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Impact of meteorological parameters on black carbon mass concentrations over Silicon City "Bengaluru, Southern part of India" – A Case Study

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सार – बेंगलुरु के संदर्भ में, क्षेत्रीय जलवायु गतिशीलता पर ब्लैक कार्बन (बीसी) एरोसोल का प्रभाव जांच के एक महत्वपूर्ण क्षेत्र के रूप में उभरता है। उच्च-रिज़ॉल्यूशन BC डेटा की कमी के कारण, इसे जनवरी 2019 से दिसंबर 2019 तक बेंगलुरु, कर्नाटक में 5 अलग-अलग स्थानों पर एकत्र किया गया था। BC की औसत द्रव्यमान सांद्रता 5.91 $\mu g\ m^{-3}$ थी, जबकि BC की उच्च द्रव्यमान सांद्रता थी सिटी रेलवे स्टेशन पर 7.71 $\mu g\ m^{-3}$ था और सबसे कम (3.69 $\mu g\ m^{-3}$) जयनगर में था। उच्च-यातायात और औद्योगिक स्थानों में बीसी का योगदान आवासीय स्थानों की तुलना में लगभग 41% अधिक था, जो इंगित करता है कि कालिख कणों का एक बड़ा हिस्सा मानवजनित गतिविधियों से है, मुख्य रूप से जीवाश्म ईंधन के दहन से। बीसी की मौसमी सांद्रता ने भी एक बड़ी परिवर्तनशीलता प्रदर्शित की है, सर्दियों के मौसम के दौरान परिमाण में उच्चतम अनुक्रम (9 $\mu g\ m^{-3}$) और उसके बाद गर्मियों में (6.3 $\mu g\ m^{-3}$), मानसून के बाद (5.8 $\mu g\ m^{-3}$), और अध्ययन अवधि के दौरान मानसून (3.4 $\mu g\ m^{-3}$) मौसम। वाशआउट प्रभाव के कारण मानसून के मौसम के दौरान बीसी की सांद्रता सर्दियों के मौसम की तुलना में बहुत कम थी। बीसी नकारात्मक रूप से महत्वपूर्ण रूप से सहसंबंधित था (-0.70), जिसमें वर्षा वाशआउट प्रभाव का संकेत देती है, हालांकि, सर्दियों के मौसम के दौरान, यह सीमा परत की स्थिति के प्रभाव के कारण था। कुल मिलाकर (वार्षिक), शहरी क्षेत्र में पांच वर्षों के भीतर बीसी की औसत सांद्रता में लगभग 55% की वृद्धि हुई है, जो मानव निर्मित गतिविधियों के प्रभाव को इंगित करता है। भारत के दक्षिणी भाग में बेंगलुरु में बीसी की उच्च सामूहिक सांद्रता क्षेत्रीय जलवायु के लिए गंभीर प्रभावों का संकेत देती है, जिसकी जांच करने और इसे कम करने की आवश्यकता है। अंत में, अध्ययन से पता चलता है कि भारत के दक्षिणी भाग में शहरी वातावरण में बीसी के उत्सर्जन को कम करने के लिए तत्काल कार्रवाई की आवश्यकता है।

ABSTRACT. In the context of Bengaluru, the impact of black carbon (BC) aerosols on regional climate dynamics emerges as a crucial area of investigation. Due to the lack of high-resolution BC data, it was collected at 5 different locations in Bengaluru, Karnataka, from January 2019 to December 2019. The mean mass concentration of BC was 5.91 $\mu g\ m^{-3}$, whereas the higher mass concentration of BC was 7.71 $\mu g\ m^{-3}$ over the city railway station and the lower (3.69 $\mu g\ m^{-3}$) was in Jayanagara. The contribution of BC in higher-traffic and industrial locations was approximately 41% higher than the residential locations, which indicates a large fraction of soot particles are from anthropogenic activities mainly from fossil fuel combustion. The seasonal concentrations of BC have also exhibited a large variability, with the highest sequence in magnitude during the winter season (9 $\mu g\ m^{-3}$) followed by the summer (6.3 $\mu g\ m^{-3}$), post-monsoon (5.8 $\mu g\ m^{-3}$) and monsoon (3.4 $\mu g\ m^{-3}$) seasons during the study period. The concentrations of BC during the monsoon season were very low as compared to the winter season due to the impact of the washout effect. The BC was negatively significantly correlated (-0.70) with rainfall indicating the washout effect, however, during the winter season, it was due to impact of boundary layer condition. Overall (annually) the mean concentrations of BC have increased by around 55% within five years over the urban region, which indicates the impact of man-made activities. The higher mass concentration of BC over Bangalore in the southern part of India, indicates serious implications for the regional climate that need to be investigated and mitigated. Finally, the study suggests that immediate action is required to mitigate the emission of BC into the urban environment in the southern part of India.

