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Technical Note:

Field comparison of cyclonic separator and mass inertial impactor for PM_{10} monitoring

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Abstract

Monitoring of ambient PM_{10} concentrations was carried out using two co–located samplers at 10 different locations over the three seasons (summer, winter and post–monsoon) in Delhi, India. The samplers used for the study were the high volume sampler fitted with a cyclone (commonly known in India as respirable particulate matter sampler or RPM sampler), and a 4–channel speciation sampler (4-SS). The RPM sampler separates the PM_{10} fraction using centrifugal inertia while the 4-SS separates them using the principle of mass inertial impaction. Comparison of the measured data are made using different graphical techniques and statistical analysis, comprising classical two tailed paired t–test and the criteria recommended by the European Commission working group on particulate matter. The PM_{10} data monitored by both the samplers showed good overall correlations for the entire data set, with a regression co-efficient value of 0.61. Results indicated that inertial impaction based 4-SS consistently measures higher PM_{10} concentration compared with the cyclone fitted RPM sampler. Such results were valid for 81% of the total data set and this difference in measured concentrations was ~66% in the regulatory limit value ranges. Both the samplers have their merits and limitations and hence a conscious choice and appropriate data correction is needed when deploying them for scientific and regulatory monitoring purposes.

Keywords: Ambient air regulations; Cyclone separator; Mass intertial impactor; Particulate matter; PM_{10} monitoring

1. Introduction

The first ambient air quality monitoring station in India was installed at the famous historical monument, Taj Mahal (marble structure), in Agra (India) during 1981. The objective was to study the effect of sulfur dioxide (SO_2) emitted from the petroleum refineries in Mathura (CPCB, 1987). Following the Air Act (1981), a National Ambient Air Quality Monitoring (NAAQM) programme was initiated in 1984. The programme aimed to monitor 3 pollutants (i.e. SO_2, nitrogen oxide, NO_2, and suspended particulate matter, SPM) (CPCB, 1995). The SPM was monitored gravimetrically using the high volume sampler (HVS) under this programme. The HVS consists of a suction blower that draws air through glass fiber filter at a flow rate of 1.4 to 1.1 m^3 min^{-1}. Subsequently, the first National Ambient Air Quality Standard was notified in

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April 1994, consisting of an additional parameter i.e., thoracic particulate matter (PM_{10}). European Standard (EN481, 1993) has given nomenclature based on different PM size as thoracic and respirable particulate matter (RPM). Thoracic fraction refers to median size as PM_{10}, and respirable refers to median size as $PM_{2.5}$. The geometric standard deviation (GSD) recommended for both the fractions is 1.5µm. The Indian environment regulatory agency uses the term 'RPM' for PM_{10} (CPCB, 2003) which is inconsistent with the internationally used norm 'thoracic' fraction for PM_{10} (EN481, 1993). Since the discussion in this study refers to compliance with Indian standard monitoring protocol, the term RPM is retained for PM_{10} in this discussion.

The Indian regulatory guidelines also recommend use of the HVS, with an addition of cyclone at the inlet of air path for PM sampling; the sampling instrument is named as 'RPM sampler'. The cyclone is usually designed in such a way that the PM $\geq$10 µm in aerodynamic daimeter are removed from the sample air by centrifugal separation. The air stream with PM $\leq$10 µm is allowed to pass through the glass fiber filter (0.25 m × 0.20 m) to be collected by filtration.

Increasing urban population and consequently the anthropogenic emissions of air pollutants (Kumar et al., 2011) has forced regulatory agencies to reconsider the air quality standards in India (CPCB, 2009). Three methods of PM_{10} measurement are recommended: (i) tapered element oscillating microbalance (TEOM), (ii) beta attenuation technique, and (iii) gravimetric measurement (Buonanno et al., 2011; Gębicki and Szymańska, 2012). Since the first two methods are resource intensive and practically inconvenient, the latter method is used abundantly in India and is recommended in the new notification announced in 2009. Gravimetric method involves pre–weighing of conditioned blank filter, followed by collection of PM_{10} by filtration of ambient air PM and then the post–weighing. The concentrations are determined dividing the net PM_{10} mass deposited (i.e. the difference between the post– and pre–filter weights) by the volume of air passed through the filter media.

European reference methodology for PM_{10} sampling provides detailed guidelines for gravimetric mass determination, sampler inlet, type of filter substrate, and the flow regulation device (CEN, 1998). Similarly USEPA recommends size specific inlets, flow regulation that can precisely remove particles larger than 10 µm (USEPA, 1999).However, there is no such detailed reference mechanism available in India for PM_{10} sampling, mechanism of size separation in instruments or flow control methods, thereby leaving a scope for using different samplers that may not be scientifically accurate for the purpose. The flexibility of choosing one of these several methods of measurement allows the deployment of RPM sampler for PM_{10} monitoring in India due to its ease of operation and lower cost. This article therefore presents comparison of simultaneously measured PM_{10} in ambient air of Delhi at 10 different locations by the RPM (cyclone) and 4-SS (mass inertial impactor) samplers.

