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Blanco-Becerra, Luis Camilo; Gáfaro-Rojas, Aurora Inés; Rojas-Roa, Néstor Yezid
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Influencia del efecto barrido en la relación $PM_{2.5}/PM_{10}$ en la localidad de Kennedy de Bogotá, Colombia

Luis Camilo Blanco-Becerra[1], Aurora Inés Gáfaro-Rojas[2], Néstor Yezid Rojas-Roa[3*]

[1]Facultad de Ingeniería Ambiental, Universidad Santo Tomas. Carrera 9 # 51-11. C. P. 110311. Bogotá, Colombia.
[2]Departamento de Salud Pública, Facultad de Salud, Universidad Industrial de Santander. Carrera 32 # 29-31. C. P. 680002. Bucaramanga, Colombia.
[3]Departamento de Química e Ingeniería Ambiental, Universidad Nacional de Colombia. Carrera 30 # 45-03. C. P. 111321. Bogotá, Colombia.

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ABSTRACT: Objective: To establish whether the scavenging effect reduces the $PM_{2.5}/PM_{10}$ ratio in rainy periods in comparison with dry periods, at the Kennedy locality of Bogotá, Colombia. Materials and methods: Relationships among hourly and daily PM_{10}, $PM_{2.5}$, $PM_{2.5}/PM_{10}$ ratio, temperature, relative humidity and precipitation records from the Kennedy air quality station from January 2007 to September 2011 were analyzed. Results: The hourly mean $PM_{2.5}/PM_{10}$ ratio was 0.36 (SD= ± 0.12), with an hourly maximum of 0.96. In rainy hours, the $PM_{2.5}/PM_{10}$ ratio was 0.41 (SD= ± 0.13) and was reduced to 0.36 (DE= ± 0.12) in dry hours. On the other hand, the daily mean $PM_{2.5}/PM_{10}$ ratio was 0.36 (SD= ± 0.09) with a daily maximum of 0.79. The daily mean on rainy days was higher (0.39; SD= ± 0.09) than that recorded on dry days (0.34; SD= ±0.08). All these differences were statistically significant. Conclusions: Precipitation reduces $PM_{2.5}$ concentrations at a lower extent than it reduces PM_{10} concentrations. The analysis was not conclusive about the effect of precipitation on $PM_{2.5}$ concentrations, so it is not possible to assert that precipitation reduces the risk associated with the exposure to airborne particulate matter. To deepen our knowledge about the effect of precipitation on particulate matter pollution, it is recommended to apply additional techniques such as particle counting and particulate matter chemical characterization.

RESUMEN : Objetivo: Establecer si el efecto barrido disminuye el valor de la relación $PM_{2.5}/PM_{10}$ en horas o días lluviosos, en comparación con periodos secos, en la localidad de Kennedy de Bogotá, Colombia. Material y métodos: Se analizaron relaciones entre los registros horarios y diarios de PM_{10}, $PM_{2.5}$, relación $PM_{2.5}/PM_{10}$, temperatura, humedad relativa y precipitación, de la estación del sistema de vigilancia de calidad del aire de la localidad de Kennedy en Bogotá durante el periodo de enero de 2007 a septiembre de 2011. Resultados: La media horaria de la relación $PM_{2.5}/PM_{10}$ fue de 0,36 (DE= ± 0,12), con un máximo horario de 0,96. En horas lluviosas, la relación $PM_{2.5}/PM_{10}$ fue de 0,41 (DE= ± 0,13), disminuyendo a 0,36 (DE= ± 0,12) en horas secas. Por otra parte, la media diaria de la relación fue de 0,36 (DE= ± 0,09), con una media máxima diaria de 0,79. La media diaria en días lluviosos fue mayor (0,39; DE= ± 0,09), que la encontrada en días secos (0,34; DE= ± 0,08). Todas las diferencias de medianas fueron estadísticamente significativas. Conclusiones: La precipitación disminuye las concentraciones de PM_{10}, y en menor proporción las de $PM_{2.5}$, lo cual tiene como resultado un leve aumento de la relación $PM_{2.5}/PM_{10}$ con la precipitación. El análisis no es concluyente en cuanto a la reducción de $PM_{2.5}$, por lo cual no es posible afirmar que la precipitación reduce el riesgo a la salud asociado a la exposición a material particulado en el aire ambiente. Con el fin de profundizar sobre el conocimiento del efecto de la precipitación sobre la contaminación por material particulado, se recomienda hacer mediciones con técnicas complementarias, como el conteo y el análisis químico de las partículas.