Key words - Black carbon, Seasonal variation, Meteorology.

1. Introduction

Atmospheric aerosols have a significant impact on regional and global climate change as well as environmental change. Black carbon (BC) aerosols are among the main air pollutants that have an impact on climate both directly and indirectly by their absorption of sunlight and changes in cloud cover that influence precipitation efficiency, respectively. (Ramanathan and Carmichael, 2008). The primary source of these aerosols is incomplete combustion from a variety of fuels combustion including solid biofuels like wood, manure and crop wastes as well as fossil fuels like coal and diesel. It was discovered that the long-range transport of BC concentrations into the atmosphere is controlled by meteorological factors such as wind speed (WS), relative humidity (RH) and solar radiation (SR) (Bond *et al*., 2013). Earlier, several studies have shown the impact of rainfall on BC mass concentrations by scavenging (Ramanathan *et al*., 2005; Tiwari *et al*., 2013).

Rana *et al*. (2019) reported that India holds the second-highest position globally in emitting soot particles (BC). As a result, India has carried out monitoring programs for BC during the past two decades and the results have shown that the northern region has particularly high quantities of BC aerosol. Changes in precipitation patterns may result from these elevated BC levels in the northern India, which have implications for regional climate dynamics (Babu, 2002; Safai *et al*., 2013; Lee *et al*., 2013; Kompalli *et al*., 2014; Mukunda *et al*., 2021). According to Paliwal *et al*. (2016), the total BC emissions in India, contributed most significantly from domestic fuels (~47 %) followed by industries (~22 %), transport (~17 %), open burning (~12 %) and other sources (2 %). In view of the above importance, we provide high time-resolved (5 min) measurements of BC mass concentrations during the period from January to December in the year 2019 in the Bangalore city (called “Silicon Valley") of the Karnataka province of India. The major objectives of the present study are (*i*) to assess the variability of BC mass concentration on different environment in the city and (*ii*) to examine the impact of meteorological parameters on BC over this study region. This highlights the significant increase in human-caused emissions especially in South Asia raising serious concerns about the quality of the air. Knowing and describing the causes of air pollution and evaluating their effects on local and regional environments are therefore necessary.

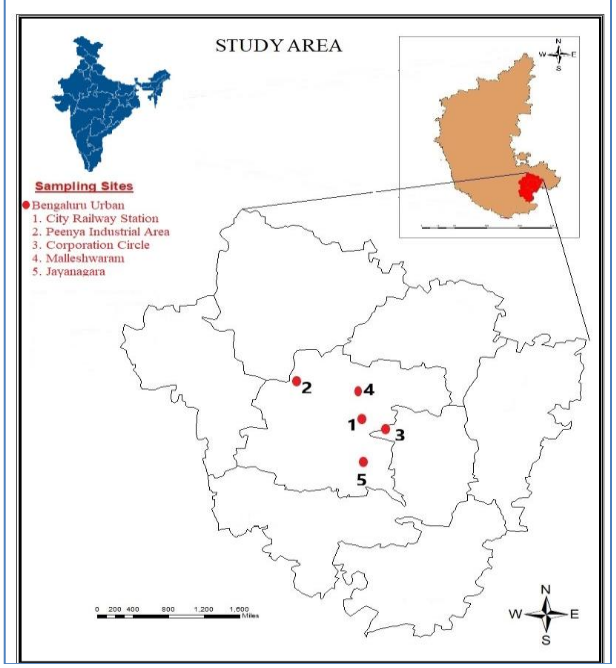

Fig. 1. Map of Bangalore indicating sampling location.