2. Materials and Method

2.1 Study background

Increased vehicular population has resulted in deterioration of air quality in Indian urban centers (Kumar et al., 2011; Nagpure et al., 2011). This led to the constitution of a committee of experts yielding a report on Auto Fuel Policy (Auto Fuel Policy, 2003; CPCB, 2010). The aims of the report were to control vehicular pollution arising from the dramatic rise in the road traffic in India. A follow up detailed study was recently carried out in six major Indian cities (i.e. Bangalore, Chennai, Delhi, Kanpur, Mumbai and Pune) to apportion the contribution of various sources towards the air pollutants (CPCB, 2012). As part of this work, 10 ambient air quality monitoring stations were established in Delhi. Measurements of various gaseous pollutants and PM_{10} were carried out continuously for 20 days in each season (winter, summer, and post–monsoon) during 2007 and 2008. As a reference instrument, a 4–channel SS (hereafter referred as 4-SS) was used to collect PM_{10} samples on teflon, quartz and nylon filters for chemical speciation that can be used in receptor modeling. The RPM sampler for PM_{10} monitoring was also operated simultaneously so that results of both the PM_{10} samplers can be used for comparison.

2.2 Description of the samplers used for PM_{10} monitoring

2.2.1 The RPM sampler

Ambient air enters from the top end of a vertical conical shaped cyclone in the RPM sampler. The PM in the air stream gains momentum while passing through the cyclone due to increased velocity through a constricted area. Large size PM possess higher momentum and get thrown out of the main whirling air flow due to centrifugal inertia and hit the inner smooth surface of cyclone body and slides down to the cup attached at the bottom and gets separated. The inner whirling air flow carrying smaller size PM leaves the cyclone and then passes through a filter (mostly glass fiber; size: 0.25 m × 0.20 m). The filter strains PM and releases the relatively cleaner air outside the sampler through a suction blower that draws air at a flow rate of 1.1 to 1.4 $m^3\ min^{-1}$. The cyclone geometry (inlet area, inside diameter, length and taper of cyclone) along with the flow rate can be designed in such a way that it can remove PM larger than 10 μm (with theoretically a 50% cut off). As the sampling time progresses, the PM_{10} accumulated on the filter causes increase in pressure drop across the filter. This process thereby reduces the air flow rate and lead to two major concerns. Firstly, the reduced air flow causes reduced cyclone inlet velocity and hence changing the PM cut off size. For large size PM to get thrown out of the main air stream, the particles need to attain designed momentum by virtue of velocity gained inside the cyclone. Secondly, this causes error in air volume estimation due to changing air flow rate. For maintaining lower cost of the sampler, the RPM sampler is not usually provided with flow controller or recording device. This flow is usually recorded manually at hourly intervals for subsequent air volume estimation. Field experience of RPM sampler operation has shown that over a period of 8 hours, the air flow rate reduces from 1.4 to 1.1 $m^3\ min^{-1}$ (George et. al. 2012).

2.2.2 The 4–channel speciation sampler (4-SS)

The 4-SS (R&P Partisol 2300) samples PM by simultaneously using 4 suction blowers on 4 different filter media. Unlike the RPM sampler, speciation sampler separates PM_{10} from the main air stream using the principle of mass inertial impaction (USEPA APTI 435; Marple, 2004). Ambient air is allowed to enter the sampler assembly and the flow path is suddenly changed by providing pressure gradient in a different direction. The large size particles, which have higher momentum, moves straight due to mass inertia and hence leaves the air flow path and enters empty chamber or well. The empty chamber is named as 'well impactor' that contains oil or grease to prevent rebound of particles. The main air flow encounters the obstruction and hence changes its path and passes through a filter that samples the remaining PM. The components of 4-SS are designed in such a way that main inlet air stream attains a designed velocity at which the PM larger than 10 μm having higher momentum are not able to negotiate the bend and enters the well impactor. The suction blower draws air at 16.7 lit min^{-1} and the flow is regulated by a mass flow controller, which is an integrated part of the 4-SS. PM_{10} samples are collected on circular (47 mm ϕ) filters of different media (teflon, quartz, nylon).

2.2.3 Common principles of operation

Both the samplers first remove PM ≥10 μm in aerodynamic diameter from the ambient main stream and then the air containing PM ≤10 μm pass through the filter media and collected by filtration. Thus there are two operations in place: size separation and filtration. At the end of sampling period, the filter paper is conditioned and weighed for determining the mass of collected PM_{10}. Due to the pre– and post–weighing of filters, these samplers are considered as the one using gravimetric technique.

