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Simulation of the influence of cloud density on the removal of particulate matter and gaseous pollutants at the Dangote cement factory by rain

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Abstract

This study analyzes the dynamics of atmospheric pollution and its removal by rainfall in an industrial area, with a focus on the relationship between emissions, precipitation, and air quality. Nonlinear mathematical model equations were designed to mimic the interplay between particle and gaseous contaminants, human population density, water vapor, and rainfall. The governing model equations were then solved using the sixth-order Runge-Kutta-Fehlberg technique, which was integrated with the shooting method and the Newton-Raphson method, and numerical simulations were performed using MATLAB software. The results show that rainfall has an important role in pollution reduction, with rain growth rate (q) and cloud droplet creation (k) greatly improving pollutant elimination. However, excessive industrial and urban emissions can saturate this natural cleansing process, resulting in consistently high pollution levels. Increased particulate (Q_p) and gaseous (Q_g) emissions are associated with poor health outcomes and decreased population density, highlighting the critical need for strict emission limits. Furthermore, water vapor (V) and cloud density (W) help to purify the atmosphere by stimulating raindrop formation; but, excessive pollution can discourage cloud development, limiting rainfall efficiency. The study emphasizes the importance of strong environmental policies, sustainable industrial practices, and proactive pollution management strategies for protecting air quality and public health.

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1. Introduction

The mining industry's air quality poses a significant environmental risk and is linked to a number of health issues. Due to our poor understanding of meteorological factors and physical removal mechanisms, there are many challenges in regulating air quality in mining settings [1]. All life on Earth depends on air to exist and develop. It affects health and influences economic growth. Nowadays, industrialization, the expansion of private automobiles, and the burning of fossil fuels have resulted in a decrease in air

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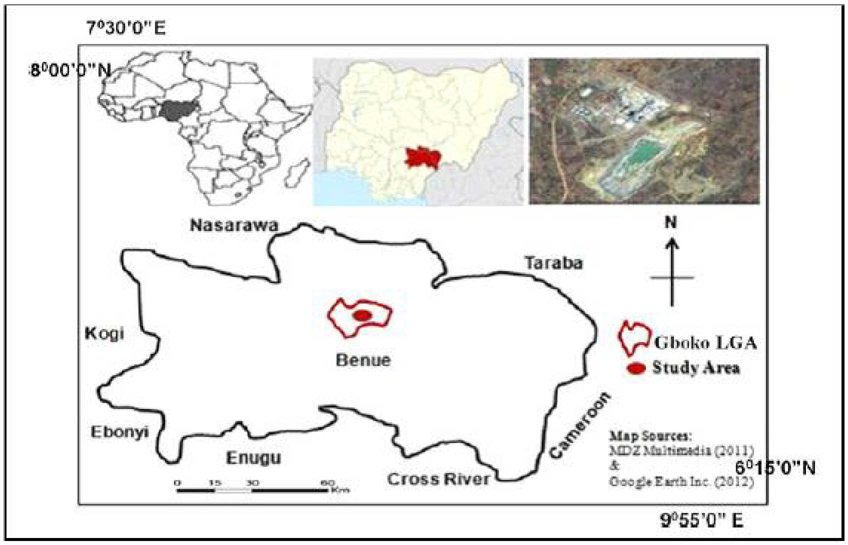

Figure 1. Map of Benue State showing the study area.

quality and an increase in severe air pollution [2]. In contrast to secondary pollutants, which are created by chemical conversion, primary pollutants, which come from industrial sources, are released into the atmosphere directly [3].

Environmental pollution has been recognized as one of the most challenging problems facing both developed and developing countries due to the increasing amounts of gaseous pollutants and particulate matter released into the atmosphere from a variety of sources, including household discharges, vehicle exhausts, and industrial emissions [4, 5]. Rainfall and atmospheric radiative transmission are greatly influenced by cloud density, which also affects Earth's radiative energy balance and is a crucial uncertainty in global circulation model (GCM) predictions of the doubling of atmospheric pollutants [6]. Saturated air parcels are necessary to store all of the water vapor in the form of visible water droplets or ice crystals that result from the condensation of air vapor [7].

Both direct air emission and conversion from gaseous precursors (such as ammonia, sulfur dioxide, nitrogen oxides, and non-methane volatile organic compounds) generated from both natural and man-made sources are the two primary processes that give rise to particulate matter (PM) [8]. Burning solid fuels (coal, lignite, heavy oil, and biomass), industrial and agricultural operations, and pavement erosion from traffic are only a few examples of the many anthropogenic causes [8]. It is well recognized that the effectiveness of PM exposure is greatly influenced by local characteristics such as weather, seasons, geography, particle sources, emission concentrations, and microenvironments. Because PM can quickly enter the bloodstream and travel throughout the body, its effects on human health are much worse [2]. Exposure to PM is linked to negative health outcomes such as increased emergency room visits, respiratory symptoms, worsening chronic and cardiovascular disorders, reduced lung function, and early death [4]. PM pollution has significantly altered the surrounding environment, which has an impact on plant morphology, biochemistry, physiology, and genetic state [6]. Acid rain is created when gases like SO_2 and NO_2 from factories, power plants, and other emission sources enter the atmosphere at high altitudes and mix with moisture, creating acid rain, which is extremely harmful to ecosystems [3, 9]. In fact, some removal mechanisms—such as chemical transformation, dry deposition, precipitation scavenging, and tree plantations—occur naturally and help remove contaminants from the atmosphere [10]. Precipitation (rain) is intimately related to the formation of cloud droplets in the atmosphere due to cooling water vapor. When certain meteorological conditions are satisfied, cloud droplets change into raindrops, which can then interact with gaseous contaminants and particulate matter in the atmosphere to remove them (absorption, impaction, etc.) [10]. The removal of pollutants from the atmosphere by precipitation has been the subject of numerous scientific investigations. This work aims to model and simulate the process by which rain at the Dangote cement mill eliminates particulate matter and gaseous pollutants.

2. Materials and methods

Here, we present a nonlinear mathematical model designed to simulate the dynamics of particulate matter and gaseous pollutants, taking into account the effects of rainfall and cloud density. The equations developed here will aid in the interactions between human population density, pollutant concentrations, water vapor, and raindrop density. The model's insights will inform strategies for mitigating pollution through improved rainfall dynamics and cloud management. Air pollution poses serious health risks and environmental concerns, particularly in industrial areas like cement plants. The basic materials used for these numerical simulations are MATLAB software and Laptop with High-speed processor.