TABLE 1

Details of the Sampling Sites

Station No.	Locations	Coordinates	Elevation (m)	Zone Classified
1	City Railway Station (CRS)	12° 58' 39" N 77° 34' 13 " E	902	High traffic & Commercial
2	Peenya Ind Area (PEE)	13° 01' 42" N 77° 31' 11" E	905	Industrial & Commercial
3	Corporation Circle (COR)	12° 58' 02" N 77° 35' 13" E	907	High traffic & Commercial
4	Malleshwaram (MALL)	13° 00' 32" N 77° 33' 50" E	940	Residential with traffic
5	Jayanagara (JAY)	12° 55' 18" N 77° 35' 00" E	909	Residential

2. Site description, data and instrumentation

The data on BC and meteorological parameters, were collected at five different environments in an urban area “Bangalore” (capital of Karnataka) from January 2019 to December 2019 (Fig. 1). Bangalore, renowned as the "Garden City" of India, stands as the epicentre of the country's information technology sector. The details of the sites along with the site description are shown in Table 1.

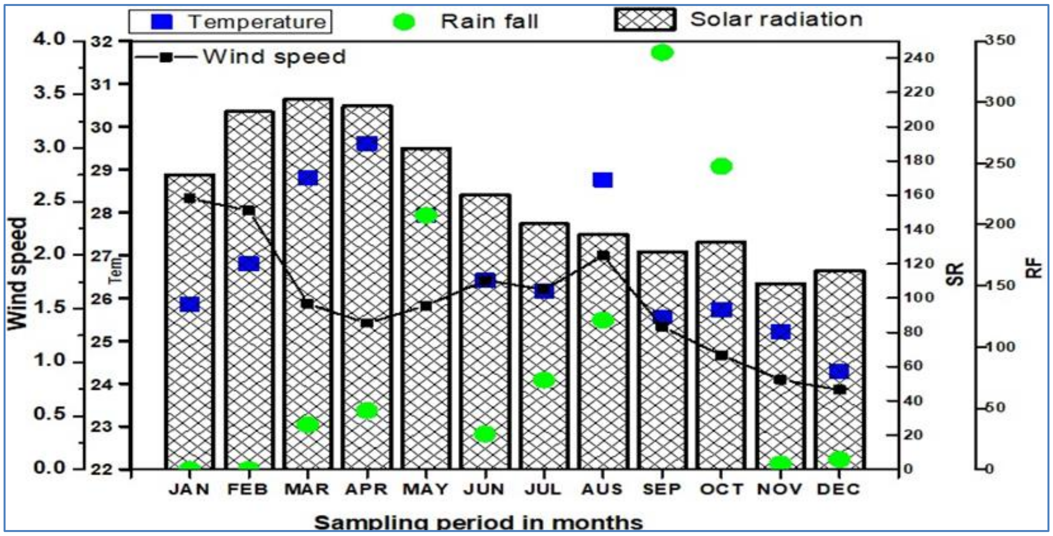

Fig. 2. Monthly mean values of the various meteorological parameters such as temperature (^{0}C), wind speed (m/s), solar radiation (W/m^2) and total monthly rainfall in mm during the study period over Bangalore.

The BC mass concentrations over Bangalore were measured by a real-time a portable micro-Aethalometer (model: AethLabs AE-51; San Francisco, CA, USA; https://aethlabs.com) during the study period (Chakrabarty *et al*., 2012; Tiwari *et al*., 2015). Details of the instrument (AethLabs AE-51), data correction schemes (loading and/or shadowing effects) and its analysis described in detail in earlier studies (Arnott *et al*., 2005; Cheng *et al*., 2014; Dumka *et al*., 2013; Tiwari *et al*., 2016; Gupta *et al*., 2022) were applied. In a recent study, Cheng *et al*. (2014) conducted a comparative measurement of two aethalometers (models AE-51 and AE-31) in different relative humidity (55% to 90%) was tested, and their results were recorded satisfactorily. 5 minutes interval on each site, the BC data were collected twice in a month. Selected sites were over the Bangalore (12º 58' N; 77º 34' E; 900 m above sea level) region.

