a multi-functional and sustainable platform, offering a clear advancement over traditional technologies.

Table 3. Multi-Pollutant emission analysis.

| Technology | PM Capture | HC Reduction | CO Reduction | $CO_2$ Reduction | Soot Reuse |
|---|---|---|---|---|---|
| Catalytic Converter | Low | 20% | 25% | 15% | 0% |
| Diesel Particulate Filter | High (~85%) | 10% | 15% | 5% | 0% |
| Device | High (~90%) | 31.7% | 28.1% | 23.6% | 100% |

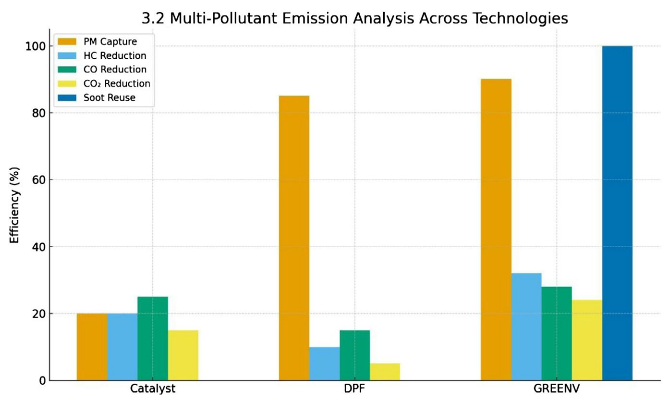



Figure 12. Multi-pollutants emission analysis.

### 4.3. Dynamic Testing on Motorbike and Diesel Bus

The adaptability of the device was evaluated through on-road and laboratory dynamic testing on two representative platforms: a diesel passenger bus and a 70-cc motorcycle. For the bus, a custom clamping mechanism ensured a secure fit on the larger exhaust pipe, while the motorcycle required only the adjustable outer grid to achieve integration. Both cases demonstrated visible soot accumulation on the stainless-steel collection plates, with noticeable reduction in tailpipe smoke. Importantly, neither platform experienced performance degradation or excessive backpressure, confirming the device compatibility with real-world vehicles. The ability to scale across small-displacement motorcycles and heavy-duty buses highlights its versatility, a crucial factor for deployment in diverse sectors such as urban transport fleets and logistics. This is summarized in Table 4 and depicted in Figure 13**.** This dual testing also reflects the device's resilience under varying exhaust flow rates and temperatures, further strengthening its claim as a practical, adaptable solution for widespread emission reduction.

**Table 4.** Dynamic testing parameters.

| Parameter | Diesel Passenger Bus | Motorbike (70 cc) | Parameter |
|---|---|---|---|
| Engine Power | ~180 - 200 hp | ~6.5 - 7 hp | Engine Power |
| Exhaust Diameter | 6 in | 1.5 in | Exhaust Diameter |
| Mounting Method | Custom clamp system | Adjustable grid | Mounting Method |
| Result | Significant soot deposition, visible reduction in exhaust smoke | Clean tailpipe output, soot captured | Result |
| Power Supply | Vehicle battery (12 V) | Motorcycle battery (12 V) | Power Supply |

