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REVIEW

Atmospheric Carbonaceous Matter over South Asian Region: A Review of Variation in its Thermal, Optical and Molecular Properties During Last Two-Decades

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Linear growth of atmospheric particulate matter (PM) over south Asia is one of the significant problems affecting human health and climate change. In addition, these particulate matters have the potential to absorb and scatter solar radiation, causing a disturbance in the earth radiation budget resulting in this region facing several floods and droughts, excessive glacier melting, loss of a million lives, and many more in the last two decades. This context aim to provide a brief knowledge of $PM_{2.5}$ chemical composition and their optical properties. To assess, existing field studies conducted after the year 2000 were reviewed and summarized in terms of geographical, temporal and seasonal variation across the region. It is seen that $PM_{2.5}$ were significantly increased by 25.04% in the last two decades. Annual $PM_{2.5}$ was up to 10 times the prescribed limit set by world health organization (WHO) guidelines. Annual $PM_{2.5}$ was higher in the northern than southern cities, and more increased in Indo-Gangetic plains (IGP) than coastal and southern region (CASR) and high altitude (HA) regions. The highest seasonal variation occurred in the winter months. Organic carbon and elemental carbon contribute nearly 31% of the annual average $PM_{2.5}$ ranged from 14 to 70%. Higher variability in the percentage contribution of organic carbon and elemental carbon suggests different sources mainly influences this region. Biomass and fossil fuels, vehicular emission, and secondary aerosol are the major source factors in the inland region, while marine salt and soil dust are dominant fractions observed in a coastal area. Light absorbing brown carbon contributes significant amount in this region, and it's clearly seen by aerosol optical depth, varied from 0.04 to 1 in the entire region.

Keywords: Particulate Matter, Light absorbing aerosol, Molecular characterization, Optical properties, Aerosol.

INTRODUCTION

To address global and regional air quality and climate issues, an essential requirement is to understand spatiotemporal variations in chemical and optical properties of atmospheric particulate matter (PM) [1]. In the last two decades, aerosol concentration over south Asia has been highly concentrated caused by economic development, urbanization, energy consumption, transportation, and motorization [2]. An atmospheric PM affects air quality, visibility, human health and climate change [3]. Ambient PM levels are affected by meteorological parameters. Emissions from industries, forest fires, and various anthropogenic activities are the primary sources of ambient particulate matter. The significant component of PM includes metals, carbonaceous matter [organic carbon (OC), elemental carbon (EC)], sulfate, nitrates, ammonium and other ions [4]. Carbonaceous matters are usually a significant part of particulate matter and thus significantly contributes to climate change [5]. In South Asia, carbonaceous species contributed 40-70% to the ambient particulate matter [6]. Carbonaceous aerosol can also absorb and scatter solar radiation and remains the largest source of uncertainty in the radiative forcing of climate, and thereby it affects the abundance and distribution of atmospheric trace gases [7,8]. The atmospheric emergence of light-absorbing carbonaceous aerosols, collectively known as brown carbon (BrC) [9], is produced by slow-burning organic matter. Biomass burning and emissions of carbonaceous aerosol from the combustion of domestic biofuel can give stronger light absorption

[10-12]. Radiative effects and optical properties of atmospheric carbonaceous species can be determined by their physical properties. This assumption is prime to modelling how anthropogenic activities affect climate [13] was the first to make a model for carbon dioxide, after some years, models for greenhouse gases [14], sulphate aerosol [15,16], mineral dust [17] and carbonaceous aerosol [18,19] were also introduced. Thus, the present review addresses the current scenario of physical and optical properties of particulate matter over the South Asian region.

This review has been prepared by summarizing more than 110 research articles published during 2001-2020 in national and international journals (Tables 1 and 2). The articles were searched through the web of science, science direct, research gate, google scholar, and sci-hub using keywords atmospheric carbonaceous matter, ambient $PM_{2.5}$, PM_{10}, South Asia region, light absorbing aerosols, brown carbon chromophore, optical properties, thermal fractions of carbonaceous matter. Almost all articles showed measurements of carbonaceous matter in ambient $PM_{2.5}$ only. Conversion factor, for converting PM_{10} and associated carbon fraction to $PM_{2.5}$ fractions, is applied in findings of few locations of southern India where $PM_{2.5}$ and carbon data are unavailable. Conversion factor is used for converting PM_{10} to $PM_{2.5}$ (0.61), PM_{10} (OC) to $PM_{2.5}$ (OC) (0.67) and PM_{10} (EC) to $PM_{2.5}$ (EC) 0.68 for those articles that reported

TABLE-1
SUMMARY OF ANNUAL MASS CONCENTRATION OF $PM_{2.5}$, ORGANIC CARBON (OC) AND ELEMENTAL CARBON (EC) OVER SOUTH ASIA REGION

Location	Sampling period	Site	Size fraction	Mass (μg/m^3)	OC (μg/m^3)	EC (μg/m^3)	Ref.
Trivandrum, India	1998-2000	CASR	$PM_{2.5}$	43.00	–	–	[20]
Dhaka, Bangladesh	2000-2001	IGP	$PM_{2.5}$	38.95	–	12.70	[21]
Delhi, India	2001-2002	IGP	$PM_{2.5}$	138.42	51.77	10.30	[22]
Kolkata, India	2001-2002	IGP	$PM_{2.5}$	107.60	47.70	12.00	[22]
Chandigarh, India	2001-2002	IGP	$PM_{2.5}$	–	9.50	3.70	[22]
Mumbai, India	2001-2002	CASR	$PM_{2.5}$	55.67	21.00	5.83	[22]
Hyderabad, India	2003	CASR	$PM_{2.5}$	26.00	–	–	[23]
Kanpur, India	2002-2003	IGP	$PM_{2.5}$	100.67	–	–	[24]
Delhi, India	2003	IGP	$PM_{2.5}$	82.90	–	–	[25]
Delhi, India	2005	IGP	$PM_{2.5}$	98.70	–	–	[26]
Lahore, Pakistan	2005-2006	IGP	$PM_{2.5}$	167.00	–	–	[27]
Manora peak, India	2005-2006	HA	TSP	83.67	8.40	1.10	[28]
Mt. Abu, India	2005-2006	HA	TSP	64.42	3.55	0.45	[28]
Kolkata, India	2006	IGP	$PM_{2.5}$	71.20	12.20	5.80	[29]
Dhaka, Pakistan	2006	IGP	$PM_{2.5}$	66.20	–	–	[30]
Karachi, Pakistan	2006-2008	CASR	$PM_{2.5}$	83.53	–	–	[31]
Agra, India	2006-2008	IGP	$PM_{2.5}$	104.90	–	–	[32]
Lahore, Pakistan	2007-2008	IGP	$PM_{2.5}$	196.22	64.36	11.21	[33]
Islamabad, Pakistan	2007-2010	IGP	$PM_{2.5}$	75.22	–	–	[34]
Mt Abu India. India	2007	HA	$PM_{2.5}$	16.55	2.55	0.55	[35]
Delhi, India	2007	IGP	$PM_{2.5}$	97.00	–	–	[36]
Chennai* India	2007	CASR	$PM_{2.5}$	–	6.29	2.75	[37]
Mumbai, India	2008	CASR	$PM_{2.5}$	42.00	–	–	[38]
Kanpur* India	2007-2008	IGP	PM_{10}	–	33.52	13.33	[39]
Mumbai, India	2007-2008	CASR	$PM_{2.5}$	69.21	–	–	[40]
Jorhat, India	2007-2008	IGP	$PM_{2.5}$	21.50	–	–	[41]
Lucknow, India	2007-2009	IGP	$PM_{2.5}$	87.30	–	–	[42]
Agra, India	2007-2009	IGP	$PM_{2.5}$	116.00	–	–	[43]
Kanpur, India	2008-2009	IGP	$PM_{2.5}$	127.20	37.40	6.80	[44]
Chennai, India	2008-2009	CASR	$PM_{2.5}$	65.95	–	–	[45]
Durg*, India	2009-2010	CASR	PM_{10}	154.33	–	–	[46]
Agra, India	2009	IGP	TSP	216.30	25.40	3.30	[47]
Barapani, India	2009-2010	IGP	$PM_{2.5}$	152.10	–	–	[48]
Kolkata, India	2010-2011	IGP	$PM_{2.5}$	–	24.10	7.20	[49]
Agra, India	2010-2011	IGP	$PM_{2.5}$	165.42	69.96	9.53	[50]
Islamabad, Pakistan	2011	IGP	$PM_{2.5}$	66.10	–	–	[34]
Agra, India	2010-2011	IGP	$PM_{2.5}$	79.70	22.80	3.40	[51]
Delhi, India	2011	IGP	$PM_{2.5}$	122.70	–	–	[52]
Hyderabad, India	2011	CASR	$PM_{2.5}$	50.00	8.65	1.50	[53]
Delhi* India	2011	IGP	PM_{10}	121.35	14.95	5.90	[54]
Kolkata* India	2011	IGP	PM_{10}	102.89	9.09	5.32	[54]
Varanasi* India	2011	IGP	PM_{10}	123.70	11.17	5.87	[54]
Delhi. India	2011-2013	IGP	$PM_{2.5}$	117.6	37.5	7.05	[55]
Kangra, India	2012-2013	HA	$PM_{2.5}$	123.70	11.17	5.88	[35]
Bhubneshwar, India	2012-2013	CASR	$PM_{2.5}$	60.72	11.16	6.00	[56]

