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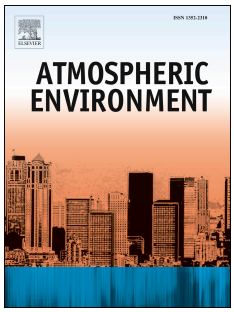

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PII: S1352-2310(22)00537-4

DOI: https://doi.org/10.1016/j.atmosenv.2022.119472

Reference: AEA 119472

To appear in: *Atmospheric Environment*

Received Date: 8 March 2022

Revised Date: 27 October 2022

Accepted Date: 6 November 2022

Please cite this article as: Hassan, M.A., Mehmood, T., Liu, J., Luo, X., Li, X., Tanveer, M., Faheem, M., Shakoor, A., Dar, A.A., Abid, M., A review of particulate pollution over Himalaya region: Characteristics and salient factors contributing ambient PM pollution, *Atmospheric Environment* (2022), doi: https://doi.org/10.1016/j.atmosenv.2022.119472.

A review of particulate pollution over Himalaya region: Characteristics and salient factors contributing ambient PM pollution

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Abstract

The Himalayas, which include delicate and unspoiled ecosystems, have the third-largest glacier ice store in the world. Recent research reveals that anthropogenic and natural factors contribute to the deteriorating air quality in the region. Rising particulate matter (PM) levels might have devastating effects on the regional climate, hydrologic cycles, and ecology. Given the scarcity of studies (the majority of which are of short duration and focus on a single pollutant and satellite-based observation), unique topography, meteorological characteristics, monsoon dynamics, temperature inversion, and mixing of pollution emission from local and distant sources, it is difficult to understand the general pollution trend in the Himalaya. Nonetheless, past studies indicate that local biomass burning, long-distance transport, especially from the Indo-Gangetic Plain (IGPs), dust storms, and tourist activities are the primary drivers to rising PM pollution in the Himalayas region. Emissions from these sources develop exponentially and encompass severe pollution episodes because of the IGP's complicated hilly terrain, cloud condensation nucleation process, atmospheric brown clouds (haze), dust storm, and transport of PM from crop residue burning (especially during the post-monsoon season). In light of this, the current work outlines the sources, factors, and variables that contribute to the Himalayan region's rising pollution levels and sheds light on significant areas of recent research. The present study examines in depth the consequences of the monsoon, the dynamics of pollution in IGP, and the movement of PM from IGP to the Himalayan region. This review aims to highlight research gaps and limitations in the existing literature for a better understanding of the current PM pollution in the Himalayas and surrounding sites, which is essential for understanding climate change and health consequences in this region, and to provide significant theoretical and practical implications for assessing particulate pollution in the Himalayas region.

Keywords: Chemical composition; Classification and sources; Formation mechanism; Health effects; Crop burning

1 Introduction

The Himalayan belt of the highest mountainous regions and foothills runs along the northern edge of the Indian and Pakistani plateau. While Indo-Gangetic Plain (IGP) extends over 2000 kilometers, comprising a large land region in northern South Asia: nearly all of Bangladesh, the southern portion of Nepal, much of eastern and northern India, and the eastern areas of Pakistan. The South Asian zone has witnessed considerable economic development; however, it has been considered one of the most toxic and problematic air pollution "hotspots" globally [1]. Swift industrialization and rapid urbanization have enhanced air pollution in IGP. For instance, Novakov et al. estimated fossil-fuel black carbon (BC) emission increased from ~1.3 Tg/year to ~1.6 Tg/year between 1950 to 1990 [2], and an alarming increase in airborne particulates was witnessed, especially in cities [3]. Singh et al. reported that suspended particulate matter (PM) in seven big industrial and residential cities of India ranged from 50 to 550 μgm^{-3} between 1995 and 2000, increasing over time [4]. In most environmental scientific studies on Asian cities, emphasis has been noticed on large cities of China and the IGP. Extreme $PM_{2.5}$ (PM with an aerodynamic diameter of less than 2.5 micrometers) pollution has domestic and transboundary repercussions, resulting in an average life expectancy (LE) rate loss for Bangladesh, India, and Pakistan of more than 2.8 years in 2018 [5, 6], and it is responsible for more than a third of all deaths caused by poor air quality worldwide [7]. However, studies on the region's air quality are scarce.

As a result of the IGP's proximity to the Himalayas, this formerly pristine environment has become contaminated and burdened by increased air pollution from IGP-influenced areas, so sustaining habitats are especially sensitive to severe risks of pollution [8, 9]. Air pollution is a severe health problem, particularly in mega-cities, i.e., New Delhi, with an excess of 3500 cardiovascular mortality annually [10]. PM has been considered one of the major causes of cardiovascular illnesses and strokes in urban areas [11, 12], pneumonia, respiratory diseases [13], and intellectual disorders in elders [14]. Moreover, PM is responsible for millions of annual preventable deaths worldwide [15].

However, in IGP, studies of $PM_{2.5}$ and PM_{10} (PM with an aerodynamic diameter less than 10 micrometers) have focused on urban areas [16, 17]. Very few high-altitude station studies in IGP have been recorded [18]. In January – December 2005, a study

recorded fine ($PM_{2.5}$) and coarse ($PM_{2.5-10}$) particulate matter over Darjeeling (2200 m above mean sea level (AMSL)) in the eastern range of the Himalayas showed an average concentration of 29.5±20.8 μg m^{-3} ($PM_{2.5}$) and 19.6±11.1 μg m^{-3} ($PM_{2.5-10}$) [19]. In Sinhagad (1450 m AMSL), a rural high-altitude site in the Western mountainous Himalayas region, from Nov. 2008 to Apr. 2009, Satsangi et al. [20] recorded mean concentrations for $PM_{2.5}$ (14.1 ± 8.2 μg m^{-3}) and PM_{10} (35.8 ± 15.2 μg m^{-3}).

However, multiple studies have mainly studied air quality in the Himalayan region employing a few residential or ecological stations. Studies reported that $PM_{2.5}$ and PM_{10} dominated monsoon periods [21, 22]. Moreover, long-range dust aerosol induction was observed in Western India (arid regions) during pre-monsoon. As a result, the IGP and the surrounding areas face several air quality problems, including post-monsoon pollution episodes, drastic annual growth of regional air-polluting plumes identified as atmospheric brown clouds (ABCs), over the dry, long pre-monsoon and winter seasons each year [23].

In addition, the relatively high optical aerosol depth value along the whole IGP area displays the region's air pollution intensity. A previous study demonstrated that higher PM concentrations are related to the intensification of cold water and winter fog in that area [24]. PM plays a leading role in many atmospheric phenomena, i.e., higher air pollution, loss of visibility, acidic deposition, precipitation, and radiation balance [25, 26]. PM's chemical composition and size distribution influence air quality globally. In addition, $PM_{2.5}$ transport from remote sources and regions often contributes to regional air quality [27]. The key factors contributing to IGP air pollution and the Himalayan area include releases from industries, vehicles, biomass and fossil-based fuel, thermal power plants, cooking activities, crop waste combustion, farming, and forest fires. Noticeably, the information regarding the factors regulating the local emissions sources (such as weather and tourist activities) and the contribution of long-range transport of pollutants (crop residual burning) to the overall pollution over the Himalayan region is inadequate. Likewise, the relative contribution of emission sources and other factors (e.g., topography and meteorological attributes) to air pollution in Himalaya mountainous area and adjacent IGP region still lacks in onsite studies.. This review aims to improve knowledge and determine the source of PM in the Himalayan sites and its implication for the regional climate to better understand the particulate

matter load phenomenon because, in recent years, the level of PM has been increasing at high-altitude sites in the Himalayan region.

