Environmental Science and Pollution Research (2022) 29:74784–74796
https://doi.org/10.1007/s11356-022-21150-9

RESEARCH ARTICLE

Quantitative assessment and mitigation measures of air pollution from crematoria in NCT of Delhi

Prachi Goyal[1,2] · Sunil Gulia[1,2] · Sanjeev Kumar Goyal[1,2]

Received: 16 February 2022 / Accepted: 24 May 2022 / Published online: 31 May 2022

Abstract
The modernization of crematoria and replacement of existing fuel requirements for better air quality is a key challenge in view of the associated religious beliefs in India where conventional open pyre funeral practices are followed. Unlike developed nations, the lack of appropriate site selection criteria, combustion efficient crematorium oven designs, and pollution control devices at these facilities necessitates formulation of appropriate policy measures to reduce emissions. The existing practices do not address such localized sources that affects the micro air pollution patterns owing to their marginal contribution in the total air pollution load of the city. The present study is thus an attempt to estimate emissions from 51 cremation grounds identified in NCT of Delhi. The study considers both particulate and gaseous pollutants which are released due to burning of fuels like wood, CNG, and cow dung. It is estimated that cremation activities contributed 393 tons/year of $PM_{2.5}$, 142 tons/year of NO_x, 29 tons/year of SO_2, and 2686 tons/year of CO in year 2019. The maximum load was emitted from Central district as only Nigambodh Ghat crematoria receives on an average 60 bodies per day. Furthermore, air quality impact zone around crematoria has been demarcated using dispersion modelling considering crematorium with minimum and maximum number of bodies burnt in a day. The study also suggests control measures for reduction of pollution from cremation activities and delineates a buffer zone that could aid policymakers in establishing a site selection criterion to prevent the immediate population from likely exposure.

Keywords Crematoria · Localized air pollution · Biomass fuel · Emission inventory · Control intervention · Siting criteria

Introduction

Cremation is a customary ritual performed by Hindus, Jains, Buddhists, and Sikhs as a part of ancient rite to purify the soul from the defunct body across the globe. In the process, as a part of religious beliefs, the deceased is honored by washing its body with honey, ghee, and milk and anointing its head with sandalwood oil. Furthermore, the body is subjected to funeral pyre as offering to the god of fire to free the astral body and leading it to a better life (Arnold 2016). However, scientifically, cremation is an incineration process wherein the corpse/human body is subjected to high temperatures to reduce them to ashes, thereby becoming a considerable source of air pollution (Santarsiero et al. 2005; Decker Junior et al. 2018; Cui et al. 2021). Respecting the religious sentiments regarding these funeral practices, the air quality governance has come up with cremation-related acts in different countries like United Kingdom (UK), United States (US) Australia, Canada, and South Africa as environmental safeguards (Lesile Banks 1938; National Health Act 2003; EPA 2005, 2016; O'Keeffe 2020). In 2008, Stockholm Convention came up with best crematoria practice guidelines considering crematoria installation design (with 850°C minimum furnace temperature, pre-preparation (for example, removal of metal and chlorinated compounds), use of cleaner fuel (gas based or electricity based), and combustion and process-based control technologies such as sealed furnace with heat recovery systems; fabric filters; activated carbon injection; etc. (UNEP 2008). These acted as quintessential measures for countries around the globe. In alignment to

Responsible Editor: Philippe Garrigues

✉ Sunil Gulia
s_gulia@neeri.res.in

1 CSIR-National Environmental Engineering Research Institute (NEERI), Delhi Zonal Centre, New Delhi 110028, India

2 Academy of Scientific and Innovative Research (AcSIR), Ghaziabad, Uttar Pradesh 201002, India

this, several other precautionary actions have been proposed by different developed countries. In UK's statutory guidance for crematoria, these are calculations of suitable chimney heights for gaseous release and avoidance of melamine and PVC usage in coffin constructs (DEFRA 2012). In Australia, complete combustion and installation of wet scrubbers, bag filters, and honeycomb-designed selenium catalytic filters are suggested (SEWPAC 2011). However, in Europe, the focus is on efficient burner design, selenium salts for mercury removal, and greener fuels with low sulfur content like natural gas and replacement of conventional wood containers with fireboards/clothed fireboards (EEA 2019).

The cremation procedure of human cadavers contributes substantially to the air pollution load leading to the simultaneous emissions of particulate and gaseous pollutants in the ambient air (Korczynski 1997; DEFRA 2012; Da Cruz et al. 2017; Xue et al. 2018; ARAI and TERI 2018). However, due to the associated beliefs, cultural sentiments, and governance, the studies quantifying such an aspect in detail are scarce. The relative emission contribution of any cremation site is largely influenced by the number of cremations, crematorium design, fuel throughputs, and the installed emission control devices (O'Keeffe 2020). To ascertain the consequential effect of these variables, $PM_{2.5}$ concentrations have been studied by González-Cardoso et al. (2018) at 40 crematoria in Mexico. Similar study has been conducted by Xue et al. (2018) at 9 cremators for particulates, gaseous pollutants, and VOCs in Beijing, China. Furthermore, though crematoria is considered small-scale installations, yet their impact at local-level/immediate surroundings is considered significant, especially the exposure to the working personnel (Mari and Domingo 2010; Green et al. 2014). Unlike developed nations, developing countries like India lack such legislative measures for siting of cremation sites adversely impacting the human health.

In India, the registered deaths witnessed an increase of 26.4% from year 2011 to year 2019. The indifferent increase in the death rates over the decade proliferated the need of registered crematoria for Hindu, Jain, and Sikh religious cremation rituals (Vital Statistics of India 2019; TERI 2021). Subsequently, the subject matter emerged as a key challenge for air quality regulators in optimizing micro-level air quality improvement plans owing to the continuous emissions. In one of the national-scale studies conducted by TERI (2021) for emission estimates in India, crematoria is known to account 47,000 tons/year of PM_{10}, 23,000 tons/year of $PM_{2.5}$, 6000 tons/year of NO_x, 1000 tons/year of SO_2, and 235,000 tons/year of CO from whole country. However, in city-specific studies, Sharma and Dikshit (2016) estimated 126 tons/year of PM_{10}, 114 tons/year of $PM_{2.5}$, 35 tons/year of NO_x, 12 tons/year of SO_2, and 777 tons/year of CO from crematoria for years 2013–2014 in Delhi in North India while for year 2016, ARAI and TERI (2018) reported the emissions as 200 tons/year of $PM_{2.5}$, 100 tons/year of NO_x, and 2200 tons/year of CO emissions. In another study in Kolkata, eastern India by NEERI (2020), the emission load was found to be 13.2 tons/year for PM_{10} and 9 tons/year for $PM_{2.5}$ which is comparatively very less than Delhi. Similar emission inventories have been developed for cremation practices for different cities such as Pune city (Western India) by Beig et al. (2017) and ARAI (2010), Kanpur city (Northern India) by Behera et al. (2011), Ahmedabad city (Western India) by Beig et al. (2020), and Chennai city (Southern India) by CPCB (2010).

In brief, it can be elucidated that small area sources like crematoria might not hold a significant sectorial share in the total air pollution load at city scale; however, these act as a potential threat at local/micro-level. The heterogeneity in the spatio-temporal patterns of the emissions in synergy with the prevailing wind directions further creates challenges in ascertaining the potential area of interest for likely exposure. The present article is thus an attempt to address one such localized source, i.e., crematoria. In view of the same, the study estimates the emission load from the current registered crematoria sites taking NCT of Delhi, India, as the reference city. Furthermore, based on the number of cremations, detailed investigation of a selected crematorium has been done for delineating the air quality impact zone. The study also briefs the zoning criteria for siting of cremation site followed in different countries to aid policy makers in establishing similar site selection criteria for countries like India as well.

