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Investigation of the Effect of Aerosol Deposition by Applying Electrostatic Fields

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Abstract

Particulate matter (PM) constitutes a significant risk factor for environmental health regarding ambient air quality. An epidemiological investigation has determined that inadequate air quality is associated with the development of lung and cardiovascular diseases, chronic ailments, respiratory infections, and a significant number of fatalities on a global scale. According to the World Health Organization (WHO), the annual mortality rate due to air pollution is around 7 million individuals. The necessity for researching air quality, climate change, and the challenges posed by particulate matter (PM) is widely recognized. While reducing ambient air quality, it is essential to consider the limitations of current technical control methods. This article focuses on developing and implementing advanced technology to mitigate particle pollution in urban environments. The comparison of empirical data and computational simulations has demonstrated the efficacy of utilizing pulsed radio waves to reduce particulate matter. The control technique exhibits a threefold increase in the rate of PM concentration reduction compared to gravity settling. The approach's efficacy was evaluated through controlled trials conducted in controlled chambers and urban environments, demonstrating up to 50% reductions. The validation of the implemented test case results of the control technology was performed using historical data while considering the existence of radio waves. The coagulation process demonstrated and verified the effectiveness of reducing particle matter. The employed methodology has been shown to encourage outcomes concerning mitigating particulate matter contamination within urban and industrial environments.

Keywords

Ambient air pollution; particulate matter; air pollution control technology; air quality

1. Introduction

The investigation of particulate matter (PM) in the ambient air has garnered attention from scholars in atmospheric chemistry and physics [1-3]. Particulate matter (PM) is often classified into three distinct size categories: ultra-fine particles measuring 0.1 µm or less, fine particles measuring 2.5 µm or smaller, and coarse particles measuring 10 µm or smaller [4]. The presence of particulate matter in the atmosphere has many direct repercussions. These include the reduction of visibility, the commencement of cloud formation, the deposition of acidic compounds, and the negative impacts on respiratory health [5, 6]. In research conducted by [7], compelling evidence supported the notion that decreasing particle pollution may efficiently mitigate airborne illnesses. Cardiovascular disease is a frequently seen consequence linked to insufficient air quality, resulting in acute health manifestations such as nasal, ocular, and throat irritation, dermatological diseases, and allergic reactions [8-10]. Multiple research [11-13] have provided data indicating a potential link between particle pollution and a decline in cognitive performance. The occurrence of surface charges induces the process of coagulation among airborne suspended particles. The possibility of enhanced global emissions is a topic of discussion in the works of [14-15], who explore the phenomena of photooxidation and particle depletion in secondary aerosols. The research undertaken by scholars demonstrated that particles harm the structural integrity of alveolar walls inside the pulmonary system. The adverse effects of pollution on both human health and the ecosystem are significant and even fatal. Alvarez [16], has shown that extended exposure to air pollution adversely impacts many physiological organs, such as the cardiovascular and respiratory systems. Glencross [17], reported decreased autoimmune responses inside the human body. There is a known association between particulate matter and adverse health effects in epidemiology [18-21]. The influence of indoor air quality on human health and financial considerations is substantial. Numerous studies have shown that air pollution substantially impacts diverse facets of society, encompassing medical expenditures, productivity, income reduction, and job efficacy [22-24]. Particles of a diameter less than 10 µm have adverse impacts on the lower respiratory tract and the tissues accountable for the exchange of gases. Cloud condensation nuclei can have an impact on the Earth's climate. Particles can travel considerable distances without suffering any changes, hence making this phenomenon a subject of worldwide importance. The adverse impacts of particle pollution on human health and plant life underscore the need to address and reduce its prevalence actively.

Various solutions exist for indoor air purification, including enhanced ventilation, efficient pollution source control, incorporation of green areas, and filter-based air purifiers. Nevertheless, due to urban constructions' dense and hermetically sealed characteristics, the strategies used are not as effective. Indoor air purifiers assume a vital function in this context. Conventional air purifiers generally utilize numerous methods such as HEPA filters, activated carbon filters, negative ions, or ozone to clean the air successfully. Although they exhibit efficacy, their functioning is restricted owing to their narrow covering area. Furthermore, the maintenance needs of these entities provide a substantial limitation, and their cost-effectiveness is hardly found. Moreover, properly managing these objects poses challenges owing to their limited capacity to degrade, leading to possible environmental persistence over an extended period and the subsequent emergence of further pollutants [25]. Alternative approaches mostly use oxidation chemistry, ion-molecule interactions, or the emission of disinfectants into the atmosphere, resulting in the production of unintended secondary metabolites. Although many management systems are available for cleaning indoor air, the options for ambient air purifiers specifically intended to reduce particle matter in urban areas are currently few. Electrostatic precipitators and high-efficiency particulate air (HEPA) filters successfully reduce ambient air pollution. However, it is important to note that their long-term performance is restricted. The effectiveness of HEPA filters decreases with time, requiring periodic replacement. Given the present circumstances, it is essential to engage in a thorough examination and execution of novel approaches designed to address and alleviate the issue of ambient air pollution for a prolonged duration.

The present work provided a novel technology that used pulsed radio waves to minimize particle pollution. The suggested technology utilizes a dry deposition technique to remove particulate matter from the atmosphere and manage the long-distance movement of atmospheric elements. Turbulence is a notable factor in dry deposition, a process highly influenced by the size of the particles involved [26]. The research conducted by Ghosh [26], aimed to investigate and document the impact of electromagnetic waves on the process of natural dry deposition. Palsmeier [27], asserts that the charging of aerosol particles occurs because of an electric field, resulting in increased coagulation and elevated deposition rates. The phenomenon of particulate coagulation via radio waves, which encompasses ion-induced nucleation, charged particle coagulation, charged condensation, and ion-induced deposition, plays a vital role in understanding charge distribution and aerosol microphysics models. The coagulation process of unipolar and bipolar aerosol particles depends on the interaction between attractive and repulsive forces, as shown by the findings of [28]. The empirical evidence derived from several model studies indicates that the implementation of charges on particulate matter may substantially influence the coagulation dynamics. This phenomenon has significant relevance for particles with dimensions less than 1 µm, as shown by the studies done by [29-31]. An omnidirectional antenna can generate a radio wave field characterized by pulsation. The pulse has the potential to generate an electromagnetic field, which in turn aids in the alignment of neutral dust particles into temporary dipoles—consequently, the phenomenon of dry deposition experiences augmentation [32]. The primary objective of this research is to investigate the effects of a spatially heterogeneous magnetic field on microparticles floating in the atmosphere. Our first research efforts primarily focused on examining the dynamic components of our subject. The primary aim of this article is to assess the effectiveness of control technologies by conducting experiments in controlled chambers. The rate of decline is evaluated with many environmental variables, such as temperature and relative humidity. The computational conclusions were compared to the experimental reduction rate results. Several control technology units have been implemented in Lucknow City, India, to examine the larger implications of urban particulate matter (PM) levels.

