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A Study of Urban Heat Island Effect on the Dispersion of Gaseous Pollutants Emitted from the Explosion of Firecrackers During the Diwali Festival in India

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ABSTRACT

The present study is an attempt to understand and assess the problem of poor air quality in an urban city developed due to the high emission of gaseous pollutants from the explosion of firecrackers during the Diwali festival in India. We know that the festival falls in the month of October or November and the climatic change plays a vital role in the dispersion of pollutants. It was observed that the urban heat island (UHI) is being formed during the time of festival in most of the urban area. Thus, we considered the effect of UHI in our study. Also, the diffusivity is considered to be temperature dependent. The overall study is divided into two intervals where in the first interval we considered the emission of pollutants in the absence of UHI and in second interval we considered the presence of UHI. The result was tabulated by considering twenty samples of firecrackers as a point sources at different positions which exploded at different times. The two-dimensional advective diffusion equations along with appropriate boundary conditions are used to define the phenomenon. The results so obtained reveals that the UHI plays a vital role in shaping the pollutants concentration. Also, the early formation of UHI aggravate the concentration level to a greater downwind distance and persist for a longer duration.

1. INTRODUCTION

Air pollution is one of the major problem the world is facing in today’s time. Due to the air pollution, the mankind is facing some serious threat and challenges like health issues, climatic change, damaging of crops and lands. Due to the lack of sufficient understanding of air quality, we are facing an alarming rise in anthropogenic emissions brought by industrialization and urbanization. In today’s rapid change, research shows a significant increase in air pollution over the last decade, (Sicard et.al. 2012) with worsening $PM_{2.5}$ levels, leading to more premature deaths, reduced life expectancy, and severe health impacts like childhood stunting, though SOx/NOx have sometimes declined in some areas while urban growth exacerbates the problem.

In past, mathematicians focussed their attention on the problem of air pollution through mathematical modelling and tried to understand the factors responsible for the dispersion of pollutants. In this regard the most commonly used model is Gaussian plume model which is still widely used (Hanna1984, Seinfeld 1986).

It was observed that the air quality in India becomes poor specially during the Diwali festival which fall in the month of October/November. The explosions of firecrackers causes a serious threat to the air quality resulting the formation of smog in most of the metropolitan cities/urban cities where there is a high density of population. The release of chemicals from firecrackers in the air undergo a combustion. This combustion produces two results: Short lived entertainment and toxic atmospheric pollutants. The release of contaminants affect the air quality and contribute to climate change. During the explosion of firecrackers there is a huge emission of sulphur dioxide, nitrogen dioxide, carbon monoxide, carbon dioxide, $PM_{2.5}, PM_{10}$, and several metals like aluminium, manganese etc which causes serious health issues (Ravindra et.al., 2003, Singh et. al., 2025). According to the Environmental Protection Agency (EPA) fine particulate matter ($PM_{2.5}$) poses substantial health risk to human and can cause premature death and other respiratory problems, irritation in eyes. Barman et.al. 2008, reported that during Diwali festival the level of SO_2 and NO_x were 6.6 and 2.7 times higher as compared to the normal days in Lucknow. Kulshrestha et al. (2004) reported a high level of different pollutants in the ambient air of Hyderabad, owing to fireworks during the Diwali festival. The study conducted by Salma et. al. (2023) in Budapest, Hungary regarding the concentration level of particulate matter due to firecrackers emission on St. Stephen's Day showed that the fireworks increased hourly mean concentrations by a factor of 5-6.

During the time of Diwali festival especially on the day of Diwali due to high emission of firecrackers and heavy traffic there is a rise of temperature in the highly populated cities. The temperature difference between urban and rural area causes the formation of urban heat island effect. It was observed that the lack of awareness and the high frequency of explosions of firecrackers intensify the existing urban heat island (UHI) (Mandal et.al. 2022). During the time of UHI the pollutants get trapped. This phenomenon creates a localized dome of warm air over cities, often acting as a barrier that prevents vertical mixing and making the situation worse. In recent times a significant amount of work has been done regarding the distribution of air pollution due to urban heat island effect (Chander 1968, Griffith 1970, Dilly and Yen 1971, Joseph and Yadav 2021). Summer (1964) expressed UHII (urban heat island intensity) as the temperature difference with respect to the surrounding area. Lee et. al., (2012) describe the scaling of the urban heat island effect using the fundamental energy balance equation (Lee and Ho, 2010).

Due to the air quality disaster occurred during the time of Diwali, the Supreme Court of India in 2017 imposed a ban on firecrackers. However, in present time we are trying to understand the impact of firecrackers on the air quality of Lucknow City. We therefore proposed a model by considering the explosions of firecrackers as multiple point sources during the first interval of time and in the second interval we considered the formation of the localized urban heat island. In the present study the diffusivity coefficient is considered to be temperature dependent. Considering the UHI effect, the temperature difference is represented by energy balance equation. The overall problem is presented in two intervals by considering two-dimensional advective-diffusion equations with appropriate boundary conditions. Analytical approach is adopted to obtain the solution by using the concept of Laplace Transform and Green's function.

2. MATHEMATICAL FORMULATION

We know that the firecrackers at the time of Diwali festival contribute significantly in uplifting air pollution. The release of gases like sulphur dioxide, nitrogen dioxide, particulate matters like $PM_{2.5}$, PM_{10} significantly enhance the level of air pollutants. The firecrackers are low intensity explosive pyrotechnic devices which can be classified as handheld, ground based, and aerial firecrackers. We considered these as point sources and hence the model we proposed in this paper considered multiple point sources which are mathematically represented as

$$\sum_{i=1}^{m} Q^i \delta(t-t_i)\, \delta(x-x_i)\delta(y-y_i)\delta(z-z_i) \tag{2.1}$$

Here, $\delta(.)$ represent Dirac-delta function.

In the present paper, we considered two phases in accordance with the time interval. The region of interest is considered to be highly densely populated region where it was assumed to have an intensive emission of firecrackers whereas the adjacent area is considered as the green area with vegetation and open area. The study focuses on the distribution of gaseous pollutants from the firecrackers in the highly densely populated area. In first phase we assumed that the pollutants in gaseous form are released as multiple point sources in the form of firecrackers in two-dimensional plane in absence of UHI. However, due to the trapping of heat emitted from the fire cracker and lack of proper wind flow and low vegetation there is a formation of UHI. Thus, we have considered the existence of UHI in the second phase after the explosion of firecrackers.

Ist Interval $0 \le t \le t_1$

In first phase we assumed the diffusivity coefficient along the vertical direction to be temperature dependent and is considered in the simplest form as $K(z) = K_0 T^{3/2}$, where K_0 is considered as the diffusivity coefficient at the reference point. Here, the temperature of the surrounding is considered as constant for the first interval.