The collected data of BC were separated into four major seasons such as monsoon (June-September), post-monsoon (October-November), winter (December-February) and summer (March-May) during the study periods. Meteorological parameters such as temperature (0 ºC), solar radiation (Wm^{-2}), wind speed (m/s) and rainfall (mm) were continuously monitored over Bangalore and their monthly average data are depicted in Fig. 2. The annual mean values of temperature (Temp.), solar radiation (SR) and wind speed (WS) were 26.8 ºC, 160.2 W/m^2 and 1.57 m/s, respectively; however, the annual rainfall was 1117 mm. The maximum rainfall was in September and there was no rainfall in the January and February months. In the case of temperature, there is no large variability in monthly temperature, with around 18% being the highest (April: 29.6 ºC) in comparison with the lower temperature (December: 24.3 ºC). Similarly, the temperature and wind speed had less variability with the highest during the winter months (>2 m/s), whereas, the rest of the months had a lower value (<2 m/s).

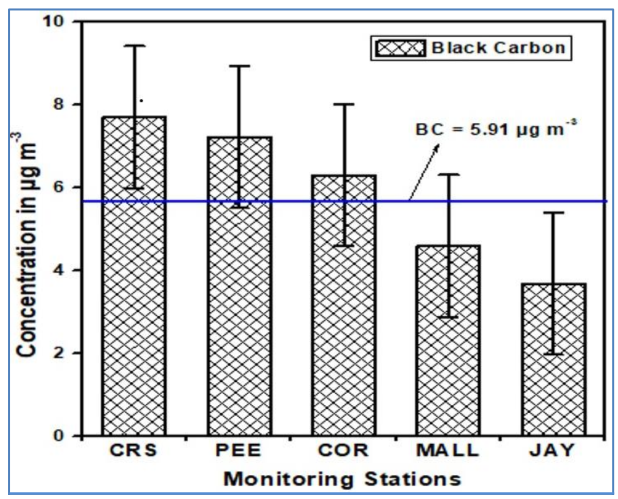

Fig. 3. Mean mass concentrations of black carbon over urban locations over Bengaluru City from Jan 2019 to Dec 2019.

3. Results and discussion

3.1. *Temporal distribution of Black Carbon*

Black carbon mass concentrations were measured at five different locations in Bangalore city from January 2019 to December 2019. The mean mass concentration of BC was 5.91 µg m^{-3}, whereas the higher mass concentration of BC was 7.71 µg m^{-3} over the city railway station and the lower (3.69 µg m^{-3}) was in Jayanagara (Fig. 3) site. The contribution of BC was higher in traffic locations which is approximately double that the

TABLE 2

The concentrations of black carbon over different part of India

Locations	BC Mass Concentrations	References
Delhi	6.7 μg m^{-3}	Tiwari *et al*., 2013
Agra	9.5 μg m^{-3}	Gupta *et al*., 2017
Kanpur	6.0 μg m^{-3}	Tripathi *et al*., 2005
Bhubaneswar	5.2 μg m^{-3}	Das *et al*., 2009
Brahmaputra River	6.91 μg m^{-3}	Chakrabarty *et al*., 2012
Pune	3.6 μg m^{-3}	Safai *et al*., 2014
Dhanbad	6.3 μg m^{-3}	Singh *et al*.,2015
Srinagar	6.00 μg m^{-3}	Bhata *et al*., 2017
Jodhpur,	5.76 μg m^{-3}	Sateesh *et al*., 2019
Ballia	4.0 μg m^{-3}	Tiwari *et al*., 2016
Anantpur	2.92 μg m^{-3}	Shaik *et al*., 2017
Kadapa	2.20 μg m^{-3}	Begam *et al*., 2016
Nainital	1.00 μg m^{-3}	Dumka *et al*., 2010
Hanley	0.07 μg m^{-3}	Babu *et al*., 2011