In summary, our research utilizes a combination of experimental analysis and simulation results to offer a technique for field verification. This method can be employed to evaluate the effects of electromagnetic wave radiation on microparticles. A verification method was developed to investigate electromagnetic wave radiation's effects on microparticles empirically.

2. Methodology

2.1 Mechanism of Control Technology

The control system's transmitter functions as a signal generator, generating a series of pulsed signals in all directions at a frequency of 2.4 GHz and a power output of 0.3 W. The signal is transformed into an electromagnetic field by the receiver. The receiver is supplied with a power of 0.001 mW, leading to an electric field strength of 0.55 V/m and a magnetic field strength of 0.0014 A/m. The pollutants experience electrification because of the impact of the electromagnetic field, leading to the production of eddy currents and subsequent deposition of particulate matter. The 2.4 GHz signal demonstrates a pulsed pattern throughout transmission and reception, leading to an electromagnetic field lacking uniformity in its power. The size of the field is influenced by the relative location of the antenna to the transmitter, as seen in Figure 1. The previously indicated technique has shown promise in reducing the aerodynamic dimensions of particle pollutants, notably PM_{10} and $PM_{2.5}$. The all-encompassing apparatus consists of an antenna, a signal generator, a power source, an Internet of Things (IoT), and many electrical safety and security components.

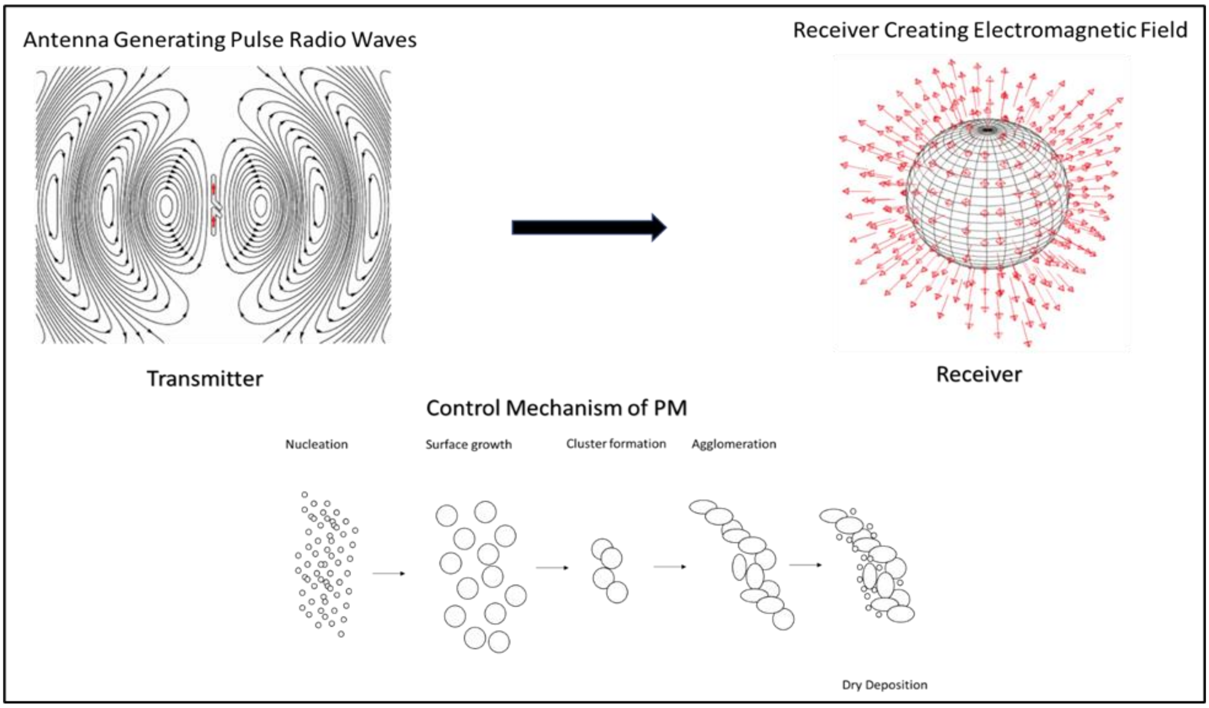

Figure 1 Schematic of working pattern of control technology.

2.2 Chamber-Based Experiment

2.2.1 Overview

Controlled experiments were conducted within controlled environments to evaluate the device's effectiveness. The experimental experiments were conducted at the National Aerosol Facility at the renowned Indian Institute of Technology Kanpur in India. Chamber-based investigations are of considerable significance because they enable experimentation inside controlled conditions, encompassing factors such as temperature, humidity, and pollution load. Evaluating the chamber's design had considerable significance for the experiment's objective. The dimensions of the chamber were determined by considering the influences of Brownian motion and the inherent process of particle deposition in a dry state. Moreover, the technique's time to attain stability and effectiveness remained indeterminate. As a result of the intrinsic limitation on the size of the chamber, an alternate strategy for sustaining the suspension of particulate matter was adopted, which included introducing a continuous supply of the matter into the chamber. Frequent assessments of dust particle concentrations were conducted before and during the application of pulsed waves using sophisticated analytical instruments such as the Scanning Mobility Particle Sizer (SMPS), Aerodynamic Particle Sizer (APS), and Optical Particle Sizer (OPS). A discrete sectional coagulation model was used to analyze charged particles to reproduce the specific conditions accurately.

2.2.2 Experiment Set-Up

The trials occurred within a 1.11 cubic meter container featuring dual walls and a vacuum-sealed enclosure. The enclosure had a frontal panel constructed from plexiglass. The experimental trials will provide the particles with adequate time for coagulation before they eventually settle due to the unique geometric shape and size of the test chamber. The chamber has multiple apertures, including an inlet for dust injection and a dedicated exit for sampling. A fan with a 12-inch diameter and a rotational speed of 900 revolutions per minute (rpm) is strategically positioned on the chamber's ceiling to provide a uniform and constant dispersion of particulate matter. Moreover, the chamber has openings that facilitate the insertion of temperature and humidity probes. The experimental setup incorporates a humidity and temperature transmitter, specifically the Vaisala model 337 HMT, known for its documented accuracy of 2K for temperature readings and 5% for humidity measurements. Furthermore, a vacuum pump is attached to the chamber to facilitate the cleaning process.

During the experiment, a double-walled container composed of mild steel was used. An optical window made of plexiglass was integrated into the container to enhance the transmission of pulsed waves. The temperature inside the chamber was controlled through a chiller and a heater. The chiller unit assumes a vital function in regulating the temperature inside the chamber during testing, as it facilitates the circulation of water that has undergone heating or cooling processes. The continuous monitoring of particulate matter (PM) concentrations is being carried out using state-of-the-art sensors, as depicted in Table 1.

Table 1 Reduction detected by the three instruments at ambient conditions.