2.3 Characteristics of study region

The study region, Delhi, is the Capital of India is situated at latitudes 28°24'17" to 28°53'00 N and longitudes 76°50'24" to 77°20'37" E at 216 m above the mean sea level. The area of Delhi is approximately 1500 km^2. The city is surrounded by other major growth centers of adjoining states such as Rajasthan, Haryana and Uttar Pradesh. Delhi has experienced a phenomenal population growth rate of about 2.16% during 2001-2011 compared with the national average rate of 1.76% for the same duration. As per the 2011 census, the population of Delhi is about 16.7 million. The climate of the region ranges between arid and semi-arid. Both summer and winter are severe, with June and January being the hottest and the coldest months, respectively. The annual rainfall is around 700 mm. Maximum rain occurs during July to August. Air pollution is one of the major environmental problems faced by Delhi today, mainly due to notable increase in number of road vehicles (Kumar et al., 2011). For instance, the vehicular pollution in Delhi has grown from 64% to 72% in the last decade (1990–2000) whereas petrol and diesel consumption have grown up by 400% and 300%, respectively, in the last two decades (CPCB, 2012). Ten ambient air quality monitoring stations were located in different activity zones in Delhi, as seen in **Figure 1**. Since the source apportionment study primarily aims at vehicular emission impact, 6 stations namely Ashram, Dhaula Kuan, Mayapuri, Anand Vihar, Inter State Bus Terminus (ISBT), and Loni Road were located at the kerbside. The other four were located in the industrial area (small scale industry, SSI), mixed use zone (Naraina), and residential area (Pitampura), together with a reference station (Prahladpur). The site features of all the stations can be seen in the recently published source apportionment report (CPCB, 2012). Equipments for meteorological data collection, gaseous sampling, PM sampling were operated at all the stations for all the three seasons. PM_{10} data set generated by the 4-SS and RPM sampler is used in this study.

3. Results and Discussion

3.1 Data analysis

To understand the large data set collected at all sites, this is first visualized pictorially for formulating a hypothesis and then statistical testing is performed. As a first approximation, the RPM and 4-SS data are considered to be independent (unpaired) and therefore accompaniment figure (i.e. box–whisker plot) is used for comparison (see **Figure 2)**. The pictorial representation is improved by arranging the station–wise data in descending order. At a first glance, the box–whisker plot shows upper 50 percentile (median) of 4-SS data larger than that of RPM data, with the exception of ISBT where the median of RPM data is slightly higher than the 4-SS data. The assumption of data independence lets each sampler data set to be mixed together and then distribute it into box and whisker based on its frequency, exhibiting that the 4-SS measured data is larger than those measured by the RPM sampler. On a particular day, it may happen that the RPM value is very high and corresponding 4-SS value is very low, and vice-versa. Therefore each RPM data should be paired with the corresponding 4-SS data. For the paired data set, null hypothesis (H_0) of equal means of RPM and 4-SS for different monitoring stations is tested using two tailed t–test. In a case when null hypothesis is rejected can be concluded that the 4-SS reports higher PM_{10} values compared with the RPM sampler. Since normality of data distribution is the assumption for t–test, the data distribution is checked using histogram plot for each station and sampler producing a total of 20 histograms. All the histograms found to follow approximate log-normal distribution. Subsequently the data is transformed logarithmically and their histograms are plotted, which appeared like a normal distribution. The two tailed t–test performed on the log–transformed data at 95% confidence interval (see **Table 1**). Graphical accompaniment of paired t–test would help in visualizing the data sets. 'Ladder plot' for comparison of paired data is a useful method, provided the number of pairs is not too large. In the present study, the data pairs are very large for the ladder plot to be clear and to arrive at a sensible conclusion. Therefore, a new graphical representation of paired data set is created that can be used to infer t–test result also. For ensuring paired data set, data of all those days when either of the samplers was not in operation is removed from the analysis. The final data set consists of pairs of data for both samplers. For all the stations, difference of 4-SS and RPM data (ΔPM_{10}) is determined and then ranked and arranged in descending order. Positive values indicate larger 4-SS data and negative values indicate larger RPM data. This station-wise data is plotted on a scatter plot and is shown in **Figure 3**. The ΔPM_{10} is shown on *y*–axis and its rank is shown along *x*–axis. It can be seen that 81% of the PM_{10} concentration data measured by the 4-SS is certainly larger than those measured by the RPM.

European Commissions working group on PM has suggested another set of criteria for comparing two samplers (EC, 2002). The requirement is that the regression equation should have a regression co–efficient (r^2) greater than 0.8 for each paired data set. In addition, the data with value of b >5 should be rejected; where b is intercept constant in the regression equation $y = ax + b$; x and y are RPM sampler and 4-SS measured PM_{10} values respectively.

3.2 Statistical analysis

Table 1 presents the results of two tailed t–test for paired data set, together with the EC recommended parameters (i.e. r^2 and b). Only for one station (ISBT), probability (p) value exceeds 0.5, thereby accepting the null hypothesis of equal means with a mean difference of 19 $\mu g\ m^{-3}$. Population estimates of all other stations reject the null hypothesis and suggest that the 4-SS measures higher PM_{10} concentrations compared to the RPM sampler. Results of the paired t–test for two extreme cases (Mayapuri and ISBT) are re–plotted in **Figure 4**. For ISBT, the data difference (ΔPM_{10}) is uniformly distributed across horizontal axis (i.e. line intercepting the *y*–axis at 0), thereby indicating the closeness of means of RPM and 4-SS for ISBT. Conversely, for Mayapuri, the data differences (ΔPM_{10}) are mostly present on the positive side, indicating larger PM_{10} values measured by the 4-SS than those by the RPM. The differences in mean values for both the samplers are plotted in **Figure 5**. The mean of 4-SS data is higher than that of RPM data at all the stations. These differences are the smallest at the ISBT site which is also confirmed by the paired t–test.