Lucknow, India	2013-2014	IGP	$PM_{2.5}$	77.30	–	–	[57]
Kolkata, India	2013-2014	IGP	$PM_{2.5}$	313.00	–	–	[58]
Delhi, India	2013-2016	IGP	$PM_{2.5}$	131.00	15.70	7.31	[59]
Varanasi, India	2013-2014	IGP	$PM_{2.5}$	81.78	–	–	[60]
Guwahati, India	2013-2014	CASR	$PM_{2.5}$	52.40	–	–	[61]
Delhi, India	2013-2014	IGP	$PM_{2.5}$	125.50	17.70	10.30	[62]
Delhi, India	2013-2014	IGP	$PM_{2.5}$	335.00	–	–	[63]
Dehradun, India	2014-2015	HA	$PM_{2.5}$	51.00	–	–	[64]
Delhi, India	2014-2015	IGP	$PM_{2.5}$	133.27	–	–	[65]
Patna, India	2015	IGP	$PM_{2.5}$	52.78	–	–	[66]
Dhaka, Bangladesh	2013-2018	IGP	$PM_{2.5}$	86.10	–	–	[67]
Jammu, India	2015-2017	IGP	$PM_{2.5}$	66.70	–	–	[68]
Agra, India	2015-2017	IGP	$PM_{2.5}$	91.00	–	–	[69]
Raipur, India	2015-2016	CASR	$PM_{2.5}$	133.00	36.39	15.45	[70]
Pune, India	2016	CASR	$PM_{2.5}$	–	9.71	3.11	[71]
Delhi, India	2016-2017	IGP	$PM_{2.5}$	113.89	–	–	[72]
Delhi, India	2016-2017	IGP	$PM_{2.5}$	130.60	25.60	19.56	[73]
Delhi, India	2016-2017	IGP	$PM_{2.5}$	137.69	–	–	[65]
Delhi, India	2017	IGP	$PM_{2.5}$	187.50	–	–	[74]
Guwahati, India	2017-2018	HA	$PM_{2.5}$	102.00	–	–	[75]
Islamabad, Pakistan	2017	IGP	$PM_{2.5}$	51.59	–	–	[76]
Mumbai* India	2018	CASR	PM_{10}	114.42	13.17	3.33	[77]
Karachi, Pakistan	2015-2017	CASR	$PM_{2.5}$	234.60	24.55	5.80	[78]
Garhwal, India	2017	HA	$PM_{2.5}$	76.07	15.28	5.20	[79]
Darjeeling, India	2018-2019	HA	$PM_{2.5}$	37	3.56	1.93	[80]

*A conversion factor is used for converting PM_{10} to $PM_{2.5}$ (0.61), PM_{10} (OC) to $PM_{2.5}$ (OC) (0.66) and PM_{10} (EC) to $PM_{2.5}$ (EC) 0.68 for those article that reported values for PM_{10} masses. HA = high altitude, IGP = Indo-Gangetic plains, CASR = Coastal and southern region.

TABLE-2
CONVERSION FACTOR TABLE*

$PM_{2.5}$	PM_{10}	$PM_{2.5}$		PM_{10}		Ratio			Ref.
		OC	EC	OC	EC	$PM_{2.5}/PM_{10}$	OC of $PM_{2.5}/PM_{10}$	EC of $PM_{2.5}/PM_{10}$	
81.2	156.46	8.60	2.55	11.60	4.01	0.52	0.74	0.64	[81]
50.00	69.00	8.65	1.50	14.05	2.12	0.72	0.62	0.71	[82]
133.35	260.40	25.6	19.56	45.64	31.76	0.51	0.56	0.62	[73]
162.50	242.50	45.8	8.20	60.30	10.60	0.67	0.76	0.77	[44]
					Mean	0.61	0.67	0.68	

*The reported values in terms of PM_{10} masses and associated OC, EC were converted to corresponding $PM_{2.5}$, OC, EC using pre-determined conversion factors. A conversion factor is used for converting PM_{10} to $PM_{2.5}$ (0.6), PM_{10} (OC) to $PM_{2.5}$ (OC) - (0.66) and PM_{10} (EC) to $PM_{2.5}$ (EC)-0.68 for those article that reported values for PM_{10} masses. Conversion factor is determined using earlier reported values of $PM_{2.5}$, PM_{10} and associated OC and EC values in the studies conducted in India and China [44,73,81,82].

concentrations of mass and carbon fractions for PM_{10} only. Conversion factors are determined using earlier reported values of $PM_{2.5}$, PM_{10} and associated OC and EC values [73,82,83].