Diameter Range (µm)	Instrument	Average Reduction (%)
<0.3 (15-300 nm)	SMPS	49.7
0.3-0.6	SMPS	62.2
0.6-1	OPS	No Reduction
1-2.5	APS	18.7
2.5-5	APS	54.1
5-10	APS	41.9

The dust used for the study was Dolomite DMT. The Dolomite Test is a widely used technique to ascertain dolomite's existence and relative abundance inside individual specimens. The testing methodology used dust particles with a maximum size of 30 microns. This composition focuses on the compound known as calcium magnesium carbonate.

The subject matter under discussion pertains to dolomite. The investigation detected a maximum particle size of 20 µm. The material has a density of 2.85 grams per cubic centimeter.

Figure 2 depicts a sample setup for the chamber-based experiments.

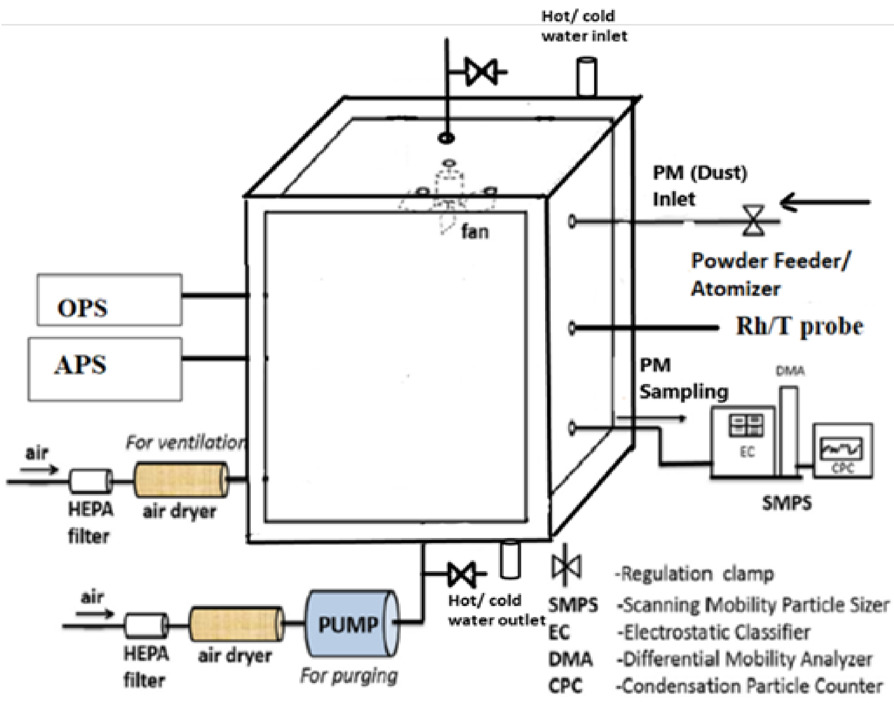

Figure 2 The schematic representation and all the experimental setup instruments to perform chamber-based analysis.

2.2.3 Test Conditions

The trials were carried out at atmospheric pressure settings of 760 Torr, with the temperature and humidity levels adjusted to match the ambient conditions at 1 atm. The present investigation used a dust generator (MEC, PF-3350) in conjunction with nitrogen as the carrier gas to reliably introduce dolomite (calcium magnesium carbonate) into the test chamber at a rate of 9.5 g/sec. A variety of aerosol measuring equipment, including the Scanning Mobility Particle Sizer (SMPS), Optical Particle Sizer (OPS), and Aerodynamic Particle Sizer (APS), are used to evaluate particle size and charge distributions. TSI is a manufacturer of many devices designed for the assessment of particle size and charge distributions. The instruments mentioned above include the TSI 3936 and 3938 Scanning Mobility Particle Sizers (SMPS), the TSI 3330 Optical Particle Sizer (OPS), and the TSI 3321 Aerodynamic Particle Sizer (APS). The chamber's temperature and relative humidity data were acquired using humidity and temperature transmitters. A circulation system circulated water that had been heated or cooled inside the jacketed reaction chamber to provide a uniform temperature.

2.2.4 Test Methodology

Each experimental trial consisted of two iterations: an initial iteration that served as a baseline without deploying any technological intervention, followed by a later iteration that included a control system using the same technology. Baseline runs were undertaken before each experiment to provide a control condition for comparison. After each first test, the following experiment was carried out in which all variables remained consistent, except for the technology implementation. The trials were replicated at three distinct intervals to bolster the reliability of the findings. To achieve the lowest possible overall background concentration, the chamber underwent an initial cleaning procedure involving the application of a moist cloth, followed by a subsequent purging step employing a high flow rate of filtered dry air (approximately 35 liters per minute) facilitated by a pump for two hours. The introduction of particulate matter into the chamber was performed continuously, using a carrier gas with a predefined flow rate of 5 liters per minute (lpm). Following the introduction of the dust, a series of ongoing measurements were conducted to monitor the levels of particulate matter until the experiment concluded. At this time, the concentration of particulate matter returned to its original background level.

2.3 Computational Analysis

To enhance comprehension of the mechanisms behind charge acquisition and the coagulation process in the presence of charges, a computer model was devised to mimic the conservation of volume and charge. The results obtained from experimental studies conducted by [33, 34] were compared to the findings of this research. Crump and Seinfeld [35] created a computational modification that provided a dynamic semi-implicit approach capable of swiftly finding a solution that preserves both volume and charge conservation. The methodologies have been enhanced to assist scholarly investigations on the coagulation phenomena of charged particles by incorporating an extra element of deposition velocity referred to as electrostatic deposition. Consequently, the model was adjusted to incorporate a term representing electric charge, thereby facilitating the examination of the collective dynamics exhibited by charged particles in the ongoing study. The research findings indicate that the presence of an electric charge significantly influences the coagulation dynamics, especially when comparing scenarios without charge to those exhibiting bipolar features. The researchers [34] have thoroughly analyzed their modeling data and have successfully shown congruity between the experimentally acquired data from their prior study and the results produced from the model. This work aimed to investigate the coagulation process of particles with Boltzmann/bipolar charge distributions using the suggested model.

2.3.1 Model Description

The computational calculations were performed using MATLAB software, incorporating C code. This approach was adopted to validate and corroborate the results obtained from the experimental studies. The calculations utilized the dynamic equation that delineates the behavior of charged particles under coagulation and other loss effects, as detailed in previous investigations [36, 37]. Scientists used a methodology that includes the amalgamation of aerosol microphysics and computational fluid dynamics (CFD) to investigate the properties of the aerosol. The model's governing equation comprises the Navier-Stokes equation, which characterizes the movement of fluids, and the dynamic equations about aerosol particles. The suggested formulation demonstrates innovation by including the equations that regulate time-dependent aerosol dynamics into classic k-epsilon techniques. The model can reproduce the spatial and temporal attributes of the aerosol spectrum by using input parameters that have been experimentally documented. Ghosh [34], has observed that incorporating computational fluid dynamics (CFD) into aerosol dynamics models has yielded better accurate results than traditional aerosol microphysics models [38]. The aerosol microphysics model also incorporated charge by accounting for ion-induced nucleation, charged particle coagulation, charged condensation, and ion-induced deposition. Ghosh [26], has posited that electric charge creation in nanoparticle systems at elevated temperatures is attributed to thermo-ionic emissions. The inclusion of charge terms was undertaken to analyze particle aggregation phenomena, drawing upon previously reported data. The validation of the model was conducted by comparing particle sizes under both unipolar and bipolar charge conditions. The influence of charge on the coagulation dynamics in neutral and bipolar circumstances was significant. The results of this investigation suggest that the model's outputs were somewhat compatible with the experimental findings provided by [39].