* Corresponding author: Néstor Yezid Rojas Roa
E-mail: nyrojasr@unal.edu.co
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1. Introduction

Air pollution is a concerning issue in several cities in Latin America and the Caribbean (LAC), owing to unplanned urbanization processes with a fast growth in population and vehicular fleet, poor maintenance practices and industrial facilities with obsolete technologies [1]. The main air pollutant is particulate matter (PM), measured both as PM_{10} – particles with an aerodynamic diameter smaller than 10 micrometers – and $PM_{2.5}$ – smaller than 2.5 micrometers, or fine PM –. The difference between PM_{10} and $PM_{2.5}$ is referred to as coarse particles. In general, fine and coarse particles have different chemical compositions, are generated by different processes, emitted by different sources, and removed from the atmosphere by different mechanisms [2]. The $PM_{2.5}/PM_{10}$ ratio represents the fraction of fine particles, mostly produced by incomplete fuel combustion, and the sum of fine and coarse particles [3]. Particles of different sizes are deposited in different sections of the respiratory tract and have different effects on human health [4]. Fine particles are more harmful than coarse particles because they have a higher fraction of toxic compounds [5] and present a higher surface area, interacting more easily with airway and alveolar cells.

One of the PM removal mechanisms from the atmosphere is the wet deposition or precipitation scavenging, a natural process in which the interaction between hydrometeors (cloud droplets, mist, rain, ice crystals) and particles interact, resulting in particle growth and deposition on the Earth's surface. Interactions include nucleation scavenging and impaction scavenging. Nucleation scavenging involves water condensation over particles that act as condensation nuclei and ice-formation nuclei. Impaction scavenging results from the particle capture by cloud droplets, ice crystals and falling hydrometeors [2]. Precipitation scavenging is the most important sink of PM in the troposphere [6] and coarse particles are removed more efficiently than fine particles through these mechanisms [7].

As it is usual in urban centers around the world, Bogotá and other Colombian cities have records of poor air quality, associated with high concentration levels of PM_{10} [8]. It has been estimated that point sources in Bogotá emit nearly 1,440 ton/yr of total suspended particles (TSP), and mobile sources emit 1,100 ton/yr of $PM_{2.5}$ [9, 10]. The annual PM_{10} average concentration for the city was 48 μg/m^3 in 2012, but Kennedy, the most polluted locality in the SW area the city, had a much higher annual average for the same year, 71 μg/m^3. The Kennedy air quality station is the only one in the city equipped with a $PM_{2.5}$ monitor for several years, since 2007. The PM2.5 annual average for 2012 was 28.5 μg/m^3 [11]. Both PM_{10} and $PM_{2.5}$ concentration levels in Kennedy are well above the WHO air quality guideline values of 20 μg/m^3 and 10 μg/m^3, respectively.

Air pollution sources in Kennedy are varied. It is one of the most densely populated areas of the city. Its land use is mixed, so there are numerous small and mid-sized industrial facilities. Furthermore, it has a heavy traffic of passenger cars, public buses and heavy-duty trucks that carry raw materials, agricultural produce and manufactured goods in and out of the city. Many roads in the locality are unpaved or in a poor maintenance state.

In a situation like this, precipitation scavenging is supposed to mitigate the impacts of PM pollution. However, records of Bogotá's health authority have shown that the number of events related with respiratory illness increase during the wet seasons and decrease during the dry seasons. Therefore, it is worthwhile to examine the extent at which the precipitation scavenging effect is occurring.