Spatio-temporal variation pattern of $PM_{2.5}$ mass: Fig. 1 shows the temporal variations of $PM_{2.5}$ for the biggest south Asian countries (India, Pakistan and Bangladesh) from the year 2000-2020. Most of the studies have been carried out in the North region associated with the Indo-Gangetic plain (IGP), and very few studies have been conducted in the Coastal and Southern region (CASR), and as well as in high altitude (HA) region. To evaluate the South Asian region's temporal variation pattern, a year-long measurement has been used in the present review. $PM_{2.5}$ levels have been increased by 25.04% in the last two decades. According to a monitoring database among all the major cities in South Asian countries *e.g.* Delhi, Agra, Kanpur and Lahore have shown higher $PM_{2.5}$ levels throughout the year. During these last 20 years, the highest annual mean data of $PM_{2.5}$ was found in Delhi (335 μg m^{-3}) [63]. The lowest annual mean data for $PM_{2.5}$ was found 43 μg.m^{-3} at Trivandrum [20], respectively. WHO [84] suggested that Delhi, Mumbai, and Dhaka were the most polluted cities in the world, while

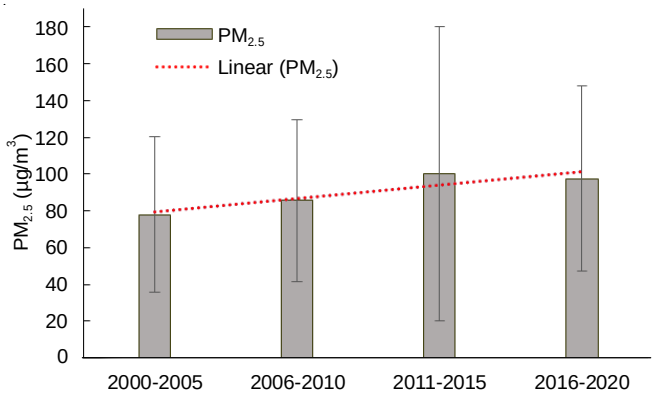

Fig. 1. Temporal variation of $PM_{2.5}$ from year 2000-2020 with filter-based measurement in south Asia region

Delhi ranked first in terms of the highest concentration of PM_{10} level between 2011-2015, which is more than 10 times higher than the limit set by WHO 2016 [84] (annual mean value of 20 μg m^{-3} (for PM_{10}) and 10 μg m^{-3} (for $PM_{2.5}$). A higher concentration of particulate matter over Delhi might be due to middle IGP region, where most of the time particulate matter is highly concentrated [85]. Particulate matter was highly concentrated over India (range 56-277 μg m^{-3}) as compared to other Asian countries, *viz*. Pakistan (66-107 μg m^{-3}) and Bangladesh (61-106 μg m^{-3}) [84]. The elevated $PM_{2.5}$ loading over these countries due to acceleration of industrialization and urbanization. Relatively lower $PM_{2.5}$ concentrations were reported by Afghanistan (68-86 μg m^{-3}), Bhutan (13-29 μg m^{-3}), Nepal (25-59 μg m^{-3}), Maldives (13-19 μg m^{-3}) and Sri Lanka (23-36 μg m^{-3}), which have been shown lesser anthropogenic emissions due to comparatively less industrialization and urbanization [86].

Spatio-temporal variation of $PM_{2.5}$ and its major component (OC and EC): Similar trends in OC and EC were observed, like PM, where the Northern region of south Asia has shown significantly higher atmospheric carbon fraction concentrations compared to those reported for southern region. In this section, carbonaceous species (OC and EC) with respect to the $PM_{2.5}$ study have been chosen according to a geographical location such as IGP, CASR and high altitude. Fig. 2 shows the geographical distribution of OC and EC in these three different regions of the south Asia. Both OC and EC have showed increasing trend in all three IGP, CASR and high altitude regions of south Asia during the period of 2000-2020, with OC increased by 20%, 25% and 113%, respectively. While 12.5%, 5% and 7-fold increase in EC was also observed in IGP, CASR and high altitude regions, respectively, during the same period. Higher variability have been seen in OC and EC over the south Asia region suggested different sources, which were influenced by region activities. During a study of 2001-2002, primary emissions from fossil fuels contribute 25-33% to $PM_{2.5}$ in Delhi, 21-36% in Mumbai, 37-57% in Kolkata, while emissions from biomass combustion contribute 7-20% for Delhi and Mumbai, and 13-18% for Kolkata [87]. In upper IGP region such as Delhi, total carbonaceous aerosol (TCA) shares 28% and 19% during summer and winter, reflecting fossil fuels and biomass burning contributed large fraction to ambient PM [88]. Positive matrix factorization (PMF), a tool to identify source, resolved that secondary organic aerosols, biomass burning and fossil fuel contributing more than 50% to $PM_{2.5}$ [54]. Another studies from Kolkata (located at lower IGP) reported that OC and EC contribute to 27% and 25% of total $PM_{2.5}$, respectively, emitted from burning biomass and fossil fuels [89]. A higher value was obtained at Lahore, where carbonaceous aerosol accounts for 37% of $PM_{2.5}$ [33], where the findings also revealed that the carbonaceous aerosol was not a dominant fraction in coarse particles. A similar value was also noted by Ram & Sarin [44] where carbonaceous aerosol contributes 34% to fine particles during the same study period of 2007-2008. Previous studies [54,90] have found that OC primarily derives from biomass burning emissions, which are the largest contributor to ambient fine particulate matter in south Asia. These type of emission mainly comes from burning of crop waste, fuel made up of cow dung, raw wood, a mixture of solid and liquid waste dumped by a municipal corporation, In south Asia, 70-80% people

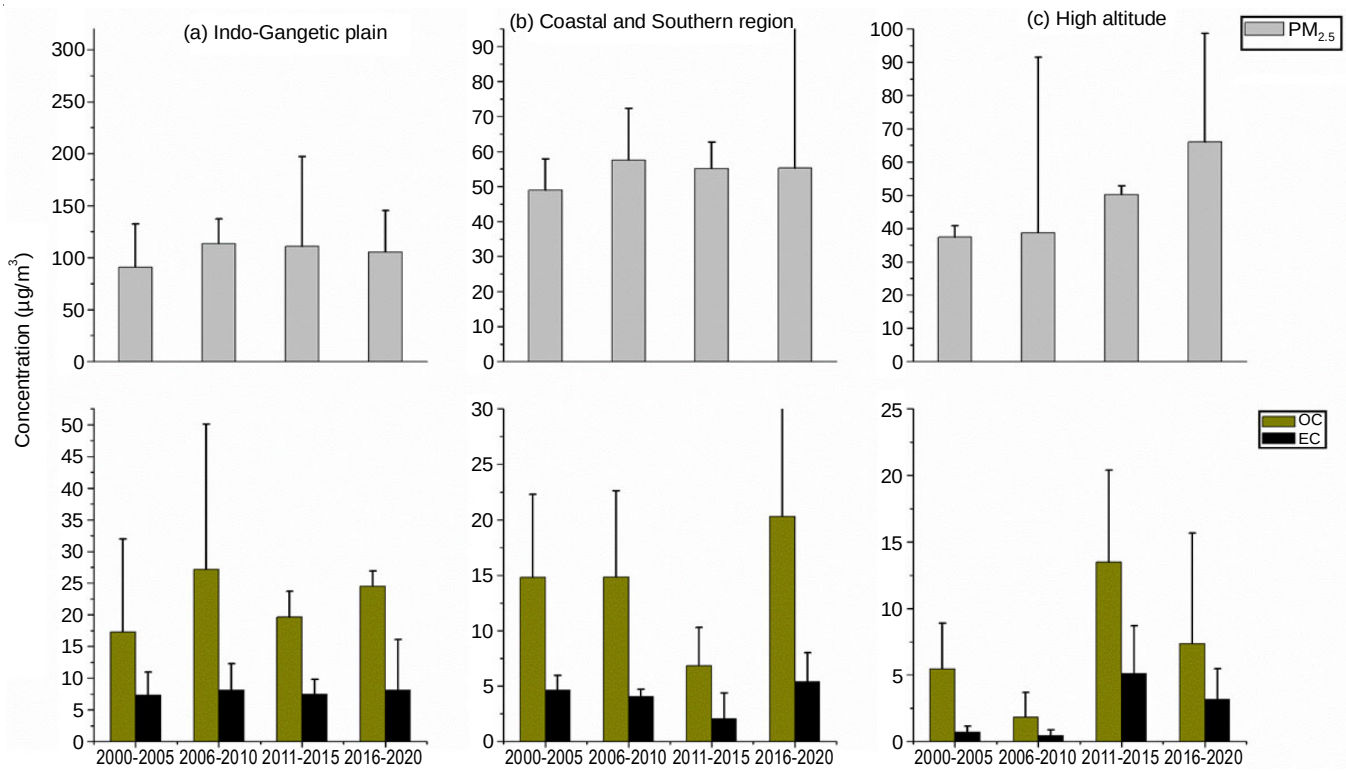

Fig. 2. Inter-annual variation in $PM_{2.5}$ and its dominant component (OC and EC) in (a) Indo-Gangetic plain (b) peninsular plain and (c) high altitude region