In this critical review, we assessed the phenomenon of PM pollution, its characteristics, and its effects on the air quality of the Himalayan region by various natural and anthropogenic factors. To achieve this objective, we analyzed studies that discussed PM characteristics and associated chemical species (carbonaceous and water-soluble species), sources, and factors that influence the air quality of various Himalaya and adjacent regions, shown in Fig. 1. Himalaya region spanning five countries (Bhutan, India, Nepal, China, and Pakistan). The adjacent area, such as IGP, has many metropolis cities such as New Delhi, Dhaka, Kolkata, Lahore, and Karachi, while Kabul, Kathmandu, Srinagar, Peshawar, Quetta, Xinning are major cities of HKH. The air pollution situation ($PM_{2.5}$) in major cities of this area is depicted in Fig.2, and different circles represent the severity of corresponding pollution levels reported in these cities. Likewise, a caparison of $PM_{2.5}$ and PM_{10} reported in the literature regarding this region is provided in Fig. 3. The detailed description of air pollution ($PM_{2.5}$ and PM_{10}) characteristics is addressed in section 2. The potential long-range transport of PM during the dust event days was investigated for different seasons to determine the source area.

Moreover, unique features of the Himalayas and adjacent regions and pollution episodes (post-monsoon) were discussed critically. From a health perspective, the changes between pre-monsoon, monsoon, and post-monsoon concentrations are fascinating to know how rapidly monsoon season affects aerosols' physical and optical impacts [28]. This review provides critical information to guide policymakers in creating successful air pollution management policies in the targeted region.

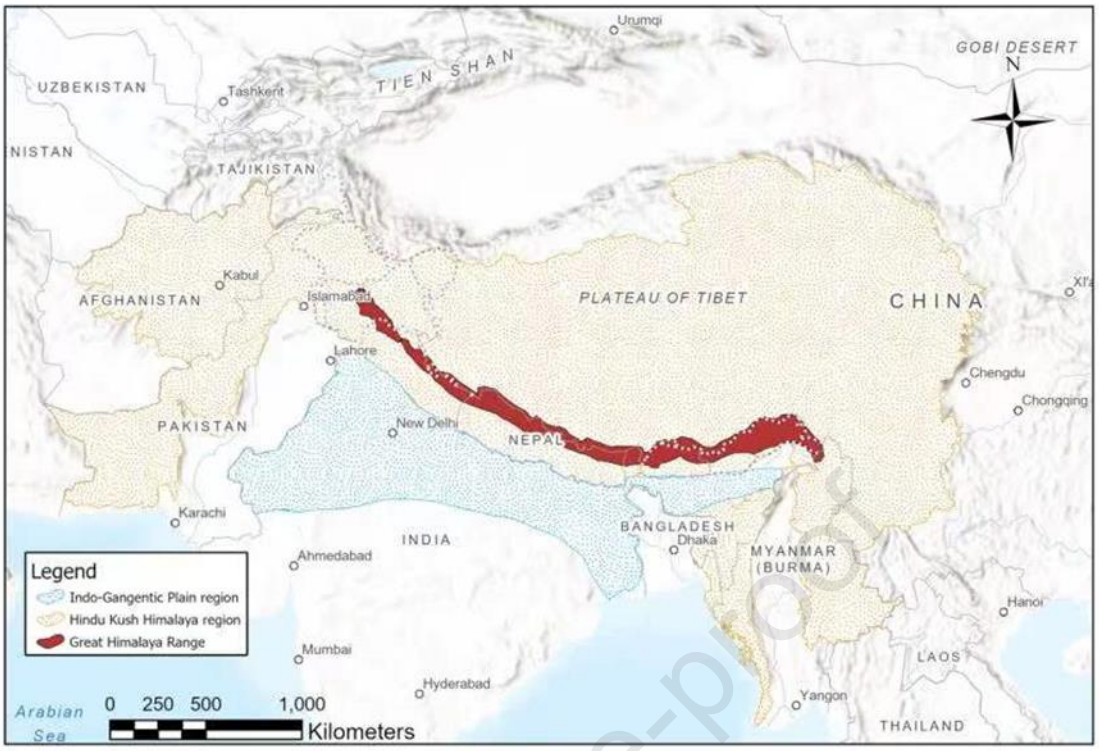

***Fig.* 1** *Himalaya range with reference to Hindu Kush Himalaya (HKH) region and IGP region*

2 Air pollution in the Himalayas region

PM exposure increases the risk of many adverse health issues, including morbidity, cardiovascular mortality, respiratory disorders, and the possible development of respiratory mortality [29]. Generally, fine PM is produced by vehicle emissions and is further worsened by secondary pollution [30]. The total mass of suspended PM in the air can be quantified by describing the mass of total suspended particles (TSP). However, this term should be used by scientists but has not been used widely since the monitoring of PM_{10} started in the US in 1987 [31]. The inability of particles larger than 10 µm to penetrate into the respiratory system, where they cause adverse health effects, is well-acknowledged [32, 33], which supports the research and evidence of a theory that fine and ultra-fine particulate matter promotes a higher prevalence of health problems, sickness, and mortality, particularly $PM_{2.5}$ due to their deeper penetration [34, 35]. Table 1 provides the ambient PM_{10}, $PM_{2.5,}$ and TSP-bound inorganic water-soluble ionic species (WSIs) concentrations at different IGP and Himalayas region sites. The seasonal comparison depicts the higher concentrations of these ions in the pre-monsoon period. Moreover, it can also be seen that the overall relative concentrations of SO_4^{2-} to NO_3^- were higher in these areas, indicating a higher level of

regional transport of PM and probably the burning of wood, biofuel, crop residue, and fossil fuel [36].

Increasing PM pollution concentrations in different sections of the Himalayas region have become a severe concern. Because of the extensive damage PM pollution has cast on the Himalayas region, the consequences for both people and ecosystems are significant, as the impact on climate, monsoon patterns, the cryosphere, water supply, agriculture, and socioeconomic issues. While the information available is not comprehensive, the Himalayas are surrounded by a large quantity of pollution outside (neighbor areas), such as IGP, and inside the region.

Source appointment studies revealed air quality in the northern and eastern Himalayan region is deteriorating by polluted air masses arising from near urban cities of the IGP region. In addition, due to the low dispersion rate, pollutants generated from the IGP region near complex hilly terrain (sharp curved, irregular basin and plateau, and steep sloped mountains) could accumulate, boosting pollutant concentration levels [37]. For example, Chatterjee et al. [19] studied air pollution in the eastern Himalayas area (Darjeeling). They reported temporal air pollution trends in eastern regions (e.g., Darjeeling). Likewise, Kuniyal et al. [22] studied western Himalayas cities (Kothi and Mohal) both reported temporal trends in the dominance of emission sources, i.e., local emission (e.g., biomass burning) contributes more to the winter season while long-range transport appeared to be the primary cause in summer days.

Fig. 2 *$PM_{2.5}$ concentration (μgm^{-3}) in Himalayas and adjacent regions*

Similarly, those mentioned above, especially hilly terrain features over the Himalayas, resulted in irregular aerosol concentration patterns in the central and southern parts of the Himalayas that cannot be accurately simulated by models, which hinders aerosol observation, especially in these regions [38]. For example, it can be seen from table 2 that PM pollution showed variation irrespective of the height

elevation of the sampling site, but somehow, PM pollution was lower at most of the sampling sites 1000 m high or more. However, this is not true in the case of Srinagar, which has a greater height (1500 m) with comparatively higher concentrations (PM_{10}: 135 μg m^{-3} and $PM_{2.5}$: 85 μg m^{-3}) [39]. Likewise, the Himalayas regions also observed severe PM pollution, as in the case of Katmandu (height:1400 m), in which the 17 days average $PM_{2.5}$ reached 195 μg m^{-3} in winter [40]. In the Indian region, biomass burning occurs mainly from January to May [41].

Moreover, the studies are sparse in this region. This review also mainly focuses on studies discussing monsoon-attributed changes in PM characteristics, so the trend may be more complicated when combining other studies in the Himalayas. Therefore, more ground-based studies are warranted to use accurately simulated models here.