Analysis of European Commission recommended parameters (r^2, b) reveals that only at SSI and Pitampura the criteria of $r^2 > 0.80$ is fulfilled; however, the second parameter (b) is much higher than 5 and thus rejecting data of all stations for equivalence.

The regulatory requirement prescribed by the CPCB (India) for monitoring PM_{10} is the use of gravimetric method of measurement. This provides the flexibility of using either of the two samplers (4-SS and RPM sampler). While selecting the sampler for field measurements, preference is normally given to the factors such as the cost of the sampler, required accessories and maintenance, ease of handling and transportation, and skill level required for operation; all these are available with the RPM sampler. Another favorable point with the RPM sampler is its ability to sample relatively large amount of air. For instance, the RPM sampler filters 1584 m^3 of air (1.1 m^3 min^{-1}) compared to mere 24 m^3 of air by the 4-SS (16.7 lit min^{-1}) in 24 hours of operation. If the precision of sampler for PM_{10} sampling is concerned, 4-SS could be preferred over the RPM due to proper omnidirectional inlet that eliminates wind speed and orientation effects as well as use of mass flow controller for monitoring the sample air flow. Performance of different high volume PM10 samplers is described in detail by Buser et.al. (2007).

Based on the values of 'r^2' and 'b', it is evident that RPM can not be equivalent to 4-SS. Since the use of the RPM is likely to be continued in Indian subcontinent despite this being scientifically imprecise and making the comparison of measured PM_{10} values with standards uncertain, a pragmatic approach is adopted and an estimate of RPM sampler measured equivalent PM_{10} is determined by correlating with the PM_{10} concentrations measured by the 4-SS. Lines of scatter plot and regression line are drawn which passes through the origin to ensure that both the sampler measures zero concentration in clean air environment. Since the regulatory limit of ambient air PM_{10} in India (CPCB) and USA (USEPA) is 100 and 150 μg m^{-3}, respectively. Therefore correlation analysis of data that are close to these regulatory limit values makes reasonable sense compared to very large values. This is because if the observed PM_{10} values are very large, it is immaterial, whether it is from either of the two samplers. Therefore, we have split the data into two parts (i.e. below and over 200 μg m^{-3}), besides drawing an overall average best fit line to provide a general best fit for the entire data set (see Figure 6). The results indicated that the 4-SS measured 1.66 and 1.22 times higher PM_{10} concentrations for below and above 200 μg m^{-3} concentrations, respectively, compared with those measured by the RPM sampler. The best fit line on entire data set showed an average difference in measurements of ~1.24 (Figure 6).

4. Conclusion

Our study indicated that 4-SS measures 66% higher PM_{10} concentrations compared with the RPM sampler in the regulatory limit value ranges (see Section 3.2). Such differences are not trivial, especially for the expsoure assessment studies (Heal et al., 2012). Regulatory guidelines should therefore clearly indicate the inlet type and size separation principle (cyclone or mass inertia) used in PM_{10} monitoring and scientifically robust method of transforming the data from one instrument to another.

5. Abbreviations

Thoracic PM	Particulate matter that can enter the Thoracic duct of human respiratory system
PM_{10}	Particulate matter less than 10 μm size that can enter Thoracic duct
RPM	PM_{10} or Respirable Particulate Matter (Indian terminology)
RPM Sampler	PM_{10} sampler (flow rate: 1 to 1.4 m^3 min^{-1} (used in India)
4-SS	4-channel speciation sampler (flow rate: 16.7 lit min^{-1}) for PM_{10} sampling