We assumed that the mean concentration of pollutants is constant along crosswind distance and hence the governing advection-diffusion equation is considered to be two-dimensional.

$$\frac{\partial C_1}{\partial t} + u\frac{\partial C_1}{\partial x} = \frac{\partial}{\partial z}\left(K(z)\frac{\partial C_1}{\partial z}\right) + \sum_{i=1}^{m} Q^i \delta(t-t_i)\, \delta(x-x_i)\delta(z-z_i) \tag{2.2}$$

Or

$$\frac{\partial C_1}{\partial t} + u\frac{\partial C_1}{\partial x} = K_0 T^{3/2}\frac{\partial^2 C_1}{\partial z^2} + \sum_{i=1}^{m} Q^i \delta(t-t_i)\, \delta(x-x_i)\delta(z-z_i) \tag{2.3}$$

Here, C_1 is the concentration of pollutants at any point (x, z), u represent the wind speed along the downwind distance and is considered as constant.

It was assumed that initially there was no contamination and have zero concentration for the simplicity of the problem. Thus,

$$C_1(x,z,t) = 0, t = 0, x \geq 0, z \geq 0 \qquad (2.4)$$

The pollutants emitted from the sources are assumed to be perfectly reflected when contacted with the ground, which can be mathematically expressed as

$$K(z)\frac{\partial C_1}{\partial z} = 0 \quad \text{at } z = 0 \qquad (2.5)$$

It was assumed that the pollutants could not penetrate through the top of the inversion/mixed layer and therefore the mathematical expression becomes

$$K(z)\frac{\partial C_1}{\partial z} = 0 \quad \text{at } z = H \qquad (2.6)$$

where H is an inversion height.

IInd Interval $t \geq t_1$

We know that the heating of the urban surfaces in the daytime sets the initial temperature, and after sunset the overheating starts to cool down through mean convection motion over the urban surface. Thus, according to the paper Lee et.al. 2012 we assumed the decay of temperature to be an exponential decay. In such a situation during night, we assumed the high emission of gaseous pollutants as well as heat emitted out from firecrackers and this accelerates the possibility of forming the urban heat island effect in the area of the urban city considering the urban length to be from L =30 km to L = 40 km. Under such situation, we considered the temperature difference to be time-dependent and therefore, according to the paper Lee et. al. 2012, the temperature evolution of the UHI intensity is given by

$$T_u - T_r = \lambda exp\left(-k\frac{u}{L}t\right) \qquad (2.7)$$

where $\lambda = (T_u - T_r)_0$ as initial temperature difference. L represent the urban length scale and is considered to be 30 km, T_u represent the urban temperature and T_r represent the temperature of adjacent rural area, u represent the wind speed, k is considered as constant and is taken as 0.45 corresponding to the average wind speed as $3.3 m/s$ (Lee et.al. 2012).

We considered the urban temperature as

$$T_u = \lambda exp\left(-k\frac{u}{L}t\right) + T_r \qquad (2.8)$$

Considering the value of $k\frac{u}{L}t$ to be small for large value of L and short duration of urban heat island effect, we can approximate $exp\left(-k\frac{u}{L}t\right)$ as a linear term $\left(1 - k\frac{u}{L}t\right)$. While considering the time duration of the urban heat island effect to be of 30 minutes, the error of approximation is found to be .00385. Whereas, considering the time of urban heat effect to be of 1 hour we have the error of approximation to be 0.015. For the simplicity of the problem, we considered the UHI effect to be short-lived and therefore the approximation as linear term is taken into the account of consideration.

Hence, $T_u = \lambda\left(1 - k\frac{u}{L}t\right) + T_r \qquad (2.9)$

This mean that the temperature of the urban area is dependent upon the urban length scale, temperature of adjacent area and time.

The diffusion coefficient along the vertical direction will be represented as

$$K(z) = K_0 {T_u}^{3/2}$$

$$= K_0\left(\lambda\left(1 - k\frac{u}{L}t\right) + T_r\right)^{3/2}$$

$$= K_0 {T_r}^{3/2}\left(\frac{\lambda}{T_r}\left(1 - k\frac{u}{L}t\right) + 1\right)^{3/2}$$

Using the Binomial expansion, we get

$$= K_0 T_r^{3/2}\left(\left(1 + \frac{3}{2}\frac{\lambda}{T_r}\right) - \frac{3}{2}\frac{\lambda}{T_r}.k\frac{u}{L}t\right)$$

(Neglecting higher terms as $\frac{\lambda}{T_r}\left(1 - k\frac{u}{L}t\right)$ is small).

$$= K_0 T_r^{3/2}\left(1 + \frac{3\lambda}{2T_r}\right)(1 - \alpha t) \text{ where } \alpha = \frac{3}{2}\frac{1}{\left(1 + \frac{3\lambda}{2T_r}\right)}.\frac{\lambda}{T_r}.k\frac{u}{L}$$

$$= \beta(1-\alpha t) \text{ where } \beta = K_0 T_r^{3/2}\left(1+\frac{3}{2}\frac{\lambda}{T_r}\right) \tag{2.10}$$

In this situation, the advection-diffusion equations corresponding to gaseous pollutants becomes

$$\frac{\partial C_2}{\partial t} + u\frac{\partial C_2}{\partial x} = \frac{\partial}{\partial z}\left(K(z)\frac{\partial C_2}{\partial z}\right) \tag{2.11}$$

Or $$\frac{\partial C_2}{\partial t} + u\frac{\partial C_2}{\partial x} = \beta(1-\alpha t)\frac{\partial^2 C_2}{\partial z^2} \tag{2.12}$$

At $t = t_1$, it was assumed that the concentration of pollutants in both the intervals is same

$$C_1(x,z,t) = C_2(x,z,t) \text{ at } t = t_1 \tag{2.13}$$

In second interval, the pollutants are assumed to be perfectly reflected when contacted with the ground, which can be mathematically expressed as

$$K(z)\frac{\partial C_2}{\partial z} = 0 \quad \text{at } z = 0 \tag{2.14}$$

In second interval, the pollutants could not penetrate through the top of the inversion/mixed layer and therefore, the mathematical expression becomes

$$K(z)\frac{\partial C_2}{\partial z} = 0 \quad \text{at } z = H \tag{2.15}$$

3. METHOD OF SOLUTION:

In the Ist interval, we use the Green's function methodology, Laplace Transform and method of separation of variables to solve the equations (2.3) – (2.6). The solution corresponding to the first interval is represented as

$$C_1(x,z,t) = \sum_{i=1}^{m}\sum_{n=1}^{\infty} Q^i \frac{cos(\rho\eta_n z_i)cos(\rho\eta_n z)}{\int_0^H cos^2(\rho\eta_n z)dz}.exp\left(-\frac{\eta_n^2}{u}(x-x_i)\right).\delta\left(t-t_i-\left(\frac{x-x_i}{u}\right)\right) \tag{3.1}$$

where η_n represent the eigenvalues and is represented as $\eta = \frac{n\pi}{\rho H}$ where $\rho = \frac{1}{K_0^{1/2}T^{3/4}}$ (3.2)