Relationships among hourly and 24-h records of PM_{10}, $PM_{2.5}$ and meteorological parameters such as temperature, relative humidity, wind speed and precipitation at the Kennedy station, from January 2007 to September 2011, were analyzed with the aim to determine the impact of the precipitation scavenging on particulate matter concentrations and the fine/coarse particle ratio. Wet deposition is supposed to have a stronger effect on coarse particles than on fine particles, so the $PM_{2.5}/PM_{10}$ should increase during wet periods with respect to dry periods.

2. Methods

2.1. Study location

Bogotá D.C is located at a latitude of 4° 35' 56" a longitude of - 74° 4' 51" and an altitude between 2,500 and 2,800 masl, with an annual mean temperature between 12 º C and 15 ºC over the urban area. The annual mean temperature is virtually constant throughout the year (Table 1). Monthly precipitation distribution is bimodal, with two rainy periods and two dry periods annually. The first rainy period occurs roughly in April and May and the second in October and November. The dryer periods occur in January-February and July-August. March, June, September and December are transition months [12].

Bogotá's official population in 2011 was 7,467,804 inhabitants, 14% of which (1,019,949) lived in the Kennedy locality. In Kennedy locality 8.5% of the population are children under 4 and 8.67%, adults aged 60 and over [13]

2.2. PM_{10}, $PM_{2.5}$ and meteorological variables

Hourly records of PM_{10}, $PM_{2.5}$, together with temperature, relative humidity (RH), wind speed, barometric pressure

Table 1 Monthly average of temperature (° C). Dorado airport station. Bogotá

Temperature (°C)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Mean	13.1	13.5	13.8	14.0	14.0	13.8	13.3	13.3	13.3	13.4	13.5	13.2
Maximum Mean	19.9	20.0	19.8	19.5	19.2	18.6	18.2	18.5	18.9	19.1	19.3	19.5
Minimum Mean	5.6	6.6	7.7	8.7	8.8	8.4	7.8	7.4	7.2	7.8	8.0	6.6

(BP) and precipitation were obtained from the Kennedy station, which is part of Bogotá's Air Quality Monitoring Network. PM_{10} and $PM_{2.5}$ concentrations are measured using Beta attenuation monitors [11].

This station is classified as "urban background", without a significant influence of a specific source, but aimed to show the influence of multiple sources at a neighborhood scale [14]. It is located at the Cayetano Cañizales Park, in the SW area of the city, at 40 meters from the closest street (Avenida Carrera 86) and less than 1 km from Corabastos, the largest agricultural produce collection center of the city, which generates an intense activity of heavy-duty trucks [3].

2.3. Statistical analysis

An exploratory analysis of hourly PM_{10}, $PM_{2.5}$ and $PM_{2.5}/PM_{10}$ ratio data was carried out to identify and discard outliers. Meteorological variables were also examined to check their quality. 24-h averages were then analyzed for all variables, except precipitation, which was analyzed as a 24-h cumulative variable. Only days with less than 25% of missing data were taken into account for the statistical analysis.

Days with a cumulative precipitation above 0 mm were considered as rainy days. The equivalent criterion was used for rainy hours. Since the pollutant concentrations and meteorological data did not have normal distributions, non-parametric tests were used to establish correlations (Spearman test) and difference of means (Kruskal-Wallis test) between rainy and dry periods. The STATA 11® software application was used to run the tests.

3. Results

3.1. Hourly data

Of the 41,616 hours of the study period, a total of 29,146 valid records of PM_{10} and $PM_{2.5}$ (70%) concentration were counted. The hourly average of PM_{10} concentration was 87.91 μg/m^3 (standard deviation SD = ± 37.86), with a maximum hourly value of 240 μg/m^3. For $PM_{2.5}$ the hourly average was 31.65 μg/m^3 (SD = ± 17.13), with a maximum hourly concentration of 98 μg/m^3. The Spearman correlation between PM_{10} and $PM_{2.5}$ was 0.75 showing a statistically significant association between variables. The hourly average of the $PM_{2.5}/PM_{10}$ ratio was 0.36 (SD= ± 0.12) with a maximum hourly value of 0.96 (Table 2).