living on rural areas use cow dung, fuelwood, charcoal, and crop waste to meet their energy required to support their lifestyle [86]. Around, more than 60% population from Bangladesh, Srilanka, India and Pakistan [91-93] depends on biomass fuels for their primary energy. These fuels can emit a large number of organic and inorganic gases and particulate matter to ambient air.

Optical properties of $PM_{2.5}$ carbonaceous matter: Optical properties include absorption coefficient (b_{abs}), scattering coefficient (b_{sp}), mass absorption efficiency (MAE), aerosol optical depth (AOD) and angstrom exponent (AE), it has the ability to provide qualitative data on particle size. The preponderance of fine particles is represented by higher AE values, whereas the dominance of coarse particles is represented by lower AE values [94]. The inverse of the mega metre (M m^{-1}) unit is used to measure absorption and scattering coefficients, although AOD, AAE, and SSA are unitless quantities. Only a few optical property studies have been carried out in India.

In south Asia, comparatively, very few studies have been carried out on aerosol optical properties than chemically resolved $PM_{2.5}$ data. The relationship between optical properties and $PM_{2.5}$ mass concentration is influenced by various variables, including refractive index, aerosol size distribution, climatic conditions, and single-scattering albedo. MODerate-resolution Imaging Spectroradiometer (MODIS) data is mainly used to calculate aerosol optical depth (AOD), the total light extinction coefficient exhibited by aerosol within a vertical column, and it may be high when PM concentrations increase [95]. This section discusses the spatio-temporal pattern of aerosol optical characteristics such as b_{sp}, b_{ap}, MAE, AE, SSA and AOD measured in south Asia. The AOD varied from 0.1 to 1.2 with the maximum in IGP, followed by CASR and HA regions. Among the reported locations of IGP region, central IGP has shown highest AOD value due to the associated highest aerosol mass loading over this location of IGP [54,74]. In winter, extensive local sources of fine-mode aerosols (anthropogenic origin) predominate, while coarse-mode absorbing aerosol flown from the upper IGP is responsible for high AOD during the summer [96,97]. A long-term study also suggests that upper IGP aerosol mass loaded with coarser particles while central and lower IGP exhibit by the dominance of fine and mixed particles and observed growth of AOD 0.002/year statistically during 2006-2015 [98]. A comprehensive study on measurement of AOD was conducted during 2009-2017 in various locations of IGP region. Upper IGP locations showed significantly lower values of AOD compared to those reported for central and lower IGP with higher trend in wintertime measurements in central and lower IGP locations (Kanpur and Dhaka). While, monsoon season AOD values are reported to be higher in upper IGP locations. This might be due to the impact of southwest Monsoon, causes an aerosol mass force to shift towards upper IGP locations [99].

In CASR, mean AOD varied from 0.39-0.70, with maximum observed at Vizag and lowest at Goa [93,100]. The higher spatial variability of AOD at Vizag is due to the continental outflow from the Bay of Bengal containing complex aerosol mass of different sizes and species spread over near and far eastern coastal regions. In Goa, a lower mean value of AOD is responsible for extreme rainfall during monsoon and nearly a flat line spectra observed during June-September months. Alam *et al*. [101] studied aerosol optical properties over Karachi a northwestern coastal region of south Asia and found AOD varied from 0.31-0.92 with an annual mean of 0.48 ± 0.18 and found a similar Angstrom exponent 0.49 ± 0.31, these value of exponent less than 1 indicates a dominance of coarser particles. In tropical urban site, southern part of south Asia during 2007-2008, a high variability observed for AOD and exponent value in post-monsoon, pre-monsoon and winter season, higher value of AOD and AE in winter seasons suggests increases in anthropogenic emissions [102]. A long term study conducted during 2008-2018 at a rural site (Gadanki) of CASR region observed positive trends in AOD and AE value and concluded that the site exhibited a strong spectral and seasonal dependence, indicating the presence of different natural and anthropogenic activity. Fewer studies have been conducted in HA regions to date, with the majority of investigations were reported for locations of foothills of Himalayan HA regions [103]. The absorption coefficients for HA locations were varied from 5.84-18 Mm^{-1} [104,105,107,109]. The lower value of absorption coefficient at this site may be due to the thar desert, where coarser particles are likely to be the dominant fraction [104,105]. The AE greater than one was observed in the Manora peak 1.13 [106] and 1.12 [107] comparing these AE values to other Himalayan sites such as Lhasa and the average AE over these sites are 0.48 [108], suggesting that there is a dominance of fine particles of aerosol over Manora peak (located at central Himalayan region). Manoharan *et al*. [109] observed 18 M m^{-1} in Nainital close to Manora peak. The previous study also reported that the AOD over the Manora peak dominated other Himalayan peaks. The lowest value of AOD (0.04) was observed at Hanle [110], while the highest value (0.16) was found in Manora peak, respectively [111]. A higher value of AOD at the Manora peak is associated with this site near the central Indo-Gangetic plain, where highly concentrated PM levels are found throughout the year. Positive trends in an annual mean of AOD was found in 56% of regions of south Asia [112]. Such increasing trends may be attributed to increased sub-micron particles generated by biomass burning [113].

Molecular study of organic aerosol (OA): Light-absorbing organic aerosols (LAOA), optically defined as brown carbon (BrC) are known to absorb solar and terrestrial radiation efficiently, and therefore have the ultimate impact on climate forcing [114]. However, quantitative predictions of BrC contribution to the overall light absorption are still challenging because of the chemical complexity and source diversity of BrC [115].

Among numerous BrC chromophores, nitrated aromatic compounds (NACs) have been observed as the most abundant BrC chromophores in ambient aerosol with strongest absorption [116] and in cloud, water impacted by biomass burning in eastern China [117]. It has been proposed that methyl nitrocatechols are formed by photooxidation of *m*-cresol emitted from wood combustion and could be used as tracers for secondary organic aerosol (SOA) formed by secondary photo-

oxidation of primary biomass burning emissions [118]. During biomass burning, substituted phenols such as alkyl phenols and methoxy phenols are produced from the pyrolysis of lignin [119], which is the second most abundant component of plant material after cellulose [120], these phenols are suggested to yield nitrophenols through reactions with atmospheric radicals such as OH, NO_2, NO_3, *etc*. [121]. A source study conducted in Haryana shows that BrC chromophores emitted from burning dung cake and brushwood are largely $C_xH_yO_z$ compounds [122]. Polycyclic aromatic compounds (PAHs) and methoxy phenols (MOPs) are also the strongest light absorbing BrC chromophores in ambient air. Yuan *et al*. [123] measured the light absorption contribution of methanol soluble PAHs, NACs and MOPs at 356 nm and found that fluoranthene (FLU), benzo(a)-pyrene (BaP), benzo(ghi)perylene (BghiP), 4-nitro-1-naphthol (4N1N), 4-nitrocatechol (4NC), vanillin (VAN) and 3-methyl-4-nitrophenol (3M4NP) are the major contributors to ambient air of Xian province, Northwest China.