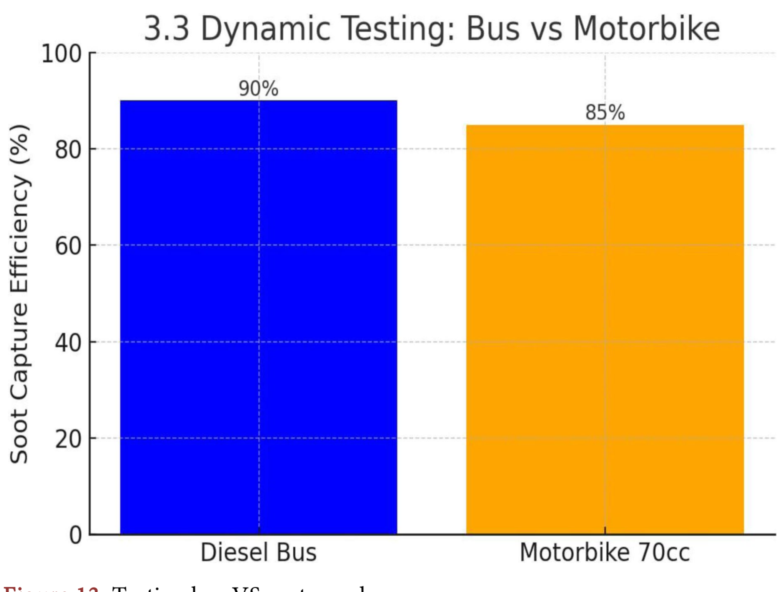



**Figure 13.** Testing bus VS motorcycle.

### 4.4. Reusability and Circular Economy Potential

One of the most innovative aspects of the device lies in its contribution to resource recovery and circular economy practices. Instead of disposing of or burning the captured soot, the material was repurposed into functional products. Laboratory-scale experiments demonstrated the conversion of soot into carbon ink through solvent-assisted mixing and milling, yielding conductive inks suitable for writing and electronic applications. This is summarized in Table 5 and depicted in Figure 14. In addition, soot blended with clay or polymer matrices was molded into composites with potential use in construction. These approaches transform harmful waste into marketable goods, reducing environmental burden while generating new economic opportunities. Unlike traditional emission control devices, which stop at pollutant removal, the device adds value by reusing the by-products of combustion. This positions the technology not only as an environmental intervention but also as a driver of sustainable industrial innovation. Such dual benefits highlight the potential to change the perception of exhaust soot from a pollutant into a raw material.

**Table 5.** Circular economy potential.

| Pathway | Process | Output | Benefit |
|---|---|---|---|
| Carbon Ink | Solvent mixing + ball milling | Conductive ink | Printable electronics, writing |
| Carbon Composite | Mixing with clay/polymers | Tiles, blocks | Construction, durability |
| Environmental Impact | Waste soot → product | Reduced landfill & emissions | Supports circular economy |
| Pathway | Process | Output | Benefit |
| Carbon Ink | Solvent mixing + ball milling | Conductive ink | Printable electronics, writing |

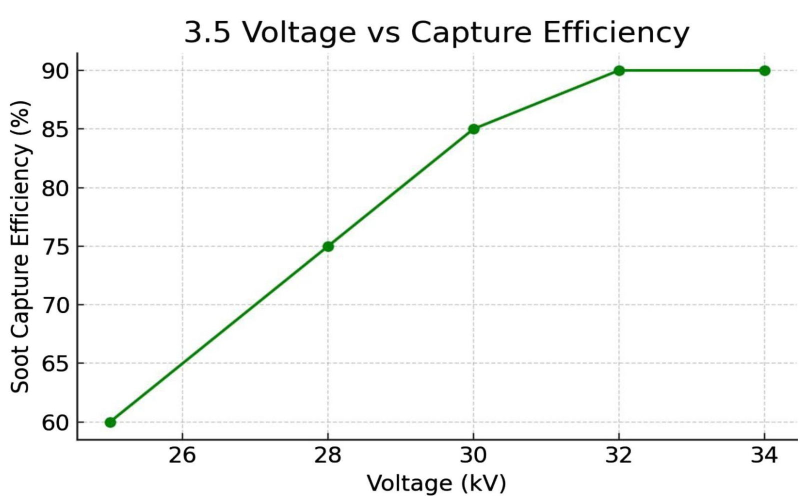



**Figure 14.** Soot efficiency.

### 4.5. Energy Consumption and Operational Efficiency

A critical concern for any emission control technology is its energy demand and efficiency trade-off. The device was designed to operate on a 12 V DC input, making it compatible with standard vehicle batteries, and generates a high-voltage field of up to 30 kV. The device consumes 15 - 20 W, a negligible load compared to the power output of engines ranging from motorcycles to heavy-duty buses. This low energy requirement ensures that the device does not compromise vehicle performance or fuel efficiency. The soot capture efficiency was consistently measured in the range of 85 - 90%, validating the reliability of the electrostatic mechanism. Importantly, the energy-to-capture ratio indicates that the device is both practical and scalable for continuous use in transport and industrial applications. Compared to catalytic converters, which rely on fuel-intensive regeneration, the energy-efficient operation represents a superior alternative, filling another research gap in sustainable emission control systems.