Figure 2. Map of the study area.

Figure 3. Arial view of the study area.

2.1. Study area

The study region in this research work is at Dangote Cement, Gboko Local Government Area (LGA) of Benue State. Dangote Cement Plc is located at Yandev, near Gboko town, in Gboko LGA of Benue State in Nigeria's north-central region as shown in Figures 1 and 2. Gboko LGA lies between latitudes 07°08′16″ and 07°31′58″ N, and longitudes 08°37′46″ and 09°10′31″ E. The central location of the factory is at 7°24′42.45″ N and 8°58′31.28″ E, at about 532 feet above mean sea level (Figure 3).

The research area is situated in a sub-humid tropical climate, with mean annual temperatures ranging between 23 °C and 34 °C, and a mean annual precipitation of 1,370 mm. According to the Nigeria Meteorological Agency (2012), the average ambient air temperature is approximately 30 °C, and the average wind speed over the study area is about 1.50 m/s.

2.2. Theoretical consideration

2.2.1. Formulation of nonlinear mathematical models

As a natural scavenger, rain can remove pollutants through wet deposition processes as rainout (removal within clouds) and washout (removal below clouds), according to atmospheric sciences. Ordinary differential equations (ODEs) that characterize the relationships between the variables of interest make up the models. We go into great detail on the main parameters and variables that make up our system. It is observed that evaporation may occur due to the properties of the gas (temperature, etc.) and precipitation may not occur when the gaseous pollutants released from the plant's numerous sources reach the upper atmosphere and interact with cloud droplets. Additionally, when it rains, the raindrops interact with the gaseous pollutants and particle matter, removing them from the atmosphere by impaction for particulate matter and absorption for gases (11).

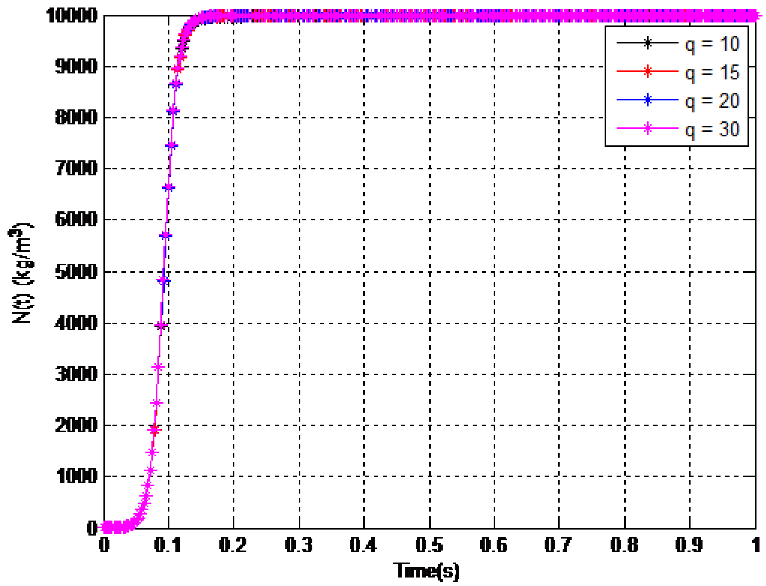

Figure 4. Variation of N with time t for different values of growth rate of rain, q.

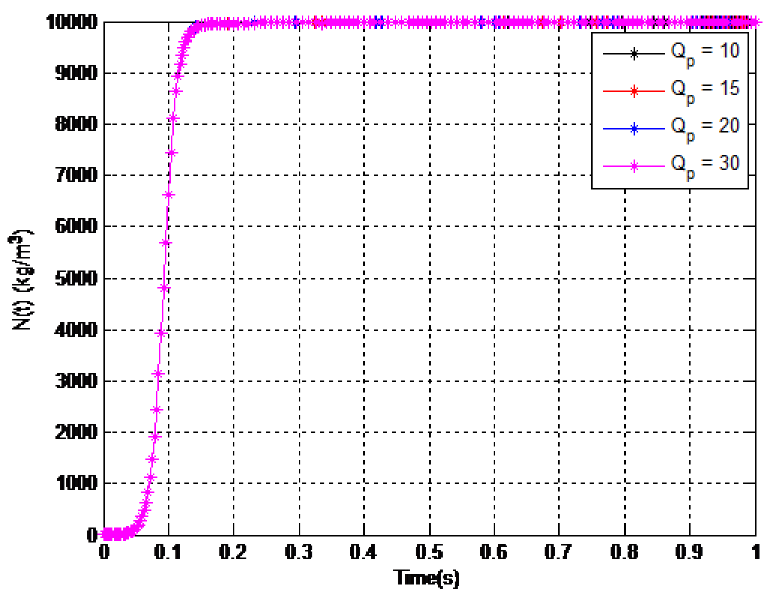

Figure 5. Variation of N with time t for different values of emission rates of particulate matters, Q_p.

2.2.2. Assumption of the models

To model the phenomenon, the following assumptions are made:

1. The population does not migrate out of its environment.
2. Human population density declines as a result of pollution's various harmful consequences. The rate of decline in the human population is thought to be related to the product of the population density and the pollution concentration.
3. Water vapor naturally forms in the atmosphere.
4. The density of water vapor directly correlates with the growing rate of cloud droplets.
5. The density of cloud droplets directly correlates with the growing rate of raindrops.
6. Chemical reactions with gaseous contaminants and other natural processes cause raindrops to diminish. The rate of emission of gaseous pollutants and particulate matters is taken to be constant, though it may be a function of time.