2.3.2 Modeling Methodology

To assess the efficacy of pulsed wave technology in terms of the rate of dust particle deposition, it is feasible to conduct a two-dimensional modeling of the current experimental configuration with minor adjustments to the existing model. Like the abovementioned study, the fundamental equations may also be found within it [40]. The use of sophisticated aerosol microphysics, computational fluid dynamics (CFD), and electrical charge inside the model will provide valuable insights into the performance and effectiveness of the instrument in precisely evaluating deposition rates in real-world settings. The results obtained from the model will provide vital insights for the development and execution of an improved experimental setup to attain a significant enhancement in the rate of deposition of aerosol particles [41].

2.4 Field Studies

The Lucknow municipal administration undertook the adoption of control technologies to assess the system's efficacy under real-world atmospheric conditions. A transmitter and receiver can provide wireless coverage across 30,000 square meters when used together. The study was conducted over six discrete zones: the Indira Nagar Zone, Talkatora Zone, Vidya Nagar Zone, Lalbagh Zone, Aliganj Zone, and the Gomti Nagar Zone. The researchers chose these three specific areas as the primary sites for the investigation. Figure 3 depicts the spatial configuration of the transmitter and receiver sites inside each zone of the control system. In each of the six selected zones, six control systems were installed. The atmospheric conditions were assessed in each designated area both before and after the installation of the regulatory mechanism. At each site, a solitary ambient air quality monitoring equipment, namely the TSI Bluesky sensor, was deployed to measure the concentration of $PM_{2.5}$ particles. The sensors in these zones were chosen based on their proximity to the control system, which was centralized within a two-kilometer radius, as seen in Figure 3. The data collected from the continuous ambient air quality monitoring (CAAQM) station in the previous year were employed to create a reference point for air quality. A comparative analysis assessed the air quality before and after implementing the control system at the designated site.

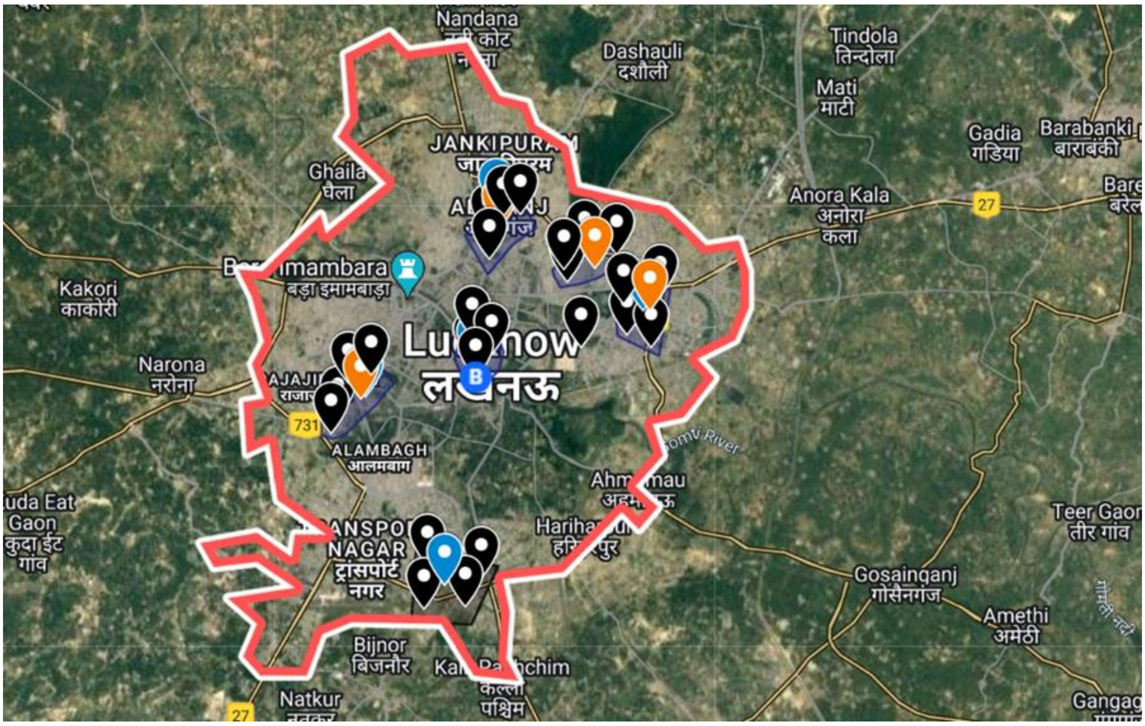

Figure 3 Location of sensors and Control technology devices in six designated zones in Lucknow (source: Google Earth).

2.4.1 Study Locations

A sophisticated control system comprising both a transmitter and receiver has been deployed in the Lalbagh zone for comprehensive coverage. The control system is situated 100 meters away from the CPCB CAAQMS station in Lalbagh. The control system responsible for the entire coverage of Gomti Nagar is at RTI Bhawan. A complete control system was developed at the LDA Cricket Stadium in Aliganj to ensure extensive coverage over the Aliganj zone. The three residential areas evaluated are Indira Nagar, Talkatora, and Vidya Nagar. The spatial configuration of the control technology, transmitter, and receiving stations, together with the sensors in each zone, is shown in Figure 4.

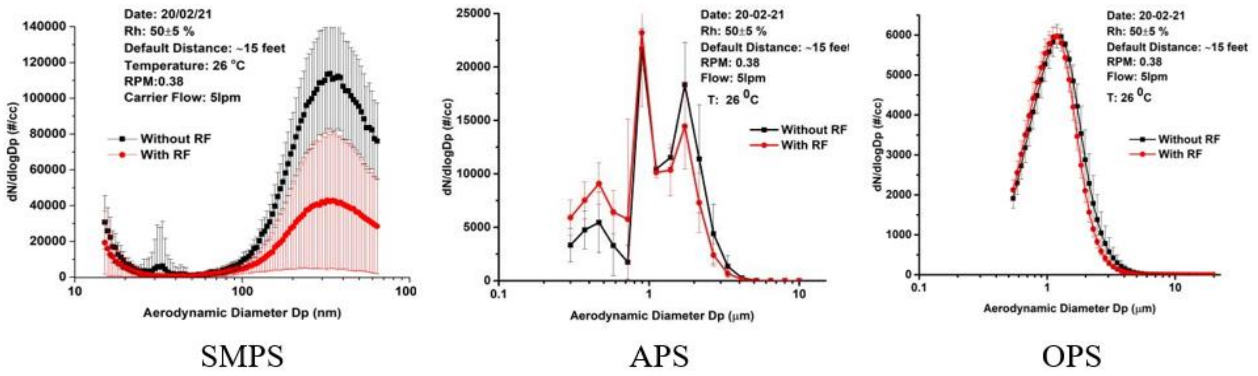

Figure 4 Experimental results carried out at ambient conditions (26 ± 2)°C and at (50 ± 5)% of RH.