When stratified by rainy or dry hours, from the 29,146 obtained hourly records, 93% (n=27,098) corresponded to dry hours, while the remaining percentage (n=2,048) were rainy hours. In the rainy hours, a higher hourly average value of RH compared with dry hours (RH rain=78.9%; RH dry=68.6%) was observed. Temperature showed an inverse relation to hourly RH, which was evidenced in the correlation value (-0.77), which was statistically significant. The finding in the correlation was confirmed with the meteorological variables recorded values, which show that in dry hours the average temperatures was 14.6°C and the average RH was 68.55%, while in rainy hours the average temperature was 13.48°C and RH was 78.91%. All differences between average meteorological variables in the dry and rainy hours, except BP, were statistically significant. The decrease in temperature is one characteristic of the rain formation processes, which can be convective, orographic and frontal or cyclonic; clouds are formed by cooling humid air parcels (masses), which may be caused by an ascent of the parcel or a barometric process. The mass is cooled gradually during the ascent until the dew point temperature is reached at which the water vapor condensation occurs with the subsequent transformation from vapor to tiny droplets of water [15].

The hourly average of the $PM_{2.5}/PM_{10}$ ratio in rainy hours was 0.41 (SD= ± 0.13), higher than the one found in dry hours (0.36; SD= ± 0.12). The $PM_{2.5}/PM_{10}$ ratio showed a negative correlation with the temperature (-0.36) and positive with the RH (0.44). With an average temperature of 13.48°C, the average value of the $PM_{2.5}/PM_{10}$ ratio was 0.41 and decreased to 0.36 with a higher temperature (14.6°C in dry hours). For RH, with a value of 68.6% (dry hours) a $PM_{2.5}/PM_{10}$ ratio of 0.36 was obtained, which increased to 0.41 with a RH of 78.9% (Table 2). The correlations and medium difference were statistically significant.

In order to identify the effect of precipitation in hourly concentration of particulate matter, 913 hours for PM_{10} and $PM_{2.5}$ were analyzed, in which the reduction percentage of concentration of a dry hour followed by a rainy hour was calculated; The reduction of PM_{10} was 30% and $PM_{2.5}$ was 21%, additionally it was observed that the $PM_{2.5}/PM_{10}$ ratio for a rainy hour was higher than the one for a dry hour

Table 2 Hourly time distribution of particulate matter and meteorological variables in Kennedy Locality in Bogotá 2007-2011

Variable	Observations			Average			SD			Maximum		
	WP	D	R	WP	D	R	WP	D	R	WP	D	R
PM_{10} (μg/m³)*	29,146	27,098	2,048	87.91	89.52	66.65	37.86	38.03	27.85	240	240	202
$PM_{2.5}$ (μg/m³)*	29,146	27,098	2,048	31.65	31.99	27.16	17.13	17.33	13.54	100	100	98
WV (m/s)*	28,781	26,743	2,038	2.24	2.25	2.08	1.41	1.43	1.16	13	13	6.4
TEMP (°C)*	21,779	20,144	1,635	14.52	14.60	13.48	2.57	2.62	1.56	25.4	25.4	20.1
BP (mm of Hg)	19,837	18,237	1,600	563.99	564.00	563.95	1.03	1.02	1.10	567.1	566.9	567.1
RH (%)*	21,000	19,393	1,607	69.34	68.55	78.91	11.80	11.80	6.23	91.9	91.9	91.66
Rain (mm)*	29,146	27,098	2,048	0.08	0	1.11	0.61	0	2.05	28.8	0	28.8
$PM_{2.5}/PM_{10}$*	29,146	27,098	2,048	0.36	0.36	0.41	0.12	0.12	0.13	0.96	0.96	0.88

* Medium Difference was statistically significant. WV: Wind Velocity; TEMP: Temperature; BP: Barometric Pressure; RH: Relative humidity; SD: Standard deviation; WP: Whole Period; D: Dry; R: Rainy

(Rainy hour =0.40; Dry hour =0.39). Medium difference was statistically significant (Table 3).