Multiple studies based on ground observation of PM show that the annual mean concentration of $PM_{2.5}$ and PM_{10} is approximately 1.2–6 times greater than Bangladesh National Air Quality Standard (BNAQS, 50 μg m^{-3} for $PM_{2.5}$ and 100 μg m^{-3} for PM_{10}) [42, 43]. Based on daily measurements for over 75% of the days each year, Dhaka has been regarded as the world's most polluted city [44, 45]. Moreover, PM levels vary significantly from location to location in Bangladesh [46]. During the rainy season, pollution levels are lower than the yearly mean; however, the rest of the time, pollution levels in Dhaka, Gazipur, and Narayanganj rise to much higher values than the BNAQS limit [47]. The annual average concentration of PM_{10} was recorded as more than 150 μg m^{-3} over Gazipur, Narayanganj, and Dhaka during 2012–2015 [48]. A comprehensive study by [42] observed higher annual average concentrations of $PM_{2.5}$ (80–100 μg m^{-3}) and PM_{10} (140–200 μg m^{-3}) during 2013–2017 over Gazipur, Narayanganj, and Darus Salam. Annual concentration of 14.7-91 μg m^{-3} for $PM_{2.5}$ and 24-114 μg m^{-3} for PM_{10} was recorded during June 2013–May 2014 over Brahmaputra Valley (eastern-northeastern Himalayan range) [49]. A recent study reported ground concentrations of $PM_{2.5}$ (76.34 ± 34.12 μg m^{-3}) and PM_{10} (136.25 ± 68.94 μg m^{-3}) observed during 2013–2018 in 8 big cities of Bangladesh (Dhaka, Gazipur, Chittagong, Rajshahi, Sylhet, Khulna Narayanganj, and Barisal) [42].

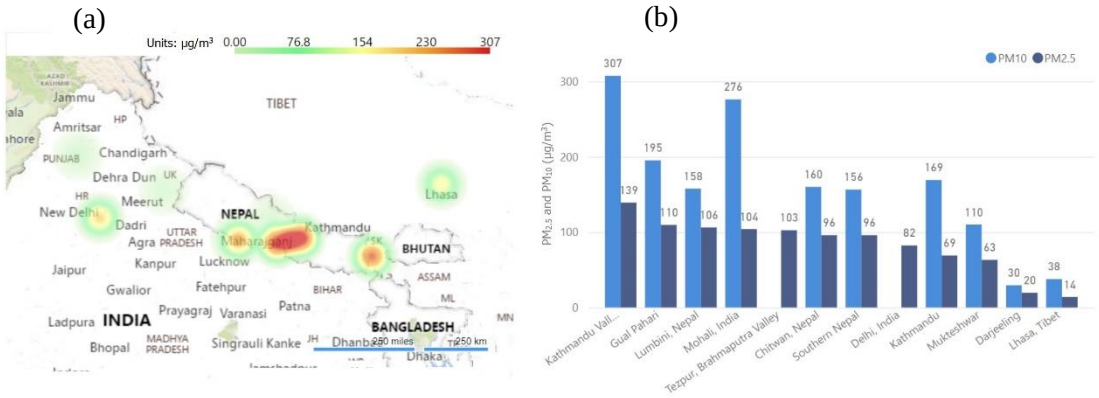

Fig. 3 *a) PM_{10} concentration heatmap b) City-wise $PM_{2.5}$ and PM_{10} in Himalayas and adjacent regions*

Very few studies have investigated PM distribution in the entire Himalayas and Nepal specifically, and those have been confined to locations at considerable altitudes. Therefore, wind currents on the valley floor might carry pollution from the valley to the mountain peaks. No previous campaigns have been completed to explore the range of PM sizes in ridge-valley valleys and mid-altitude ridge-valley regions. Many significant cities and rural areas surrounding the HKH and IGP lack PM data monitoring.

The information gaps are a direct result of a variety of problems. While Himalaya is exceptionally rugged, its varied topography and atmospheric fluctuations require a denser network of stations. Furthermore, the current usage of many instruments or methods at different locations necessitates the immediate creation of a single database through standardized measurements. Additionally, a measuring approach that adds to the testing done at the surface would also entail measuring the vertical variation of pollution. We must also upgrade the tools for detecting and characterizing PM contamination, mainly for major components (e.g., water-soluble ions, metals ions, PAHs, organic and inorganic carbon) bound to PM in Himalaya and adjacent IGP areas, which are supposed to influence the regional air quality. Pre-monsoon concentrations of PM_{10} exhibited maximum values, whereas higher concentrations of $PM_{2.5}$ occurred in winter. When it came to the monsoon season, the PM_{10} and $PM_{2.5}$ concentrations were the lowest [50].

2.1 Monsoon Impact

More than 60% of the world's population depends on the Asian summer monsoon for its water requirements. The monsoon relieves the dangerous pollution accumulated during the spring and winter with water supplies. The “ABCs,” covering an area of 10 million km^2 over Southern Asia, is the most significant and persistent of these pollution

hazes [51, 52]. Based on the literature, it is estimated that this particulate air pollution originates from fossil fuel and biomass burning (BB). Significantly, New Delhi is a challenging city because of its large population and air pollution hazard [10]. Similar to other big cities in IGP, the air quality significantly changes during monsoon. The wet deposition processes during monsoon rain wash out ambient PM and transport them to the Earth's surface. In addition, it is widely recognized that aerosols can affect the monsoon and, by extension, the entire water cycle [53, 54]. These factors give a complete rationale for measuring the impact of the monsoon on aerosols in the region.

Moreover, satellite data analysis and modeling have conclusively proven that rice residue burning raises ambient $PM_{2.5}$ concentrations throughout the IGP from October to November during the post-harvesting season. In addition, after the monsoon season, crop residue is burned, which has increased the annual variability of atmospheric dynamics following the monsoon season. These conclusions are perfectly consistent with Ojha et al. [55], who discovered that the increased crop residue burning (CRB) emissions on $PM_{2.5}$ and reduced meteorological ventilation cause extensive PM increases within the IGP. The earlier onset and later refuge of monsoon weather are projected as governed by climate variability. It is anticipated that future Indian southwest (SW) monsoon behavior will influence potential IGP air pollution.

In contrast to agricultural CRB emissions, the influence of $PM_{2.5}$ increases can be noticed far from the emission source regions. Hence, weather variables and current post-monsoon meteorological circumstances control the overall intensity of poor air quality episodes in IGP. However, the main factor for rising concentrations of $PM_{2.5}$ is greater CRB [56]. Sembhi et al. [57] found poorer air quality (3 percent above Delhi) in Northern India due to Northwest Indian CRB scheduling modifications.

Recent studies have discovered that a 10-day shift in the time of rice CRB has appeared in some parts of Punjab and Haryana since 2009. This was done to lessen reliance on groundwater irrigation and bring planting closer to the commencement of the Indian SW monsoon (late June). This change also shifted the post-monsoon rice harvest, delaying the burning of the post-harvest rice residue [58]. However, concerning $PM_{2.5}$ concentration, change in magnitude and direction is not very sensitive to meteorological circumstances and is significantly more dependent on the prevalent specific conditions. Reducing CRB emission decreases $PM_{2.5}$ concentrations no matter when residue burning is performed. The use of suitable systems for collecting, storing, and processing agricultural residues will also help the reduction of pollutants as well as

energy generation. Cost-effective measures may help farmers decrease the severe human health repercussions of CRB's proliferation by providing affordable alternatives to speed up its effective prohibition. As a result of the same agricultural fires, the air quality in Ludhiana, the CRB source region, and Delhi could have declined by 30% and 4.4%, respectively [57].

In Mukteshwar, monsoon onset and withdrawal transitions happened between 7 and 10 days on average, while in Gual Pahari, it expanded from 17 to 31 days [28]. It can easily interpret that the aerosol distribution and concentration mechanisms were distinct at the two different locations. This is likely due to the height of the two stations, as Gual Pahari is a downwind semi-urban site almost entirely in the free troposphere. While in Mukteshwar, the higher altitude and mountainous terrain helped boost the precipitation resulting in an adequate washout at the start of the monsoon. The post-monsoon season featured low concentrations, and aerosol properties were virtually identical to the monsoon season. While the accumulation of rain from 2008 to 2009 varied greatly on both stations, Gual Pahari had similar transitions in the commencement of the aerosol decline. This implies that the decrease in aerosols was a large-level phenomenon. However, it is curious that aerosol concentrations could be determined exclusively using rainfall data in the monsoon season.