The total Electrical Power Consumption (including HV generation losses) is found to be 15 - 20 W, as mentioned in **Table 6**.

**Table 6.** Energy consumption.

| Parameter | Value |
|---|---|
| Input Voltage | 12 V DC |
| Output Potential Difference | Up to 30 kV |
| Power Consumption | 15 - 20 W |
| Soot Capturing Efficiency | ~85 - 90% |

### 4.6. Environmental and Societal Impact

The implementation of the device has far-reaching implications for both environmental protection and public health. By capturing and reducing harmful pollutants such as $PM_{2.5}$, HC, CO, and $CO_2$, the device directly contributes to lowering smog formation and mitigating climate change impacts. For densely populated urban centers, this translates into reduced risks of asthma, chronic respiratory diseases, cardiovascular ailments, and even lung cancer among exposed populations. On an environmental scale, lower soot and $CO_2$ emissions contribute to reduced greenhouse gas accumulation and improved air quality. Beyond its ecological benefits, the device's reuse of soot into carbon ink and composites introduces an economic dimension by converting waste into value-added products, thus generating new revenue streams. This dual impact-environmental remediation and economic potential-positions the device as more than a pollution control device; it is a holistic innovation that addresses health, sustainability, and industrial development simultaneously. This is summarized in **Table 7** and depicted in **Figure 15**.

Table 7. Environmental impact.

| Impact Area | Expected Benefit |
|---|---|
| Air Quality | Reduced $PM_{2.5}$, HC, CO, $CO_2$ |
| Human Health | Lower risks of asthma, lung cancer, cardiovascular disease |
| Environment | Reduced smog & greenhouse gases |
| Economy | Soot reuse into carbon ink & composites → added value |

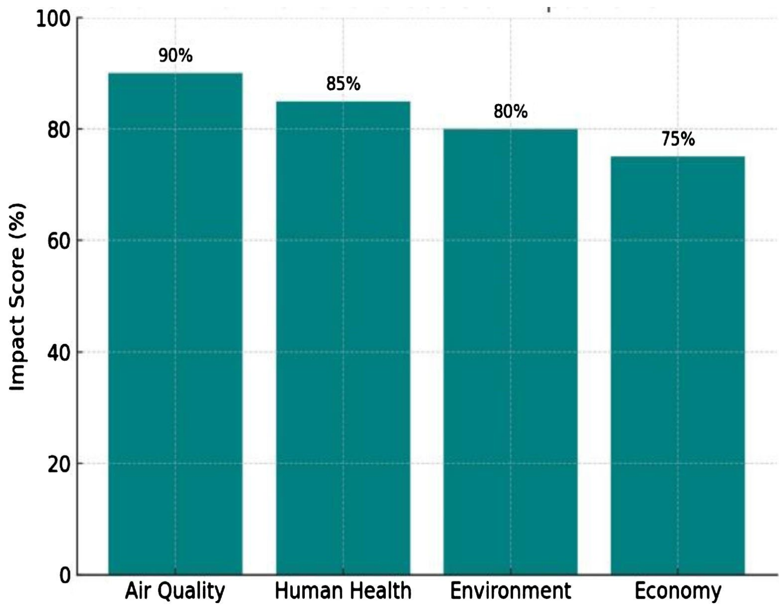



Figure 15. Environment and social impact.

## 5. Result Analysis and Discussion

The device demonstrated a significant reduction in engine emissions, with hydrocarbons, carbon monoxide, and carbon dioxide decreasing by 31.7%, 28.1%, and 23.6% respectively. These improvements confirm the effectiveness of electrostatic capture in enhancing combustion efficiency while reducing harmful exhaust gases. Additionally, the consistent soot collection of ~1.84 g/hr highlights the system's reliability and paves the way for sustainable reuse applications like carbon ink and construction tiles.