Materials and methods

Study area

Delhi, the capital city of India, hosts a population of 16.9 million (Census 2011) over 1483 km^2 area. Of the total population, 81.68% are Hindus, 12.86% are Muslims, 3.40% are Sikhs, 0.99% are Jains, 0.87% are Christians, 0.11% are Buddhists, and 0.09% are from other religions. In 2019, Delhi witnessed a total of 145,284 total deaths (Vital Statistics of India 2019). Being largely dominated by Hindus, ritualistic cremation ceremony is the common phenomenon for the human remains of the deceased. Considering the religion data, 13.73% of the population follows inhumations while the rest 86.27% follows cremation practices for disposing the human cadavers (excluding those below 5 years of age). There are 51 registered crematoria across NCT of Delhi wherein Nigambodh Ghat owes the maximum number of cremations per day. The district-wise distribution of the cremation sites is summarized in Table 1. Furthermore, the cremation sites in Delhi are known to operate on different fuel types, i.e., cow dung, wood, and CNG. A few sites are electric based as well. The fuel-category-wise distribution

Table 1 District-wise details of crematoria and their fuel requirements

Sr. No.	District	Total population following cremation rituals	No. of registered crematoria	Fuel requirement	Total cremations/day*
1.	Central	452,749	2[$]	CNG, electric, wood	64
2.	New Delhi	151,642	6	Wood	16
3.	North	981,486	7	Wood	22
4.	North West	3,954,797	6	Wood	34
5.	North East	2,343,733	1	Wood	4
6.	West	2,801,747	5	Wood	29
7.	East	1,728,672	2	Wood	15
8.	Shahdara[#]		2	Wood	9
9.	South	2,645,064	12	Wood	38
10.	South East[#]		6	Cow dung, electric, wood	18
11.	South West	1,901,083	2	Wood	19
	Total	**16,960,973**	**51**		**268**

*Distribution based on total death rate, area wise religious population, and surveyed data at crematoria

[$]Out of two, one is Nigambodh Ghat site which is the biggest crematorium where bodies are also brought from other parts of Delhi

[#]Based on 2011 census data when Delhi had 9 districts wherein Shahdara and South East Delhi regions were already included in East and South districts

of these is presented in Fig. 1. An existing conventional pyre design for the cremation practices in India is shown in SI, Fig. S1.

Methodology

The study defines a methodology for estimating air pollutant emission load from cremation practices and delineating the air quality impact zone for likely exposure within a city. The methodology includes mapping of locations of registered cremation grounds on Google map and its verification on ground through physical visits. The open-ended questionnaire survey has been prepared for collection of data considering the type of crematorium, fuel type used, fuel quantity requirements, and number of cremations (SI, Fig. S2). The data has been collected for 23 sites

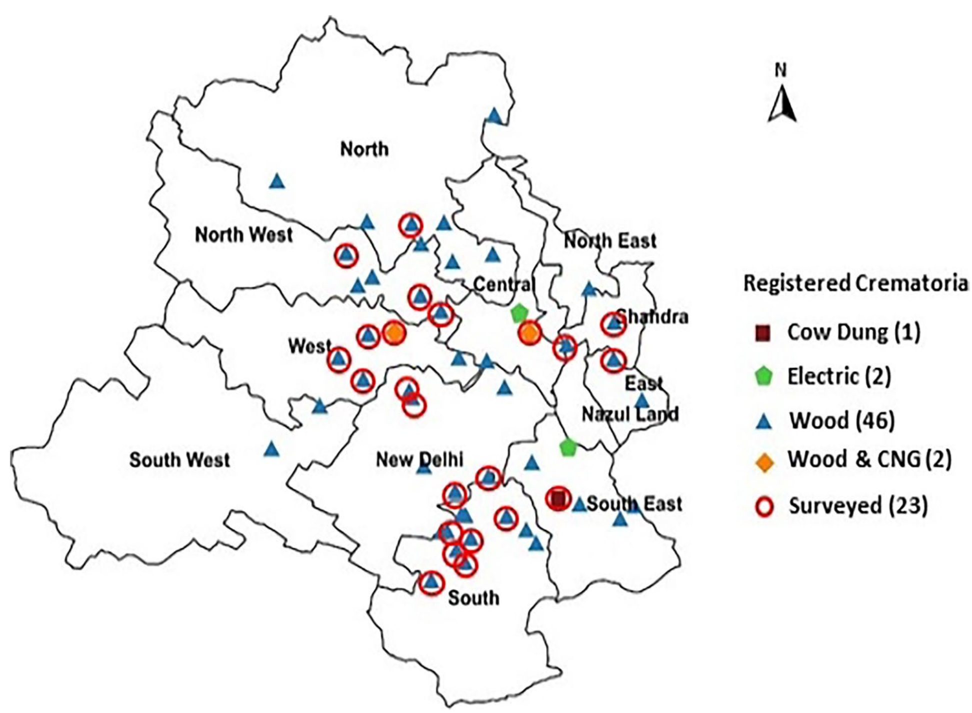

Fig. 1 Map showing distribution of crematoria and their fuel requirements in NCT of Delhi

in person at each site's office (SI, Table S1). The data is authentic and accurate. However, some sites have not been surveyed (28 in nos.) in physical and collected the information through telephonic conversations. Furthermore, the fuel consumption rate for these non-surveyed sites has been incorporated from the surveyed data. However, for the number of cremations/day at these 28 sites, data has been acquired from authentic/reliable secondary database (government sites/Economic Handbooks such as Census 2011; Vital Statistics of India 2019). The total death rate has been used to spatially distribute the bodies of the deceased at different cremation sites based on the population following the said rituals. The multi-pollutant emission inventory has been then developed for the whole city considering $PM_{2.5}$, NO_x, SO_2, and CO using Eq. (1). Moreover, certain toxic and harmful pollutants like VOCs, organics like polychlorinated dibenzo-p-dioxins (PCDDs) and dibenzofurans (PCDFs) and polycyclic aromatic hydrocarbons (PAH), and heavy metals like mercury are also released from cremation rites; however, they have not been studied considering the importance of criteria pollutants (DEFRA 2012; EEA 2019; O'Keeffe 2020). The pollutant, body, and fuel-specific emission factors have been reviewed comprehensively and suitably adopted in the present study. Based on the developed emission inventory, Nigambodh Ghat cremation site has been selected in view of the maximum cremated bodies in a day. For the selected site, air quality prediction has been carried out using dispersion modelling for delineating the zone of influence for likely exposure. Considering the impact in the immediate surroundings, further, several localized interventions have been proposed for managing air quality at micro-scale. The process flow chart followed in the present study is shown in Fig. 2.

$$E_{j=} \sum_{c=1}^{n} \left(N_c * EF_{body,j}\right) + \left(\Sigma N_c * Q_f * EF_{f,j}\right)/1000 \quad (1)$$

where E_j is emission load estimated for pollutant "j" in kg/day, $c = 1$ to n are cremation sites, N_c are number of bodies burnt/day, $EF_{body,\,j)}$ is emission factor of the body in g/body for pollutant "j," Q_f is the quantity of fuel type "f" required in kg per body, $EF_{f,\,j}$ is emission factor for fuel type "f" for pollutant "j" in g/kg. Furthermore, the input data for the application of the equation has been summarized for Nigambodh Ghat site in SI, Table S2.