Conclusion

Particulate distributions and their dominant components over the entire south Asia are largely heterogeneous and uncertain with variation mostly driven by seasonality, geographical region, and socio-economic conditions. Limited study of particulate matter are available for Bangladesh, Srilanka and Nepal. During winter and the post-monsoon, >80% of the Indian subcontinent shows increasing trends in particulate matter levels, which could be due to the increase in biomass burning emissions and shallow boundary layer heights during the winter. Trends in pre-monsoon and monsoon show decreasing trends in the northern part of south Asia, and over most of the land regions during the monsoon, this could be the result of precipitation in the northern part of South Asia. Higher OC/EC ratio found in HA over this region compared to IGP and CASR suggesting a huge amount of biomass used in this region. Study of optical properties of aerosol in the entire region are fewer. A lower value of AE was observed over the Thar desert and dust-dominated areas of western India and Pakistan. While > 1 value of AE was observed over central, north and some parts of southern and eastern India, suggesting a high proportion of sub-micron aerosols over the regions. No information is available for the composition of Light absorbing organic aerosol or brown carbon (BrC) over this region Therefore, in this region, a study is needed that characterizes molecular composition of light absorbing aerosol and its impact on earth radiation budget.

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CONFLICT OF INTEREST

The authors declare that there is no conflict of interests regarding the publication of this article.

REFERENCES

1. J. Tao, L. Zhang, J. Cao and R. Zhang, *Atmos. Chem. Phys.*, **17**, 9485 (2017); https://doi.org/10.5194/acp-17-9485-2017
2. A.K. Gorai, P.B. Tchounwou, S.S. Biswal and F. Tuluri, *Environ. Health Insights*, **12**, (2018); https://doi.org/10.1177/1178630218792861
3. A. Farah, P. Villani, C. Rose, S. Conil, L. Langrene, P. Laj and K. Sellegri, *Atmosphere*, **11**, 172 (2020); https://doi.org/10.3390/atmos11020172
4. K. Adams, D.S. Greenbaum, R. Shaikh, A.M. van Erp and A.G. Russell, *J. Air Waste Manag. Assoc.*, **65**, 544 (2015); https://doi.org/10.1080/10962247.2014.1001884
5. G. Engling and A. Gelencsér, *Elements*, **6**, 223 (2010); https://doi.org/10.2113/gselements.6.4.223
6. M. Kanakidou, J.H. Seinfeld, S.N. Pandis, I. Barnes, F.J. Dentener, M.C. Facchini, R. Van Dingenen, B. Ervens, A. Nenes, C.J. Nielsen, E. Swietlicki, J.P. Putaud, Y. Balkanski, S. Fuzzi, J. Horth, G.K. Moortgat, R. Winterhalter, C.E.L. Myhre, K. Tsigaridis, E. Vignati, E.G. Stephanou and J. Wilson, *Atmos. Chem. Phys.*, **5**, 1053 (2005); https://doi.org/10.5194/acp-5-1053-2005
7. P.J. Crutzen and M.O. Andreae, *Science*, **276**, 1052 (1997); https://doi.org/10.1126/science.276.5315.1052
8. J. Haywood and O. Boucher, *Rev. Geophys.*, **38**, 513 (2000); https://doi.org/10.1029/1999RG000078
9. J.P. Haynes, K.E. Miller and B.J. Majestic, *Environ. Sci. Technol.*, **53**, 682 (2019); https://doi.org/10.1021/acs.est.8b05704
10. Y. Chen and T.C. Bond, *Atmos. Chem. Phys.*, **10**, 1773 (2010); https://doi.org/10.5194/acp-10-1773-2010
11. A. Hecobian, X. Zhang, M. Zheng, N. Frank, E.S. Edgerton and R.J. Weber, *Atmos. Chem. Phys.*, **10**, 5965 (2010); https://doi.org/10.5194/acp-10-5965-2010
12. T.W. Kirchstetter, T. Novakov and P.V. Hobbs, *J. Geophys. Res. D Atmospheres*, **109(D21)**, 1 (2004); https://doi.org/10.1029/2004JD004999
13. J. Hansen, D. Johnson, A. Lacis, S. Lebedeff, P. Lee, D. Rind and G. Russell, *Science*, **213**, 957 (1981); https://doi.org/10.1126/science.213.4511.957
14. V. Ramanathan, R.J. Cicerone, H.B. Singh and J.T. Kiehl, *J. Geophys. Res.*, **90(D3)**, 5547 (1985); https://doi.org/10.1029/JD090iD03p05547
15. R.J. Charlson, J. Langner, H. Rodhe, C.B. Leovy and S.G. Warren, *Tellus B Chem. Phys. Meterol.*, **43**, 152 (1991); https://doi.org/10.3402/tellusb.v43i4.15404
16. J.T. Kiehl and B.P. Briegleb, *Science*, **260**, 311 (1993); https://doi.org/10.1126/science.260.5106.311
17. I. Tegen and A.A. Lacis, *J. Geophys. Res. D Atmospheres*, **101(D14)**, 19237 (1996); https://doi.org/10.1029/95JD03610
18. J.E. Penner, C.C. Chuang and K. Grant, *Clim. Dyn.*, **14**, 839 (1998); https://doi.org/10.1007/s003820050259
19. J.M. Haywood and K.P. Shine, *Geophys. Res. Lett.*, **22**, 603 (1995); https://doi.org/10.1029/95GL00075
20. P.S. Pillai, S. Suresh Babu and K. Krishna Moorthy, *Atmos. Res.*, **61**, 149 (2002); https://doi.org/10.1016/S0169-8095(01)00136-3
21. S.K. Biswas, B.A. Begum, S.A. Tarafdar and A. Islam, Characterization of Air Pollution at Urban Sites at Dhaka and Rajshahi in Bangladesh. Atomic Energy Centre, Dhaka, Bangladesh, pp. 1-20, May (2016).
22. M.Z. Chowdhury, Ph.D. Thesis, Characterization of Fine Particle Air Pollution in the Indian Subcontinent, Georgia Institute of Technology, Atlanta, USA (2004).
23. K.M. Latha and K.V.S. Badarinath, *Int. J. Environ. Health Res.*, **15**, 63 (2005); https://doi.org/10.1080/09603120400018964
24. M. Sharma and S. Maloo, *Atmos. Environ.*, **39**, 6015 (2005); https://doi.org/10.1016/j.atmosenv.2005.04.041
25. N. Kumar, A. Chu and A. Foster, *Atmos. Environ.*, **41**, 4492 (2007); https://doi.org/10.1016/j.atmosenv.2007.01.046
26. S. Tiwari, M.K. Srivastava and D.S. Bisht, *e-J. Earth Science India*, **1**, 72 (2008).