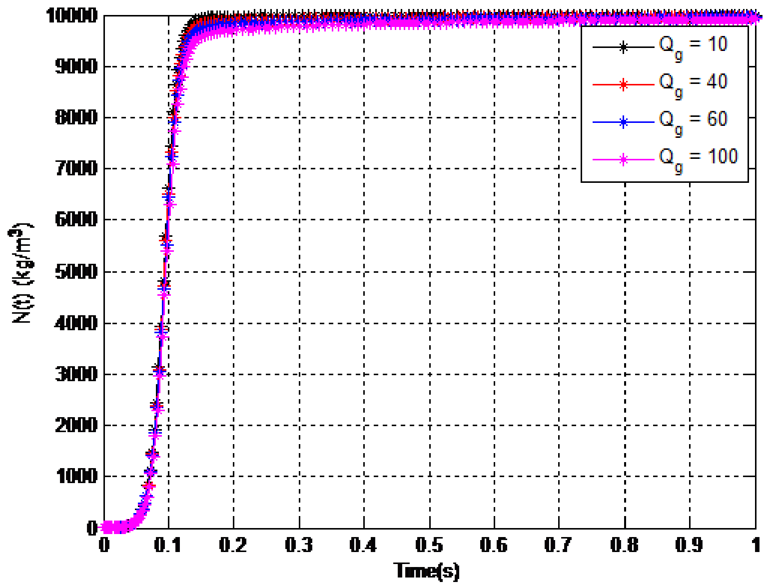

Figure 6. Variation of N with time t for different values of emission rates of gaseous pollutants, Q_g.

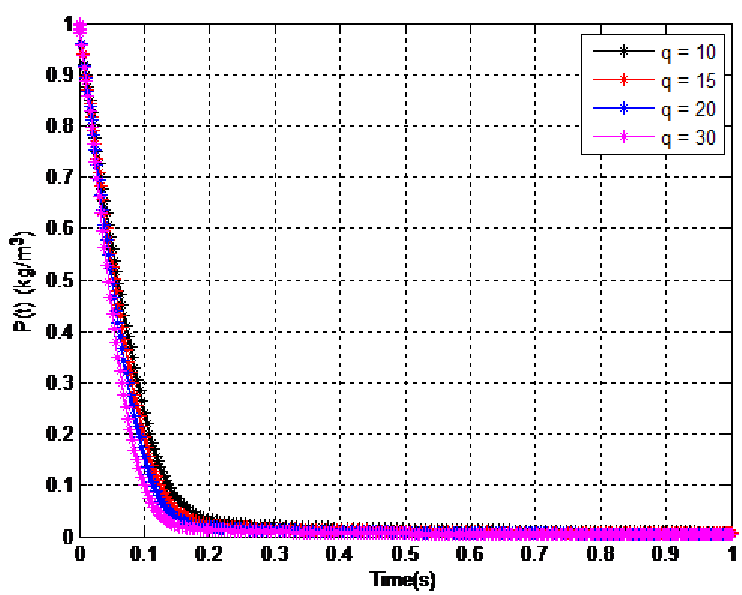

Figure 7. Variation of N with time t for different values value of growth rate of rain, q.

7. The atmosphere of the plant, under consideration, is assumed to be calm and therefore the effects of convection and diffusion in the atmosphere have not been taken into account.
8. If the pollutant species (gaseous) are hot, the raindrops upon interaction with these gaseous pollutants get vaporized and a fraction of it may re-enter the atmosphere enhancing the growth of the vapor phase [12]).

According to Ref. [11], there exist five interacting phases in the atmosphere. These phases are as follow:

1. The cloud droplets phase—formation of cloud droplets by condensation of vapors.
2. The raindrop phase, which is brought on by atmospheric precipitation from cloud droplets.
3. The phase of gaseous pollutants, which is created when sources like automobiles, manufacturing stacks, home chimneys, etc. release gaseous pollutants into the atmosphere.

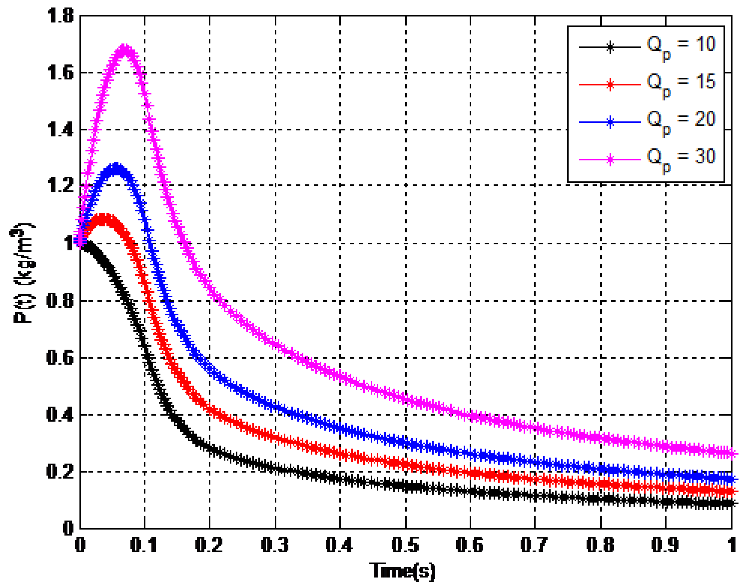

Figure 8. Variation of P with time t for different values of emission rates of particulate matters, Q_p.

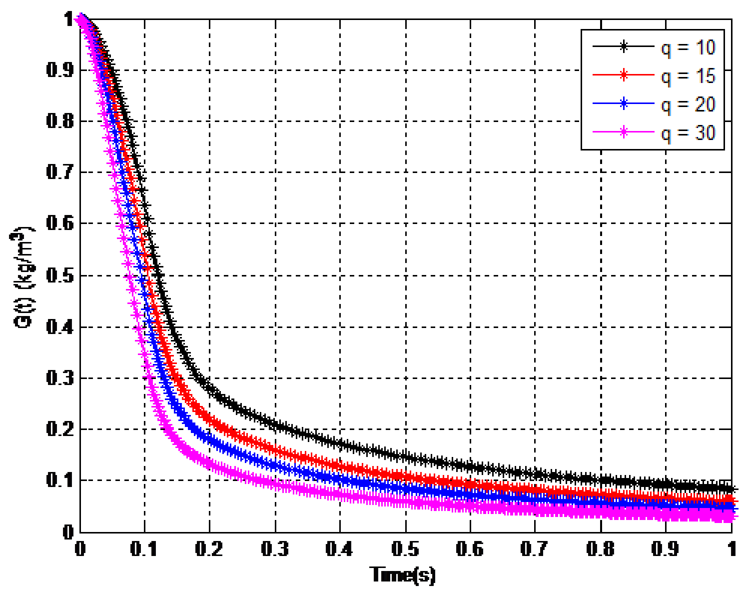

Figure 9. Graph of G with time t for different values of growth rate of rain, q.

4. The particulate matter phase, which can be brought on by cars, industrial sources, and other sources of particulate matter emissions into the atmosphere.
5. The phase of gaseous pollutants collected in raindrops is known as the "gas absorbed phase."