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Fig_1

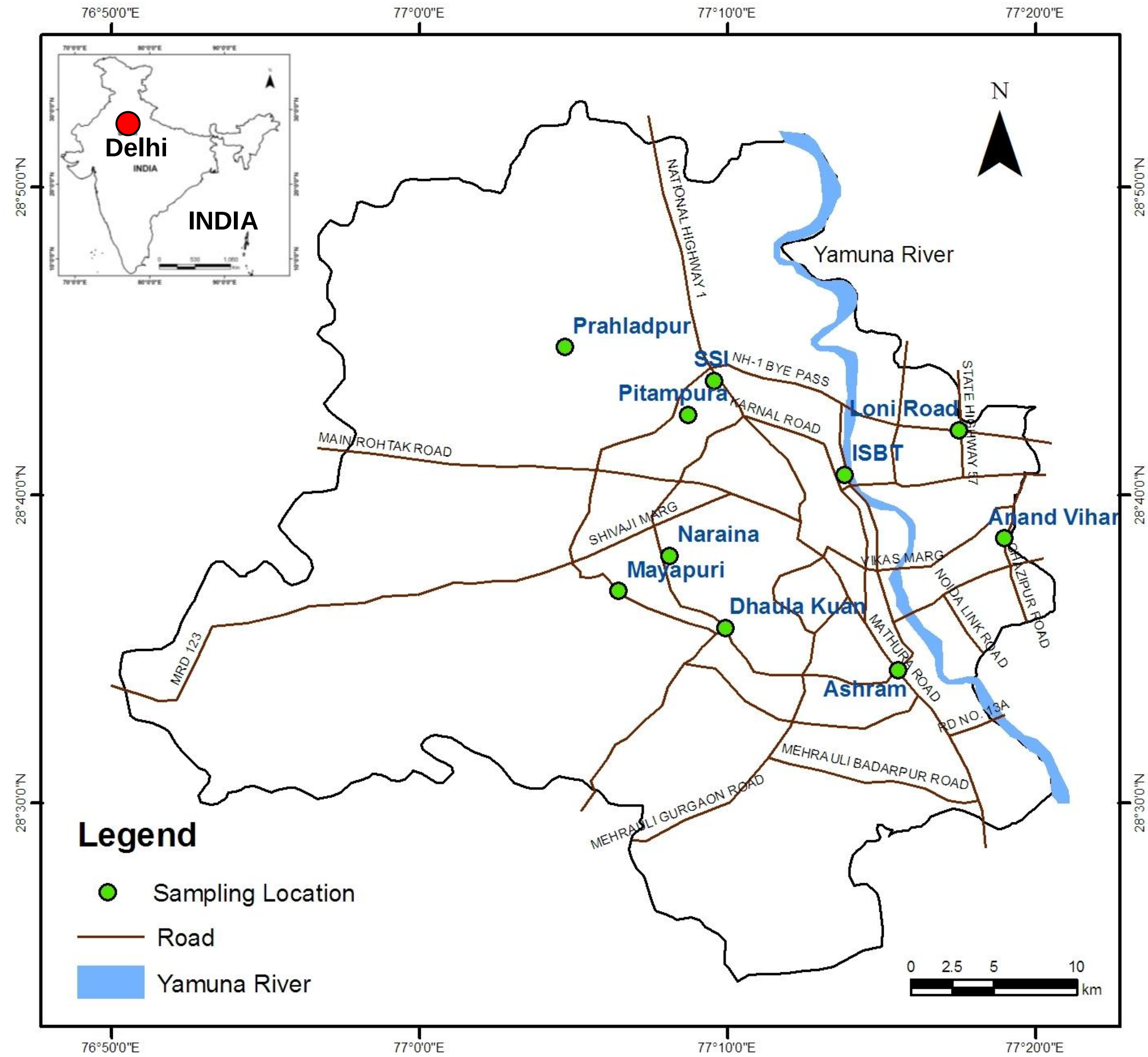

Figure 1: Air quality monitoring locations in Delhi shown by the circular dots.