3. Results and Discussion

3.1 Experimental Results in Controlled Conditions

The efficacy of pulsed radio waves technology was evaluated in a controlled environment, where the ambient conditions were carefully regulated. The experiment maintained a constant input particle concentration and a steady ejection rate of 9.54 µg/sec. The illustration of particle size analyzers is shown in Figure 5 and concisely outlined in Table 2. Particles of diameters ranging up to 10 µm are seen in all graphs. A comparative analysis examines the statistical distribution of aerodynamic dimensions, both with and without the incorporation of radio frequency. This analysis generates a figure that visually represents the observed differences between the two scenarios. In natural conditions, there has been a significant decrease in the concentration of particulate matter in the atmosphere. Based on the data presented in Table 2, it is evident that the Scanning Mobility Particle Sizer (SMPS) has documented an average decrease of 49.7% in the concentration of particles within the size range of 0.3 µm (15-300 nm) and a reduction of 62.2% for particles ranging from 0.3 to 0.6 µm (300-600 nm). Based on the OPS measurement, Table 1 and Figure 4 demonstrate a decrease in the 17.4% to 49.1% range for particles above a size of 1 m. The use of the Aerodynamic Particle Sizer (APS) yielded a decrease ranging from 18.7% to 54.1% for particles exceeding a size of 1 meter. The empirical findings indicate that pulsed wave technology effectively reduces particle concentrations.

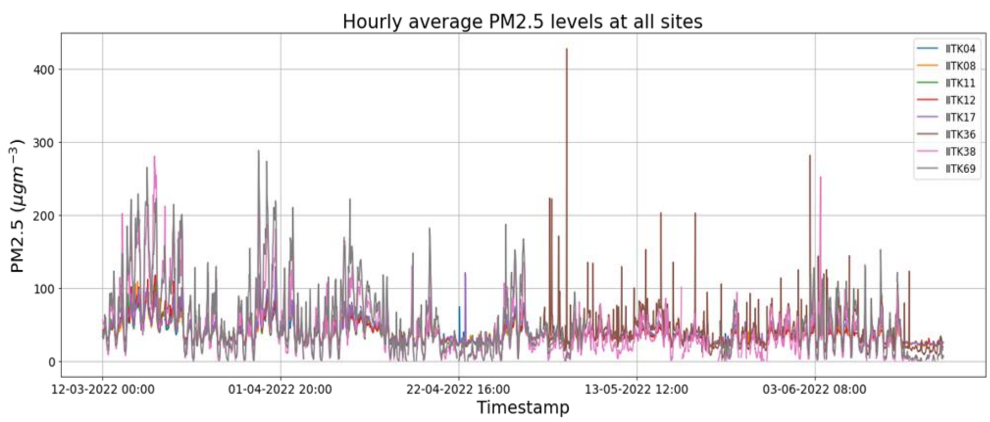

Figure 5 Time series of hourly $PM_{2.5}$ levels at selected locations in Lucknow.

Table 2 Percentage reduction in $PM_{2.5}$ concentration at incremental biweekly intervals compared with baseline values at three selected zones in Lucknow.

Reduction estimation at Gomti Nagar Zone		
Bi-weekly phase	**Mean $PM_{2.5}$ (µg/m^3)**	**Reduction percentage (%)**
First (Baseline data)	76.42	
Second	60.25	21.16
Third	35.49	53.56
Fourth	34.39	54.99
Fifth	38.94	49.04
Sixth	40.87	46.52
Reduction estimation at Lalbagh Zone		
Bi-weekly phase	Mean $PM_{2.5}$ (µg/m^3)	Biweekly Reduction percentage (%)
First (Baseline data)	41.8	
Second	31.1	25.72
Third	36.2	13.42
Fourth	33.2	20.64
Fifth	20.7	49.4
Sixth	31.8	23
Reduction estimation at Aliganj Zone		
Bi-weekly phase	Mean $PM_{2.5}$ (µg/m^3)	Biweekly Reduction percentage (%)
First (Baseline data)	54.85	
Second	28.38	48.26
Third	34.87	36.42
Fourth	26.55	51.6
Fifth	37.8	31.08
Sixth	19.28	64.85
Reduction estimation at Vidya Nagar Zone		
Biweekly Phase	Mean $PM_{2.5}$ (µg/m^3)	Biweekly Reduction percentage (%)
First (Baseline data)	21.24	
Second	23.18	-9.133709981
Third	17.12	19.39736347
Fourth	14.23	33.00376648
Fifth	12.15	42.79661017
Sixth	10.65	49.85875706
Reduction estimation at Indira Nagar Zone		
Biweekly Phase	Mean $PM_{2.5}$ (µg/m^3)	Biweekly Reduction percentage (%)
First (Baseline data)	40.31	
Second	28.69	28.8265939
Third	25.54	36.641032
Fourth	33.18	17.68791863
Fifth	24.79	38.5016125
Sixth	24.57	39.04738278
Reduction estimation at Talkatora Zone		

Biweekly Phase	Mean $PM_{2.5}$ (µg/m^3)	Biweekly Reduction percentage (%)
First (Baseline data)	51.67	
Second	37.96	26.53377201
Third	26.93	47.88078189
Fourth	32.94	36.24927424
Fifth	32.78	36.55893168
Sixth	30.17	41.6102187

3.2 Field Installations

3.2.1 Averaging PM Concentration at Six Zones

The field testing was conducted in the city of Lucknow with the collaboration of the Lucknow Municipal Corporation. The findings of the investigation are succinctly summarized in Table 2. The graph in Figure 5 illustrates the hourly averaged time series for the six zones that constitute the city of Lucknow. The provided data depicts the geographical dispersion of $PM_{2.5}$ concentration within various regions. The Gomti Nagar zone had a 24-hour average concentration of 52.20 ± 34.35 µg/m^3, as shown by the mean and standard deviation. The recorded values in the Lalbagh zone were 43.99 ± 13.52 µg/m^3, but in the Aliganj zone, the values were 39.26 ± 32.35 µg/m^3.