In second interval, corresponding to the equations (2.12) – (2.15) we use the transformations

$$X = \int(1-\alpha t)\,dx = (1-\alpha t)x \tag{3.3}$$

$$T = \int_0^t (1-\alpha t)dt = \left\{\frac{1-(1-\alpha t)^2}{2\alpha}\right\} \tag{3.4}$$

Using the above transformations, the equation (2.12) becomes

$$\frac{\partial C_2}{\partial T} + u\frac{\partial C_2}{\partial X} = \beta\frac{\partial^2 C_2}{\partial z^2} \tag{3.5}$$

The equations (2.13) – (2.15) are transformed accordingly as

$$C_1(X,z,T) = C_2(X,z,T) \text{ at } T = T_{t=t_1} \tag{3.6}$$

$$\frac{\partial C_2}{\partial z} = 0 \text{ at } z = 0 \tag{3.7}$$

$$\frac{\partial C_2}{\partial z} = 0 \text{ at } z = H \tag{3.8}$$

The concept of Green's function, Laplace Transform and method of separation of variables along with the appropriate conditions (3.6) – (3.8) are used to find the solution. The corresponding solution for the concentration of pollutants in second interval is represented as

$$C_2(x,z,t) = \sum_{k=1}^{\infty}\sum_{i=1}^{m}\sum_{n=1}^{\infty} Q^i exp\left(-\frac{\mu_k^2}{u}(1-\alpha t)x\right).\frac{cos\left(\frac{\mu_k}{\beta^{\frac{1}{2}}}\right)z}{\int_0^H cos^2\left(\frac{\mu_k}{\beta^{\frac{1}{2}}}z\right)dz}.cos(\rho\eta_n z_i).$$

$$\frac{\int_0^H cos\left(\frac{\mu_k}{\beta^{\frac{1}{2}}}z\right)cos(\rho\eta_n z)dz}{\int_0^H cos^2(\eta_n z)dz}exp\left(-\eta_n^2\left(\left\{\frac{1-(1-\alpha t_1)^2}{2\alpha}\right\}-t_i\right)\right).$$

$$\delta\left(\left(1+\alpha\frac{x}{u}\right)t-t_1-t_i-\frac{x}{u}+\frac{x_i}{u}+\left\{\frac{1-(1-\alpha t_1)^2}{2\alpha}\right\}\right) \tag{3.9}$$

where $\mu_k=\frac{\beta^{\frac{1}{2}}k\pi}{H}, k=1,2,3,\dots$

4. RESULT AND DISCUSSIONS:

The report of Lucknow's air quality significantly deteriorated during Diwali in 2025 (October 20), with AQI levels soaring into the **"hazardous" (419)** and **"severe"**, due to gaseous pollutants, $PM_{2.5}$ and PM_{10} emitted from firecrackers spiking over permissible limits, though unseasonal rain and wind later brought temporary improvement to "satisfactory" levels. Pre-Diwali (Oct 19), levels were moderate (around 123-174), while Diwali night and the day after saw major spikes (e.g., 419 AQI, $PM_{2.5}$ /PM_{10} several times above norms), followed by a dip to moderate (around 250) and then further drops with the changes in weather. To understand the various factors influencing the concentration of gaseous pollutants like carbon monoxide and carbon dioxide emitted from the explosions of firecrackers, in absence and presence of UHI, we considered the following data in order to compute and analyze the structural behavior of the dispersion of gaseous pollutants emitted from the firecrackers. It was observed that the urban heat island effect is created in an urban city during the Diwali festival. The temperature difference between the highly densely populated area and the and adjacent rural area becomes significant due to the lack of heat release due to the buildings and houses, reduced vegetation, lack of natural landscape due to which heat get trapped in the densely populated area and therefore creates a temperature difference between the densely populated area and urban green area creating the urban heat island effect.

In this regard, we considered the Ist region of highly densely populated region and the neighboring region as the green area (rural area). The emission of the firecrackers is taken as point source placed at different locations in the Ist region considered as the region of interest. The region of interest is considered to be of length L = 30 km which is the urban area. The wind speed is considered to be constant and the value is taken to be 3.3 m/sec. The temperature of the urban area in Ist interval is 300.15K. However, in second interval the temperature of adjacent area (T_r)is considered to be 300.15K i.e. 27°C. The value of the parameter ρ is taken to be .0062. Also, the value of $K_0=1m^2/s$. The suitable value of k is considered as 0.45 (Lee et.al. 2012). The value of λ is 5K. We have taken the Lucknow city, capital of Uttar Pradesh, India as a part of the study. The Lucknow city is in the Northern part of India where the average temperature in the month of October-November varies from $35°C-15°C$.

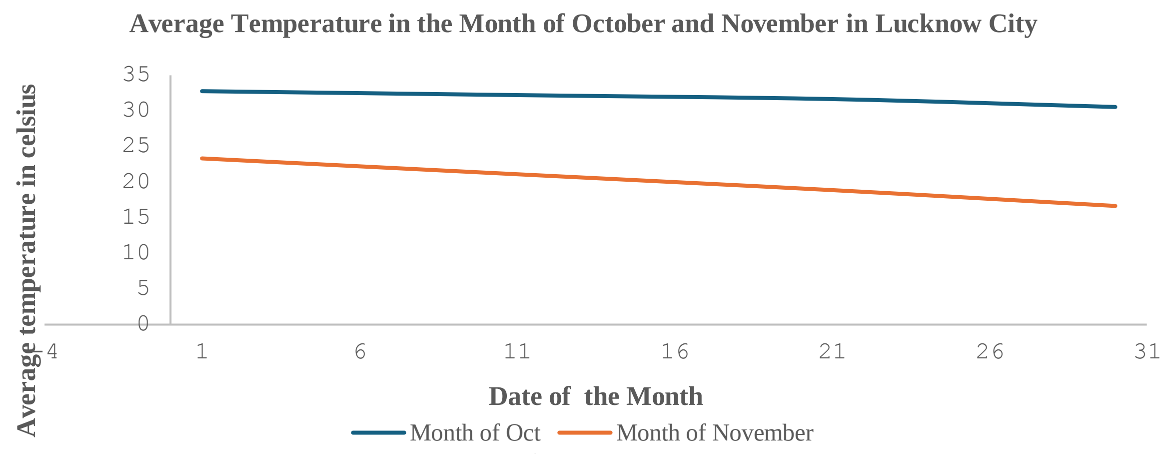

Figure: 1

The avaerage temperature of city of Lucknow in the month of October and November from 2021-2025

(Data is taken from www.weatherspark.com)

To understand the impact of pollutants in two different time-interval we considered a small-scale measurement. We considered the downwind distance up to 250m. Also, we considered the different phases of the explosions of the firecrackers i.e. within one minute, two-minute and three-minute span of time. In one-minute span of time we considered 8 explosions of firecrackers at different locations. During the time from 60 sec to 120 sec we again considered 8 explosions at different locations and finally from 120 sec to 180 sec we considered the 4 explosions of firecrackers. These firecrackers are taken as an aggregated source. The following table 4.1 illustrate the quantity, time and position of explosions.