Fig_2

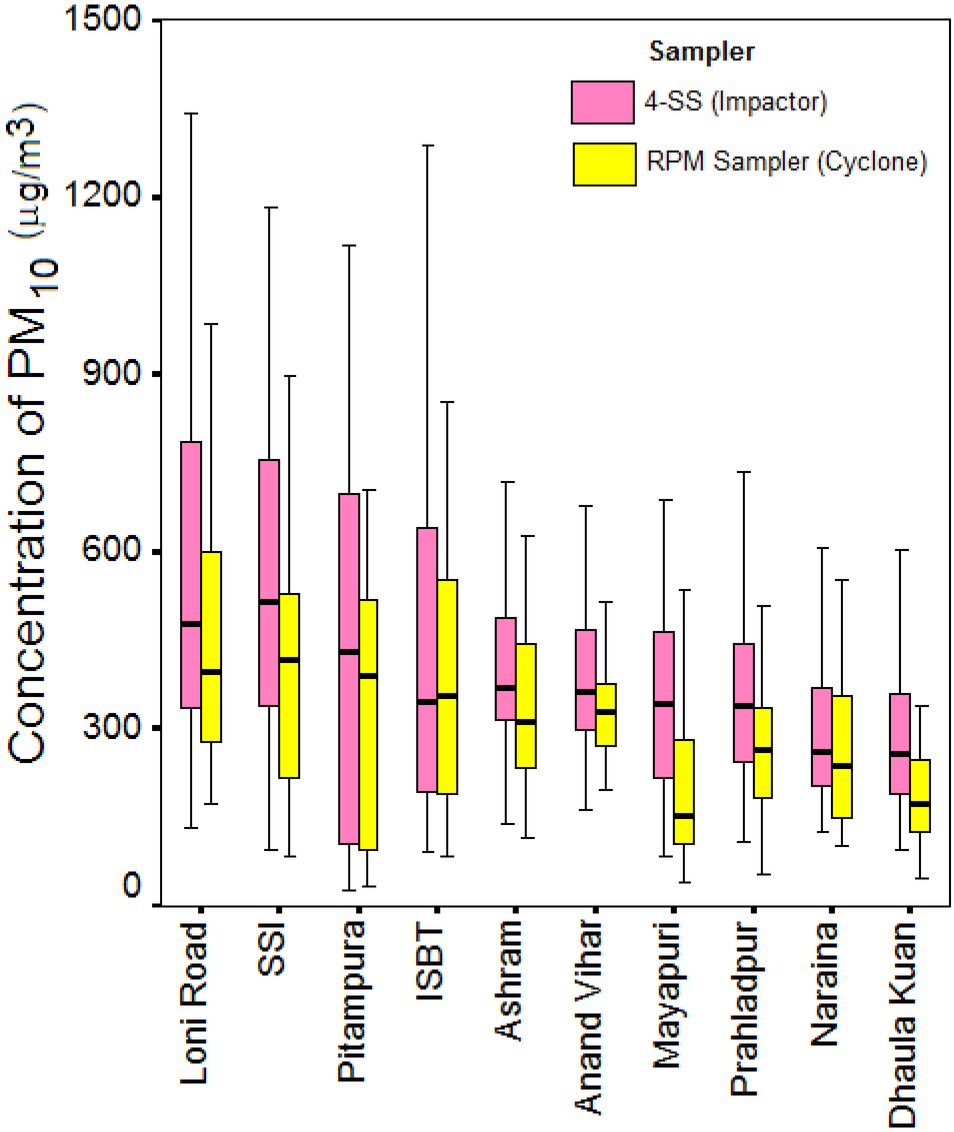

Figure 2: Box-whisker plot for comparison of PM_{10} values at 10 monitoring sites in Delhi. The upper and lower end of box shows the 75 and 25 percentile values respectively. Dark horizontal lines shows median values and the upper and lower end of the error bars represent highest and lowest values.

Fig_3

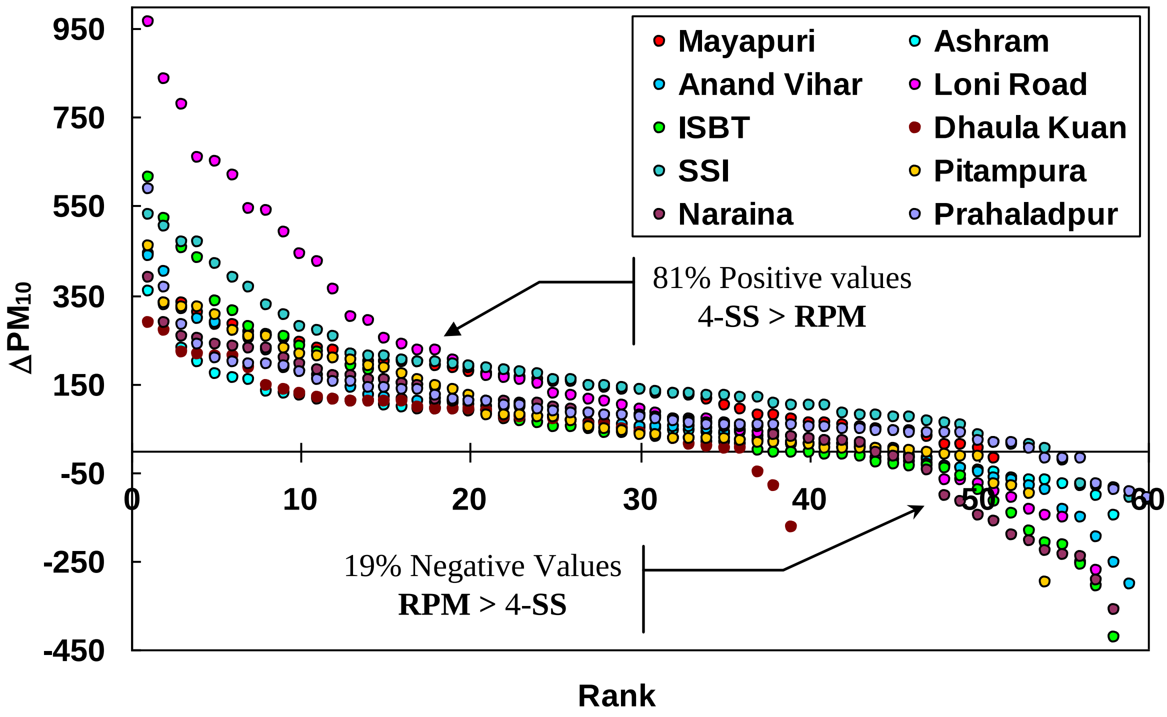

Figure 3: Scatter plot of difference in pairs (4-SS ~ RPM).