3.2. Daily data

Of the 1,734 days of the study period, a total of 1,189 records of daily average concentration for PM_{10} and $PM_{2.5}$ (69%) were obtained. The daily average concentration of PM_{10} was 89.9 μg/m³ (SD= ± 25.76), with a maximum daily average value of 183.3 μg/m³. For $PM_{2.5,}$ the daily average was 32.7 μg/m³ (SD= ± 12.29) with a maximum daily average of 75.1 μg/m³. The Spearman correlation between PM_{10} and $PM_{2.5}$ was 0.74, showing an association between variables, which was statistically significant. The daily average $PM_{2.5}/PM_{10}$ ratio was 0.36 (SD= ± 0.09), with a maximum daily Average of 0.79 (Table 4).

When stratified by rainy or dry day, from 1,189 days, 51% (n=610) were dry days, while 49% (n=579) were rainy days. As same as the hourly analysis, it was found that in rainy days there is a higher daily average of RH compared with dry days (RH rainy day=72.9%; RH dry day= 65.5%). Temperature showed a statistically significant inverse relation with daily RH (-0.69) equal to what was found in the hourly analysis. The finding in the correlation was confirmed with the meteorological variables records, in which the daily average temperature in dry days was 14.8°C, with a daily average RH of 65.5%, while in rainy days the daily average temperature was 14.2°C, with a RH of 72.9%; All differences between medium meteorological variables in the dry and rainy days, except BP, were statistically significant.

As in the hourly analysis, the daily average of $PM_{2.5}/PM_{10}$ ratio in rainy days was higher (0.39; SD= ± 0.09) that the one found in dry days (0.34; SD= ± 0.08). The $PM_{2.5}/PM_{10}$ ratio showed a negative correlation with temperature (-0.34) and positive with RH (0.54). With a temperature of 14.2°C, the value of the $PM_{2.5}/PM_{10}$ ratio was 0.39 decreasing to 0.34, with a higher temperature (14.8°C in dry days). For RH with a value of 65.5% (dry day) a $PM_{2.5}/PM_{10}$ ratio of 0.34 was found, which increased to 0.39 with a RH of 72.9% (Table 4). The correlations and medium difference were statistically significant.

In order to identify the effect of precipitation on daily concentrations of particulate matter, 120 days for PM_{10} and $PM_{2.5}$ were examined; the percentage reduction was calculated in the concentration of a dry day followed by a rainy day. The daily reduction of PM_{10} was 17% and for $PM_{2.5}$ was 11%, in which the $PM_{2.5}/PM_{10}$ ratio for a rainy day was higher than the one for a dry day (rainy day=0.37, dry day=0.35). The difference of medium by Kruskal-Wallis was statistically significant, indicating that the values found in dry and rainy days are different (Table 5).

3.3. Discussion

These results confirm the hypothesis that the scavenging action of rain reduces PM_{10} and, to a lesser extent, $PM_{2.5}$ concentrations. The effect is demonstrated using both 24-h and hourly data. As a result, the $PM_{2.5}/PM_{10}$ ratio increases during periods of higher precipitation, as shown in Figure 1 ($PM_{2.5}/PM_{10}$ rainy hour = 0.41 - $PM_{2.5}/PM_{10}$ dry hour = 0.36; $PM_{2.5}/PM_{10}$ rainy day = 0.39; $PM_{2.5}/PM_{10}$ dry day = 0.34).

These results differ from those found by other researchers in the same monitoring site. In Bogotá [3] a study found an average $PM_{2.5}/PM_{10}$ ratio of 0.416, 0.290 for rainy conditions and 0.375 for dry conditions. Other monitoring stations localized in different localities of the city, showed a similar behavior. The difference may be due to the monitoring time of the year, since [3] analyzed data from August to October

Table 3 Reduction of particulate matter between dry and rainy hours in Kennedy, locality in Bogotá. 2007-2011

Variables	Observations			Average			SD			Maximum		
	WP	D	R	WP	D	R	WP	D	R	WP	D	R
PM_{10} (µg/m³)*	1,826	913	913	76.02	91.44	60.65	33.89	36.29	22.52	240	240	194
$PM_{2.5}$ (µg/m³)*	1,826	913	913	30.16	35.84	24.49	16.16	18.15	11.34	96	96	86
$PM_{2.5}/PM_{10}$*	1,826	913	913	0.40	0.39	0.40	0.12	0.12	0.12	0.96	0.96	0.81
Reduction PM_{10}	913			0.30			0.19			0.79		
Reduction $PM_{2.5}$	913			0.21			0.41			0.91		

* Medium Difference was statistically significant. SD: Standard deviation; WP: Whole Period; D: Dry; R: Rainy

2005, which are mostly dry, whereas this work analyzed 4 years of data, covering several rainy and dry seasons throughout that period.