2.3. *Governing equations for pollutants removal*

Rain-induced pollution removal is controlled by intricate atmospheric mechanisms that include both deposition (rain-induced pollution removal) and convective transport (pollutant movement). A set of nonlinear mathematical models that take into consideration the movement of pollutants in the atmosphere and the rate at which raindrops remove them can be used to model these processes.

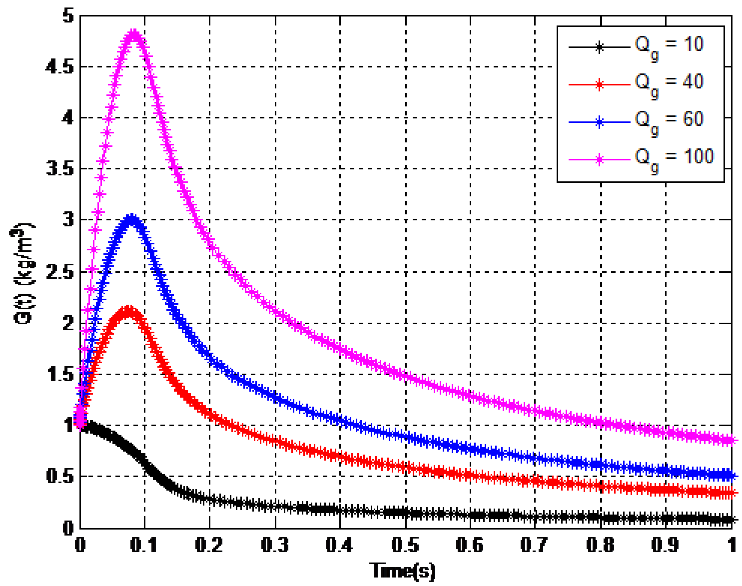

Figure 10. Variation of G with time t for different values of gaseous emission rates, Q_g.

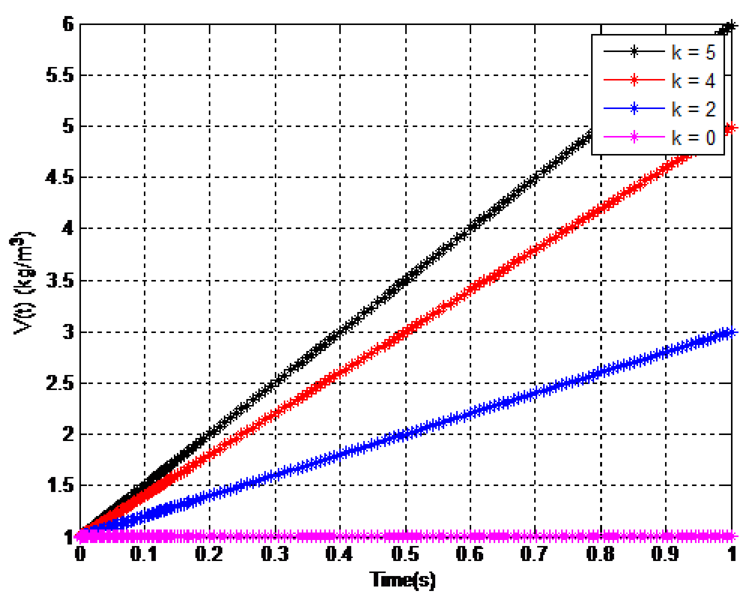

Figure 11. Variation of Water Droplet Number Density $W(t)$ with Time for Zero formation of vapors, k.

2.3.1. Dynamics of human population density

The first equation describes how the human population density N changes over time, accounting for natural growth, death, and the negative impacts of air pollutants. The logistic growth term reflects the carrying capacity K of the environment, while the pollutant terms illustrate the detrimental effects of both particulate matter P and gaseous pollutants G on population health [12].

$$\frac{dN}{dt} = \delta_g \left(N - \frac{N^2}{K} \right) - \delta_n N - \beta PN - \beta_o GN. \tag{1}$$

In the above model, N is the density of human population in the company, P is the concentration of PM pollutants, G is the concentration of gaseous pollutants, δ_g the intrinsic growth rate of human population density N with carrying capacity K, δ_n is the natural death rate due to some natural factors, β and β_o are coefficient rates of human population due to particulate and gaseous pollutants.

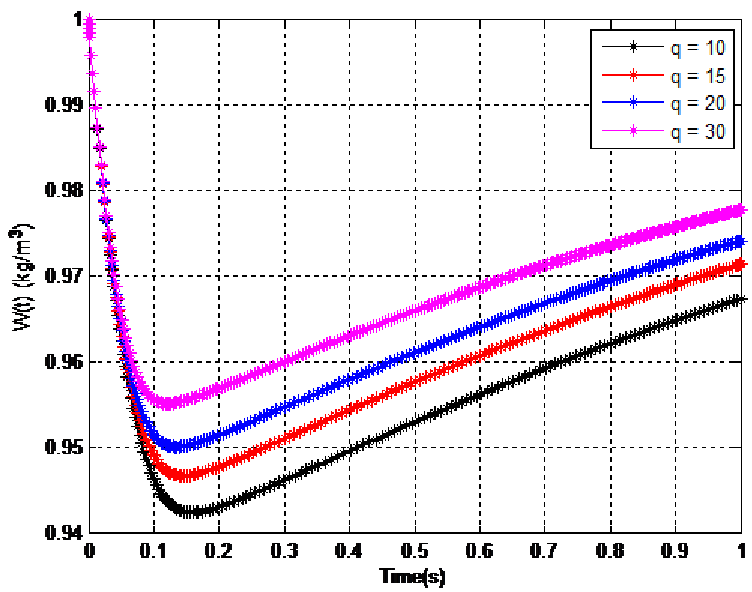

Figure 12. Variation of Number density of water droplets in cloud W with time t for zero value of the growth rate of rain, q.