Fig_4

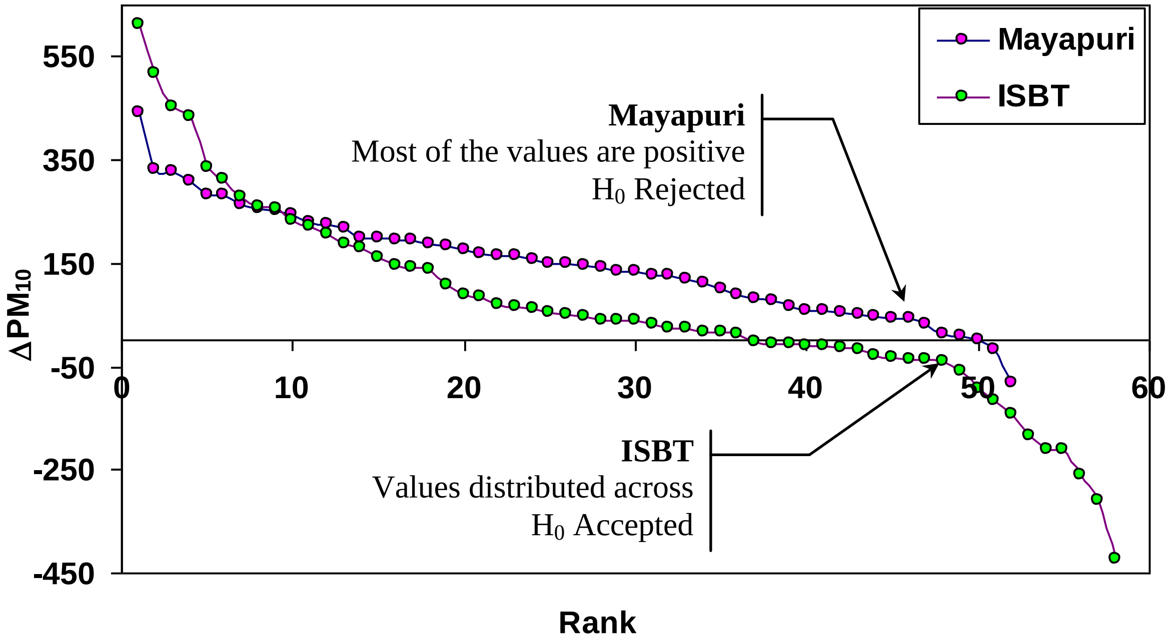

Figure 4: Plot of difference in pairs for accepted and rejected null hypothesis.

Fig_5

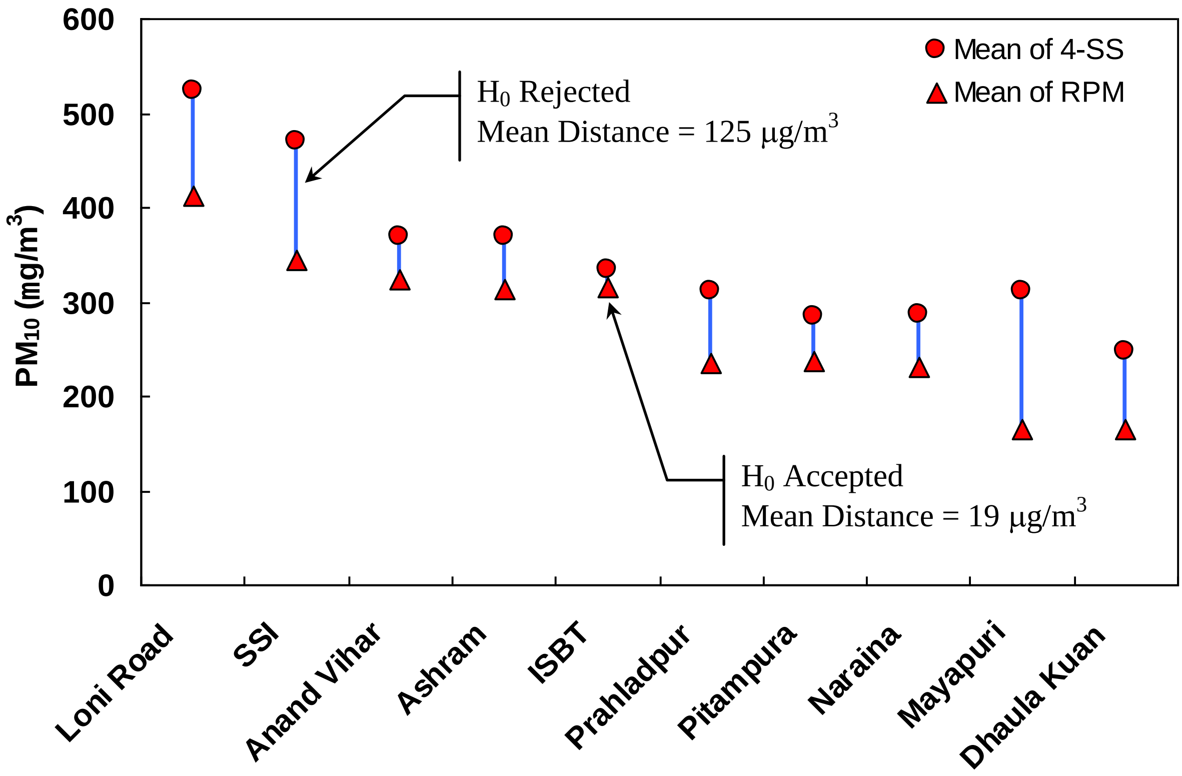

Figure 5: Mean PM_{10} values measured by SS and RPM sampler.