The average $PM_{2.5}/PM_{10}$ ratio of 0.36 in this study is lower when compared with the values measured in several cities around the world, which are normally between 0.6 and 0.8 [3]. This is presumably due to a high contribution of coarse particulate matter associated with dust resuspension from the roads surrounding the park where the monitoring station is located. These roads regularly have a visible layer of dust and are not cleaned frequently. Other study [16] state that $PM_{2.5}/PM_{10}$ ratios higher than 0.60 would be expected under the direct influence of combustion sources, while ratios lower than 0.30 would have a strong influence of resuspended dust or erosion, which corresponds to this case at the Kennedy locality.

Similar studies conducted in other countries show dissimilar results. In Mexico City, researchers [17] found a $PM_{2.5}/PM_{10}$ ratio of 0.44 for the rainy season and 0.47 for the dry season, that is, a higher $PM_{2.5}/PM_{10}$ ratio during dry periods than during rainy periods, in contrast with the present study. However, Salazar et al. analyzed a 1-year period, from June 1998 to May 1999. Also in México City from 1992 to 1995, a study [18] determined a ratio of 0.8 during rainy season (May to November), versus 0.5 during dry season (December to April), in agreement with the results from the present study.

In Hong Kong, researchers [19] determined a ratio of 0.84 in Summer (April to September) and 0.69 in Winter (October to March), at a station located on the side of an urban road with heavy traffic. The summer months recorded a value of 1912.7 mm of rainfall compared to the winter months which registered a value of 201.5 mm; June was the rainiest month with 814.5 mm and a ratio of 0.83 compared to February where rainfall had a value of 0 mm and a ratio of 0.69. This study showed an apparent scavenging effect over Total Suspended Particles (TSP) and PM_{10}. PST and PM_{10} concentrations increased when monthly precipitation was lower, whereas $PM_{2.5}$ concentrations did not show a significant correlation with rain.

In Thumba, India, a study [20] analyzed the responses of PM concentrations in a tropical coastal station strongly affected by rapid winds and precipitation associated with the Monsoon season, between October 1998 and December 2000. The $PM_{2.5}/PM$ ratio was 0.9 in Winter (December to February), 0.79 in pre-Monsoon (March to May), 0.8 in Monsoon (June to September) and 0.87 in post-Monsoon (October and November), showing a higher ratio in the Winter months with respect to those with higher precipitation in the Monsoon season. High wind speed and relative humidity, as well as torrential rains during the Monsoon reduce PM10 and $PM_{2.5}$, whereas low wind speed and dry soil during the dry winter season are related with high PM concentrations, which affect $PM_{2.5}/PM_{10}$ ratios and explain the differences with the present results.

In China [7] a study established that coarse particles ($PM_{>10}$ and $PM_{2,5-10}$) can be washed by rain more efficiently than fine particles ($PM_{2,5}$ and $PM_{1,0}$) and, thus, wet deposition rates are generally lower for fine particles. This is because the rain scavenging coefficient for particles with a semi-diameter 0.1 < r < 1.0 µm is very low. Furthermore, precipitation moistens the soil, reducing dust resuspension by traffic and other activities.

Temperature and relative humidity (RH) in Kennedy agree with findings for Bogotá and other Colombian cities. A research [21] found that minimum RH is coincident with minimum precipitation and maximum temperature and viceversa. The increase in $PM_{2.5}$ during rainy periods may be attributed to an increase in RH. One study [22] found that for particles with an aerodynamic diameter between 0.3 and 1.0 µm, RH can affect the particles' mass more strongly than precipitation, potentially increasing their mass concentration.