3.2.2 Biweekly Percentage Reduction in $PM_{2.5}$ Concentration of Baseline Values at Three Zones

Table 2 presents the biweekly mean $PM_{2.5}$ concentrations and the related reduction percentages recorded throughout the three zones' pre- and post-installation periods. A notable reduction in $PM_{2.5}$ concentrations was seen in the Gomti Nagar area, with a maximum decline of 55% from the first baseline measurement of 76.42 µg/m^3 to the test taken during the third phase, which recorded a level of 34.39 µg/m^3. The Lalbagh zone significantly declined air pollution levels during the fifth phase, with a drop of 49.4% or 20.7 µg/m^3 compared to the original baseline measurement of 41.86 µg/m^3. A persistent decline in the average $PM_{2.5}$ levels was observed throughout the investigation. During the sixth biweekly phase, the Aliganj zone saw a substantial reduction of 64% in air pollution levels. This decline was evident in the concentration of particulate matter, which decreased from 54.85 µg/m^3 to 19.28 µg/m^3. A notable decrease in $PM_{2.5}$ concentrations was observed at Vidya Nagar, with a maximum decline of 50% from the baseline period (21.4 µg/m^3) to the fifth phase (10.6 µg/m^3). The most significant decreases in air pollution levels were observed during the fifth research phase at Indira Nagar. The reductions corresponded to a decrease of 39.4% or 24.5 µg/m^3, compared to the initial conditions when the pollution level was 40.3 µg/m^3. During the third biweekly phase, a notable decline of 47.8% was seen in the Talkatora zone, as shown by the reduction in the average concentration of particulate matter from 51.6 µg/m^3 to 26.9 µg/m^3.

This research investigates the diurnal fluctuations in $PM_{2.5}$ concentrations during pre and post-installation periods. During the 7:00 hour, the Gomti Nagar zone had the highest recorded value and the most significant decline. A substantial reduction of 71% was found in practically all diurnal timings throughout the post-installation phases compared to the baseline period. The data from the Lalbagh stations showed similar results to those of Gomti Nagar, particularly regarding the notable reductions recorded throughout the morning. Moreover, a discernible decline is also seen throughout the evening period. However, in the afternoon hours with low concentration, some measurement periods that occurred twice a month showed slightly higher values than the baseline period. The most significant decrease in percentage was seen around 7:00 Hrs, notably at a rate of 45%, during the post-installation stages. Like Lalbagh, the Aliganj zone demonstrated a consistent decrease in $PM_{2.5}$ levels throughout the post-installation stages compared to the baseline period before installation. The most significant percentage drop range was also observed at around 7:00 AM, namely a reduction of 75% throughout the times after the installation.

Figure 6 illustrates the contrast of diurnal $PM_{2.5}$ concentrations in Vidya Nagar during the pre-installation and post-installation periods. The Vidya Nagar zone showed no noticeable diurnal patterns compared to the Indira Nagar and Talkatora zones. During the scheduled bimonthly assessment sessions throughout the day, the Indira Nagar station did not demonstrate a substantial decrease in the numerical value, as seen in Figure 7.

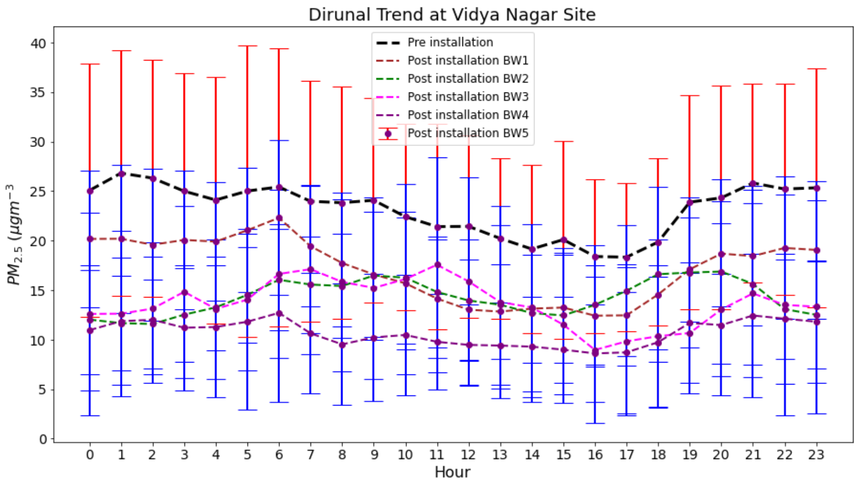

Figure 6 Diurnal plot showing comparative results of average hourly variation between pre and post-installation of control system devices at Vidya Nagar (*BW -Biweekly time series).

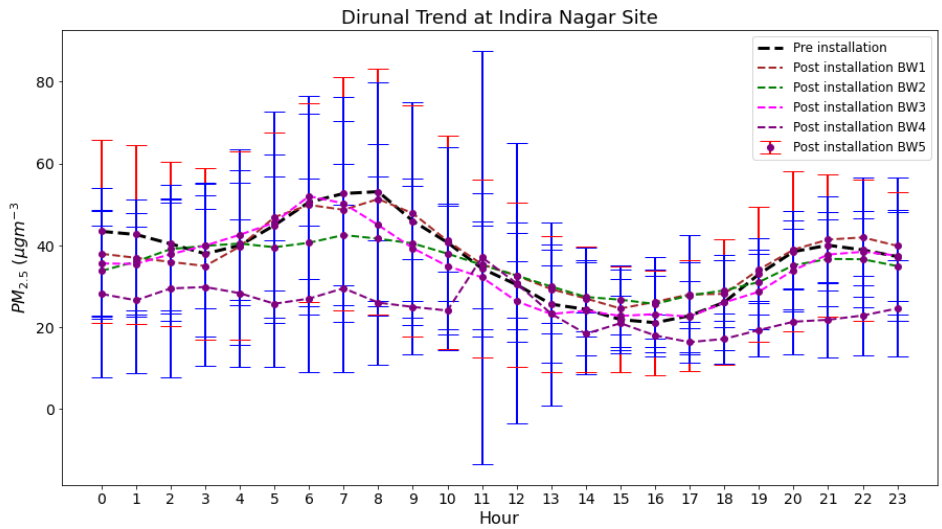

Figure 7 Diurnal plot showing comparative results of average hourly variation between pre and post-installation of control system devices at Indira Nagar zone (*BW -Biweekly time series).

The successive phases of the biweekly mean showed a decreasing trend in magnitude throughout the day. Throughout the testing, the Talkatora location showed findings like the other locations, with the most notable decrease recorded during nighttime. Figure 8 depicts a consistent decline in PM2.5 concentrations throughout the day in the post-installation phase compared to the baseline period before the installation. The alteration showed a noteworthy improvement. The diurnal examination revealed that the highest degree of decreased efficiency occurs during the peak hours in the morning and evening. This suggests that the control system has enhanced efficacy in mitigating $PM_{2.5}$ concentrations during increased levels.