S.No	Time	Position (x, z) in m	Quantity
1	15 seconds	(50, 0)	100 gm/sec
2	15 seconds	(40, 100)	100 gm/sec
3	30 seconds	(100, 0)	100 gm/sec
4	30 seconds	(150, 0)	100 gm/sec
5	45 seconds	(170, 50)	100 gm/sec
6	45 seconds	(20, 300)	200 gm/sec
7	60 seconds	(50, 200)	200 gm/sec
8	60 seconds	(30, 0)	200 gm/sec

Table: 4.1

In next minute we again considered eight explosions of firecrackers at different locations which are as follows:

S.No	Time	Position (x, z) in m	Quantity
1	75 seconds	(20, 0)	100 gm/sec
2	75 seconds	(90, 0)	100 gm/sec
3	90 seconds	(60, 100)	200 gm/sec
4	90 seconds	(120, 50)	200 gm/sec
5	105 seconds	(150, 0)	100 gm/sec
6	105 seconds	(100, 0)	100 gm/sec
7	120 seconds	(140, 70)	200 gm/sec
8	120 seconds	(180, 100)	200 gm/sec

Table: 4.2

In last span of time, we consider four explosions of firecrackers whose position, time and the amount of emission is mentioned below.

S.No	Time	Position (x, z) in m	Quantity
1	135 seconds	(60, 0)	100 gm/sec
2	150 seconds	(120, 0)	100 gm/sec
3	165 seconds	(140, 0)	200 gm/sec
4	180 seconds	(200, 0)	200 gm/sec

Table: 4.3

To understand the distribution of gaseous pollutants emitted from the fire explosions during the three-minute time in the first interval we tabulated the data for the GLC (Ground level concentration). We considered the position as x = 100m, 150m, 200m, 250m for the evaluation of the concentration of pollutants at different time. During the one- minute explosions of firecrackers at different positions the time span of calculation of concentration is taken to be from 30.5 seconds to 105.5 seconds. It was observed that the concentration level of the pollutants decreases with the increase of time and also with the increase of downwind distance. We also observe a slight variation (i.e. slight increase) in the concentration of pollutants (Figure-2) at different time which occur due to the repetition of explosions of firecrackers at same location at different time as shown in the table 4.1.

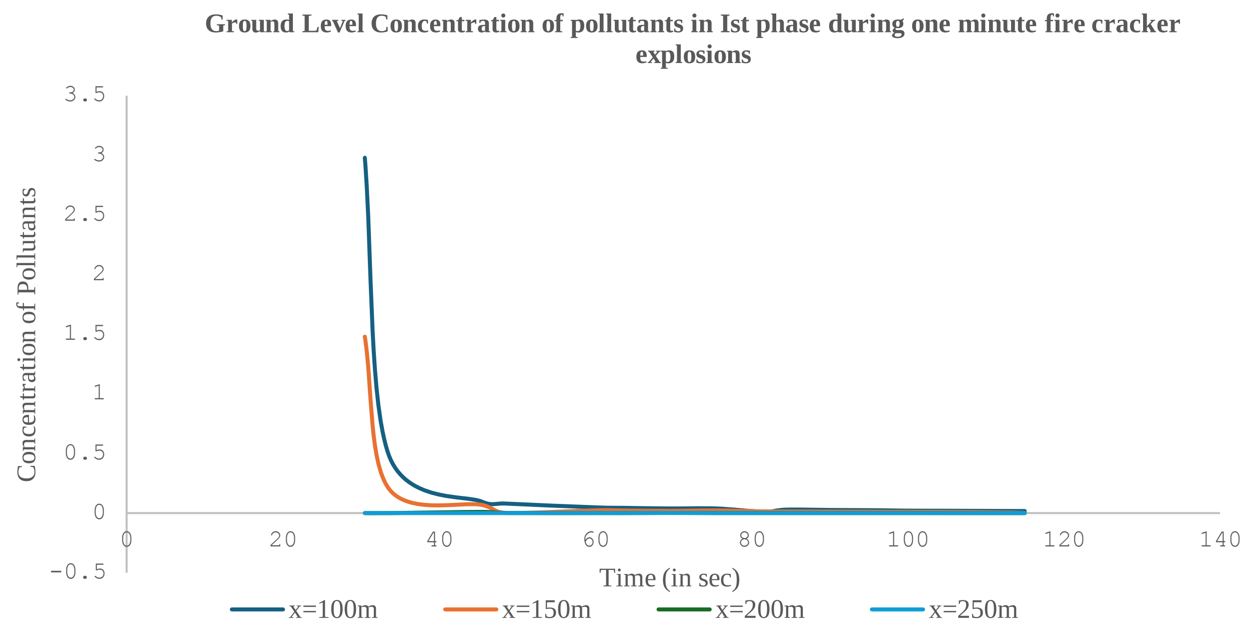

Figure-2

(Concentration of pollutants while considering eight explosions according to Table 4.1 in the region when the is temperature 300.15K)

However, during the two-minute span of time of explosions, it was found that there are several spikes in the ground level concentration (GLC) at different time between 70 sec -140 sec as shown in Figure -3. Also, the variation in the concentration is highest at x =150m which is due to the position of the fire explosions. Thus, the position of the firecrackers also plays a vital role in the contribution of the dispersion of pollutants. Further, the GLC level of the pollutants propagates to the greater downwind distance as compared with the figure 2. This shows that increase in the frequency of the explosions not only increases the spikes of the GLC level but also accelerates the propagation of pollutants to a greater downwind distance.