Emission load estimation in Delhi

The emission inventory of the registered crematoriums has been developed by collecting fuel requirement data and average bodies burnt at 23 sites in different districts of Delhi

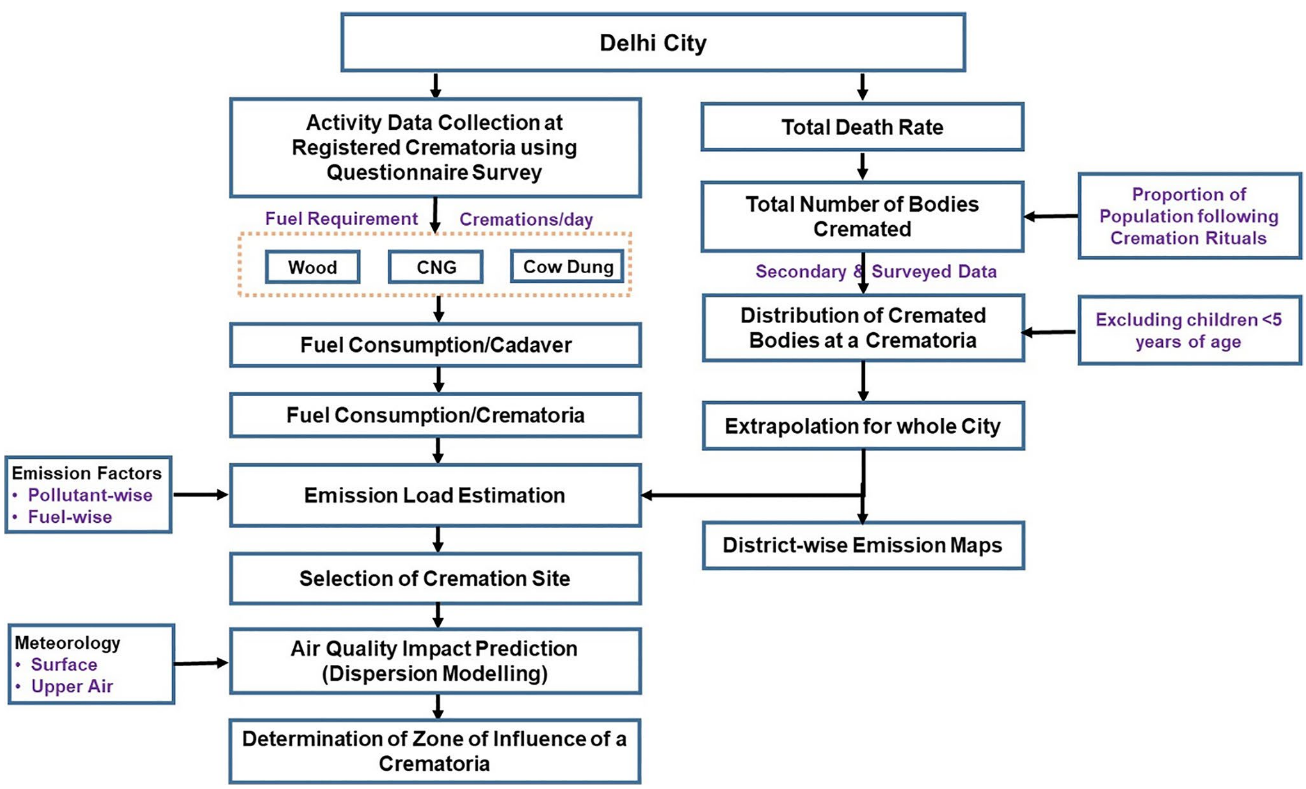

Fig. 2 Methodology adopted in the present study

(Fig. 1). The different fuel types used for these practices were found to be wood, half steam (different pyre design based on wood fuel), CNG, and cow dung with the average consumptions being in the range of 300–500 kg/body, 200 kg/body, 12 kg/body, and 150 kg/body, respectively. Half steam is a type of pyre based on wood fuel in which body is kept at certain height (approximately 0.5 m from ground). The quantity of wood required per body is approximately 50% of the conventional one. Furthermore, after identifying the type of crematoria and cremations in a day at non-surveyed sites through secondary database (Census 2011; Vital Statistics of India 2019), emissions have been estimated at all the sites. Based on the distribution of the crematoria, district-wise emission load has been estimated for four pollutants, $PM_{2.5}$, NO_x, SO_2, and CO using Eq. (1) and reviewed emission factors (SI, Table S3). The findings of which are summarized in Table 2.

The maximum emission load has been estimated from Central district followed by South, North West, and West districts contributing 242 kg/day, 156 kg/day, 144 kg/day, and 118 kg/day of $PM_{2.5}$, 91 kg/day, 56 kg/day, 51 kg/day, and 43 kg/day of NO_x, 18 kg/day, 11 kg/day, 10 kg/day, and 9 kg/day of SO_2 while 1644 kg/day, 1061 kg/day, 982 kg/day, and 805 kg/day of CO. The maximum contribution from Central district is due to the Nigambodh Ghat wherein about 60 bodies are being cremated on daily basis, South Delhi cremating 38 bodies/day at 12 sites, North West Delhi cremating 34 bodies/day at 6 sites, and West Delhi cremating 29 bodies/day at 5 sites. The minimum emissions were estimated at North East district with 15 kg/day of $PM_{2.5}$, 6 kg/day of NO_x, 1 kg/day of SO_2, and 100 kg/day of CO attributable to a single crematorium witnessing 4 cremations/day. The district-wise emission load of these pollutants is presented in Fig. 3.

Furthermore, for whole NCT of Delhi, crematoria activities (due to fuel and human body) are found to contribute 1075 kg/day (393 tons/year) of $PM_{2.5}$, 388 kg/day (142 tons/year) of NO_x, 78 (29 tons/year) kg/day of SO_2, and 7359 kg/day (2686 tons/year) of CO. The emissions due to average number of bodies cremated at all the sites are observed as 8 kg/day (1%) for $PM_{2.5}$, 219 kg/day (56%) for NO_x, 30 kg/day (38%) for SO_2, and 37 kg/day (0.5%) for CO. However, the emissions due to fuel requirement were found to be 1067 kg/day for $PM_{2.5}$, 169 kg/day for NO_x, 48 kg/day for SO_2, and 7322 kg/day for CO. The estimated emissions are comparatively higher (1.5–2 times) as compared to those estimated by researchers in the past. This could be attributed to the fact that the average fuel requirements and the bodies burnt per day taken for emission calculation were obtained for the respective study periods and by conducting surveys at few locations only in the previous studies. However, the present study used the data based on the survey at more than 45% of the sites. Moreover, the total death rates have witnessed a tremendous increase over the years (Directorate of Economic and Statistics 2019).

Air quality impact zone assessment through modelling around selected crematoria

Model domain set-up

The study has used AERMOD, a USEPA recommended model for regulatory purposes, for air quality impact

Table 2 Pollutant-wise estimated emission load at the crematoria in different districts of NCT of Delhi

Crematorium in the district	Pollutant-wise emission load (kg/day)							
	Fuel used*				Cremated bodies			
	$PM_{2.5}$	NO_X	SO_2	CO	$PM_{2.5}$	NO_X	SO_2	CO
Central	240	38	11	1635	2	53	7	9
New Delhi	83	13	4	569	0.5	13	2	2
North	80	13	3	545	0.7	18	2	3
North West	143	23	6	978	1	28	4	5
North East	15	2	1	99	0.1	3	0.5	1
West	117	19	5	801	0.9	24	3	4
East	73	11	3	495	0.5	12	2	2
Shahdara	42	7	2	289	0.3	7	1	1
South	155	24	7	1056	1.2	31	4	5
South West	69	11	3	470	0.6	16	2	3
South East	50	8	3	385	0.5	14	2	2
Total	1067	169	48	7322	8.3	219	29.5	37