27. A. Lodhi, B. Ghauri, M.R. Khan, S. Rahman and S. Shafique, *J. Braz. Chem. Soc.*, **20**, 1811 (2009); https://doi.org/10.1590/S0103-50532009001000007
28. K. Ram, M.M. Sarin and P. Hegde, *Atmos. Environ.*, **42**, 6785 (2008); https://doi.org/10.1016/j.atmosenv.2008.05.031
29. A. Chatterjee, C. Dutta, T.K. Jana and S. Sen, *J. Atmos. Chem.*, **69**, 83 (2012); https://doi.org/10.1007/s10874-012-9231-8
30. A. Salam, T. Hossain, M.N.A. Siddique and A.M.S. Alam, *Air Qual. Atmos. Health*, **1**, 101 (2008); https://doi.org/10.1007/s11869-008-0017-8
31. M. Mansha, B. Ghauri, S. Rahman and A. Amman, *Sci. Total Environ.*, **425**, 176 (2012); https://doi.org/10.1016/j.scitotenv.2011.10.056
32. A. Kulshrestha, P.G. Satsangi, J. Masih and A. Taneja, *Sci. Total Environ.*, **407**, 6196 (2009); https://doi.org/10.1016/j.scitotenv.2009.08.050
33. E. Stone, J. Schauer, T.A. Quraishi and A. Mahmood, *Atmos. Environ.*, **44**, 1062 (2010); https://doi.org/10.1016/j.atmosenv.2009.12.015
34. A. Rasheed, V.P. Aneja, A. Aiyyer and U. Rafique, *Aerosol Air Qual. Res.*, **15**, 426 (2015); https://doi.org/10.4209/aaqr.2014.10.0269
35. A. Kumar, K. Ram and N. Ojha, *Atmos. Environ.*, **125**, 371 (2016); https://doi.org/10.1016/j.atmosenv.2015.07.039
36. S. Tiwari, A.K. Srivastava, D.S. Bisht, T. Bano, S. Singh, S. Behura, M.K. Srivastava, D.M. Chate and B. Padmanabhamurty, *J. Atmos. Chem.*, **62**, 193 (2009); https://doi.org/10.1007/s10874-010-9148-z
37. C.M. Pavuluri, K. Kawamura, S.G. Aggarwal and T. Swaminathan, *Atmos. Chem. Phys.*, **11**, 8215 (2011); https://doi.org/10.5194/acp-11-8215-2011
38. P. Kothai, I.V. Saradhi, G.G. Pandit, A. Markwitz and V.D. Puranik, *Aerosol Air Qual. Res.*, **11**, 560 (2011); https://doi.org/10.4209/aaqr.2011.02.0017
39. S.N. Behera and M. Sharma, *Environ. Sci. Pollut. Res. Int.*, **22**, 13464 (2015); https://doi.org/10.1007/s11356-015-4603-7
40. E.J. Abba, S. Unnikrishnan, R. Kumar, B. Yeole and Z. Chowdhury, *Int. J. Environ. Health Res.*, **22**, 134 (2012); https://doi.org/10.1080/09603123.2011.613112
41. P. Khare and B.P. Baruah, *Atmos. Res.*, **98**, 148 (2010); https://doi.org/10.1016/j.atmosres.2010.07.001
42. P. Pandey, D.K. Patel, A.H. Khan, S.C. Barman, R.C. Murthy and G.C. Kisku, *J. Environ. Sci. Health Part A Tox. Hazard. Subst. Environ. Eng.*, **48**, 730 (2013); https://doi.org/10.1080/10934529.2013.744613
43. D. Massey, A. Kulshrestha, J. Masih and A. Taneja, *Build. Environ.*, **47**, 223 (2012); https://doi.org/10.1016/j.buildenv.2011.07.018
44. K. Ram and M.M. Sarin, *Atmos. Environ.*, **45**, 460 (2011); https://doi.org/10.1016/j.atmosenv.2010.09.055
45. B. Srimuruganandam and S.M. Shiva Nagendra, *Sci. Total Environ.*, **433**, 8 (2012); https://doi.org/10.1016/j.scitotenv.2012.05.082
46. D.K. Deshmukh, M.K. Deb, D. Verma, S.K. Verma and J. Nirmalkar, *Bull. Environ. Contam. Toxicol.*, **89**, 1098 (2012); https://doi.org/10.1007/s00128-012-0834-1
47. A. Satsangi, T. Pachauri, V. Singla, A. Lakhani and K.M. Kumari, *Atmos. Res.*, **113**, 13 (2012); https://doi.org/10.1016/j.atmosres.2012.04.012
48. P. Rajput, M. Sarin and S.S. Kundu, *Atmos. Pollut. Res.*, **4**, 214 (2013); https://doi.org/10.5094/APR.2013.022
49. B. Priyadharshini, S. Verma, A. Chatterjee, S.K. Sharma and T.K. Mandal, *Aerosol Air Qual. Res.*, **19**, 129 (2019); https://doi.org/10.4209/aaqr.2017.12.0606
50. A.S. Pipal, R. Jan, P.G. Satsangi, S. Tiwari and A. Taneja, *Aerosol Air Qual. Res.*, **14**, 1685 (2014); https://doi.org/10.4209/aaqr.2014.01.0017
51. T. Pachauri, A. Satsangi, V. Singla, A. Lakhani and K.M. Kumari, *Aerosol Air Qual. Res.*, **13**, 977 (2013); https://doi.org/10.4209/aaqr.2012.10.0263
52. S. Tiwari, A.K. Srivastava, D.S. Bisht, P.D. Safai and P. Parmita, *Nat. Hazards*, **65**, 1745 (2013); https://doi.org/10.1007/s11069-012-0449-1
53. D.S. Bisht, A.K. Srivastava, A.S. Pipal, M.K. Srivastava, A.K. Pandey, S. Tiwari and G. Pandithurai, *Environ. Sci. Pollut. Res. Int.*, **22**, 5293 (2015); https://doi.org/10.1007/s11356-014-3836-1
54. S.K. Sharma, T.K. Mandal, S. Jain, Saraswati, A. Sharma and M. Saxena, *Bull. Environ. Contam. Toxicol.*, **97**, 286 (2016); https://doi.org/10.1007/s00128-016-1836-1
55. S. Tiwari, A.S. Pipal, P.K. Hopke, D.S. Bisht, A.K. Srivastava, S. Tiwari, P.N. Saxena, A.H. Khan and S. Pervez, *Environ. Sci. Pollut. Res. Int.*, **22**, 10744 (2015); https://doi.org/10.1007/s11356-015-4272-6
56. S. Panda, S.K. Sharma, P.S. Mahapatra, U. Panda, S. Rath, M. Mahapatra, T.K. Mandal and T. Das, *Nat. Hazards*, **80**, 1709 (2016); https://doi.org/10.1007/s11069-015-2049-3
57. A.K. Verma, A. Saxena, G. Gaur and A.H. Khan, *J. Environ. Res. Dev.*, **11**, 272 (2016).
58. R. Das, B. Khezri, B. Srivastava, S. Datta, P.K. Sikdar, R.D. Webster and X. Wang, *Atmos. Pollut. Res.*, **6**, 742 (2015); https://doi.org/10.5094/APR.2015.083
59. S. Jain, S.K. Sharma, N. Vijayan and T.K. Mandal, *Environ. Pollut.*, **262**, 114337 (2020); https://doi.org/10.1016/j.envpol.2020.114337
60. V. Murari, M. Kumar, S.C. Barman and T. Banerjee, *Environ. Sci. Pollut. Res. Int.*, **22**, 1329 (2015); https://doi.org/10.1007/s11356-014-3418-2
61. S. Tiwari, U.C. Dumka, A.S. Gautam, D.G. Kaskaoutis, A.K. Srivastava, D.S. Bisht, R.K. Chakrabarty, B.J. Sumlin and F. Solmon, *Atmos. Pollut. Res.*, **8**, 13 (2017); https://doi.org/10.1016/j.apr.2016.07.008
62. S.K. Sharma, A. Sharma, M. Saxena, N. Choudhary, R. Masiwal, T.K. Mandal and C. Sharma, *Atmos. Pollut. Res.*, **7**, 110 (2016); https://doi.org/10.1016/j.apr.2015.08.002
63. P.K. Nagar, D. Singh, M. Sharma, A. Kumar, V.P. Aneja, M.P. George, N. Agarwal and S.P. Shukla, *Environ. Sci. Pollut. Res. Int.*, **24**, 25179 (2017); https://doi.org/10.1007/s11356-017-0171-3
64. A. Soni, U. Kumar, V. Prabhu and V. Shridhar, *J. Atmos. Sol. Terr. Phys.*, **199**, 105205 (2020); https://doi.org/10.1016/j.jastp.2020.105205
65. S.M.L. Hama, P. Kumar, R.M. Harrison, W.J. Bloss, M. Khare, S. Mishra, A. Namdeo, R. Sokhi, P. Goodman and C. Sharma, *Sustain Cities Soc.*, **54**, 102003 (2020); https://doi.org/10.1016/j.scs.2019.102003
66. M. Arif, R. Kumar, R. Kumar, Z. Eric and P. Gourav, *Sci. Total Environ.*, **624**, 1387 (2018); https://doi.org/10.1016/j.scitotenv.2017.12.227
67. M.M. Rana and M.H. Khan, *Asian J. Atmos. Environ.*, **14**, 47 (2020); https://doi.org/10.5572/ajae.2020.14.1.047
68. S. Yadav, S. Bamotra and A. Tandon, *Environ. Sci. Pollut. Res. Int.*, **27**, 18875 (2020); https://doi.org/10.1007/s11356-020-08374-3
69. A. Agarwal, A. Satsangi, A. Lakhani and K.M. Kumari, *Chemosphere*, **242**, 125132 (2020); https://doi.org/10.1016/j.chemosphere.2019.125132
70. R.K. Sahu, S. Pervez, J.C. Chow, J.G. Watson, S. Tiwari, A.S. Panicker, R.K. Chakrabarty and Y.F. Pervez, *Environ. Geochem. Health*, **40**, 2205 (2018); https://doi.org/10.1007/s10653-018-0093-0
71. R.D. Gawhane, P.S.P. Rao, K. Budhavant, D.C. Meshram and P.D. Safai, *Meteorol. Atmos. Phys.*, **131**, 1497 (2019); https://doi.org/10.1007/s00703-018-0653-y
72. R. Gadi, Shivani, S.K. Sharma and T.K. Mandal, *Chemosphere*, **221**, 583 (2019); https://doi.org/10.1016/j.chemosphere.2019.01.067
73. M. Bawase, Y. Sathe, H. Khandaskar and S. Thipse, *J. Atmos. Chem.*, **78**, 35 (2021); https://doi.org/10.1007/s10874-020-09412-7
74. M.H. Rahman, V.P. Sharma, S. Kundu and A. Datta, *Open J. Air Pollut.*, **9**, 1 ((2020); https://doi.org/10.4236/ojap.2020.91001