Studies showed dust occurrences from the Thar Desert might alter aerosol concentrations in the early monsoon season [59, 60]. The percentage of equivalent black carbon (BCe) was present in significant concentrations in Gual Pahari through the monsoon, which supports the hypothesis that New Delhi is responsible for the anthropogenic impact [28].

2.2 Significant PM contributors

Ambient particulates consist of various biological and chemical components [61]. The chemical constituents of PM include minerals (metal oxides), secondary inorganic particles, rare earth metals, elemental carbon (EC), seas salts, water-soluble ions, organic species(e.g., polyaromatic hydrocarbons (PAHs), organic carbon (OC), organic matter (OM) and volatile organic compounds (VOCs)) and trace elements [62]. Secondary inorganic species (SIs) such as ammonia, nitrate, sulfate, and carbonaceous species (OC, EC) and PAHs are of great concern due to their toxicity and carcinogenicity [63].

2.3 Carbonaceous species

A large share of total PM mass concentration was Carbonaceous species could comprise a significant percentage in total PM, i.e., 20-40% and 25-50% of PM_{10} and $PM_{2.5}$ [64], and urban air usually holds about 40% of carbonaceous species in ambient PM [65]. These species are further divided into EC and OC groups [66]. OC has primary and secondary emission sources and forms by burning fossil fuel (primary) and in the secondary particle formation process [67]. These species are also present in low-volatile compounds formed during the photochemical process in the atmosphere [68].

EC, also called BC, emits during the incomplete combustion process of carbon fuel and is a crucial tracer of diesel exhaust [67]. It emits in ultrafine form and represents the primary emission (mostly transportation) [69]. Even its lower percentage in $PM_{2.5}$ makes it worst regarding health prospectus [29, 70]. In Nepal, the predominant component of aerosol was OC (64-68%), EC (7% to 10%), and water-soluble inorganic ionic species (WSIIs) (27%) [45]. The relative concentration of OC and EC reported in various studies in the Himalayas region and adjacent IGP is presented in Table 3. The OC and EC levels were several times higher in the dry season than at other times of the year.

Moreover, except for Lhasa, China, all other cities have higher OC than EC, indicating secondary particles were contributors to ambient PM pollution. Likewise, the OC/EC ratio is comparatively lower in the monsoon season, showing the dominance of primary source contribution [67]. For convenience, various natural and anthropogenic sources of PM, which were further categorized into primary and secondary types, are enlisted in Table 4. It can be seen from Table 4 that mostly fine particulates are associated with anthropogenic and secondary types of sources, while natural and primary sources emit coarse particles. Elemental carbon is mostly dominated by fine particles [71]. Likewise, the carbonaceous species (OC and EC) contribute 24-32 % of $PM_{2.5}$ over Srinagar [39].

The one-year study at Tezpur showed that the average BC level was 6 ± 1.5 μg m^{-3}, showing that Tezpur is less polluted than other northeastern Indian areas [49]. Another study by Mehra et al. reported that the BC levels were 11.3 ± 6.2 μg m^{-3} in Lumbini, Nepal, in November 2016 and 11.0 ± 8.3 μg m^{-3} in April 2017 [72]. Between December 2005 and December 2008, BC concentration in Mukteshwar's Himalayan rural environment was 0.85 μg m^{-3}. When the monsoon season arrives, the average BC concentration tends to fall (especially in July and August) [47]. Wet scavenging of aerosol, the small incidence of forest fire, and biomass burning in Srinagar lower the

OC/EC concentrations (11.64 ± 1.75 μg m^{-3} OC and 3.46 ± 0.19 μg m^{-3} EC) during the monsoon period. The highest amounts of OC and EC were observed in post-monsoon (17.67 ± 1.1 μg m^{-3} and 6.34 ± 0.75) and in winter (17.31 ± 3.04 μg m^{-3} and 6.32 ± 0.58 μg m^{-3}) [39].

EC levels are generally known for anthropogenic air pollution and decisive global warming factor[73]. Incomplete fossil fuel combustion and burning biomass produce atmospheric EC. However, in addition to primarily emitted OC, VOC oxidation releases secondary organic carbon (SOC) into the atmosphere [67]. The results of the EC-tracer method for segregation of primary organic carbon (POC) and secondary organic carbon (SOC) revealed that the impact of SOC on PM_{10} concentration increased by nearly 5% after the monsoon and by 16% in winter at homes. In contrast, at traffic sites, it increased by 2% after the monsoon and by 7% in winter [74]. Noticeably, this region observes forest fires during the pre-monsoon season, which could help assess its impact on air quality. The source appointment diagnostic ratios approach is among the extensively employed semi-quantitative methods. It is anticipated that the quantities of various organic species will vary based on the source and due to distinct modes of molecule generation under particular combustion settings. Because organic species may change their properties from the emission inventories to the receptor site, the diagnostic ratios technique suits polluted areas close to point sources. Therefore, due to forest fires as a point source, this region is also vital for identifying diagnostic ratios for source appointment studies [30, 75]. The survey in other areas (e.g., Himachal Pradesh) showed PM_{10} concentration increased due to regional traffic, industrial pollution, and long-range transport of pollutants; thus, these sources also contribute in total pollution. They further observed the generation of SOC causes OC/EC ratio variations in various periods of the year [48].

Moreover, oxygen availability and temperature are the main elements determining the concentration of EC generated in combustion activity. Low temperatures and less oxygen availability in closed-chamber combustion yield greater EC and vice versa [76]. The aging processes modify these aerosols' hygroscopic, morphological, and chemical properties. Experiment results show that EC is chemically inactive but catalyzes photochemical soot aging by improving the oxidation of organic components [77]. Furthermore, vehicle exhaust and BB have been recognized as local pollution sources. The ratio of OC/EC implies that local pollution production dominates long-distance transport throughout this region [39].

A colder and more stable environment always favors the condensation process of newly formed organic substances from vehicular emission [78]. Cong et al.[79] vividly demonstrate high-altitude BB Himalayas spread through mountain wind system mechanisms. The concentrations of carbonate aerosols exhibit a typical trend, with a minimum in monsoon, a maximum in the pre-monsoon season, and a sluggish recovery in the post-monsoon noticed in various Himalayan sites [80, 81]. Decesari and coworkers [81] collected samples for two consecutive days in the afternoon (14:00 to 18:00) and claimed that light-absorbing aerosol produced by combustion sources, with non-negligible EC concentrations of 0.36 µg scm^{-1} (standard cubic meters), can be carried up Himalayan glaciers. However, due to the complicated geography of the Himalayas, the absence of PM studies in the southern and central Himalayan regions is a significant challenge to considering the impact of aerosols on diverse climate developments [38].

2.4 PM-bound Water-Soluble Inorganic Ionic Species (WSIIS)

WSIIs such as cations (K^+, Ca^{2+}, NH_4^+, Na^+, Mg^{2+}) and anions (NO_3^-, SO_4^{2-}, Br^- Cl^-, F^-) are a substantial part of PM. Table 1 lists some major WSIIs and their relative contribution to ambient PM in Himalayan regions. It was found that these water-soluble ions account for approximately 68 percent of the $PM_{1.8}$ fraction and 50 percent of the PM_{10} mass concentration. [82]. Among all WSIIs, sulfate, ammonium, and nitrate are found in higher concentrations in all PM fractions (PM_{10}, $PM_{2.5}$ and $PM_{1.8,}$ etc.) [83, 84]. A study by Ying and Kleeman [85] stated that the precursor gaseous species produced 80% of the $PM_{2.5}$ bounded ammonium released from sources upwind of the valley. At the same time, another research by Han et al. [86] addressed that these water-soluble species contribute 35-60%to $PM_{2.5}$ concentration in Korean industrial cities. Ambient sulfate mainly forms by the oxidation of sulfur dioxide (SO_2). The oxidation process of SO_2 is prolonged; therefore, the increment of sulfate within ten miles area is considered insignificant. However, with the increase of spatial gradient, it feels significant (at hundreds of miles) and very large at the whole continent level. Sometimes sulfate may be very high in an urban area; many studies consider sulfate a surrogate for $PM_{2.5}$ [87].