Fig_6

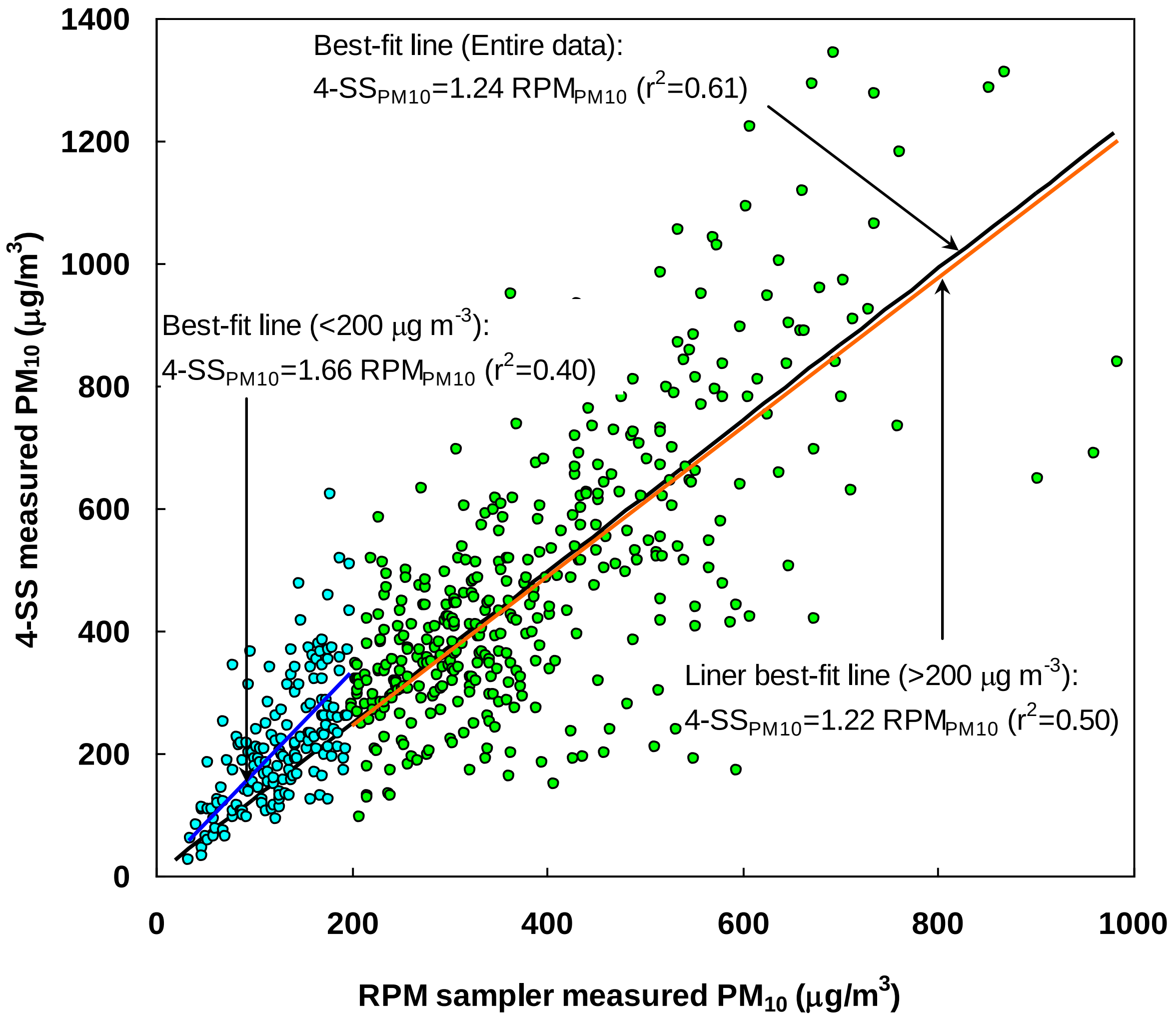

Figure 6: Correlation of 4-SS and RPM sampler measured PM_{10} values. Correlation of lower PM_{10} concentrations shown in the inset.

Table 1: Results of t-Test for paired samples taken at different monitoring sites in Delhi.

	Sample size	**Probability (p)**	**Mean Difference**	**Regression coefficient (r^2)**	**Intercept (b)***
Mayapuri	52	0.00	146	0.57	158
SSI	60	0.00	125	0.81	19
Loni Road	56	0.00	111	0.58	70
Dhaula Kuan	39	0.00	84	0.46	119
Prahladpur	61	0.00	77	0.45	84
Ashram	58	0.00	56	0.59	114
Naraina	58	0.00	55	0.13	207
AnandVihar	59	0.01	45	0.26	107
Pitampura	54	0.00	48	0.87	-19
ISBT	58	**0.27**	**19**	0.66	-35

*$y = ax + b$

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