Having seen that precipitation in Kennedy reduce PM_{10} but not $PM_{2.5}$ concentrations, it is reasonable to assert that exposure to $PM_{2.5}$ during rainy periods could have a stronger effect on morbidity and mortality associated with cardio-respiratory illness in this locality. Coarse particles are deposited more efficiently than fine particles, affecting mainly urban areas near the sources [23]. Daily mortality

Table 4 Average daily distribution of particulate matter and meteorological variables in Kennedy Locality in Bogotá. 2007-2011

Variable	Observations			Average			SD			Maximum		
	WP	D	R	WP	D	R	WP	D	R	WP	D	R
PM_{10} (μg/m³)*	1,189	610	579	89.98	95.59	84.07	25.76	25.87	24.3	189.08	189.08	183.3
$PM_{2.5}$ (μg/m³)*	1,189	610	579	32.66	32.64	32.69	12.29	11.92	12.13	83.08	83.08	75.13
WV (m/s)*	1,170	600	570	2.24	2.38	2.09	0.7	0.73	0.62	5.62	5.62	3.9
TEMP (°C)*	891	434	457	14.51	14.83	14.2	0.99	1	0.86	17.81	17.81	17.23
BP (mm of Hg)	810	368	442	563.99	564.01	563.97	0.68	0.66	0.7	565.7	565.6	565.7
RH (%)*	860	414	446	69.34	65.52	72.9	6.79	6.34	5.03	84.18	79.43	84.18
Rain (mm)*	1,189	610	579	1.85	0	3.8	4.14	0	5.27	31.7	0	31.7
$PM_{2.5}/PM_{10}$*	1,189	610	579	0.36	0.34	0.39	0.09	0.08	0.09	0.79	0.77	0.79

* Medium Difference was statistically significant. WV: Wind Velocity; TEMP: Temperature; BP: Barometric Pressure; RH: Relative humidity; SD: Standard deviation; WP: Whole Period; D: Dry; R: Rainy

is more strongly associated with fine particles [24]. Road transport, particularly based on diesel trucks and buses, is the main source accountable for excess mortality and morbidity associated with fine particles in urban areas [25]. In Santiago de Chile, a study [26] found a significant correlation between the number of acute bronchitis hospital visits and environmental factors such as an increase in $PM_{2.5}$ and lower ambient temperature. Fine aerosols are more effective than coarse particles in causing respiratory disease and premature deaths, owing to their ability to penetrate deeply into the lungs [27]. Some of the factors that increase morbidity and mortality associated with respiratory illness are biological materials and metals that are part of the fine fraction of PM. Biological material, including bacteria, polen, skin debris, spores and cellulose fragments, are in the coarse fraction, while viruses are in the fine fraction [3]. Studies suggest that metals like Fe, Ni, Cu, Zn and V play a role in causing physiological changes such as inflammatory response or injuries in the respiratory tissue. Metals have been mostly associated with fine particles [28, 29].

The findings shown here for the Kennedy locality cannot be extrapolated to the level of Bogotá or to other localities of the city, where PM_{10} y $PM_{2.5}$ concentrations can be affected by a different composition of local sources and different meteorological conditions. Nevertheless, Kennedy is the station with the longest record of simultaneous $PM_{2.5}$ and PM_{10} observations and has a complete set of meteorological data. It has the influence of mobile, stationary and area sources and is a representative receptor of exposure to high concentrations of PM in a densely populated area [30]. Many other studies have focused their interest in this locality.