*Wood at 46 sites, wood and CNG at 2 sites, cow dung at 1 site; emission factors for fuel-wood from Gadi et al. (2003), Pathak et al. (2009), Pandey et al. (2017), and Pervez et al. (2019); CNG from Sahu et al. (2011, 2015); cow dung from Reddy and Venkataraman (2002), Gadi et al. (2003), and Pathak et al. (2009); emission factors for body-EEA (2019)

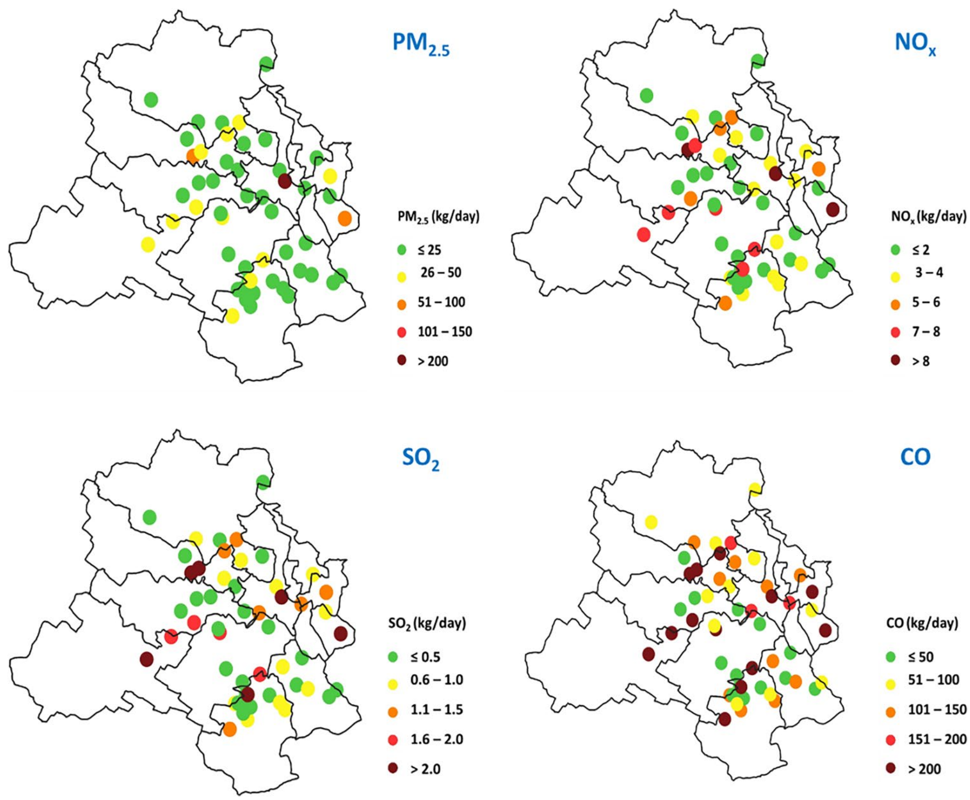

Fig. 3 District-wise spatial distribution of pollutant emissions from crematoria in NCT of Delhi. Note: Color code represents relative grading scale, green color denoting the lowest values while dark red color denoting the highest values

prediction to delineate the zone of influence at a selected crematoria. The Nigambodh Ghat cremation site has been selected based on the maximum number of bodies burnt in a day to address the likely maximum contribution. The site has been selected to evaluate the air quality impact zone that could suggest the crematorium site selection criteria. The default regulatory setting considering flat terrain and urban area dispersion coefficients has been used for model set-up. The emissions calculated for the selected cremation site along with the meteorological data of Delhi have been used as the input parameters (SI, Table S4). The meteorological data has been considered for most critical month for year 2019, i.e., January (low atmospheric dispersion potential). The surface and upper air meteorological data have been processed from Weather Research Forecast (WRF) model for Central Delhi location. The average wind speed was found in the range 0.50–2.10 m/s with winds blowing dominantly from WNW-NW direction (SI, Fig. S3). Furthermore, the relative humidity and ambient temperature were found in the range 9–29 °C and 9–79%, respectively. Since the crematoria is operational from 7:00 am to 6:00 pm in winters, the data and the model run have been done accordingly. Furthermore, the receptor grids have been used at an interval of 50 m cell size with total number of grids as $201 \times 201 = 40401$ number of grids and the total length in x and y direction is 5 km each.

Air quality impact prediction at Nigambodh Ghat site

The emission from different activities impacts the ambient air quality in its surrounding at certain distance, pre-dominantly in the downwind side (dominant) which varies from season to season. The contribution of pollution emission from crematoria has been predicted at different downwind distances, i.e., GLC during the study period at 10 m to 5 km. The contribution has been predicted at the selected site, Nigambodh Ghat, both, considering a single pyre and entire cremation ground. The air quality has been predicted considering 1- and 24-h concentrations for a single pyre and entire cremation ground. Furthermore, the impact zone has been considered based on the distance from crematorium where contribution was found to be ≥ 3 μg/m^3 for $PM_{2.5}$, ≥ 4 μg/m^3 for NO_x and SO_2, and ≥ 100 μg/m^3 for CO, i.e., 5% of daily average NAAQS values of 60 μg/m^3 for $PM_{2.5}$, 80 μg/m^3 for NO_x and SO_2, and 10% of 8-h average NAAQS value of 2000 μg/m^3 for CO, respectively.

Single pyre Considering the importance of the buffer zone for setting a cremation site, an in-depth investigation was further done to delineate the zone of influence of a single pyre that takes ~2.5–3 h for one body's cremation process. For $PM_{2.5}$, the

1- and 24-h maximum GLCs were 7058 μg/m^3 and 321 μg/m^3 which reduced to ≤ 3 μg/m^3 at 2 km and at 500 m distance in downwind side, respectively. For NO_x, these values were 2296 μg/m^3 for 1 h and 104 μg/m^3 for 24 h which became negligible beyond 1 km and 500 m in the respective cases. For SO_2, the maximum 1-h GLC of 468 μg/m^3 reduced to 4 μg/m^3 at 500 m while for 24-h, the maximum GLC of 21 μg/m^3 reduced to <4 at μg/m^3 at 100 m. Similar observations were made for maximum 1- and 24-h GLCs of CO which reduced to <100 at 1 km and 500 m in the respective cases (Table 3). Thus, considering the 24-h averages, the contribution at 500 m was found less than the 5% of daily average NAAQS for $PM_{2.5}$, NO_x, and CO while 100 m for SO_2, respectively (Fig. 4).

One day cremation activities at Nigambodh Ghat The air quality has been assessed for 1- and 24-h time averaging periods for likely impact during a single cremation activity, all the cremation activities conducted in a day and after the maximum dispersion and dilution under the influence of prevailing meteorological conditions. The details of which are shown in Table 4.