In Gual Pahari (Himalaya site at the north-west of IGB), soluble inorganic species were substantially improved (~23 percent). In comparison to Delhi, Gual Pahari's major secondary inorganic (SI) species were around 52% higher post-monsoon than Delhi during January-December 2008 [46]. In comparison, Delhi's main crustal elements (Al, Si, Fe, Ca, and Na) were around 76% higher than in Gual Pahari during the monsoon

and summer seasons. This shows considerable spatial inter-seasonal flexibility in aerosol source and composition at these locations [46]. Half of the mass comprises organic material, EC, and inorganic ions, the remainder of which is mineral dust. For instance, organic matter (OM) amounted to 2.0 μg m^{-3} per year, and apart from mineral oxides, it is by far the main component of PM_{10}. The quantities of ionic aerosols are consistent with carbonate, higher in the pre-monsoon season, minimum throughout the monsoon period, and a sluggish recovery in post-monsoon [81].

An ambient nitrogen dioxide (NO_2) forms nitrate on oxidation; regarding PM studies, ammonium nitrate is a primary form of nitrate in the atmosphere. These nitrates remain in equilibrium by reacting with nitric acid and atmospheric ammonia [88]. NO_2 oxidizes more rapidly than SO_2, and ammonium nitrate concentration in the atmosphere is sensitive to ammonia, increasing dissociation. Sometimes, sodium nitrate may also be the dominant form of nitrate. Compared to sulfate, the spatial gradients of nitrate are less uniform.

The neutralization of sulfuric acid and nitric acids is carried by atmospheric ammonia [89]. Such a neutralization process displaces hydrogen ions, and nitrogen ions in concentration reach higher than hydrogen ions, particularly in an urban environment [90]. The events of sea spray form chloride, which further disperses in the atmosphere even a hundred miles away from the coast. The chloride also comes into the atmosphere from the power station and incinerators, where ammonia neutralizes hydrochloric acids. The combustion of fossil fuels enriched with sulfur is a significant source of SO_2. These are essential precursor gas for particle nucleation in the atmosphere [91], while the highest values in the western Himalayas during winter, and the lowest were observed in the same year's monsoon [48].

2.5 PAHs

The benzene contained organic species with two or more benzene rings [30]. These are usually partitioned into the particle and gas phase due to half combustion of fossil fuel and organic materials' carbonization [92]. Fuel combustion in vehicles (gasoline and diesel) and coal, wood, and biomass combustion is a critical PAH source [30]. The organic species bond to fine fractions of PM as 95% of total PAHs bound to particles of less than 3 μm diameter; studies reported that an excessive number of PAHs present in a respirable fraction of PM and dominant PAHs species of $PM_{2.5}$ are fluoranthene, benzo-anthracene, benzo-pyrene, pyrene, benzo-fluoranthene and chrysene [93, 94]. Mehmood et al. [30] reported that higher ring PAHs (4, 5, and 6 rings) comprise 70-

90% and 78 to 91% of total PAHs in $PM_{2.5}$ and PM_{10}, respectively. Mostly 90% of PAHs emits from stationary sources; however, it is also valid in the case of urban sites where vehicles (mobile sources) are abundantly used [95].

Generally, megacities are reported with elevated PAH levels due to people's higher mobility via transportation and energy sources (heating systems). Moreover, a source of benzo-fluoranthene, fluoranthene, chrysene, benzo-anthracene, pyrene, and anthracene indicates that dominant PAH species evolve from the coal combustion process. In contrast, benzo-pyrene anthracene, benzo-perylene, and phenanthrene emanate from the coke oven. Some other PAHs species, including pyrene, anthracene, fluoranthene, and phenanthrene, emits from wood burning, while benzo-pyrene, benzo-anthracene, and benzo-perylene are significant petrol tracers in engine combustion. Waste incinerators produce fluoranthene, pyrene, and phenanthrene, while industrial incinerators produce indeno [1,2,3-cd] pyrene and chrysene [75].

The mean concentration of total PAHs associated with PM_{10} in ambient air in Kolkata was discovered 5 times greater than in Darjeeling, indicating significantly increased PAH pollution at IGP compared to a high-altitude Himalayan station during 2017–2018 dry seasons [96]. Nevertheless, both locations found PAH concentrations in pre-monsoon were low. The shallower border layer could concentrate PAH close to the surface and increase the concentration over Kolkata throughout the winter. Darjeeling is above the boundary layer (BL) and does not affect the dynamic BL. Local anthropogenic emissions may be one of the most critical variables shaping the seasonal variance of PAHs at Darjeeling. The minimum PAH loading over Kolkata during the pre-monsoon was mainly because of a BL improvement, which favored the pollutant diffusion with high sunlight fluxes that catalyzed the photo demolition of PAH particles. Solar radiation also plays a crucial impact in controlling atmospheric PAH in Darjeeling during post-monsoon and pre-monsoon [96].

2.6 Biogenic source

The particulates with the biological origin are termed bioaerosols; moreover, some studies also consider and enlist them as OC. These bacteria, pollens, and plant-oriented fragments are usually found in coarse particulates [97]. However, some bacterial and fungal spores were also reported in $PM_{2.5}$ [98]. They tend to attach to coarser particulate fractions. The biogenic contributions of SOA to $PM_{2.5}$ OC content were between 2-19% for isoprene in the 2005 monsoon and post-monsoon seasons, 1-5% for monoterpenes, and 1-4% for sesquiterpenes. In the late summer months, high isoprene derivatives in

aerosols indicate that biogenic SOA is a substantial resource of OC in the Himalayas region [99].

3 Factor contributing to PM pollution

Diurnal PM variations were associated with differences in the planetary BL, mountain-valley winds, and changes in local emission sources [50]. The study shows that during the post-monsoon to winter transformation, both meteorological processes (winds, temperature, mixing boundaries) and the relative influence of emissions (BB versus anthropogenic) have changed dramatically, leading to an increase in $PM_{2.5}$ values in the IGP region [50]. Likewise, high-altitude Himalayan station Nepal alley breeze circulation substantially impacted the chemical composition of PM_{10}, PM_1 and is an efficient way to transfer anthropogenic aerosols into Asia's high troposphere (>5000 m a.s.l.). In addition, valley breezes influence mineral dust concentrations, which have a yearly cycle that suggests sources in central and south-west Asia. [81]. Valley breezes influence mineral dust concentrations, which have an annual cycle that offers sources in central and southwest Asia. Moreover, residential energy use is estimated to significantly impact the annual average $PM_{2.5}$ in the region among different anthropogenic sectors. Future regulations adopting these would complement the Indian Government's current measures to reduce the home use of biomass cook fuels. BB sources dominate West cities, and east cities are predominated by anthropogenic sources after the monsoon; with winters, this gradient is weakened when anthropogenic sources dominate the entire region from west to east [96]. However, a generic emissions reduction policy does not produce the intended outcomes. It advocates a seasonally-based approach for source-focused mitigation that Omni presently considers adverse regional dynamics to improve air quality and limit the climate effect [55]. Kanpur is a large industrial city in North India that represents the patterns of urban agglomeration, weather conditions, and atmospheric seasonal variability in the IGB region. Behera and coworker [74] stated increase in primary emissions along with unfavorable meteorological conditions (low temperature and poor dispersion) during winter could enhance the process of nucleation, condensation, agglomeration, and aging, leading to higher levels of carbonaceous aerosols in the study area.