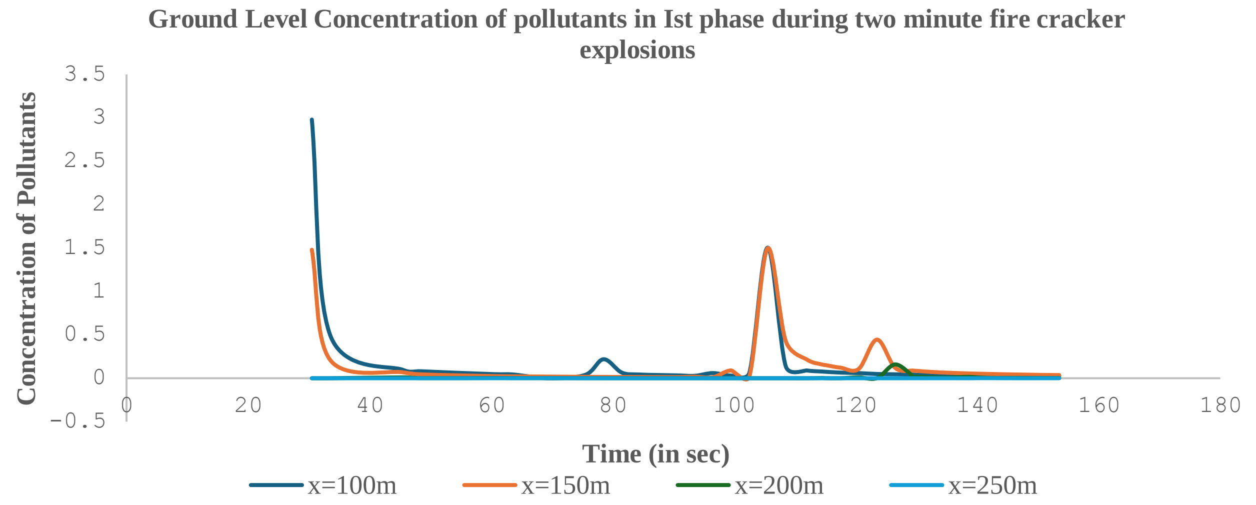

Figure-3

(Concentration of pollutants while considering sixteen explosions according to Table 4.2 in the region when the is temperature 300.15K)

Now, when we increase the time span of the explosions from two minute to three minutes then the concentration of pollutants for different downwind distance at different time was calculated as showed in Figure 4. While considering the total number of explosions to be 20 during three-minute time span, we observed that the number of spikes in the concentration level increases as compared to Figure 2 and 3. Also, the pollutants propagates to greater downwind distance as compared to Figure 2 and 3. Thus, the increase in the frequency of firecrackers as well as explosions for a longer period of time will definitely enhance the ground level concentration to a greater downwind distance and also persist for a longer duration.

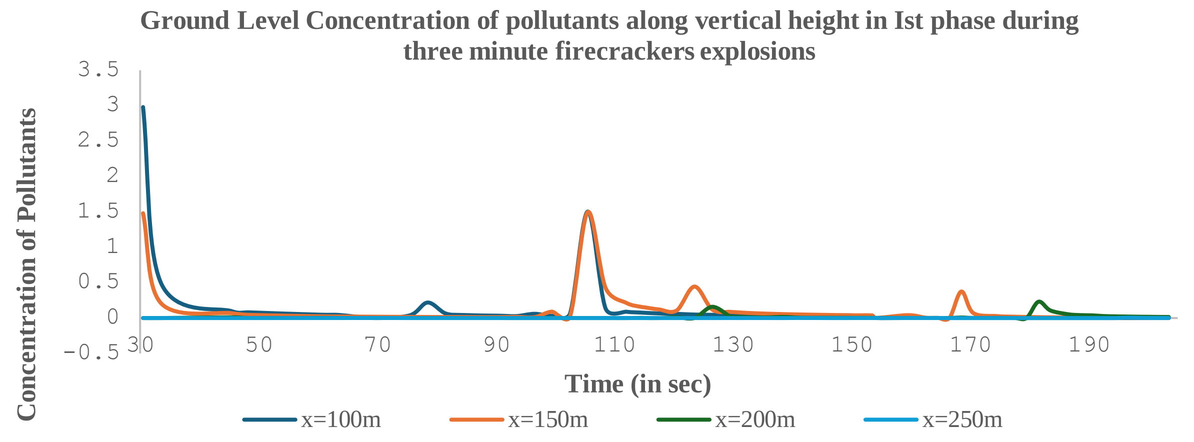

Figure-4

(Concentration of pollutants while considering twenty explosions according to Table 4.3 in the region when the is temperature 300.15K)

In computing the concentration level of the pollutants along the vertical height at x = 100m, the Figure 5 ,6 and 7 exhibit the concentration level due to the explosion of firecrackers during one-minute, two-minute and three-minute span of time respectively. In Figure 5 it was observed that the concentration level of the pollutants decreases with the increase of time as well as with the increase of the vertical height. Whereas in Figure 6 and 7, we observed that there are spikes in the concentration level at different time which shows the increase in the concentration level. The highest peak was observed in between the time of 100 - 120 seconds. Also, the concentration of pollutants last for the much larger time as compared with the Figure 5. This indicates that when the frequency of the explosions increases then the concentration level not only increases along the downwind distance but also along the vertical height and persist for a much longer time. Thus, ambient air quality becomes very poor in majority of the urban cities of India during the day of Diwali.

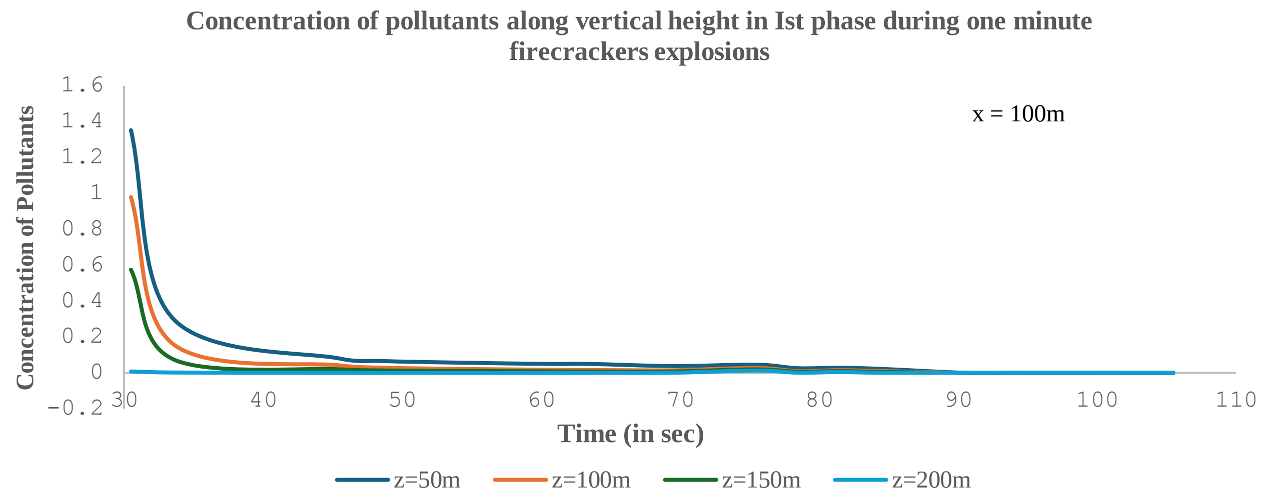

Figure-5

Concentration of pollutants along while considering the explosions according to Table 4.1 in the region when the is temperature 300.15K