For $PM_{2.5}$, the 1- and 24-h maximum GLCs were 21890 μg/m^3 and 3224 μg/m^3 which reduced to ≤ 3 μg/m^3 at 3 km and 1 km distance in downwind side. For NOx, these values were 7668 μg/m^3 for 1 h and 1129 μg/m^3 for 24 h which reduced to ≤ 4 at 2 km and 1 km in the respective cases. For SO_2, the maximum GLC of 1167 μg/m^3 and 173 μg/m^3 reduced to 4 μg/m^3 beyond 2 km and 500 m for 1- and 24-h averages. Similar observations

Table 3 Assessment of zone of influence for a single pyre on ambient air quality

Pollutant	Concentration at different distances in downwind direction (μg/m^3)										
	< 3 m	10 m	20 m	50 m	100 m	200 m	500m	1km	2km	3km	5km
	Source	Immediate vicinity		Crematorium premises			Outside crematorium				
1-h average											
$PM_{2.5}$	7058	6750	4480	535	184	21	9	4	<3	<3	<3
NO_x	2296	1730	1540	367	125	17	5	<4	<4	<4	<4
SO_2	468	405	259	42	15	7	<4	<4	<4	<4	<4
CO	48023	42450	39428	7100	3504	1480	604	<100	<100	<100	<100
24-h average											
$PM_{2.5}$	321	307	282	67	27	9	3	<3	<3	<3	<3
NO_x	104	88	77	22	12	5	<4	<4	<4	<4	<4
SO_2	21	19	17	5	<4	<4	<4	<4	<4	<4	<4
CO	2182	1703	1494	521	255	104	<100	<100	<100	<100	<100

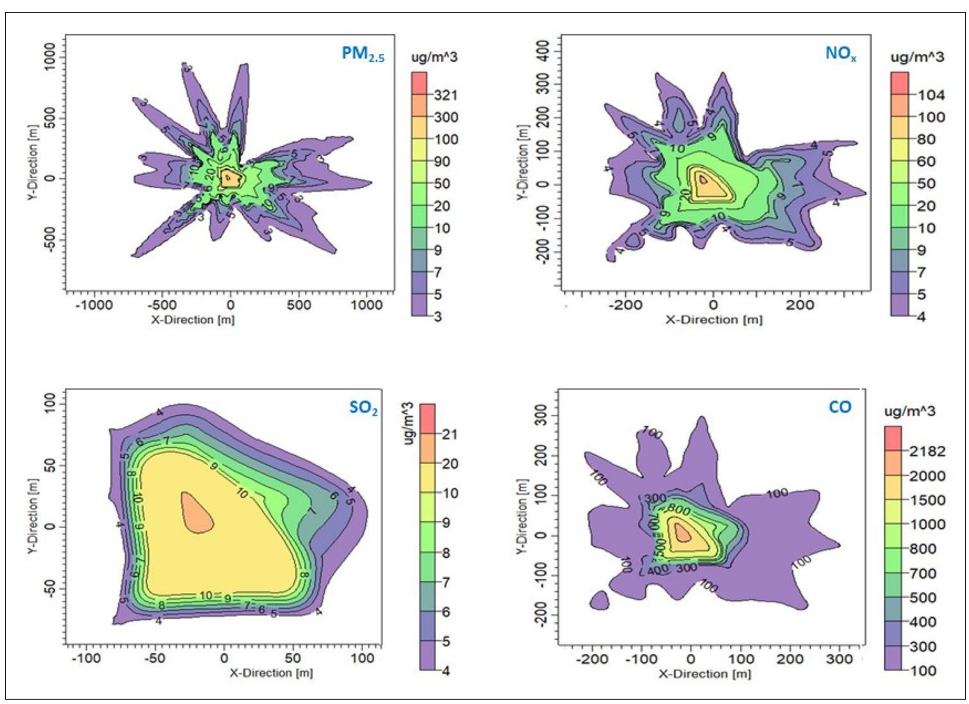

Fig. 4 Isopleth showing 24-h predicted pollutant concentrations during January from a single pyre

Table 4 Assessment of air quality impact zone of Nigambodh Ghat crematorium

Pollutant	Concentration at different distances in downwind direction (µg/m^3)										
	< 3 m	10 m	20 m	50 m	100m	200 m	500 m	1 km	2km	3 km	5 km
	Source	Immediate vicinity		Crematorium premises			Outside crematorium				
1 h											
$PM_{2.5}$	21890	10200	3160	1830	552	136	31	9	5	< 3	< 3
NO_x	7668	4820	1724	746	263	54	18	7	4	< 4	< 4
SO_2	1167	971	682	61	46	23	9	5	< 4	< 4	< 4
CO	166740	113950	89754	28200	13000	5542	2194	649	140	<100	<100
24 h											
$PM_{2.5}$	3224	2920	1211	289	95	36	9	3	<3	<3	<3
NO_x	1129	910	753	105	54	21	5	<4	<4	<4	<4
SO_2	173	155	134	29	12	7	<4	< 4	<4	<4	<4
CO	24560	22100	19325	10018	1880	940	312	<100	<100	<100	<100

were made for maximum GLC values of CO for 1 h (166740 µg/m^3) and 24 h (24560 µg/m^3) which reduced to <100 at 3 km and 1 km in the respective cases. Thus, considering the 24-h averages, the contribution at 1000 m was found less than the 5% of daily average NAAQS for $PM_{2.5}$, NO_x, and CO while 500 m for SO_2, respectively (Fig. 5).

Source-specific policy measures

The study also addressed the public perception for the possible impacts of crematoria activities on their lifestyle by surveying the individuals residing within 1 km of the premises boundary. The survey has been conducted near 23 cremation grounds. About 61 families have been surveyed using open-ended questionnaires as shown in SI, Fig. S4. These families were asked to get their perception regarding the awareness about cremation emissions, odor and smoke visibility, respiratory issues, eye irritation, and cardiovascular problems. Most of the surveyed families had limited knowledge of the subject. Furthermore, based on the findings, it is observed that smoke and odor are being felt by resident around cremation sites (as responded by ~50% of the surveyed people). However, the after-effects did not lead to any chronic respiratory or cardiovascular diseases; however, eye irritation was the common ailment (experienced by ~25 families; 41% of

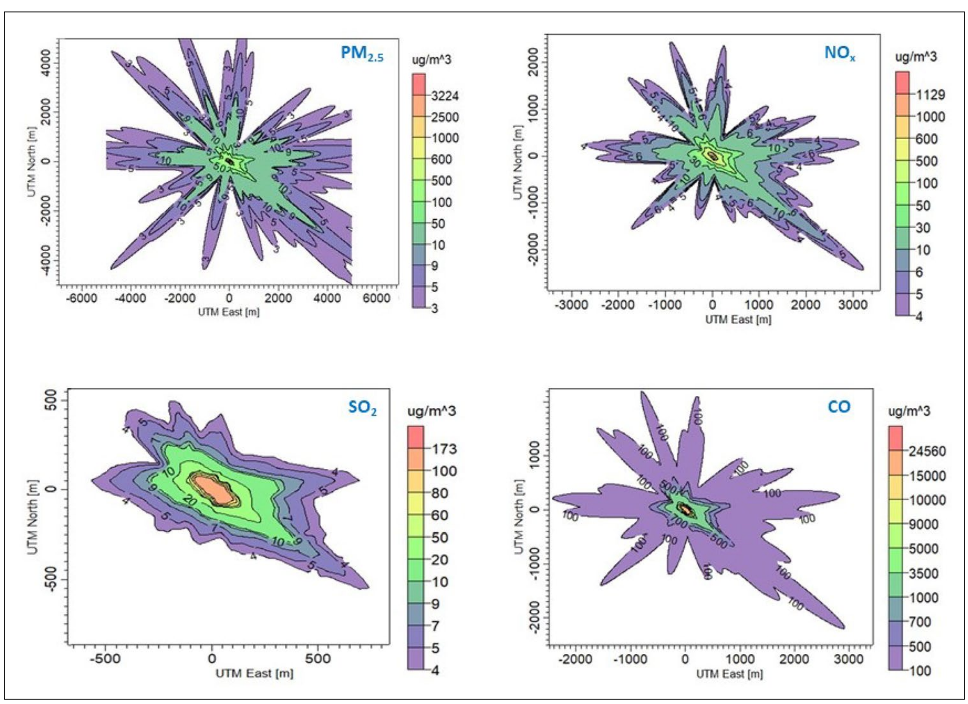

Fig. 5 Isopleth showing 24-h predicted pollutant concentrations during January at Nigambodh Ghat cremation site

the total surveyed population), especially at cremation sites where comparatively higher number of bodies were burnt and were located in the vicinity of the habitable areas. Satnagar Cremation ground, Nigambodh Ghat were such sites where 7 and ~60 bodies were cremated on an average basis and the consequential effects were reflected in the public opinion. Also, the surveyed data in the study provided only the glimpse of general public opinion and did not consider the critical assessment of health impacts and thus, other acute/chronic diseases could also be experienced.