75. A. Dutta and W. Jinsart, *Hum. Ecol. Risk Assess.*, **27**, 1094 (2021); https://doi.org/10.1080/10807039.2020.1807902
76. T. Mehmood, Z. Tianle, I. Ahmad and X. Li, *Chemosphere*, **257**, 127187 (2020); https://doi.org/10.1016/j.chemosphere.2020.127187
77. C. Sarkar, C. Venkataraman, S. Yadav, H.C. Phuleria and A. Chatterjee, *Environ. Pollut.*, **254**, 113077 (2019); https://doi.org/10.1016/j.envpol.2019.113077
78. P. Chen, S. Kang, C. Gul, L. Tripathee, X. Wang, Z. Hu, C. Li and T. Pu, *J. Environ. Sci. (China)*, **90**, 286 (2020); https://doi.org/10.1016/j.jes.2019.12.006
79. K. Sandeep, R.S. Negi, A.S. Panicker, A.S. Gautam, D.S. Bhist, G. Beig, B.S. Murthy, R. Latha, S. Singh and S. Das, *Asia-Pac. J. Atmos. Sci.*, **56**, 455 (2020); https://doi.org/10.1007/s13143-019-00158-1
80. S.K. Sharma, S. Mukherjee, N. Choudhary, A. Rai, A. Ghosh, A. Chatterjee, N. Vijayan and T.K. Mandal, *Environ. Sci. Pollut. Res. Int.*, **28**, 51642 (2021); https://doi.org/10.1007/s11356-021-14361-z
81. X. Zhang, Z. Li, F. Wang, M. Song, X. Zhou and J. Ming, *Atmosphere*, **11**, 1368 (2020); https://doi.org/10.3390/atmos11121368
82. D.S. Bisht, A.K. Srivastava, A.S. Pipal, M.K. Srivastava, A.K. Pandey, S. Tiwari and G. Pandithurai, *Environ. Sci. Pollut. Res.*, **22**, 5293 (2015); https://doi.org/10.1007/s11356-014-3836-1
83. K. Ram, M.M. Sarin and P. Hegde, *Atmos. Chem. Phys.*, **10**, 11791 (2010); https://doi.org/10.5194/acp-10-11791-2010
84. WHO, Ambient (Outdoor) Air Pollution Database, by Country and City. World Health Organization (2016); http://www.who.int/phe/health_topics/outdoorair/ databases/cities/en
85. M. Kumar, S. Tiwari, V. Murari, A.K. Singh and T. Banerjee, *Atmos. Environ.*, **104**, 162 (2015); https://doi.org/10.1016/j.atmosenv.2015.01.014
86. N. Singh, V. Murari, M. Kumar, S.C. Barman and T. Banerjee, *Environ. Pollut.*, **223**, 121 (2017); https://doi.org/10.1016/j.envpol.2016.12.071.
87. V. Choudhary, P. Rajput, D.K. Singh, A.K. Singh and T. Gupta, *Atmos. Pollut. Res.*, **9**, 494 (2018); https://doi.org/10.1016/j.apr.2017.11.012
88. S.K. Sharma, T.K. Mandal, A. Sharma, S. Jain and Saraswati, *Bull. Environ. Contam. Toxicol.*, **100**, 695 (2018); https://doi.org/10.1007/s00128-018-2313-9
89. A. Chatterjee, C. Dutta, T.K. Jana and S. Sen, *J. Atmos. Chem.*, **69**, 83 (2012); https://doi.org/10.1007/s10874-012-9231-8
90. V. Murari, M. Kumar, N. Singh, R.S. Singh and T. Banerjee, *J. Atmos. Chem.*, **73**, 165 (2016); https://doi.org/10.1007/s10874-015-9321-5
91. M.F. Elledge, M.J. Phillips, V.E. Thornburg, K.H. Everett and S. Nandasena, *Int. J. Environ. Res. Public Health*, **9**, 1097 (2012); https://doi.org/10.3390/ijerph9041097
92. A.S. Nagpure, B.R. Gurjar and J.C. Martel, *Atmos. Pollut. Res.*, **5**, 371 (2014); https://doi.org/10.5094/APR.2014.043
93. K, Niranjan, V. Sreekanth, B.L. Madhavan, T.A. Devi and B. Spandana, *J. Earth Syst. Sci.*, **117(Suppl. 1)**, 421 (2008); https://doi.org/10.1007/s12040-008-0018-x
94. S. Tiwari, A.K. Srivastava and A.K. Singh, *Atmos. Environ.*, **77**, 738 (2013); https://doi.org/10.1016/j.atmosenv.2013.05.035
95. S. Tiwari, P.K. Hopke, A.S. Pipal, A.K. Srivastava, D.S. Bisht, S. Tiwari, A.K. Singh, V.K. Soni and S.D. Attri, *Atmos. Res.*, **166**, 223 (2015); https://doi.org/10.1016/j.atmosres.2015.07.007
96. H. Jethva, S.K. Satheesh and J. Srinivasan, *J. Geophys. Res. D Atmospheres*, **110**, D21204 (2005); https://doi.org/10.1029/2005JD005938
97. K. Ram, M.M. Sarin and S.N. Tripathi, *Environ. Sci. Technol.*, **46**, 686 (2012); https://doi.org/10.1021/es202857w
98. M. Kumar, K.S. Parmar, D.B. Kumar, A. Mhawish, D.M. Broday, R.K. Mall and T. Banerjee, *Atmos. Environ.*, **180**, 37 (2018); https://doi.org/10.1016/j.atmosenv.2018.02.027
99. S. Ramachandran, M. Rupakheti and M.G. Lawrence, *Environ. Int.*, **142**, 105814 (2020); https://doi.org/10.1016/j.envint.2020.105814