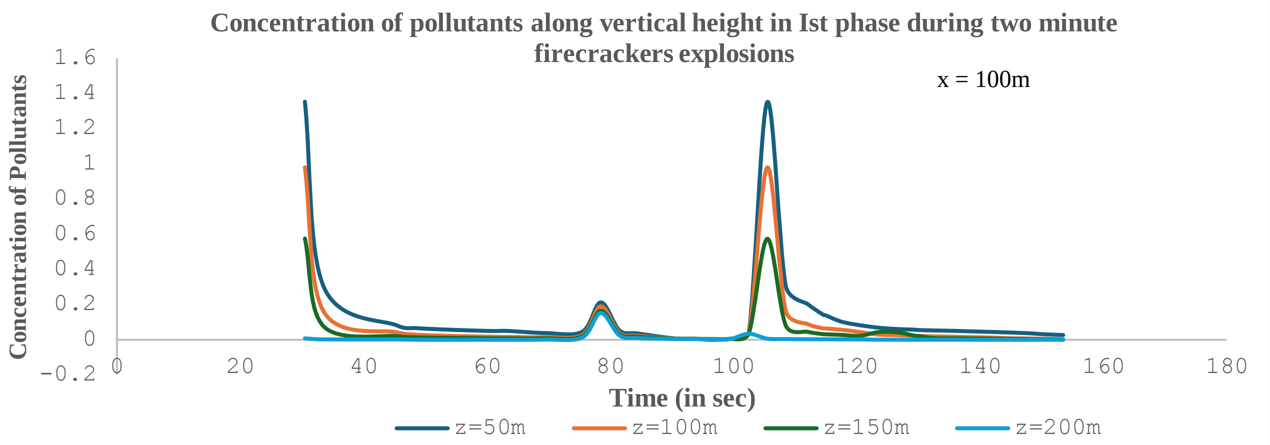

Figure-6

(Concentration of pollutants along while considering the explosions according to Table 4.2 in the region when the is temperature 300.15K)

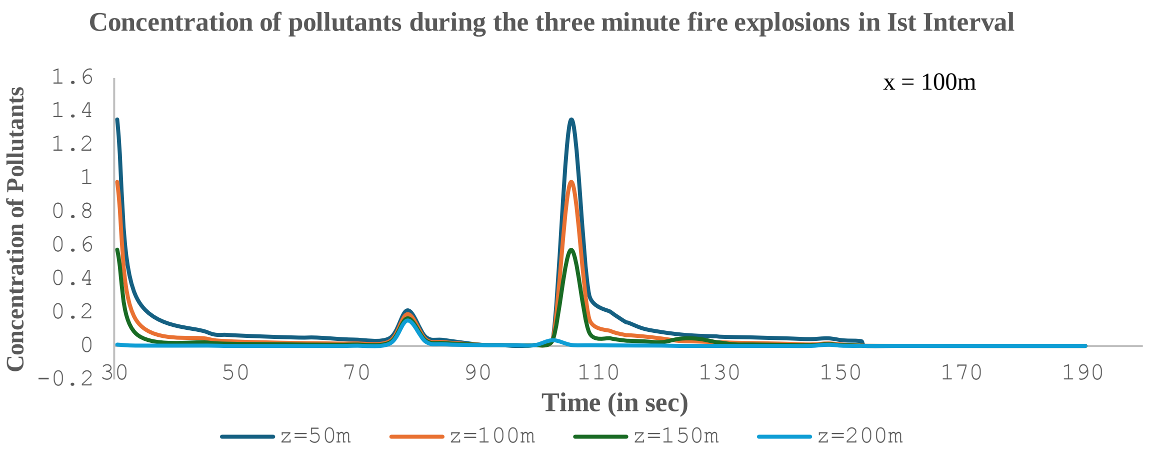

Figure: 7

(Concentration of pollutants along while considering the explosions according to Table 4.3 in the region when the is temperature 300.15K)

We considered that the urban heat island becomes effective at $t_1 = 180$ seconds in the region of concern. The Figure 8 shows that the concentration level under UHI effect after the explosions during the three-minute time span. The concentration level is calculated for different downwind distance from time $t = 196.5\ seconds$ to $203.5\ seconds$. It was observed that the concentration level is almost zero for x = 100m and corresponding to x =150m and 200m, the concentration level remain almost same with the increase in time. However, there is a higher level in the concentration at t = 196.5 sec for x =250m and the magnitude is significant in the later time also. This shows the impact of UHI on the pollutant in longer duration and at higher downwind distance.

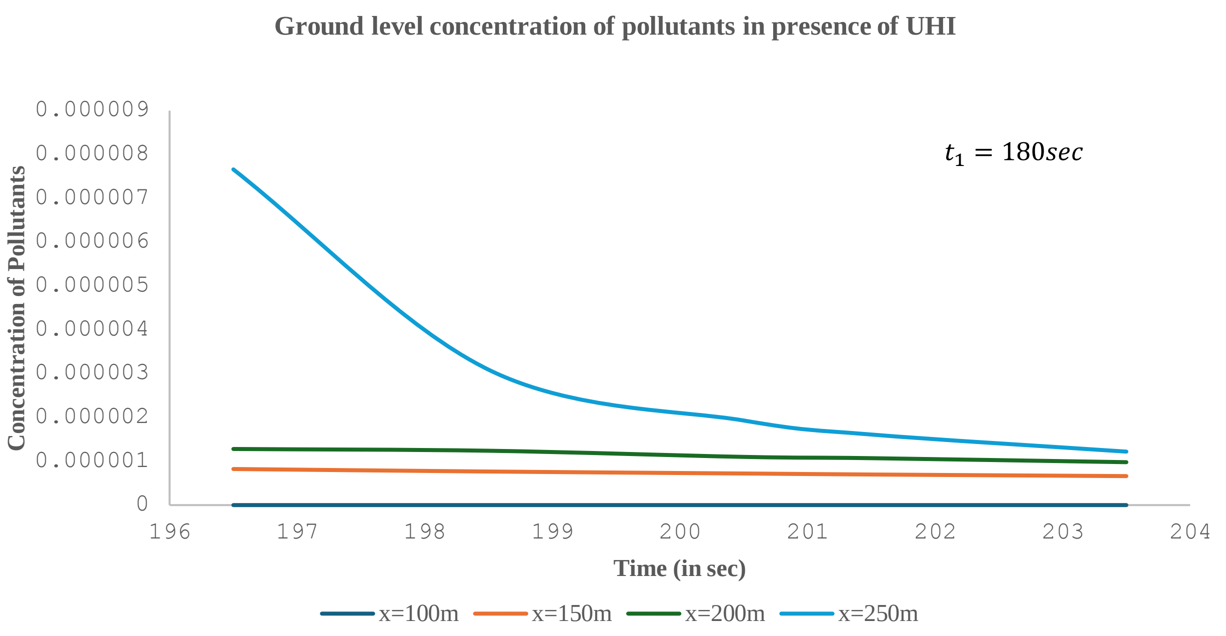

Figure: 8

(The effect of UHI is assumed to be commenced at 180 seconds onward in the region of interest of length 30 Km)

The early formation of urban heat island during the festival time where an intensively high frequency of explosion takes place in an urban area is harmful can be seen in Figure 9. The Figure 9 reveals the time lag of the formation of UHI, which shows that the early formation of UHI always increases the concentration level with a rapid pace. We considered the formation of UHI at two different time via $t_1 = 180\ seconds$ and $t_1 = 190\ seconds$. The calculation showed that the concentration level corresponding to $t_1 = 180\ seconds$ is higher as compared with the concentration corresponding to $t_1 = 190\ seconds$, for x = 150m, 200m, 250m. From the Figure 9, we observed that the concentration level for x =250m is higher and decreases gradually with the increase in time in both cases. This shows that under the UHI, the persistence of higher level of concentration existed towards higher downwind distance and also in latter time. Hence, we believed that the possibility for the formation of smog not only depend upon the higher frequency of explosion but also on early formation of UHI.