Considering the predicted air quality impact zone and the conformity of the impacts on the immediate residents in the downwind direction of the cremation site, the study proposes and prioritizes certain control measures in view of the operational process, fuel requirement, and the associated cost investments. The details of which are given below.

Control strategy 1 (CS1): Change in design of pyre - Considering the funeral practices followed since ancient times, a change in design of pyre has been suggested by increasing the height of the bench for pyre preparations which enhances the combustion efficiency and accordingly reduces the average wood requirement per body (from average 396 to 200 kg/body) (NEERI 2019). The measure has been adopted from the already existing pyre design at Nigambodh Ghat, which is rarely followed by the people. Thus, if implemented at all the 46 wood-based cremation sites, the emission will reduce from 1064 to 605 kg/day for $PM_{2.5}$, 168 to 96 kg/day for NO_x, 47 to 27 kg/day for SO_2, and 7252 to 4125 kg/day for CO**.** The dispersion potential is generally high for this elevated pyre design compared to ground-based conventional design.

Control strategy 2 (CS2): Install air pollution control device in conventional pyre/with modified pyre design - In this measure, a hood and a duct with venturi scrubber are suggested to be installed as air pollution control device at the shed of the pyre. Hood covers the surface area of the gaseous release while the duct transfers the release to venturi scrubber for effective removal of dust and gaseous pollutants (NEERI 2019). Thus, due to the installed air pollution control technology, emissions are considered to be reduced by ~65% for both particulates and gases. The implementation of measure, however, requires additional cost for the installation of the same (NEERI 2019). Furthermore, release of high-temperature smoke from chimney hood further increases the dispersion and reduces the impact.

a. **Conventional pyres (CS2.1):** In conventional pyres, the air pollution control devices are proposed to be installed at existing pyres which reduces gaseous and particulate emissions by 65% (NEERI 2019).
b. **Modified pyre design (CS2.2):** In modified pyre design, the control technology is proposed to be deployed at the new pyre design (as described in CS1) with 200 kg/day of wood consumption.

Control strategy 3 (CS3): Replace conventional wood-based pyres with CNG-based facilities - The replacement of the existing wood-based practices is proposed which will bring down the emissions to 30 kg/day for $PM_{2.5}$, 82 kg/day for NO_x, and 452 kg/day for CO as compared to base case, i.e., 1064 kg/day, 168 kg/day, 47 kg/day, and 7252 kg/day, respectively. However, the installation of the entire set-up would require huge infrastructural, operation, and maintenance costs.

Control strategy 4 (CS4): Development of green barrier around the premises of the crematorium - This is suggested in view of the air pollution tolerance index of several evergreen plants in capturing gaseous and particulate pollutants (Kapoor and Chittora 2016; Barwise and Kumar

Table 5 Evaluation for proposed control strategies w.r.t $PM_{2.5}$

Parameter	Single pyre (1 body per day)					Multiple pyres (60 bodies per day)				
	CS1	CS2.1	CS2.2	CS3	CS4	CS1	CS2.1	CS2.2	CS3	CS4
$PM_{2.5}$ emissions										
Base (kg/day)	5	5	5	5	5	242	242	242	242	242
CS (kg/day)	2	2	0.86	0.2	No change	128	85	45	9	No change
Reduction (kg/day)	3	3	4.14	4.8	-	114	157	197	233	-
Reduction (%)	60	60	83	96	-	47	65	81	96	-
$PM_{2.5}$ concentration (24 h)										
Base (μg/m^3)	321	321	321	321	321	3224	3224	3224	3224	3224
CS (μg/m^3)	136	112	37	12	183	1424	1129	499	324	2553
Reduction (μg/m^3)	185	209	284	309	138	1800	2095	2725	2900	671
Reduction (%)	58	65	88	96	43	55	65	85	90	21

Note: *CS*, control strategies; *CS1*, change in design of pyre; *CS2*, install air pollution control device in conventional pyre (CS2.1)/with modified pyre design (CS2.2); *CS3*, replace conventional wood-based pyres with CNG-based facilities; *CS4*, develop green barrier around the premises of the crematoria

Table 6 Review of site selection criteria for cremation ground in different countries

Country	Buffer zone	Land use	Reference study
UK	183 m	Residential	Lesile Banks (1938)
Western Australia	200-300 m	Sensitive area	EPA (2016)
Southern Australia	150 m	-	EPA (2005)
California	152 m	Residential	O'Keeffe (2020)
South Africa	500 m	Agricultural/residential	National Health Act (2003)
Ontario, Canada	20-70 m	Residential	O'Keeffe (2020)
Proposed for India (based on $PM_{2.5}$ concentrations)			Present study
Single pyre base case	500 m	Any type	
Control strategies	170 m (CS1)	Any type	
	235 m (CS2.1)		
	40 m (CS2.2)		
	50 m (CS3)		
	350 m (CS4)		
Multiple pyres base case	1000 m	Any type	
Control strategies	500 m (CS1)	Any type	
	750 m (CS2.1)		
	280 m (CS2.2)		
	300 m (CS3)		
	800 m (CS4)		

CS, control strategies; *CS1*, change in design of pyre; *CS2*, install air pollution control device in conventional pyre (CS2.1)/with modified pyre design (CS2.2); *CS3*, replace conventional wood-based pyres with CNG-based facilities; *CS4*, develop green barrier around the premises of the crematoria

2020). The selection of plant species that can be planted as a part of green belt/green infrastructure depends on adsorption, absorption, metabolization, and accumulation of toxic air pollutants (Das and Prasad 2012; Kapoor and Chittora 2016). In the measure, a green barrier consisting of evergreen trees is suggested to construct in the 200 m radius area around the single pyre and entire cremation ground to ascertain its impact on the ground level concentrations. Furthermore, considering the Indian tropical conditions and the reviewed studies conducted in similar domain, these plants can be Arjun, Morus, Ashok, and Neem (Gupta et al. 2016).

Furthermore, to evaluate the impact of aforementioned control strategies on the pollutant concentrations, simulations have been done considering a single pyre and Nigambodh Ghat (60 pyres) for the most critical pollutant, $PM_{2.5}$ (as described in Tables 3 and 4). The simulations have been done considering 24-h concentrations. The details of which are given in Table 5. Based on the summary of the findings, it can be inferred that significant reduction can be achieved by replacement of existing wood practices with CNG-based facilities (CS3), being 96% for single pyre and 90% for multiple pyres followed by installation of air pollution control device at modified pyre design (CS 2.2), i.e., 88% reduction for single pyre and 85% for multiple pyres. The conventional pyre design (CS2.1) can be reduced at about 65% in both cases. Furthermore, minimum reduction has been observed for development of green barrier, being 45% for single pyre and 21% for multiple pyres.

Assessment of zone of influence for cremation site selection

Due to the likely impact of smoke and resulting emissions as detailed above, a review of siting criteria for crematorium has been done for delineating the buffer zone. It is observed that the air quality impact zone predicted by air quality modelling in the present study is comparable to the ones prescribed in the legislations of different countries as summarized in Table 6. The zoning criteria have been set for different land-use types in different countries with residential as sensitive areas, being the prime focus in view of the potential effects that can be caused in the close proximity.