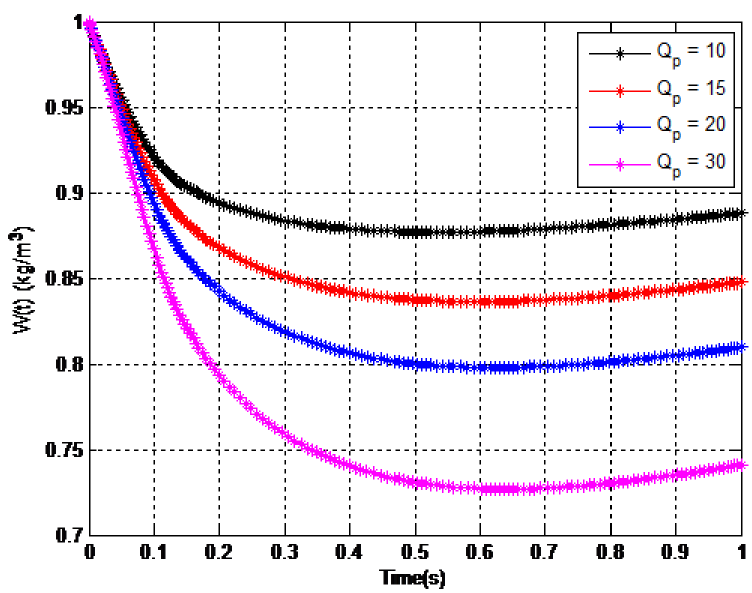

Figure 13. Variation of W with time t for different values particulate matters emission rates.

2.3.2. *Particulate matter concentration dynamics*

The removal of particulate matter from the atmosphere by rainfall is a size-dependent process. Larger particles are more readily captured by raindrops due to their higher gravitational settling velocities and their increased likelihood of collision with rain droplets.

The second equation models the concentration of particulate matter P, considering emission rates, natural decay, and the uptake of pollutants by the population and rain [13].

$$\frac{dP}{dt} = Q_p - \omega_o P - \omega_1 NP - \omega_2 RP. \tag{2}$$

Here, P is the concentration of PM pollutants, t is time taken, Q_p is the emission rates of particulate matters pollutants, ω_o is the rate of removal of particulate matters, ω_1 and ω_2 are the removal coefficients of pollutants due to its uptake by human population and rain, R is the density of raindrops.

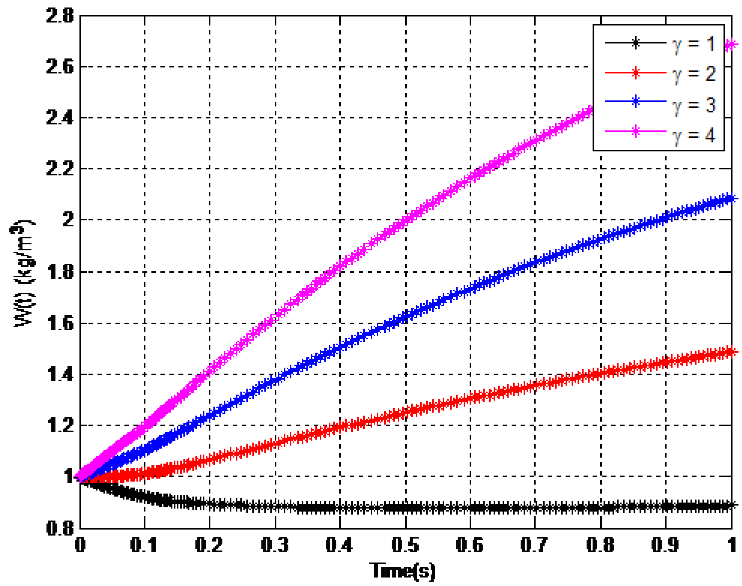

Figure 14. Variation in concentration of water droplet with time t for different values of the strength of formation of water droplets within the cloud, γ.

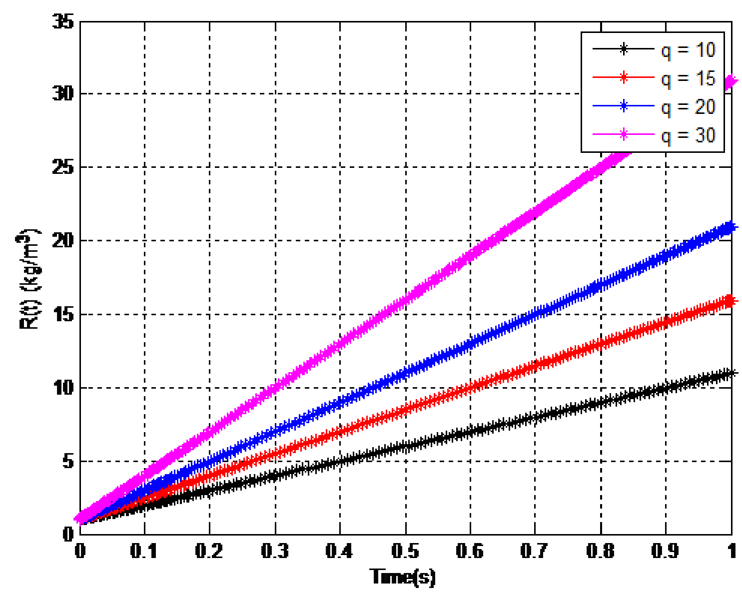

Figure 15. Variation of R with time t for different values of the growth rate of rain, q.

2.3.3. Gaseous Pollutants Dynamics

The third equation captures the dynamics of gaseous pollutants G, incorporating emission rates and interactions with human population density and rain [8].

$$\frac{dG}{dt} = Q_g - \alpha_o G - \alpha_1 GN - \alpha_2 GR, \tag{3}$$

where G is the concentration of gaseous pollutants, Q_g is the emission rates of gaseous pollutants, α_o is the rate of removal of gaseous pollutants, α_1 and α_2 are the removal coefficients of gaseous pollutants due to its uptake by human population and rain.

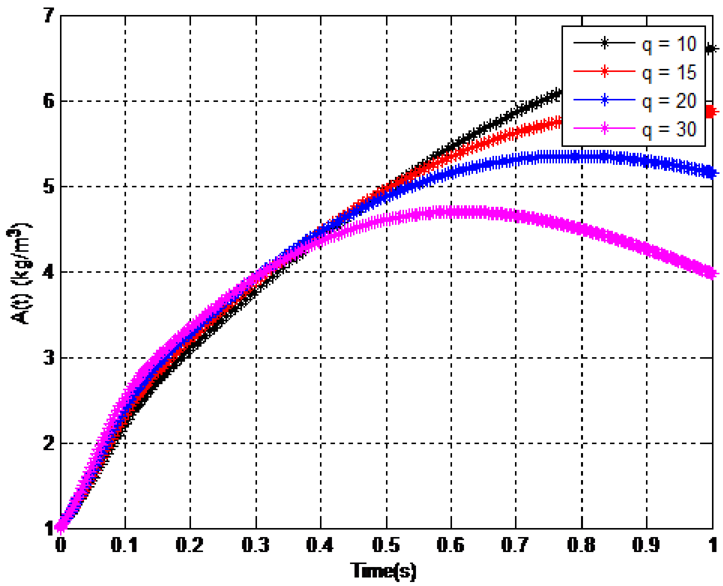

Figure 16. Concentration of gaseous pollutant due to interaction with water vapor against time t for different values of the growth rate of rain, q.