100. S. Shirodkar and H.B. Menon, *J. Atmos. Sol. Terr. Phys.*, **130–131**, 182 (2015); https://doi.org/10.1016/j.jastp.2015.06.002
101. K. Alam, T. Trautmann and T. Blaschke, *Atmos. Res.*, **101**, 773 (2011); https://doi.org/10.1016/j.atmosres.2011.05.007
102. D.G. Kaskaoutis, K.V.S. Badarinath, S. Kumar Kharol, A. Rani Sharma and H.D. Kambezidis, *J. Geophys. Res. D Atmospheres*, **114**, D22204 (2009); https://doi.org/10.1029/2009JD012423
103. B.L. Madhavan, A.S. Krishnaveni, M.V. Ratnam and V. Ravikiran, *Atmos. Res.*, **249**, 105345 (2021); https://doi.org/10.1016/j.atmosres.2020.105345
104. K. Ram and M.M. Sarin, *Environ. Sci. Technol.*, **43**, 8233 (2009); https://doi.org/10.1021/es9011542
105. R. Rengarajan, M.M. Sarin and A.K. Sudheer, *J. Geophys. Res. D Atmospheres*, **112**, D21307 (2007); https://doi.org/10.1029/2006JD008150
106. R. Sagar, B. Kumar, U.C. Dumka and K.K. Moorthy, *J. Geophys. Res.*, **109**, 1 (2004); https://doi.org/10.1029/2003JD003954
107. U.C. Dumka, D.G. Kaskaoutis, M.K. Srivastava and P.C.S. Devara, *Atmos. Chem. Phys.*, **15**, 1555 (2015); https://doi.org/10.5194/acp-15-1555-2015
108. J. Xin, Y. Wang, Z. Li, P. Wang, W.M. Hao, B.L. Nordgren, S. Wang, G. Liu, L. Wang, T. Wen, Y. Sun and B. Hu, *J. Geophys. Res. Atmospheres*, **112**, D05203 (2007); https://doi.org/10.1029/2006JD007075
109. V.S. Manoharan, R. Kotamarthi, Y. Feng and M.P. Cadeddu, *Atmos. Chem. Phys.*, **14**, 1159 (2014); https://doi.org/10.5194/acp-14-1159-2014
110. S.S. Ningombam, S.P. Bagare, N. Sinha, R.B. Singh, A.K. Srivastava, E. Larson and V.P. Kanawade, *Atmos. Res.*, **138**, 308 (2014); https://doi.org/10.1016/j.atmosres.2013.11.025
111. K. Ram, M.M. Sarin and P. Hegde, *Atmos. Chem. Phys.*, **10**, 11791 (2010); https://doi.org/10.5194/acp-10-11791-2010
112. A.K. Srivastava, K. Ram, S. Singh, S. Kumar and S. Tiwari, *Sci. Total Environ.*, **502**, 287 (2015); https://doi.org/10.1016/j.scitotenv.2014.09.015
113. S.K. Satheesh, K. Krishna Moorthy, Y.J. Kaufman and T. Takemura, *Meteorol. Atmos. Phys.*, **91**, 45 (2006); https://doi.org/10.1007/s00703-004-0097-4
114. J. Liu, P. Lin, A. Laskin, J. Laskin, S.M. Kathmann, M. Wise, R. Caylor, F. Imholt, V. Selimovic and J.E. Shilling, *Atmos. Chem. Phys.*, **16**, 12815 (2016); https://doi.org/10.5194/acp-16-12815-2016
115. A. Laskin, J. Laskin and S.A. Nizkorodov, *Chem. Rev.*, **115**, 4335 (2015); https://doi.org/10.1021/cr5006167
116. M. Xie, X. Chen, M.D. Hays and A.L. Holder, *Atmos. Chem. Phys.*, **19**, 2899 (2019); https://doi.org/10.5194/acp-19-2899-2019
117. Y. Desyaterik, Y. Sun, X. Shen, T. Lee, X. Wang, T. Wang and J.L. Collett Jr., *J. Geophys. Res. D Atmospheres*, **118**, 7389 (2013); https://doi.org/10.1002/jgrd.50561
118. Y. Iinuma, O. Böge, R. Gräfe and H. Herrmann, *Environ. Sci. Technol.*, **44**, 8453 (2010); https://doi.org/10.1021/es102938a
119. L.R. Mazzoleni, B. Zielinska and H. Moosmüller, *Environ. Sci. Technol.*, **41**, 2115 (2007); https://doi.org/10.1021/es061702c
120. Y.J. Li, J.W.T. Yeung, T.P.I. Leung, A.P.S. Lau and C.K. Chan, *Aerosol Sci. Technol.*, **46**, 654 (2012); https://doi.org/10.1080/02786826.2011.653017
121. M.A.J. Harrison, S. Barra, D. Borghesi, D. Vione, C. Arsene and R. Iulian Olariu, *Atmos. Environ.*, **39**, 231 (2005); https://doi.org/10.1016/j.atmosenv.2004.09.044
122. L.T. Fleming, R. Weltman, A. Yadav, R.D. Edwards, N.K. Arora, A. Pillarisetti, S. Meinardi, K.R. Smith, D.R. Blake and S.A. Nizkorodov, *Atmos. Chem. Phys.*, **18**, 15169 (2018); https://doi.org/10.5194/acp-18-15169-2018
123. W. Yuan, R.-J. Huang, L. Yang, J. Guo, Z. Chen, J. Duan, T. Wang, H. Ni, Y. Han, Y. Li, Q. Chen, Y. Chen, T. Hoffmann and C. O'Dowd, *Atmos. Chem. Phys.*, **20**, 5129 (2020); https://doi.org/10.5194/acp-20-5129-2020