The studies/policy guidance reports were reviewed for countries like UK, Australia, South Africa, California, and Canada. It is observed that a common criterion was defined for site selection irrespective of air pollution impact. Furthermore, safe distance near the residential areas was prescribed as 183 m in UK, 152 m in California, and 20–70 m in Canada while a 200–300 m distance was demarcated for a sensitive area in Western Australia and 500 m zone for agricultural/residential areas in South Africa. Moreover, in Southern Australia, a 150 m safe distance was stated irrespective of the pollutant and land-use type (Lesile Banks 1938; National Health Act 2003; EPA 2005, 2016; O'Keeffe 2020).

Similarly, in the present study, a buffer/air quality impact zone has been demarcated considering different pollutants based on the analysis discussed in the "Air quality impact prediction at Nigambodh Ghat site" section. The impact zone for a single pyre has been ascertained as 500 m while for multiple pyres with 60 cremations per day, it is 1000 m considering the most critical pollutant, i.e., $PM_{2.5}$. Furthermore, an attempt has been made to re-assess the impact zone after the implementation of proposed measures. It is observed that on implementation, the buffer zone will reduce to 170 m for single pyre and 500 m for multiple pyres in CS1, 235 m and 40 m for single pyre while 750 m and 280 m for multiple pyres in CS2.1 and CS2.2, 50 m for single pyre and 300 m for multiple pyres in CS3 while 350 m for single pyre and 800 m for multiple pyres in CS4. This safe distance can further be minimized by increasing green belt area with dense canopy. Moreover, the delineated buffer zone has been ascertained based on winter month analysis, most critical month from air pollution point of view.

Conclusions

The present study attempts to critically understand the individual contribution of localized sources like crematoria. Furthermore, the study estimates the emissions from identified crematoria in NCT of Delhi considering both particulate and gaseous pollutants. The study further delineates the air quality impact zone for identification of minimum separation distance for exposure reduction. The study also suggests the control strategies for achieving better air quality levels at local-level/micro-scale. The summary of the findings is as follows:

- A total of 51 crematoria have been identified in NCT of Delhi, of which 46 are wood-based, 2 are wood and CNG-based, 2 are electric, and 1 is dung-based site.
- The average fuel requirement is found to be 300–500 kg/body for wood (396 kg/day on average basis), 200 kg/body for half-steam, 12 kg/body for CNG, and 150 kg/body for cow dung.
- Crematoria is found to contribute 1075 kg/day (393 tons/year) of $PM_{2.5}$, 388 kg/day (142 tons/year) of NO_x, 78 (29 tons/year) kg/day of SO_2, and 7359 kg/day (2686 tons/year) of CO attributable to relatively higher wood-based fuel requirements.
- Based on the distribution of the crematoria, central district witnessed maximum number of cremations and subsequently the emissions (242 kg/day of $PM_{2.5}$, 91 kg/day of NO_x, 18 kg/day of SO_2, and 1644 kg/day of CO) attributable to the maximum number of cremations at Nigambodh Ghat location wherein bodies are bought from other districts as well.
- The air quality impact zone has been delineated based on the distance from crematorium where contribution was found significant. For a single pyre–based site (1 body per day), the buffer zone was found to be 500 m and for multiple pyres (60 bodies per day), it was 1000 m.
- The simulation result of control strategies indicated the significant reduction can be achieved by replacement of existing wood practices with CNG-based facilities, being 96–90% followed by installation of air pollution control device on modified design (85–88%). Further development of green belt also reduced the pollution by 21–45%. These control strategies further reduced the zone of influence of the crematoria.
- In addition to the quantified prevention and mitigation techniques, other measures like installation of stack and adoption of electric cremation can also be the option for reduction of emission from the cremation activities.

The study provides an updated useful database on the crematoria activities in NCT of Delhi, related emission load estimation, and highlights the issues of local air pollution which nearby resident faces. Furthermore, the demarcated zone and proposed interventions in the study can aid air quality regulators in establishing site selection criteria for siting of cremation grounds as environmental safeguards keeping in view the associated beliefs and cultural sentiments.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11356-022-21150-9.

Acknowledgements The authors wish to thank Mr. Swapnil, Ms. Suruchi Kumari, and Ms. Preeti, research interns at CSIR-NEERI Delhi Zonal Centre, for their assistance in carrying out this work, especially the field survey.

Author contribution Prachi Goyal: writing-original draft and editing, data analysis, methodology.

Sunil Gulia: conceptualization, methodology, critical review, and editing of draft version; supervision.

S.K. Goyal: conceptualization, visualization, critical review, and supervision.

Data availability Not applicable. All required data included in the manuscript

Declarations

Ethical approval and consent to participate Not applicable.

Consent to publish Not applicable.

Competing interests The authors declare no competing interests.

References

ARAI (Automotive Research Association of India), TERI (The Energy Resources Institute) (2018) Source apportionment of PM2.5 and PM10 of Delhi NCR for identification of major sources. https://www.teriin.org/sites/default/files/2018-08/Report_SA_AQM-Delhi-NCR_0.pdf. Accessed 4 January 2022

ARAI (Automotive Research Association) (2010) Air quality monitoring and emission source apportionment study for Pune. https://cpcb.nic.in/displaypdf.php?id=UHVuZS5wZGY. Accessed 10 January 2022

Arnold D (2016). Burning issues: cremation and incineration in modern India. *NTM Zeitschrift für Geschichte der Wissenschaften, Technik und Medizin 24*(4):393-419. https://doi.org/10.1007/s00048-017-0158-7

Barwise Y, Kumar P (2020) Designing vegetation barriers for urban air pollution abatement: a practical review for appropriate plant species selection. *Npj Climate Atmos Sci 3*(1):1–19

Behera SN, Sharma M, Dikshit O, Shukla SP (2011) Development of GIS-aided emission inventory of air pollutants for an urban environment. *Adv Air Pollut* 279-94. https://doi.org/10.5772/17008

Beig G, Gosavi S, Mukkannawar US, Sahu SK, Tikle S, Dole S, Kamble P, Kale S, Murthy BS, Latha R, Mangaraj P, Ambulkar R, Jadhav D, Basheer I, Yadav A, Shinde N, Palampalle D, More D, Athulya S (2020) SAFAR-high-resolution (400m X 400m) gridded emissions inventory for Pune, Pimpri and Chinchwad Regions. Special Scientific Report

Beig G, Parkhi NS, Rathod A, Dole S, Shinde G (2017) Development of high resolution emission inventory for Ahmedabad Metropolitan Region (AMR). http://assets.nrdc.org/sites/default/files/media-uploads/safar-ahmedabad-ei-2017-full_report.pdf. Accessed 11 January 2022

Census (2011) Delhi Population 2011 – 2022. https://www.census2011.co.in/census/state/delhi.html. Accessed 6 January 2022

CPCB (Central Pollution Control Board) (2010) Air quality monitoring, emission inventory and source apportionment study for Chennai. https://cpcb.nic.in/displaypdf.php?id=Q2hlbm5haS5wZGY=. Accessed 13 January 2022

Cui Y, Zhai X, Wang B, Zhang S, Yeerken A, Cao X, Zhong L, Wang L, Wei T, Liu X, Xue Y (2021) Characteristics and control measures of odor emissions from crematoriums in Beijing, China. *SN Appl Sci 3*(8):1–9. https://doi.org/10.1007/s42452-021-04738-7

Da Cruz NJT, Lezana ÁGR, Dos Santos PDCF, Pinto IMBS, Zancan C, de Souza GHS (2017) Environmental impacts caused by cemeteries and crematoria, new funeral technologies, and preferences of the Northeastern and Southern Brazilian population as for the funeral process. *Environ Sci Pollut Res 24*(31):24121–24134. https://doi.org/10.1007/s11356-017-0005-3

Das S, Prasad P (2012) Particulate matter capturing ability of some plant species: implication for phytoremediation of particulate pollution around Rourkela Steel Plant, Rourkela, India. *Nature Environ Pollut Technol 11*(4):657–665