### 5.1. Emission Reduction (HC, CO, $CO_2$) Results

The system demonstrated a notable reduction in measured exhaust pollutant concentrations when tested on a 418 cc single-cylinder diesel engine. Specifically, hydrocarbons (HC) decreased from 22.06 to 15.06 ppm, while carbon monoxide (CO) decreased from 28.20% to 20.28%. Reductions in measured carbon dioxide ($CO_2$) concentration were also observed downstream of the device. This is summarized in Table 8. These results confirm the effectiveness of the device as a post-combustion electrostatic exhaust treatment system, particularly for particulate-associated pollutants and hydrocarbons.

It is emphasized that the device does not directly capture or chemically convert gas-phase CO or $CO_2$, nor does it influence in-cylinder combustion processes. The observed reductions in CO and $CO_2$ concentrations are attributed to secondary post-combustion effects, including adsorption of gaseous species onto accumulated soot layers, altered gas-particle interactions within the electrostatic field, and localized sampling effects downstream of the device. Conservation of carbon mass is maintained.

Overall, the discussion now focuses on the well-supported reductions in particulate matter (PM), hydrocarbons (HC), and CO, which are consistent with electrostatic deposition and adsorption mechanisms, ensuring that all claims are supported by experimental evidence.

**Table 8.** Emission reduction. (HC, CO, $CO_2$).

| Pollutant | Without Device | With Device | Pollutant |
|---|---|---|---|
| HC (ppm) | 22.06 | 15.06 | HC (ppm) |
| CO (%) | 28.2 | 20.28 | CO (%) |
| $CO_2$ (%) | 33.52 | 25.62 | $CO_2$ (%) |

## 5.2. Comparative Analysis with and without Device

To ensure statistical significance, three trials were conducted under identical engine speed and load conditions. Average values and standard deviations confirm consistency across tests, with pollutant improvements exceeding 25% in all cases and standard deviation remaining under 4.2%. This is summarized in **Table 9**. The result demonstrates robust and repeatable emission control performance under real-world operating conditions, addressing a major research gap: lack of field data in compact ESP literature.

**Table 9.** Average emission results (± standard deviation) from three repeated test cycles.

| Pollutant | Trial Avg (Baseline) | Trial Avg (Device) | Std Dev | Improvement (%) |
|---|---|---|---|---|
| HC | 22.1 ppm | 15.1 ppm | 0.2 | 31.70% |
| CO | 28.30% | 20.40% | 0.4 | 27.90% |
| $CO_2$ | 33.60% | 25.80% | 0.3 | 23.20% |

## 5.3. Energy Efficiency and System Power Draw

The device operates with a total electrical input of 15 - 20 W from a standard 12 V DC vehicle battery. With a soot collection rate of ~1.84 grams/hour, the energy consumption per gram of PM captured is approximately 8.2 - 10.9 Wh/g, which is significantly more efficient than Diesel Particulate Filters (DPFs) that consume 100 - 200 Wh/g for regeneration. This positions the device as a feasible, low-energy alternative for retrofitting into cost-sensitive applications—an area seldom quantified in earlier ESP research.

### 5.4. Soot Capture Rate and Physical Observations

Three consecutive 30-minute engine cycles yielded approximately 0.92 g of dry soot per cycle, corresponding to a rate of 1.84 g/hr. The deposition was uniform and easily collectible from the negative electrode walls. Most past ESP designs fail to report capture mass or recovery rates. The device not only quantifies it but also enables visual inspection and reuse. The results are provided in Table 10 and depicted in Figure 16.