residential locations, that indicates a large fraction of soot particles are from anthropogenic activities. The concentrations of BC at all five locations were 7.71 μg m^{-3} City railway station. 7.23 μg m^{-3} (Peenya), 6.63 μg m^{-3} (Corporation circle), 4.60 μg m^{-3} (Malleshwaram) and 3.69 μg m^{-3} (Jayanagara). The soot particles were significantly higher (41%) at three locations (Peenya Ind Area, Corporation Circle and City Railway Station) than two locations (Malleshwaram and Jayanagara). These lower concentrations of BC at Malleshwaram and Jayanagara were residential zones due to the lower emission of BC. Apart from this BMS College of Engineering, Bengaluru monitored BC mass concentrations of a year-long in 2013-14 (Dhanya *et al*., 2014). The mean mass concentrations of BC was 2.58 μg m^{-3}, which is much lower than both locations (Malleshwaram and Jayanagara). The lower BC mass concentrations at BMS College were due to three reasons in 2017: (*i*) the impact of meteorological parameters on BC (*ii*) high-resolution continuous monitoring for a longer period compared to the random measurement of BC and (*iii*) the residential location over Bangalore city.

The concentration of BC over Bangalore has a similar behaved pattern in other parts of Indian urban cities like Delhi (6.7 ± 5.7 μg m^{-3}: Tiwari *et al*., 2013), Agra (9.5 μg m^{-3}: Gupta *et al*., 2017); Kanpur (6.0 μg m^{-3}: Tripathi *et al*., 2005); Bhuwaneswer (5.2 μg m^{-3}: Das *et al*., 2009); Brahmaputra River Valley (6.91 μg m^{-3}: Chakrabarty, *et al*., 2012); Kolkatta (5.8 μg m^{-3}: Chatterjee *et al*., 2012); a long term monitoring of BC at Pune (3.6 μg m^{-3}: Safai *et al*., 2014), Dhanbad (6.3 μg m^{-3}: Singh *et al*., 2015), at a high altitude urban site-Srinagar (6.00 μg m^{-3}: Bhata *et al*., 2017), Jodhpur, Rajasthan (5.76 μg m^{-3}: Sateesh *et al*., 2019), however, over peri-urban was lower than the other rural sites in India as at Ballia (4 μg m^{-3} Tiwari *et al*., 2016). In another study over Anantpur (a rural environment), a semi-arid station in southern India had very low mass concentrations (0.9 and 2.92 μg m^{-3}) of BC during January-December 2013 (Shaik *et al*., 2017). Similarly, lower concentrations of BC (2.20 μg m^{-3}) over Kadapa, a tropical semi-arid site in Andhra Pradesh, than in the peri-urban region were observed (Begam *et al*., 2016). However, the mean value of BC over Bangalore is significantly higher than the measured concentrations over mountain regions such as Hanley (0.07 ± 0.03 μg m^{-3}: Babu *et al*., 2011) and Nainital (1.00 ± 0.17 μg m^{-3}: Dumka *et al*., 2010) nearby in the Himalayas area (Table 2). The value of BC particles in the study region is significantly higher (many folds) than the urban locations in the USA, Europe and Asian countries (Dasari *et al*., 2020).

3.2. *Seasonal variation in atmospheric BC mass concentration*

The seasonal concentrations of BC have also exhibited a large variability, with the highest sequence in magnitude during the winter season (9 μg m^{-3}) followed by the summer (6.3 μg m^{-3}), post-monsoon (5.8 μg m^{-3})