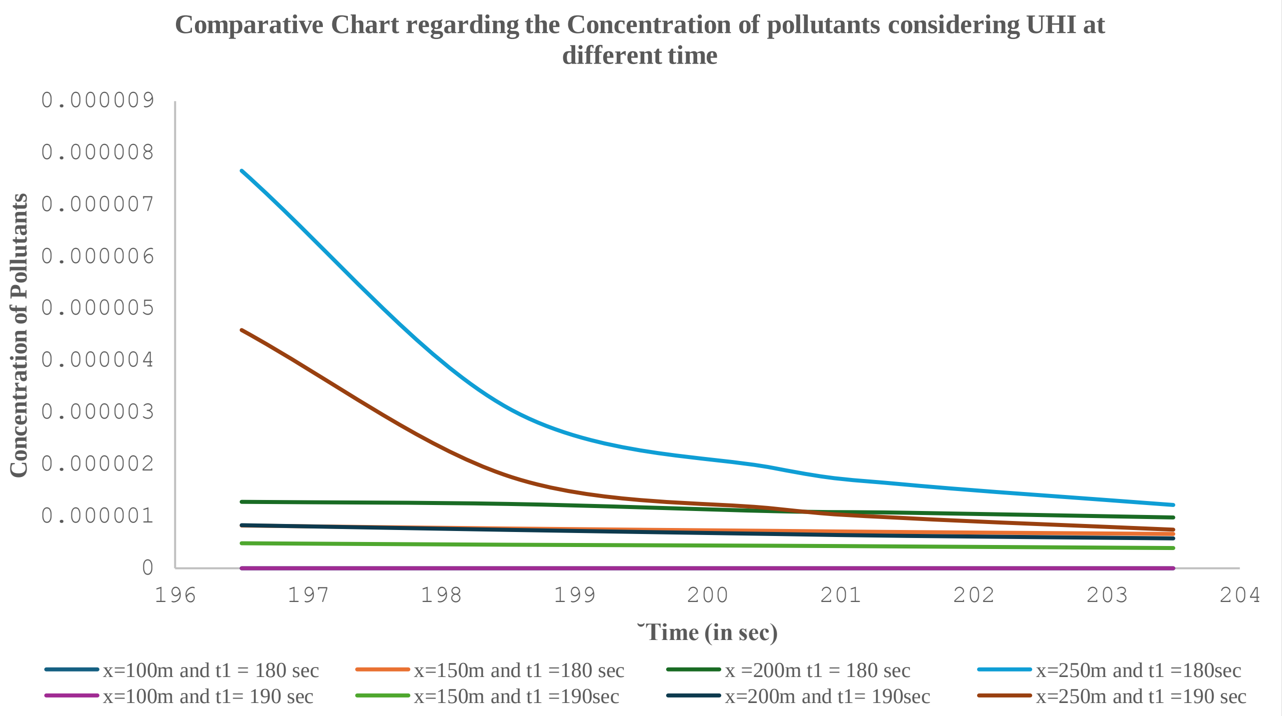

Figure: 9

(Comparative data showing the distribution of pollutants when the effect of UHI commenced at different times in region of 30 Km)

When we compared the concentration level for two different regions i.e. L =30 Km and L = 20 Km in which the urban heat island effect exists, it was found that the concentration level in the region of length L = 20 Km is slightly higher as compared to the concentration level in the region of length L = 30Km as seen in the Figure 10. We observed that the higher level of concentration is achieved towards the higher downwind distance and the persistence of the concentration level of pollutants exists for a longer duration. Thus, we conclude that when the exposed region is small and the UHI exist the situation becomes more alarming because the air quality gets poorer. This calls for the attention regarding the proper urban planning and establishment of more green area in order to avoid the formation of UHI in the local or small area of urban city during the festival time.

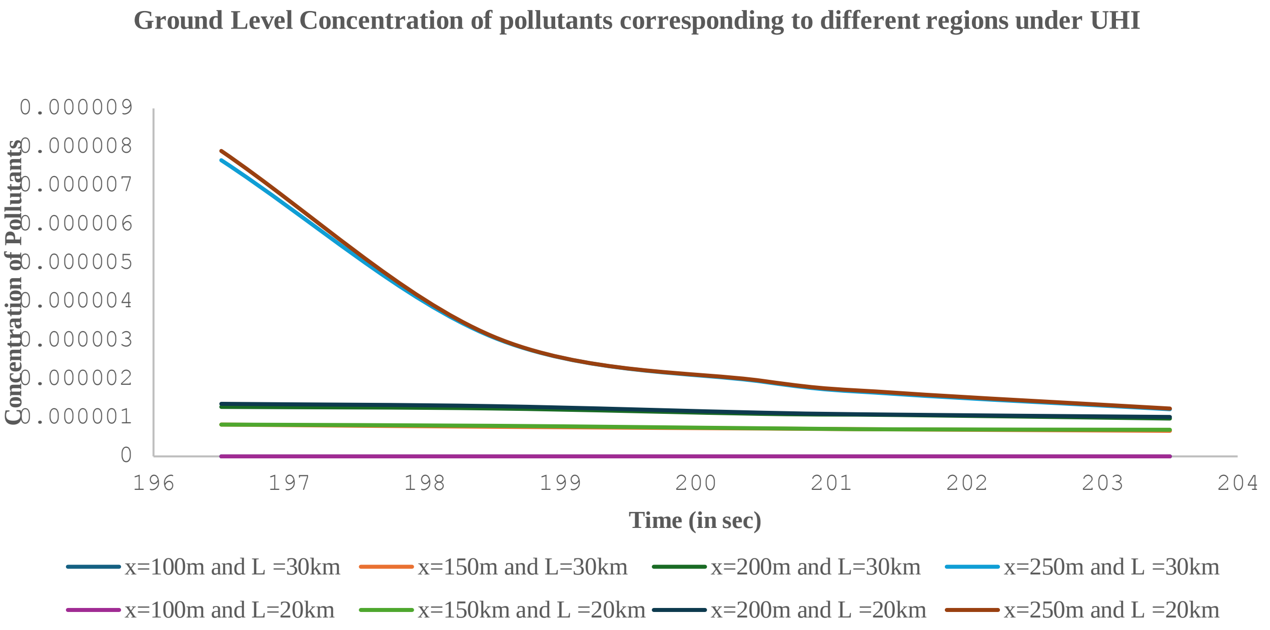

Figure: 10

(Comparative data showing the distribution of pollutants when the effect of UHI commenced at different regions i.e. L = 20 km and 30 km)