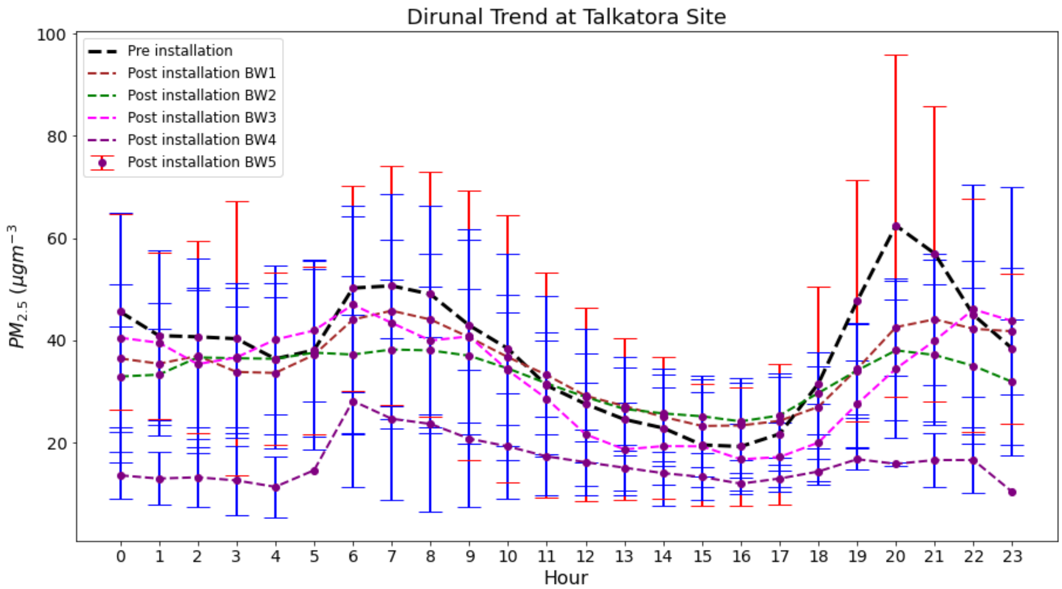

Figure 8 Diurnal plot showing comparative results of average hourly variation between pre and post-installation of Control system devices at Talkatora zone (*BW -Biweekly time series).

3.2.3 The Mechanism for Improved Dry Deposition

To understand how charge is acquired, the charges of particles inside the chamber are measured before and after applying pulsed wave signals. This evaluation uses two Scanning Mobility Particle Sizers (SMPS) units, one equipped with a neutralizer while the other lacking such a component. The data obtained from the Scanning Mobility Particle Sizer (SMPS) under both charged and uncharged conditions is input into the Computational Fluid Dynamics (CFD) integrated aerosol microphysical model. This is conducted to gain insights into the underlying mechanism responsible for the observed increase in deposition rate following the introduction of pulsed waves. The model utilizes input parameters from experimental data obtained via a Scanning Mobility Particle Sizer (SMPS) and charge fractions collected from relevant literature [30, 38]. The results of the modeling studies indicate that the application of pulsed waves leads to the induction of an electric charge on the particulate matter, resulting in an increased deposition rate. It is necessary to analyze to understand the characteristics of the charge induced on the particulate matter and the method by which the charge is acquired. The simulation has been conducted across three distinct categories, as elucidated in the preceding sections. The past publication provides a comprehensive account of the model.

The charged particle coagulation model was used to calculate changes in number concentration and particle size distribution for charged particles. The results were then compared to experimental observations, shown in Figure 9.

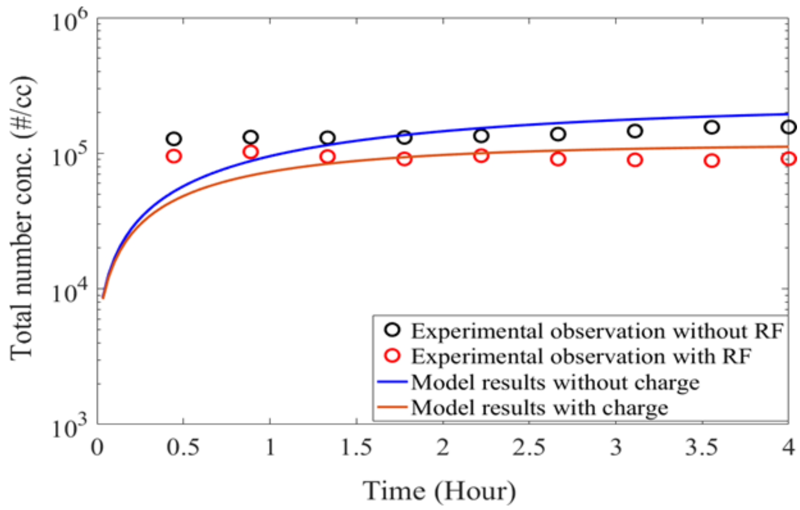

Figure 9 The computational results with and without charge case.

In the study conducted by Ghosh [34], a single unipolar Kronecker delta function was used inside the initial category for each size. Uncharged particles fall under the second group, while particles with bipolar charge belong to the third category. The first two case studies do not match our dataset, as verified by the model. According to Ghosh [34], the coagulation and gravitational precipitation phenomenon in bipolar-charged particles is facilitated by the electrostatic attraction between particles of opposite charge. The findings of our charged particle coagulation model demonstrate a notable enhancement in the coagulation phenomenon when considering bipolar charged scenarios. This observation aligns with previous investigations done by [27].

3.3 Computational Analysis

To validate the experimental findings and elucidate the underlying response mechanism, the decreased rate of particle concentrations was computationally determined and theoretically modeled using MATLAB software, explicitly utilizing the Aerosol microphysics module within the Computational Fluid Dynamics framework. The simulation experiments were carried out by following the approach outlined in the corresponding section. The findings gained from these studies are shown in Figure 10.

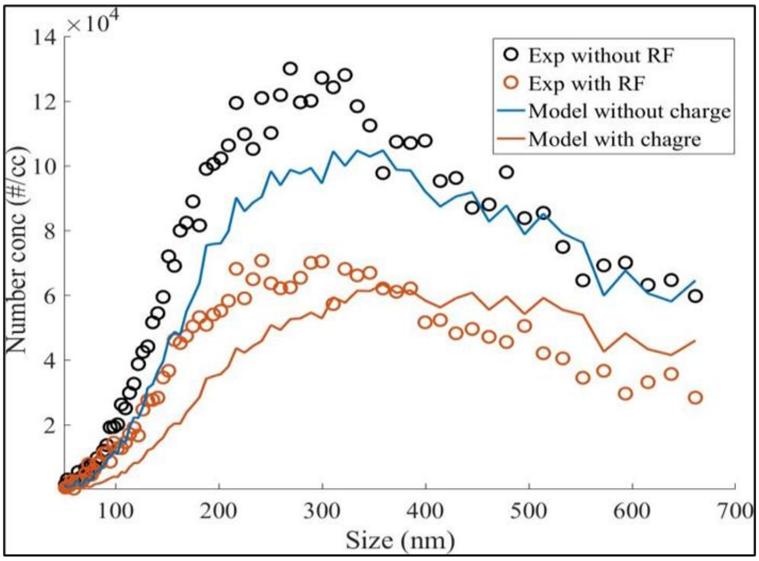

Figure 10 The computational results along with the experimental.