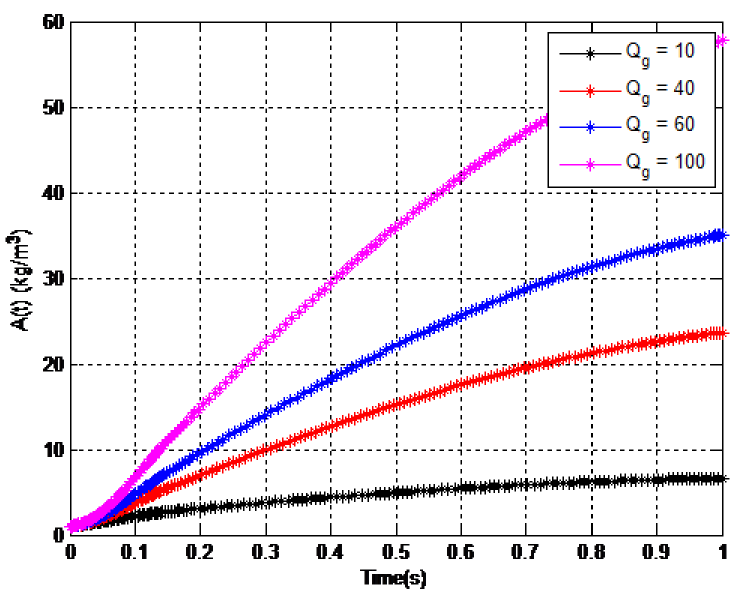

Figure 17. Variation in concentration of gaseous pollutant due to interaction with water vapor with time t for different values of gaseous emission rates, Q_g.

2.3.4. Water vapor density dynamics

The fourth equation describes changes in water vapor density V, influenced by its formation and depletion due to natural factors and cloud development [13].

$$\frac{dV}{dt} = k - \mu_o V + \mu_1 RG. \tag{4}$$

Here, V is the density of water vapor, k is the strength of formation of water vapors, μ_o is the depletion rate of water vapor phase caused by natural factors as well as by formation of cloud droplets, μ_1 is the nonlinearity factor.

2.3.5. Dynamics of water drop density

This equation captures the density of water droplets W within the cloud, incorporating both formation and depletion processes.

$$\frac{dW}{dt} = \gamma - \gamma_o W - \gamma_1 PW, \tag{5}$$

where $W\ is$ the number density of water droplets in cloud, γ is the strength of formation of water droplets within the cloud γ_o is the rate of formation of water vapors, γ_1 is the depletion coefficient of water droplets due to interaction with gaseous pollutants.

2.3.6. Raindrop concentration dynamics

The sixth equation represents the dynamics of raindrop concentration R, focusing on growth and decay influenced by pollutant interactions [13].

$$\frac{dR}{dt} = q - \varepsilon_o R - \varepsilon_1 PR, \tag{6}$$

where R is the density of raindrops, growth rate of rain drops q, ε_o and the growth rate of rain drops, ε_1 is the decay coefficient in raindrops due to pollutants.

2.3.7. Gaseous pollutant concentration in water vapor

The final equation addresses the concentration of gaseous pollutants A due to interaction with water vapor.

$$\frac{dA}{dt} = \omega_2 GR - \rho A - \tau RA, \tag{7}$$

where, A is the concentration of gaseous pollutant due to interaction with water vapor, ρ is removal rates of gaseous pollutants due to interaction, τ and is the removal coefficient due to interaction in the absorbed phase.

The associated initial conditions to the system are given below;

$$N = 1.0, \quad P = 1.0, \quad G = 1.0, \quad V = 1.0, \quad W = 1.0, \quad R = 1.0, \quad A = 1.0. \tag{8}$$

2.4. Computational method

The system of non-linear ordinary differential equations will be solved numerically using shooting iteration technique along with sixth order Runge- Kutta-Fehlberge integration scheme.

$$\begin{aligned}
k_1 &= hf(t_n, y_n), \\
k_2 &= hf\left(t_n + \tfrac{1}{4}h,\ y_n + \tfrac{1}{4}k_1\right), \\
k_3 &= hf\left(t_n + \tfrac{3}{8}h,\ y_n + \tfrac{3}{32}k_1 + \tfrac{9}{32}k_2\right), \\
k_4 &= hf\left(t_n + \tfrac{12}{13}h,\ y_n + \tfrac{1932}{2197}k_1 - \tfrac{7200}{2197}k_2 + \tfrac{7296}{2197}k_3\right), \\
k_5 &= hf\left(t_n + h,\ y_n + \tfrac{439}{216}k_1 - 8k_2 + \tfrac{3680}{513}k_3 - \tfrac{845}{4104}k_4\right), \\
k_6 &= hf\left(t_n + \tfrac{1}{2}h,\ y_n - \tfrac{8}{27}k_1 - 2k_2 + \tfrac{3544}{2565}k_3 - \tfrac{1859}{4104}k_4 - \tfrac{11}{40}k_5\right).
\end{aligned}$$

Then the approximation to the solution of the IVP was achieved using a sixth order Runge-Kutta- Fehlberg method [5, 9]. That is:

$$y_{n+1} = y_n + \frac{25}{216}k_1 + \frac{1408}{2565}k_3 - \frac{2197}{4101}k_4 + \frac{1}{5}k_5. \tag{9}$$

2.5. Simulation algorithm

To analyze the behavior of the system over time, numerical methods will be used to solve the system of ODEs. The selected method for this study is the Runge-Kutta method, which provides a reliable and efficient means of approximating solutions to differential equations.

2.6. Physical parameters used in the simulations

In order to obtain the solution numerically, it is vital to give the parameters in the problem under investigation some numerical values [9]. The parameters and boundary conditions given in tables 1 and 2 were used in the simulations.