Decker Junior C, Muniz EC, Cruz NJ (2018) Environment systems: a new concept on cremation. *J Sustain Dev Energy Water Environ Syst 6*(2):363–380. https://doi.org/10.13044/j.sdewes.d5.0190

DEFRA (Department of Environment, Food and Rural Affair) (2012) Statutory guidance for crematoria. https://www.cremation.org.uk/content/files/PG5-2%2812%29.pdf. Accessed 31 December 2021

Directorate of Economics and Statistics (2019). Annual report on registration of births and deaths in Delhi-2019. http://des.delhigovt.nic.in/wps/wcm/connect/4ac53080409a01a58f3ebfa50c073453/vital_annual_19.pdf?MOD=AJPERES&lmod=-108668931&CACHEID=4ac53080409a01a58f3ebfa50c073453. Accessed 4 January 2022

EPA (Environment Protection Authority) (2005) Guidance for the assessment of environmental factors. https://www.epa.wa.gov.au/sites/default/files/Policies_and_Guidance/GS3-Separation-distances-270605.pdf. Accessed 28 December 2021

EPA (Environment Protection Authority), (2016) Evaluation distances for effective air quality and noise management. Available at http://www.epa.sa.gov.au/files/12193_eval_distances.pdf. Accessed 7 January 2022

European Environment Agency (2019) EMEP/EEA air pollutant emission inventory guidebook 2019. Accessed 20 December 2021

Gadi R, Kulshrestha UC, Sarkar AK, Garg SC, Parashar DC (2003) Emissions of SO 2 and NO x from biofuels in India. *Tellus, Ser B: Chem Phys Meteorol 55*(3):787–795. https://doi.org/10.1034/j.1600-0889.2003.00065.x

González-Cardoso G, Hernández-Contreras JM, Santiago-DelaRosa N, Gutiérrez M, Mugica-Alvaréz V (2018) $PM_{2.5}$ emissions from urban crematoriums. *Energy Procedia 153*:359–363. https://doi.org/10.1016/j.egypro.2018.10.047

Green LC, Crouch EA, Zemba SG (2014) Cremation, air pollution, and special use permitting: a case study. *Human Ecol Risk Assess Intl J 20*(2):559–565. https://doi.org/10.1080/10807039.2012.719391

Gupta GP, Kumar B, Kulshrestha UC (2016) Impact and pollution indices of urban dust on selected plant species for green belt development: mitigation of the air pollution in NCR Delhi, India. *Arab J Geosci 9*(2):1–15. https://doi.org/10.1007/s12517-015-2226-4

Kapoor CS, Chittora AK (2016) Efficient control of air pollution through plants a cost effective alternatives. J Climatol Weather Forecast 4(184):2. https://doi.org/10.1007/s10661-013-3119-1

Korczynski RE (1997) Dust exposures and ventilation control in the Crematorium. *Appl Occup Environ Hyg 12*(2):122–125. https://doi.org/10.1080/1047322X.1997.10389471

Lesile Banks A (1938) Notes on cremation and crematoria. Public Health 52:111–114. https://doi.org/10.1016/S0033-3506(38)80079-2

Mari M, Domingo JL (2010) Toxic emissions from crematories: a review. *Environ Intl 36*(1):131–137. https://doi.org/10.1016/j.envint.2009.09.006

National Health Act (2003). https://www.gov.za/sites/default/files/gcis_document/201409/36473rg9960gon363.pdf.

NEERI (National Environmental Engineering Research Institute), (2020). PM10 and PM2.5 source apportionment study and development of emission inventory of twin cities Kolkata and Howrah of West Bengal.

NEERI (National Environmental Engineering Research Institute), (2019). Short term and localised air pollution control system for crematoria, dump site and others in Delhi. 153 Pages. Available at https://www.dpcc.delhigovt.nic.in/uploads/pdf/Report_STLAPC-SCD_Delhi_NEERI_Nagpur.pdf. Accessed 30 December 2021

O'Keeffe J (2020). Crematoria emissions and air quality impacts.

Pandey A, Patel S, Pervez S, Tiwari S, Yadama G, Chow JC, Watson JG, Biswas P, Chakrabarty RK (2017) Aerosol emissions factors from traditional biomass cookstoves in India: insights from field measurements. *Atmos Chem Phys 17*(22):13721–13729. https://doi.org/10.5194/acp-17-13721-2017

Pathak H, Jain N, Bhatia A, Mohanty S, Gupta N (2009) Global warming mitigation potential of biogas plants in India. *Environ Monit Assess 157*(1):407–418. https://doi.org/10.1007/s10661-008-0545-6

Pervez S, Verma M, Tiwari S, Chakrabarty RK, Watson JG, Chow JC, Panicker AS, Deb MK, Siddiqui MN, Pervez YF (2019) Household solid fuel burning emission characterization and activity levels in India. *Sci Total Environ 654*:493–504. https://doi.org/10.1016/j.scitotenv.2018.11.019

Reddy MS, Venkataraman C (2002) Inventory of aerosol and sulphur dioxide emissions from India: I—Fossil fuel combustion. *Atmos*

Environ 36(4):677–697. https://doi.org/10.1016/S1352-2310(01)00463-0
Sahu SK, Beig G, Parkhi N (2015) High resolution emission inventory of NOx and CO for mega city Delhi, India. *Aerosol Air Qual Res 15*(3):1137–1144. https://doi.org/10.4209/aaqr.2014.07.0132
Sahu SK, Beig G, Parkhi NS (2011) Emissions inventory of anthropogenic PM2. 5 and PM10 in Delhi during Commonwealth Games 2010. *Atmos Environ 45*(34):6180–6190. https://doi.org/10.1016/j.atmosenv.2011.08.014
Santarsiero A, Trevisan G, Cappiello G, Formenton G, Dell'Andrea E (2005) Urban crematoria emissions as they stand with current practice. *Microchemical J 79*(1-2):299–306. https://doi.org/10.1016/j.microc.2004.10.016
SEWPAC (Department of Sustainability, Environment, Water, Population and Communities) (2011) Emission estimation technique manual for crematoria version 1.0. http://www.npi.gov.au/system/files/resources/abf0a597-9740-0774-2150-983ebc4de109/files/crematoria.pdf. Accessed 20 April 2022
Sharma M, Dikshit O (2016) Comprehensive study on air pollution and greenhouse gases (GHGs) in Delhi. Final Report, Prepared by IIT Kanpur, sponsored by Delhi Pollution Control Committee, New Delhi. https://cerca.iitd.ac.in/uploads/Reports/1576211826iitk.pdf. Accessed 21 January 2022
TERI (The Energy and Resources Institute) (2021) Development of spatially resolved air pollution emission inventory of India. https://www.teriin.org/sites/default/files/2021-05/Exxon-Report.pdf. Accessed 14 January 2022
UNEP (United Nations Environmental Programme) (2008) Guidelines on best available techniques and provisional guidance on best environmental practices relevant to Article 5 and Annex C of the Stockholm Convention on Persistent Organic Pollutants. https://toolkit.pops.int/Publish/Downloads/ENG_12-Crematoria.pdf. Accessed 20 April 2022.
Vital Statistics Division Office of the Registrar General of India (2019). Vital Statistics of India based on the Civil Registration System, 2019. https://crsorgi.gov.in/web/uploads/download/CRS%202019%20report.pdf. Accessed 4 January 2022
Xue Y, Cheng L, Chen X, Zhai X, Wang W, Zhang W, Bai Y, Tian H, Nie L, Zhang S, Wei T (2018) Emission characteristics of harmful air pollutants from cremators in Beijing, China. *PloS one 13*(5). https://doi.org/10.1371/journal.pone.0194226