The figure above compares the case without charge (without radio frequency) and the case with charge (with radio frequency) for experimental and modeling research. The Y-axis represents the concentration of particles, while the X-axis represents their respective sizes. The blue and red lines show the model findings, representing the examples with and without charge, respectively. The findings indicate that the model simulation results strongly agree with the RF experimental observation in situations involving charge, as seen by the red circles. This observation suggests that the presence of radio frequency (RF) waves leads to a substantial generation of electrical charge, which notably impacts the pace at which particles are deposited. Based on the obtained data, it is evident that the red line, representing the charge model simulation case, exhibits a lower value than the blue line, representing the case without charge simulation. This discrepancy suggests a greater deposition rate in the former scenario. Furthermore, empirical evidence in the form of red circles corroborates this assertion. The findings indicate the technique's efficacy within specific temperature and humidity parameters.

3.4 Discussions

Control technology is an innovative technological approach that employs pulsed radio frequency waves to mitigate particle pollution. A specifically designed transmit-only antenna with circular polarization and omnidirectional characteristics facilitates the transmission of radio frequency waves. The use of technology aims to mitigate the levels of particle pollution, specifically targeting PM_{10} and $PM_{2.5}$. This study aims to assess the effectiveness and suitability of pulsed wave technology across different environmental contexts. The effectiveness was much greater over time under authentic field circumstances. The purpose of these studies was to examine and analyze the dynamics of particle coagulation to understand the processes involved in the reduction of particulate pollution via the use of control technologies. Coagulation is a significant phenomenon in forming aerosol particles, ultimately resulting in dry deposition. The charge and size of aerosol particles may strongly influence the coagulation of particles. The coagulation process of unipolar charged aerosol particles is inhibited due to the presence of electrostatic repulsion force. In bipolar charged particles, the coagulation process is augmented owing to multiple electrical forces, encompassing the Coulomb attraction force, ion-induced Van der Waals force, and image force. The discrete sectional coagulation model for charged particles was employed by [42] to validate the experimental results. This model subdivides each size category into numerous charge categories. This model divides each size category into many charge categories. The investigation revealed a substantial decrease in the concentration of particle matter. This phenomenon can be attributed to bipolar distributions instead of neutral distributions. The use of radio frequency (RF) waves generates a bipolar distribution of particle concentration, which facilitates the attainment of an elevated deposition rate and thus leads to a more substantial decrease in concentration [43, 44].

The technology employs Electrostatic and dielectrophoretic forces to facilitate the movement of charged dust particles. The bipolar charge particles exhibit a strong mutual attraction and affinity towards the chamber wall, leading to an increased deposition rate.

3.5 Overview of Control Technology

Experimental and modeling investigations have provided evidence that applying pulsed waves may facilitate reorientating charges inside neutral particles measuring up to 30 µm. This reorientation leads to the formation of transient dipoles within the designated field. The findings from the simulation demonstrate that the charge carried by the particle has a notable impact on the dynamics of coagulation, leading to an increase in the deposition rate. The study revealed that in the context of bipolar charge, there was a notable impact on the augmentation of the coagulation process, leading to an increase in particle size and a decrease in the concentration of particles. The findings from the experiment demonstrate that electromagnetic radiation can alter several characteristics of particles, such as their quantity and dimensions, as time progresses. Consequently, particle sedimentation and fusion correlate with magnetic field strength while unaffected by the initial concentration.

Electromagnetic fields of different frequencies and intensities influence the physical characteristics of particles. However, the precise way these fields affect particles requires extensive experimental observation and verification over an extended period.

Radiofrequency (RF) waves can potentially decrease the concentration of particulate matter in different environments but at varied speeds. The results indicated a notable decrease in the RF wave modeling findings rate, subsequently prompting field investigations and experimental research. The significant potential for reducing radio frequency (RF) waves in a controlled environment is attributed to minimal interference from ambient variables and other meteorological aspects. The modest rate of decline observed in field trials may be attributed to the low levels of particulate matter (PM) and the intensity of radio frequency (RF) waves. The rate of reduction was determined to be as follows, in Table 3.

Table 3 Comparison of rate of reduction PM levels with and without RF field.

Study Method	Rate of reduction with RF (µg/m^3)	Rate of reduction without RF (µg/m^3)
Computational results	129	59
Experimental results	87	48
Field studies	107	32

4. Conclusion

The evaluation of the air pollution control effectiveness of the Control technology was a comparison of the biweekly average decrease throughout their installation dates in eight selected locations from three different zones in Lucknow. Although a consistent linear reduction trend in terms of time advancement could not be seen across all locations, it is noteworthy that all sites exhibited a general decline in $PM_{2.5}$ pollution levels from the first pre-installation period to the concluding biweekly evaluation phase. Moreover, the decreasing pattern contradicts the measured distance within the zone of impact, suggesting a lack of substantial correlation between the two variables. The locations with high pollution baseline values, namely Aliganj zone and Gomti Nagar zone, had the greatest reduction effect, with reductions of 65% and 54%, respectively. The diurnal evaluation also reveals that the most significant decline occurs during the peak morning and evening hours, while little to no reduction is observed during the afternoon. This finding suggests that Control technology is more effective in reducing PM2.5 concentration when raised. In high-pollution zones, Control technology devices are frequently considered highly effective.

The technique's effectiveness is assessed by introducing suspended aerosol particles into the chamber using an aerosol dust generator and implementing it in a real-world setting. Research conducted using mathematical modeling techniques has shown that the presence of bipolar distributions leads to a more pronounced decrease in the concentration pattern. During the 3.5-hour study duration, a decrease in effectiveness of over 40% was reported. Furthermore, reducing particle size from the micrometer to the nanoscale range has significant implications for human existence, particularly in its effects on creatures and plant life. This reduction also leads to notable advancements in the efficiency of our technology, resulting in a reduction of over 90%. The calculation and reporting of the effectiveness of reduction under ambient circumstances were also carried out. In the present circumstances, this technology has significant potential for effectively addressing the issue of air pollution and ensuring widespread access to clean air.

Given the significance and ramifications of particulate matter to climate dynamics and human well-being, we have developed a novel technology that exhibits exceptional efficacy in mitigating particulate matter concentrations in indoor and outdoor environments. Furthermore, comprehensive safety assessments have been conducted to ensure the reliability and safety of this technology. The system's effectiveness is assessed across various meteorological conditions through installation studies conducted at multiple sites in India. This article presents the experimental findings obtained from chamber analysis conducted under ambient circumstances and evaluates the system's effectiveness. The device utilizes pulsed waves to generate an electromagnetic field that facilitates the reorientation of neutral particles into temporary dipoles. This process enhances the natural dry deposition, contributing to providing clean air for all individuals.

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Author Contributions

G S N V K S N SWAMY: Methodology, Writing - Review & Editing, Project administration, Validation, Formal analysis, Writing - Review & Editing, Visualization, Conceptualization, Methodology, Formal analysis, Writing - Review & Editing, Writing - Review & Editing. Rohith: Conceptualization, Resources, Writing - Original Draft, Writing - Review & Editing, Supervision, Project administration, Funding acquisition.

Competing Interests

The authors have declared that no competing interests exist.

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