Table 1. Simulation parameters.

Parameter	Value	Unit
δ_g	100.0	s^{-1}
δ_n	0.01	s^{-1}
K	100000.0	$kg\, m^{-3}$
β	0.0300	$kg^3\, m^3\, s^{-1}$
β_o	1.0	$kg^3\, m^3\, s^{-1}$
ω_o	0.2	s^{-1}
ω_1	0.001	$kg^3\, m^3\, s^{-1}$
ω_2	10	$kg^3\, m^3\, s^{-1}$
α_o	0.2	s^{-1}
α_1	0.001	$kg^3\, m^3\, s^{-1}$
α_2	10	$kg^3\, m^3\, s^{-1}$
μ_o	0.01	s^{-1}
μ_1	0.02	$kg^3\, m^3\, s^{-1}$
γ_o	1.0	s^{-1}
γ_1	1.0	$kg^3\, m^3\, s^{-1}$
ρ	1.0	s^{-1}
τ	1.0	$kg^3\, m^3\, s^{-1}$
ε_o	0.0003	s^{-1}
ε_1	0.02	$kg^3\, m^3\, s^{-1}$

Table 2. Boundary values.

Parameter	Values	Unit
Q_p	10, 15, 20, 30	$kg\, m^{-3}\, s^{-1}$
Q_g	10, 40, 60, 100	$kg\, m^{-3}\, s^{-1}$
γ	1, 2, 3, 4	$kg\, m^{-3}\, s^{-1}$
k	5, 4, 2, 0	$kg\, m^{-3}\, s^{-1}$
q	10, 15, 20, 30	$kg\, m^{-3}\, s^{-1}$

3. Results

This session presents the simulation results of the interaction between environmental factors and their impact on atmospheric processes, including human population density, particulate and gaseous pollutant concentrations, and water vapor dynamics. The results are depicted through various graphs that demonstrate the effects of changes in key parameters such as rain growth rate, emission rates of particulate and gaseous pollutants, and the strength of water droplet formation in clouds. These parameters significantly influence the behavior of pollutants in the atmosphere, as well as broader environmental and population dynamics. Each graph highlights the sensitivity of these variables under different conditions, providing a comprehensive view of the physical processes in the atmosphere.

4. Discussion of results

The findings presented in Figures 4 to 17 offer an in-depth perspective on the intricate relationships among pollutant dynamics, atmospheric phenomena, and environmental variables. Notable patterns and trends arise, showcasing the interactions between emission levels, precipitation, cloud development, and their combined effects on air quality and public health.

As demonstrated across the figures, a rise in particulate matter (Q_p) and gaseous pollutant (Q_g) emissions corresponds to increased concentrations of pollutants in the atmosphere. This creates a ripple effect wherein higher pollutant levels lead to detrimental impacts on human population density (N), as illustrated in Figures 4 and 6. Populations experience a sharper decline in areas with elevated emissions due to heightened health hazards, highlighting the urgent necessity for emission regulation to protect population health.

4.1. Role of rainfall in pollutant removal

The dynamics of rainfall, specifically the growth rate of raindrops (q), are crucial in reducing pollutant concentrations. As illustrated in Figures 7, 9, and 15, increased q values improve the elimination of both particulate and gaseous pollutants. Raindrops function as natural scavengers, effectively washing away pollutants through mechanisms of impaction and absorption. However, when emission rates exceed certain thresholds, as depicted in Figures 8 and 10, the pollutant removal capacity of rainfall gets overwhelmed, resulting in stubbornly high levels of pollutants.

4.2. Cloud and water vapor dynamics

Figures 11 to 14 demonstrate the essential function of water vapor (V) and the dynamics of cloud droplets in facilitating atmospheric purification. An increase in water vapor production and elevated droplet formation rates (k) result in a greater density of cloud droplets (W) and raindrops (R), which improves the natural elimination of pollutants. On the other hand, a decrease in vapor production or elevated pollutant levels can hinder the growth of clouds and raindrops, reducing their effectiveness in cleaning the atmosphere.

4.3. Impact of pollutants on atmospheric processes

The interaction between pollutants and atmospheric elements creates feedback mechanisms that influence removal effectiveness:

Particulate Matter: Elevated PM emission levels (Q_p) lead to decreased water droplet density (W) and diminished cloud efficiency (Figure 13). This suggests that PM not only adds to pollution but also disrupts the natural precipitation processes essential for its removal.

Gaseous Pollutants: Gaseous pollutants engage with water vapor, as illustrated in Figures 16 and 17. Increased emission rates (Q_p) raise pollutant levels in the water vapor phase, potentially changing its natural dynamics and impacting overall atmospheric quality.

As observed in Figures 4 to 17, indicate that atmospheric mechanisms, including rainfall and cloud behavior, are significantly influenced by the rates of pollutant emissions and environmental conditions. Although natural processes like rainfall and cloud development can effectively diminish pollutants, their effectiveness depends on controlled emission levels and suitable atmospheric circumstances.

The growth of enhanced rainfall (q) and the formation of water vapor (k) play a vital role in reducing pollution, as they enhance the processes that remove pollutants.

However, excessive emissions can exceed the capacity of natural removal, resulting in persistent pollutant levels and increased health hazards.

These findings underscore the importance of balancing natural atmospheric processes with emission control strategies. Strengthening rainfall dynamics and maintaining robust cloud formation processes can significantly mitigate air pollution, especially in industrial areas. However, such natural mechanisms must be complemented by stringent regulations on pollutant emissions to ensure sustainable air quality and protect human health.

5. Conclusion

The study reveals that rainfall plays a crucial role in reducing atmospheric pollutants, with rain growth rate (q) and cloud droplet formation (k) significantly enhancing pollutant removal. However, excessive emissions from industrial and urban sources can overwhelm this natural cleansing process, leading to persistently high pollution levels. Increased particulate (Q_p) and gaseous (Q_g) emissions are linked to declining population health, emphasizing the urgent need for emission regulations. Water vapor (V) and cloud density (W) improve air purification by facilitating raindrop formation, but high pollution levels can suppress cloud growth, reducing rainfall effectiveness. These findings highlight the delicate balance between emissions, atmospheric processes, and climate dynamics, underscoring the necessity of stricter pollution control measures and sustainable environmental policies.

Data Availability

No additional data was used beyond those presented in the submitted manuscript.