To understand the effect of temperature variation, we considered a single point source located at (200, 0) with the time of explosion as 180sec. The value of the α, β and μ_k corresponding to different temperature is calculated and mentioned in the table 4.4s

T_r(in Kelvin)	α	β	μ_1	μ_2	μ_3	μ_4
299.15K	.000001210	5303.80	.22879	.45758	.68638	.91517
298.15K	.000001214	5277.66	.22822	.45645	.68468	.91291
297.15K	.000001218	5251.56	.22766	.45532	.68299	.91065

Table: 4.4

The value of the concentration at z = 0m and z =50m due to the single point source mentioned above corresponding to different value of α while considering L =30 km at t = 188.5 sec and x =200m are mentioned below:

T_r(in Kelvin)	**GLC**	**Concentration at z = 50m**
299.15K	.0000000148	.0000000145
298.15K	.0000000152	.0000000149
297.15K	.0000000324	.0000000319

Table: 4.5

The above data showed that the concentration level contributed by the single source under UHI at t = 188.5 second increases as the temperature decreases. This reflects that the overall concentration level due to the explosion of firecrackers will increase with the decrease in temperature. This pattern was observed along the downwind distance as well as along vertical height. As, in the month of November or late October, the temperature drops in the night and hence, when the duration of firecrackers explosions existed to a very long time in night then the concentration level increases and persist to longer duration of time.

(a) Case study: Impact of firecrackers on atmospheric pollutants during Diwali festival in Tamil Nadu

The paper published by Shankar et.al. (2023) studied the impact of gaseous and particulate matter emitted from the firecrackers in Tamil Nadu during the time of Diwali festival. The data corresponding to the emission of carbon monoxide and carbon dioxide from firecrackers during the 3 days comprising of pre-Diwali, Diwali and post-Diwali period i.e. October 22 to October 26, 2022 revealed the following information's.

(i) During the three days the concentration level of CO increases and reaches its peak on the night of Diwali.
(ii) The concentration level in day time is highest on the post-Diwali day.
(iii) On Diwali day, an alarmingly high concentration of CO was reported which is 3.6 times greater than the NAAQS threshold limit.

(b) *Case study:* An Assessment of Ambient Air Quality of Lucknow City During Pre-Diwali, Diwali and Post-Diwali Festival was conducted by Indian Institute of Toxicology Research, Lucknow by Mahanta et.al. (2024). The survey of the air pollution during the pre and post Diwali festival from 30th October, 24 to 01st November, 24 in Lucknow City showed that the SO_2 mean level on Diwali night increased from $22\mu g/m^3$ to $33\mu g/m^3$ which was increased 50% from pre Diwali night. The mean NO_2 value was increased to 44 $\mu g/m^3$ from $33\mu g/m^3$ of pre Diwali night. Also, the data showed that the post Diwali day had a significant level of concentration of particulate matters and gaseous pollutants. The finding revealed that the large quantity of pollutants formed due to the burning of firecrackers during the Diwali festival, thus creating a poor air quality in Lucknow city.

The information's so revealed in the paper of Shankar et.al. (2023) and report of Mahanta et.al. (2024) supports the observations and finding obtained in this current paper. Thus, in order to maintain the suitable air quality in urban area during the time of Diwali, it is necessary to take following measurements:

(i) Reduce or ban the firecrackers so that the emission of harmful gaseous and particulate matter for a longer duration will not be happen.
(ii) The climatic change in the month of October and November plays a crucial role where the days are warm and nights are cold in the Northern part of India. This will help in trapping the pollutants when maximum number of firecrackers are exploded in night.
(iii) The prevention of UHI is also important especially during the Diwali in the urban city which can be made possible by increasing the vegetation, proper urban design so that wind can flow properly and reducing the heat waste.
(iv) Prevention of burning of crops in the rural area or villages nearby the urban city during the time of festival. It was observed that the burning crops aggravate the concentration level when the temperature difference in the month of October and November between rural and urban area is high in Northern region of India (Khaiwal et.al. 2019).

5. CONCLUSION

The study explores the impact of gaseous pollutants emitted from the firecrackers in absence and presence of UHI. The present model considered the diffusivity to be temperature dependent. Also, the urban heat island effect is represented by fundamental energy balance equation. The firecrackers are considered as a multiple point sources located at different positions. The overall process studied was divided into two intervals where the Ist interval considered to be phase of non-UHI and IInd interval is considered to be the phase of UHI effect. The overall process is defined in two-dimensional advective-diffusion equations with appropriate boundary conditions. Analytical solutions are obtained by using the concept of Laplace equation and Green's function. Twenty samples are considered for the case study along with suitable parameters in order to understand the overall situation. The following findings are stated below:

(i) Figure 2, 3 and 4 exhibit the ground level concentration of gaseous pollutants due to the explosion of firecrackers within one-, two-and three-minute span of time. The observations revealed that as the duration of explosions increases, the concentration level increases and persist to longer duration. Also, with the increase in the explosions, the pollutants propagate to greater downwind distance.
(ii) On comparing Figure 2, 3 and 4, we observed that there is no spike in Figure 2 but as we progress from Figure 2 to 3 and 4, the number of spikes in the concentration level increases.
(iii) Figure 5, 6 and 7 exhibit the concentration level along the vertical height where it was observed that as the number of explosions increases the concentration level also increases. Also, with the increase in explosions the number of spikes increases.

(iv) The time lag in the implication of UHI showed that the early formation of UHI aggravate the concentration level. Thus, it is important to reduce the possibility of the formation of UHI.

(v) Figure 10 showed that when the exposed region is small and the UHI exist the situation becomes more alarming because the air quality gets much poorer. This calls for the attention regarding the proper urban planning and establishment of more green area in order to avoid the formation of UHI in the local or small area of urban city during the festival time.

(vi) As the temperature of the city decreases in night the concentration level of the pollutants increases along the downwind distance as well as at vertical height.

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Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions: Vivek Joseph: formulation of the model, writing, data analysis, editing. Manju Agarwal: formulation of the model, data analysis, reviewing. All the authors read and approved the manuscript.

Data Availability

The data corresponding to the firecrackers location, time of emission and quantity is taken as a theoretical. However, the value of different parameters are taken from the available research like https://doi.org/10.1016/j.uclim.2012.10.005 and platform of meteorological data www.weatherspark.com.

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