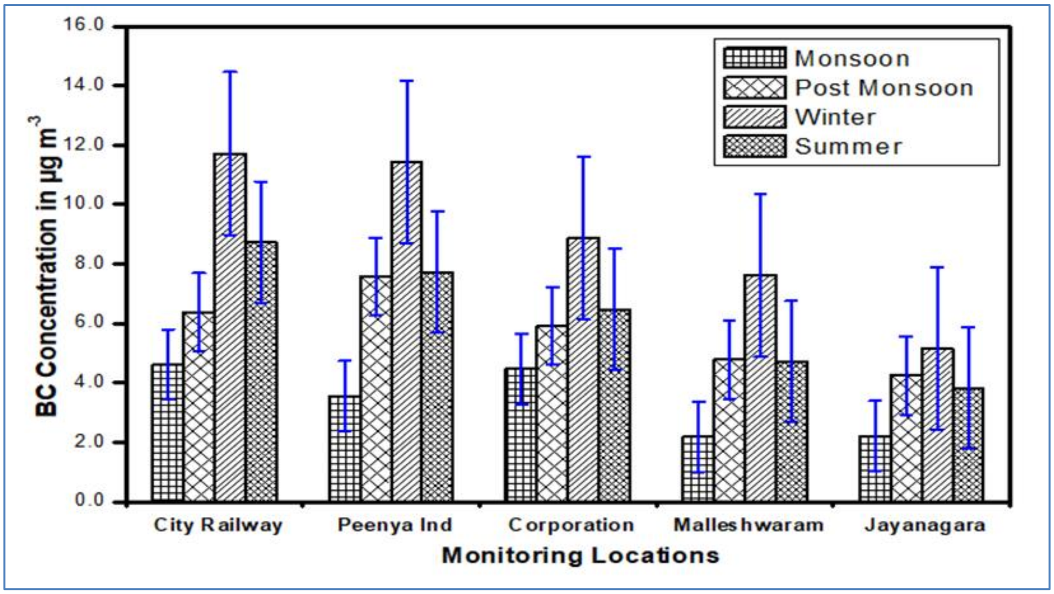

Fig. 4. Seasonal mean mass concentrations of black carbon (BC) over urban over Bangalore city from Jan 2019 to Dec 2019.

and monsoon (3.4 µg m^{-3}) seasons over the study area. It is well known that the highest BC during wintertime is due to the confinement of atmospheric aerosols within a shallow atmospheric boundary layer condition however, during the summer and post monsoon seasons, it is due to regional climatic conditions and solar radiation. The lower concentrations of BC (about 40% less than the annual mean) during the monsoon season (June-September) were as compared to the winter season, it is due to the impact of the scavenging effect as compared to a normal period. The scavenging process is an effective mechanism to remove atmospheric aerosols (Ohata *et al*., 2016). In India, more than 90% of the annual rainfall occurs in these months (Chatterjee, 2012).

The data on black carbon at BMS College of Engineering (urban site) in Bangalore, which was monitored under the Modelling Atmospheric Pollution and Networking (MAPAN) program of the Indian Institute of Tropical Meteorology, Pune was reported by Dhanya *et al*. (2014 : Fig. 4) and it was used to compare with the present study. Seasonal mass BC concentrations in 2019 were around 10% (monsoon), 44% (post-monsoon), 87% (winter) and 57% (summer) higher compared to 2013-14. Overall (annually), the mean concentrations of BC have increased by around 55% within five years over the urban region, which indicates the impact of man-made activities.

3.3. *Influence of Meteorological parameters*

Several earlier studies reported that the metrological parameters influence the local mass concentrations of BC (Safai *et al*., 2014; Tiwari *et al*., 2013; and references therein). In the present study, we also tried to investigate the impact of meteorological parameters on BC aerosol mass concentrations over Bengaluru.

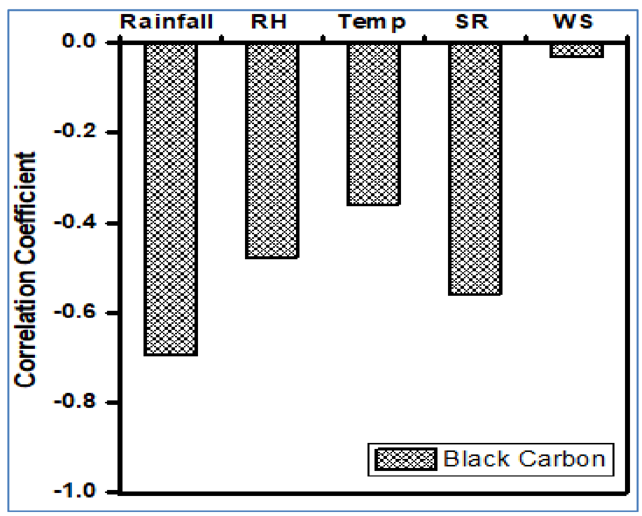

Fig. 5. Correlation Coefficient among Meteorological Parameters and BC over Bengaluru (Rainfall, RH -Relative Humidity, Temperature, SR-Solar Radiation, WS - Wind Speed).