3.1 Topography

Multiple efforts have been made to explore air pollution in Himalayan locations. For example, the complex steep topography in the eastern and northern Himalayas has indicated that contaminants from the IGP area can be trapped and, therefore, pollutant concentration increased [55]. In addition, the diurnal variation of PM_{10} and $PM_{2.5}$ might be ascribed to variations in the planetary boundaries, wind patterns, mountain valleys, and differences in emissions source intensity in the local environment [50].

The wind mechanisms caused by the mountain valley's topography and the valley's geometry seem to firmly control the synoptic-scale hazes extending from IGP to the sample region and precipitation in the PM size distribution diurnal cycle [45]. The dynamic BL plays a vital role in capturing pollutants across the region, and the reversal layer operates on the top and stops the dispersion above BL. Low border height generated a rise in carbonate aerosol concentration across the region. High concentrations of pollutants are observed in the pre-monsoon period, irrespective of deep borders, due to the increasing influx of pollution from BB in northern Indian states [39].

3.2 Influences of emissions: anthropogenic versus BB sources

In December, the effects of recorded forest fires in the sub-Himalayas are most evident in that region, with a smaller impact on the IGP. By switching anthropogenic emissions, very high (80-100%) reductions in $PM_{2.5}$ simulation of the IGP region, except for the post-monsoon north-western area, with a significant impact on the biomass combustion emissions (noticed in the left panel of Fig. 4) [55].

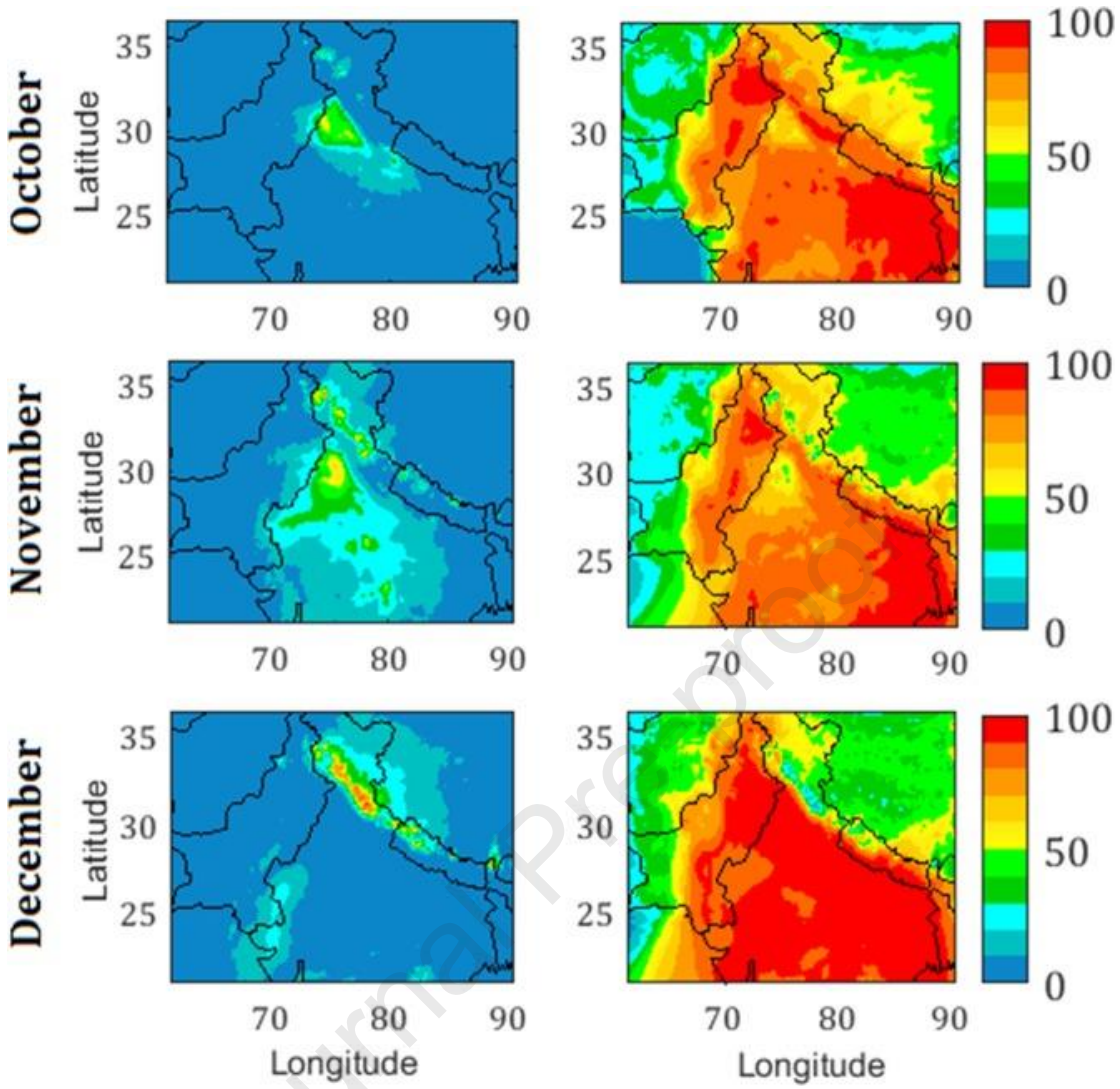

Fig. 4 *Reduction in $PM_{2.5}$ (%) concentrations due to switching off the biomass-burning (left panel) and anthropogenic emissions (right panel) as compared to the reference simulation. Reproduced from ref. [55] Copyright © 2020 Springer Nature.*

During December, anthropogenic emissions have influenced the entire IGP region by 90–100%. The model results have revealed considerable effects on $PM_{2.5}$ emissions from Delhi in the middle of October to mid-November (daily values up to 55.4%) ascribed to the upwind biomass combustion **(**Figs. 5 and 6). Such impacts from BB are also significant in other places within the IGP during this period, but effects are smaller (up to 36.3 percent reduction in $PM_{2.5}$) than in Delhi.

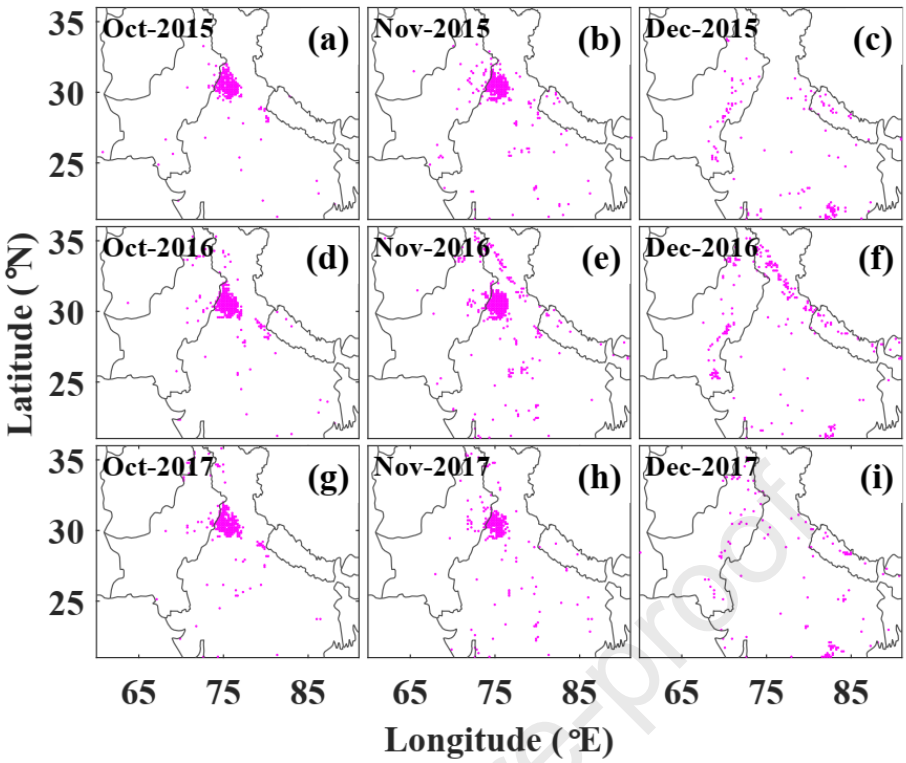

Fig. 5 *Fire locations (having fire detection confidence > 80%) over the northern Indian subcontinent during October, November, and December of years 2015, 2016, and 2017 based on the MODIS observations. Reproduced from ref. [55] Copyright © 2020 Springer Nature.*

During the post-monsoon period, the mean relative impacts of BB in Delhi, Varanasi, and Kanpur were estimated at 30.2, 9.4, and 19.6 percent for $PM_{2.5}$, respectively. However, the effects of biomass combustion reduced gradually in all stations reaching minimum values (~5 percent or less) in December from mid-November. Simultaneously, in December, the impact of anthropogenic emissions on $PM_{2.5}$ concentration at all sites raised to above 95%.