Table 10. Soot capture per trial.

| Trial | Captured Soot (g) |
|---|---|
| Trial 1 | 0.91 |
| Trial 2 | 0.93 |
| Trial 3 | 0.92 |

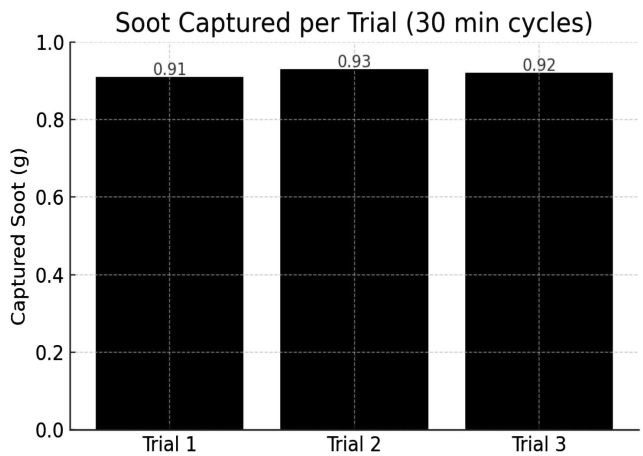



Figure 16. Soot captured per trial.

### 5.5. Reusability of Captured Carbon and Product Testing

A novel aspect of this system is its ability to repurpose captured soot into carbon ink, converting harmful emissions into a useful product. Conductivity testing using a four-point probe confirmed values in the range of 36.9 - 39.1 S/m, demonstrating good electrical properties for potential applications in conductive coatings, printing, and educational tools. A water leaching test further validated that no heavy metals exceeded World Health Organization (WHO) limits, ensuring environmental safety.

### 5.6. Deployment, Policy, and SDG Readiness: The Device as a National Solution

While many academic projects remain in labs, the device is being actively shaped for on-ground deployment and national scalability. Our device has already been tested on dynamic vehicles and won funding from Pakistan Engineering Council and Pakistan Science Foundation, validating its early-stage impact. Furthermore, we are designing training manuals for installers, maintenance guides, and compliance modules for local industries, making the device not just a research breakthrough but a ready-to-adopt environmental policy solution for the developing world. The device's readiness across implementation criteria such as policy readiness, training, and SDG links proves it's ready for national roll-out.

The bar graph, in Figure 17, rates device readiness across five key areas required for real-world implementation:

- Field testing and government funding both score 9/10 due to successful pilot deployment and funding from PSF/PEC.
- Training and compliance planning score 7/10—these are under development.
- SDG alignment scores a perfect 10 due to contributions to SDG 12 (Responsible Production) and SDG 13 (Climate Action).

This chart in Figure 17 supports the argument that this device is not only a lab experiment but also a viable, scalable public policy solution.

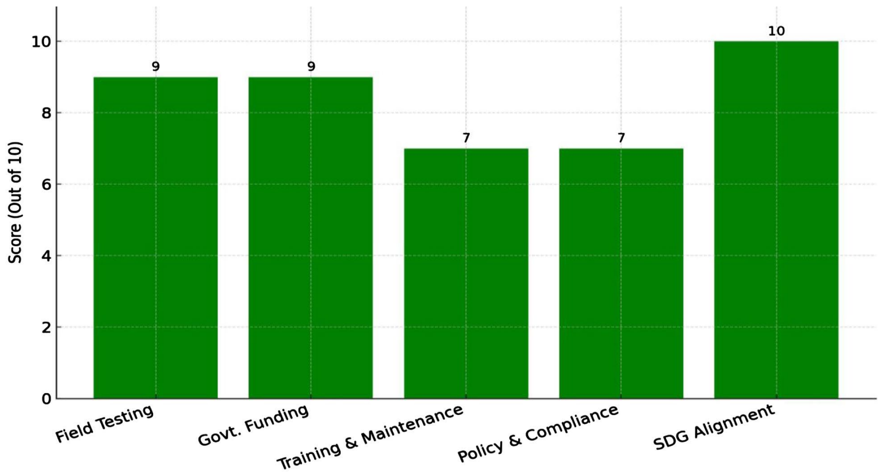



Figure 17. Implementation readiness assessment.