Generally, meteorological parameters, especially wind speed, play a vital role in lowering the aerosol concentrations in the atmosphere. In view of the above importance, a Pearson correlation analysis between meteorological parameters and BC aerosols was conducted and depicted (Fig. 5). A significant impact of meteorological factors is seen on the mass concentrations of BC mass over the study area. Meteorological data, including rainfall (RF), temperature (Temp), relative humidity (RH), solar radiation (SR) and wind speed (WS) were used in the present study. The meteorological data were retrieved simultaneously monitored met data from the Central and State Pollution Control Boards across Bengaluru during the study period. The rainfall was significantly negatively correlated with BC (-0.70). Most of the RF occurred from June to September, which is called the southwest summer monsoon period in this region. In another study reported by Ramachandran and Rajesh (2007), a significant negative correlation between BC and rainfall was observed at Ahmedabad (-0.35) in western India. Also, Babu (2002) reported a highly negative relationship (-0.74) at Trivandrum. The results clearly indicated that the washout effect plays a crucial role in the removal of atmospheric pollutants from the lower atmosphere over the study region during rainy period.

The relationship between BC and temperature is explored, which shows a lower negative correlation between BC and temperature (-0.36). This suggests that mixing height, which is directly proportional to the temperature determines the volume through which surface-emitted pollutants can be diluted and reflect boundary layer turbulence. During the winter months the surface boundary layer above Bengaluru is shallow which causes pollution to be trapped close to the surface. During the summer as surface temperatures rise and convection activity increases pollutants are diffused as the boundary layer of the atmosphere deepens resulting in a decrease in BC concentrations.

A substantial negative correlation (-0.48) is seen between relative humidity and BC mass concentrations. The size of the moisture particles gradually increases with rising humidity to the point when "dry deposition" takes place lowering the atmospheric concentrations of aerosols.

The relationship between BC and solar radiation is explored which is significantly negatively correlated (-0.56) because BC can reduce atmospheric transparency and affect the total solar radiation reaching the ground by reflecting and absorbing solar radiation. The results clearly indicate that BC in the atmosphere is absorbing solar radiation energy. However, the Pearson correlation coefficient among wind speeds was poor with BC. Also, the negative and positive relationship among meteorological parameters and other pollutants indicates that meteorological parameters play a vital role in the accumulation and dispersion of atmospheric pollutants over the Bengaluru area.

4. Conclusions

The measurements of BC mass concentration over Bengaluru were made from January 2019 to December 2019. The mean mass concentration of BC was 5.91 µg m^{-3}, whereas the higher mass concentration of BC was 7.71 µg m^{-3} over the city railway station and the lower (3.69 µg m^{-3}) was in Jayanagara. The seasonal concentrations of BC have also exhibited a large variability, with the highest sequence in magnitude during the winter season (9 µg m^{-3}) followed by the summer (6.3 µg m^{-3}), post-monsoon (5.8 µg m^{-3}) and monsoon (3.4 µg m^{-3}) seasons over the study area. The lower concentrations of BC during the monsoon season were very low as compared to the winter season. Overall (annually) the mean concentrations of BC have increased by around 55% within five years over the urban region which indicates the impact of man-made activities. The BC was negatively significantly correlated with rainfall (-0.70), temperature (-0.36), relative humidity (-0.48) and solar radiation (-0.56). It clearly indicated that during rain the washout effect plays a crucial role in the removal of pollutants. However, during summer the pollutants are dispersed due to higher solar radiation and atmospheric temperatures. Being higher mass concentrations of BC over the Bangalore region, it is necessary to take necessary stringent action for its mitigation.

Declarations: All authors have read, understood, and have complied as applicable with the statement on "Ethical responsibilities of Authors.

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