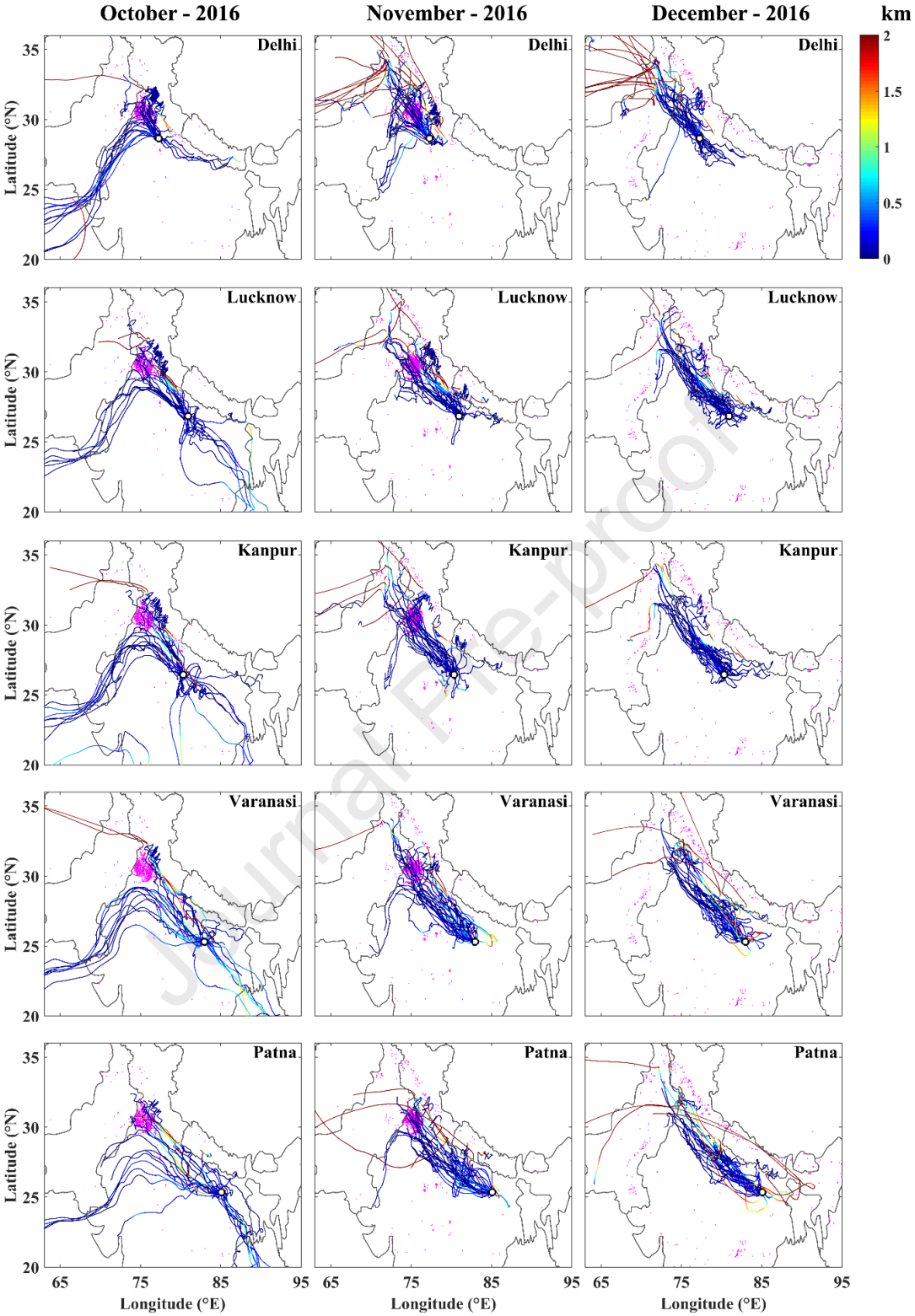

Fig. 6 *7-day back air trajectories at different stations above 200 m (agl) in the IGP region together with the MODIS fire locations during October, November, and December 2016. The Color along the trajectory shows altitude (km) of airmass above the ground level. Reproduced from ref. [55] Copyright © 2020 Springer Nature.*

Reductions of 20 μg kg^{-1} of dry air in NO_3^- were modeled in the absence of fire emissions from the Northwest IGP, and significant OM (~50 μg kg^{-1}) and EC (by ~10

μg kg^{-1}) decrease in the absence of fires were also simulated in November. Studies show that BB emissions are considerably influenced by the composition of $PM_{2.5}$ in the IGP region. Biomass combustion contributions to NO_3, NH_4^+, OM, and EC decreased greatly throughout December. In contrast, secondary inorganic (NO_3, SO_4^{-2} and NH_4^+) species often have significant anthropogenic emissions impacts (**Fig. 7**).