References

[1] Z. Asif, Z. Chen & Y. Han, "Air quality modeling for effective environmental management in the mining region", Journal of the Air & Waste Management Association **68** (2018) 1001. https://doi.org/10.1080/10962247.2018.1463301.

[2] L. Bai, J. Wang, X. Ma & H. Lu, "Air pollution forecasts: An overview", International Journal of Environmental Research and Public Health **15** (2018) 780. https://doi.org/10.3390/ijerph15040780.

[3] R. Naresh & S. Sundar, "A nonlinear dynamical model to study the removal of gaseous and particulate pollutants in a rain system", Nonlinear Analysis: Modelling and Control **12** (2007) 227. https://doi.org/10.15388/NA.2007.12.2.14337.

[4] S. Sundar, R. K. Sharma & R. Naresh, "Modelling the role of cloud density on the removal of gaseous pollutants and particulate matters from the atmosphere", Applications and Applied Mathematics: An International Journal (AAM) **8** (2013) 416. https://digitalcommons.pvamu.edu/aam/vol8/iss2/6.

[5] D. S. Igba & D. A. Otor, "Simulation of Earth planetary orbits using a modified inverse square model", International Journal of Recent Innovations in Academic Research **2** (2018) 23. https://zenodo.org/record/131210.

[6] D. D. Turner, A. M. Vogelmann, R. T. Austin, J. C. Barnard, K. Cady-Pereira, J. C. Chiu & W. Wiscombe, "Thin liquid water clouds: Their importance and our challenge", Bulletin of the American Meteorological Society **88** (2007) 177. https://doi.org/10.1175/BAMS-88-2-177.

[7] A. P. Khain, K. D. Beheng, A. Heymsfield, A. Korolev, S. O. Krichak, Z. Levin & J. I. Yano, "Representation of microphysical processes in cloud-resolving models: Spectral (bin) microphysics versus bulk parameterization", Reviews of Geophysics **53** (2015) 247. https://doi.org/10.1002/2014RG000468.

[8] B. Srimuruganandam & S. S. Nagendra, "Application of positive matrix factorization in characterization of PM10 and PM2.5 emission sources at urban roadside", Chemosphere **88** (2012) 120. https://doi.org/10.1016/j.chemosphere.2012.03.078.
[9] S. D. Igba, I. M. Echi & E. V. Tikyaa, "Simulation of thermochemical effects on unsteady magneto hydrodynamics fluids flow in two dimensional nonlinear permeable media", African Scientific Reports **3** (2024) 247. https://doi.org/10.46481/asr.2024.3.3.247.
[10] J. B. Shukla, R. Naresh & S. Sundar, "Removal by rain of two gaseous pollutants and a particulate matter formed by these two reacting gases from the atmosphere", International Journal of Applied Mathematics and Computation **4** (2012) 183. https://doi.org/10.47893/IJAMC.2012.1088.
[11] J. B. Shukla, S. Sundar, A. K. Misra & R. Naresh, "Modelling the removal of gaseous pollutants and particulate matters from the atmosphere of a city by rain: effect of cloud density", Environmental Modelling & Assessment **13** (2008) 255. https://doi.org/10.1007/s10666-007-9102-1.
[12] S. Sundar, N. Swaroop, R. Naresh & J. B. Shukla, "Modeling and analysis of the effects of gaseous pollutants and particulate matters on human health with control mechanisms", Computational Ecology and Software **11** (2021) 100. https://doi.org/10.23998/ces.2021.11.03.01.
[13] B. Dubey, "A model for the effect of pollutant on human population dependent on a resource with environmental and health policy", Journal of Biological Systems **18** (2010) 571. https://doi.org/10.1142/S0218339010003487.

APPENDIX A.

Nomenclatures

N – Density of human population, $\left(kgm^{-3}\right)$
K – Carrying capacity of human population, $\left(kgm^{-3}\right)$
t – Time, (s)
P – Concentration of particulate matters, $\left(kgm^{-3}\right)$
Q_p – Emission rates of particulate matters pollutants, $\left(kgm^{-3}\right)$
R – Density of raindrops, $\left(kgm^{-3}\right)$
G – Concentration of gaseous pollutants, $\left(kgm^{-3}\right)$
Q_g – Emission rates of gaseous pollutants, $\left(s^{-1}\right)$
V – Density of water vapor, $\left(kgm^{-3}\right)$
k – Strength of formation of water vapors, $\left(kgm^{-3}\right)$
W – Number density of water droplets in cloud, $\left(kgm^{-3}\right)$
A – Concentration of gaseous pollutant due to interaction with water vapor, $\left(kgm^{-3}\right)$
q – Growth rate of rain drops, $\left(kgm^{-3}\right)$

Greeks

δ_g – Intrinsic growth rate of human population, $\left(s^{-1}\right)$
δ_n – Natural death rate, $\left(s^{-1}\right)$
β, β_o –Coefficient rates of human population due to particulate and gaseous pollutants, $\left(kg^3 m^3 s^{-1}\right)$
ω_o – Rate of removal of particulate matters, $\left(s^{-1}\right)$
ω_1, ω_2 – Removal coefficients of pollutants due to its uptake by human population and rain, $\left(kg^3 m^3 s^{-1}\right)$
α_o – Rate of removal of gaseous pollutants, $\left(s^{-1}\right)$
$\alpha_1,\ \alpha_2$ – Removal coefficients of gaseous pollutants due to its uptake by human population and rain, $\left(kg^3 m^3 s^{-1}\right)$
μ_o – Depletion rate of water vapor phase caused by natural factors as well as by formation of cloud droplets, $\left(s^{-1}\right)$
μ_1 – Nonlinearity factor, $\left(kg^3 m^3 s^{-1}\right)$
γ – Strength of formation of water droplets within the cloud, $\left(kgm^{-3}\right)$
γ_o – Rate of formation of water vapors, $\left(s^{-1}\right)$
γ_1 – Depletion coefficient of water droplets due to interaction with gaseous pollutants, $\left(kg^3 m^3 s^{-1}\right)$
ε_o – Growth rate of rain drops, $\left(s^{-1}\right)$
ε_1 – Decay coefficient in raindrops due to pollutants, $\left(kg^3 m^3 s^{-1}\right)$
ρ – Removal rates of gaseous pollutants due to interaction, $\left(s^{-1}\right)$
τ – Removal coefficient due to interaction in the absorbed phase, $\left(kg^3 m^3 s^{-1}\right)$