Table 5 Reduction of particulate matter between dry and rainy days in Kennedy, Locality in Bogotá. 2007-2011

Variable	Observations			Average			SD			Maximum		
	WP	D	R	WP	D	R	WP	D	R	WP	D	R
PM_{10} (μg/m³)*	240	120	120	90.63	99.33	81.94	24.83	23.34	23.27	176.5	176.5	167.63
$PM_{2.5}$ (μg/m³)*	240	120	120	32.64	34.89	30.39	11.15	11.13	10.75	66.71	66.71	62.04
$PM_{2.5}/PM_{10}$*	240	120	120	0.36	0.35	0.37	0.08	0.08	0.08	0.65	0.64	0.65
Reduction PM_{10}	120			0.17			0.11			0.5		
Reduction $PM_{2,5}$	120			0.11			0.17			0.5		

* Medium Difference was statistically significant. SD: Standard deviation; WP: Whole Period; D: Dry; R: Rainy

One of the strengths of this study was the availability of a large number of data recorded in the air quality network station in Bogotá located in Kennedy locality. A total of 29.146 hourly values and 1,189 daily values of PM_{10} and $PM_{2.5}$ were obtained and made possible to capture the effect of precipitation on the $PM_{2.5}/PM_{10}$ ratio. Furthermore, the availability of these data sustained the difference in results with other studies, where monitoring was performed using manual equipment and only daily averages were obtained. In addition, such studies have not had continuous sampling during a complete year, but only on specific days or during a few months, unlike this study, which spanned four years of continuous data. On the other hand, the climate characteristics of Bogotá, represented by epidemiological an average temperature and temperature range with little changes throughout the year, a marked period of rainfall and its height above sea level, made the obtained

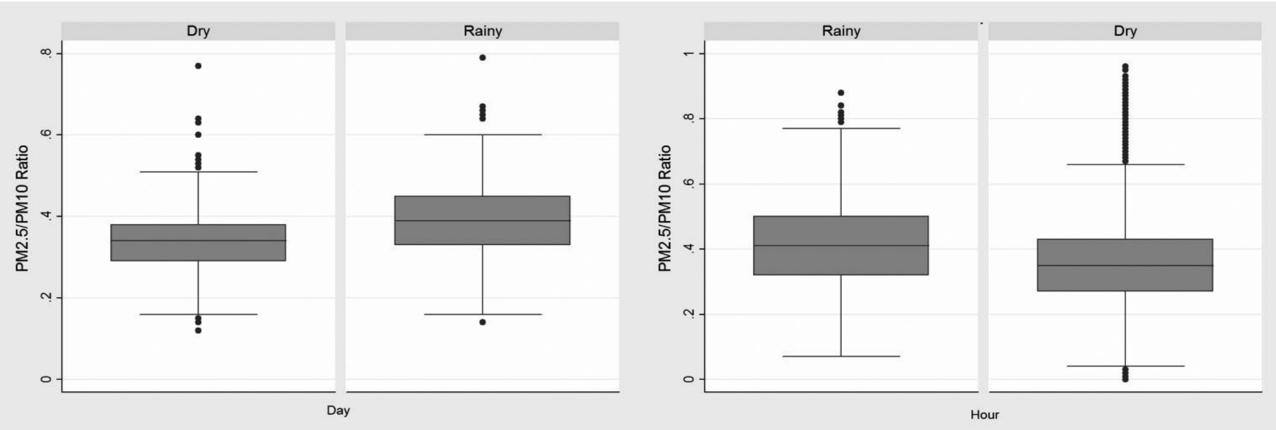

Figure 1 Hourly and daily distribution of $PM_{2.5}/PM_{10}$ ratio, for dry and rainy period in Kennedy Locality in Bogotá 2007-2011

results innovative and show an uncommon scenario when compared with studies in other countries, where the presence of seasons is determining for the behavior of air pollutants, such as particulate matter. Therefore, it is necessary to analyze more deeply the physical phenomena that make less evident the wet scavenging of particulate matter when analyzing the available dataset.

Although this analysis is not conclusive about the $PM_{2.5}$ reduction due to the scavenging action of rain, it would be of utmost interest conducting studies with analytical techniques that can observe the response of specific characteristics of PM to precipitation in Bogotá, such as the black carbon fraction, the particle size distribution and the particle number concentration. From the health point of view, it is important to conduct epidemiological studies where the precipitation variable is included in the analysis, which would show the effect of this environmental factor in cardio-respiratory morbidity and mortality in tropical countries. This information would help health authorities to make public health decisions to prevent exposure to fine particles.

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