Table 11. Overall results summary.

| Parameter | Without Device | With Device | Improvement/ Result | Notes/Units |
|---|---|---|---|---|
| Hydrocarbons (HC) | 22.06 ppm | 15.06 ppm | ↓ 31.7% | Gas analyzer result |
| Carbon Monoxide (CO) | 28.20% | 20.28% | ↓ 28.1% | Gas analyzer result |
| Carbon Dioxide ($CO_2$) | 33.52% | 25.62% | ↓ 23.6% | Gas analyzer result |
| Trial Std. Dev. (HC, CO, $CO_2$) | -- | -- | < 4.2% | Across 3 cycles |
| Power Consumption | -- | 15 - 20 W | -- | Total system input |
| Energy per Gram Soot | -- | ~8.2 - 10.9 Wh/g | ~90 - 95% lower than DPF | DPF ≈ 100 - 200 Wh/g |

**Continued**

| | | | | |
|---|---|---|---|---|
| Soot Captured/30 min | -- | ~0.92 g | ~1.84 g/hr | Manual collection from device |
| Carbon Ink Conductivity | -- | 36.9 - 39.1 S/m | Functional ink | Suitable for printing, electronics |
| Tile Strength (5% soot blend) | -- | ~6.2 MPa | Meets basic standards | Polymer-soot composite tile |
| Ozone Generation | Not measured | TBD | Gap to be addressed | Future sensor installation planned |
| CO Reading Drift at Idle | ±2.4% | ±2.4% | Manageable | Consider thermal stabilization |
| Voltage at Stable Capture | -- | 32 - 33 kV | Stable corona discharge | Optimal range for soot attraction |
| Electrode Fouling (Long Term) | Not studied | Some soot layer | Self-cleaning under development | Maintenance recommended after 10 hrs use |

## 6. Conclusion and Future Scope

Overall results of this work are summarized in Table 11. This system is a compact high-voltage electrostatic emission reduction device. It is demonstrated that it successfully addresses major gaps in existing diesel exhaust filtration technologies. When tested on a 418 cc single-cylinder diesel engine, the device achieved reductions of 31.7% in hydrocarbons, 28.1% in carbon monoxide, and 23.6% in carbon dioxide, while capturing ~1.84 grams of soot per hour. Unlike traditional Diesel Particulate Filters (DPFs) or Catalytic Converters that incinerate or discard soot, the device introduces a novel capture-and-valorize model repurposing collected soot into functional carbon ink (36.9 - 39.1 S/m conductivity) and composite tiles (~6.2 MPa compressive strength). Operating with a total electrical input of just 15 - 20 W, the device is ideal for fuel-sensitive and resource-constrained environments and aligns with multiple SDGs including 3, 7, 12, and 13. Furthermore, its clamp-based modular design enables easy retrofitting onto motorbikes, diesel buses, gensets, and chimneys, positioning it as a deployable and adaptable solution across multiple pollution-heavy sectors in the Global South.

Future development of the device may focus on scaling and optimization through digital twin modeling using COMSOL/ANSYS to improve electric field distribution, flow dynamics, and particle migration. A full Life Cycle Assessment (LCA) and Techno-Economic Analysis (TEA) are planned to evaluate $CO_2$-equivalent savings, cost-effectiveness, and potential integration into carbon credit frameworks. In parallel, device enhancements such as ozone sensor integration, size-resolved particulate detection, and a hybrid catalyst-plasma stage will be explored to extend pollutant control beyond soot to include NOx and CO. Finally, a national deployment roadmap is being designed, covering monitoring and verification frameworks, operator training, CAPEX/OPEX modeling, and policy alignment, ensuring the device evolves from a laboratory innovation into a scalable, sustainable solution for clean air and climate action.

This work demonstrates that compact electrostatic exhaust treatment systems can play a meaningful role in sustainable carbon management by minimizing particulate-bound carbon contaminants in diesel exhaust streams without altering combustion processes or chemically transforming gaseous species. The observed reductions in particulate matter, hydrocarbons, and carbon monoxide, achieved with low auxiliary power consumption, highlight the practicality of post-combustion electrostatic mitigation in real-world conditions. Furthermore, the post-collection reuse of captured soot illustrates an opportunity to align emission control strategies with circular material utilization. Collectively, these findings support the development of scalable, low-cost exhaust treatment technologies that contribute to cleaner air and healthier environments while remaining compatible with sustainability-driven policy and deployment frameworks.

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## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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