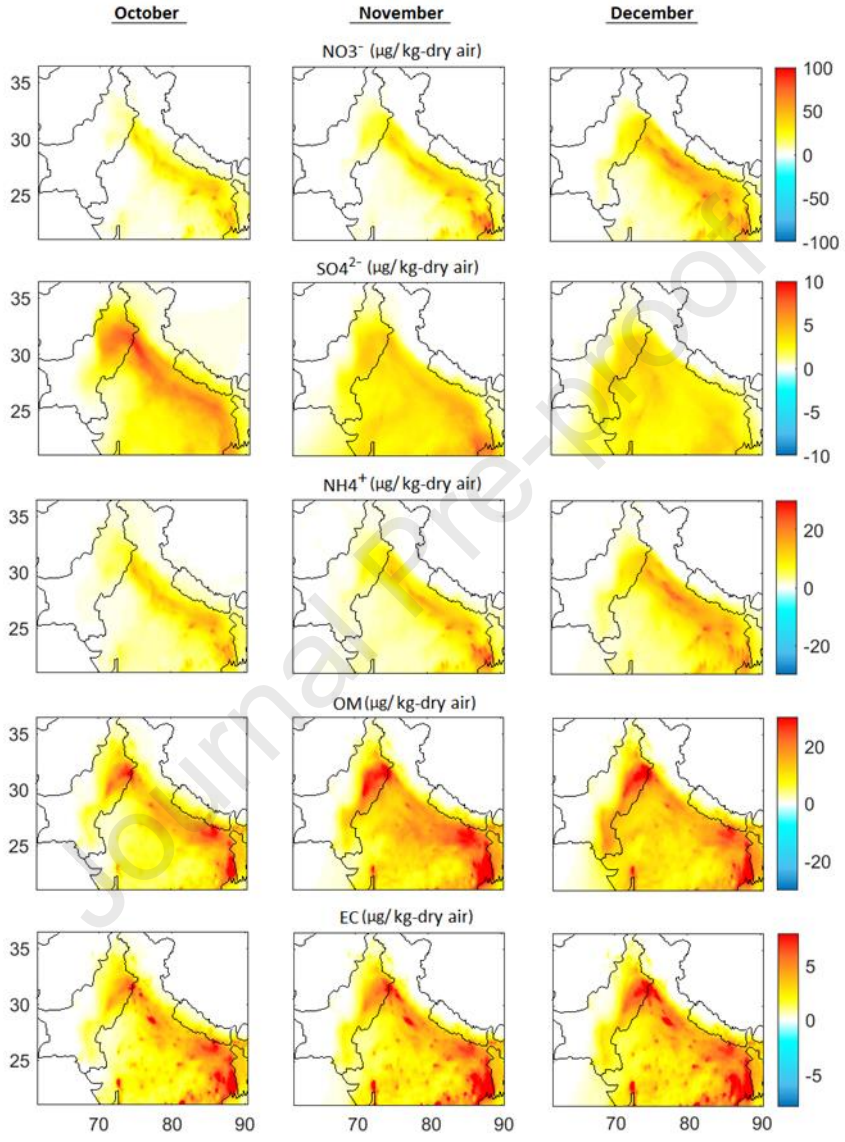

Fig. 7 *Spatial variation of difference (ref-anthro_off) in the $PM_{2.5}$ composition between WRF-Chem reference simulation and anthro_off simulation during October, November and December 2016. Reproduced from ref. [55] Copyright © 2020 Springer Nature.*

Emissions from open fires in pre-monsoon and after the monsoon are considerably affected by IGP [100, 101]. The fire sources may be natural (e.g., forest fires triggered by lightning strikes) or result from anthropogenic activities, such as burning forests and shrubs for agricultural purposes and combustion of agricultural residues [102]. Burning forests and agricultural fields serves various purposes, including mobilizing nutrients and removing insects, litter, and waste for agriculture [103, 104]. In addition, the open

586 burning of agricultural residues is a major pollution source, negatively impacting
587 climate, air quality, and human health [105].

588 Moreover, open fires release large volumes of atmospheric gases and aerosols,
589 including major anthropogenic sources driving climate like BC, methane, and CO_2
590 [106, 107]. Current patterns of agricultural burnings revealed by Sembhi et al. [57]
591 could impair the air quality of Ludhiana and Delhi by 30% and 4.4%. The bulk
592 concentration of PM increases dramatically during the summer season in May and June
593 due to the on-site burning of rice crop remains [72]. A high amount of pollutants across
594 South Asian territory due to CRB, especially during the pre-monsoon period [1, 108],
595 may damage the region's farm productivity and food security during the Summer
596 Monsoon [54].

597 BB and forest fires in IGP and neighboring areas are affected by pre-monsoon and
598 post-monsoon concentrations. The primary cause of OC/EC on sites are vehicle exhaust
599 and biomass combustion, showing that local pollutant production dominates long-range
600 transport across the region. Recent studies show that the severe occurrences of air
601 pollution were predominantly caused by CRB and regional forest fires paired with
602 weather favorable to transporting pollution [39]. The combustion of fossil fuels was
603 also considerable, representing more than half the environmental BC concentration by
604 Lumbini spectrum light absorption coefficients [109].

605 However, real-time detection of PM-bound BC from these open fires is still
606 inadequate in the Himalayas and its foothills. Operational guidelines from the
607 government encourage agricultural mechanization for the local management of crop
608 residues, which supports the farming community in the timely management of too much
609 residue [110]. The National Clean Air Program (NCAP) strives to reduce emissions
610 from different industries, including using agricultural residues, and stopping CRB
611 would help a lot with the newly established national program [57]. By NCAP, 20 – 30
612 % decrease in $PM_{2.5}$ and PM_{10} concentration annually by 2024 was proposed
613 considering the base value of 2017, with a constant focus on addressing intensive post-
614 monsoon air pollution occurrences. This is particularly crucial because almost 149,000
615 estimated disability-adjusted life years in Northern India might be prevented by
616 discontinuing CRB [111].

617 **3.3 Transport from IGB to Himalaya**

618 The average monsoon period concentration levels were 55% to 70% lower than the
619 intermediate pre-monsoon level in northern areas of India [28]. PM concentrations in

the pre-monsoon period were impacted by primary emissions, most probably due to the Thar desert dust events. In Mukteshwar, the Himalayan region provided extra dust from the station's east side [28]. The Himalayas and the nearby IGP region are facing the most deteriorating pollution problems by the regional transport of pollutants, particularly in the post-monsoon season. Moreover, BB and open burning of agriculture residuals are also causing ABCs, cloud condensation nuclei (CNN), haze, and other air pollution phenomena. The Indian sub-continent, in particular, the Indo-Gangetic Basin (IGB), is one of the most polluted and populated regions in northern India, usually considered PM hotspots globally, and has expressed great concern about the harmful effects of adverse air quality [112, 113], and human health [114].

The increase in aerosol load over the IGB results from a wide range of anthropogenic activities, including multiple emission sources, a variety of synoptic meteorology, and a distinctive terrain [115-117]. Severe smog is common in IGB during the winter months due to typical weather circumstances (such as night-time temperature inversion and calm wind conditions). Significant surface emissions, mainly agricultural and CRB, contribute to pollution deposition [118, 119]. Furthermore, in the pre-monsoon and summer seasons, IGB obtains transported particles from neighboring Desert areas [120-122]. Many previous studies characterized PM Spatio-temporal and inter-annual pollutant variation, the impact of plumes, and high local pollution being transported to downwind regions over IGB [37, 70, 118, 120]. At local to regional and shorter to longer-term levels, these studies have explained the origins and implications of the large variation in aerosol concentration over this area and linked interannual variability with changing regional climate. In the IGB region, two neighboring sites (Gual Pahari and Delhi) exhibit the high optical, chemical, and radiative transported impacts of Delhi's secondary inorganic aerosol in urban areas on the downwind semi-urban Gual Pahari site [123].

During winter, the maximum aerosol load is mainly related to increased local emissions, IGB transportation, and weak turbulent convective mixture. In contrast, the lowest values in the monsoon season are anticipated to a significantly cleaner sea air input and precipitation scavenging. Tezpur is situated in the middle of Brahmaputra valley; due to its closeness to the Kaziranga national forest, which contributes to blocking the flow of PM, it is somewhat cleaner than neighboring stations such as Agartala and Dibrugarh [49]. However, Srinagar's OC/EC ratio suggests that local pollution production dominates long-range transport across this region [39].

Furthermore, the sources of pollution were reported to vary temporarily in Darjeeling (Eastern Himalayas) [19], Kothi, and Mohal (Western Himalayas) [22], where long-range transportation became a major source in summer, while emissions from human-based activities such as BB dominated the winter [55].

At different altitudes on the southern slopes of the Himalayan range, ground-based measurements have confirmed that pollution from the low-lying IGP spreads across the region and that south-westerlies start to form in the pre-monsoon period. On the other hand, local sources always influence ground-based studies; thus, long-range transport cannot be differentiated from local emissions [45]. According to Rupakheti et al., in Lumbini, the nearby regions, primarily the Ganges Valley and some areas of Nepal and India, contributed the most to the higher pollution concentrations [124].

3.4 Influences of meteorology and dynamics.

Carbonaceous and ionic aerosol concentrations exhibit a typical time-series trend, high during the pre-monsoon, low in the monsoon, and a slow recovery in the dry and post-monsoon seasons. This is consistent with research from different studies on Nepalese Himalayan sites. PM's chemical composition is significantly influenced by the valley breeze circulation, which is nearly always active in the Himalayas during the non-monsoon season and provides an efficient route for delivering anthropogenic PM into Asia's upper troposphere (>5000 m). Mineral dust concentrations are impacted by the lesser extent of valley breezes and exhibit a different seasonal cycle, revealing the existence of many regions source throughout central and south-western Asia [81]. They found half of the PM_{10} mass at a high altitude observatory in Nepal was organic, EC, and inorganic ions, with the rest being mineral dust. Aside from mineral oxides, OM 2.0 μg m^{-3} (i.e., 3.6 μg scm^{-1}, annual average values) is the most significant component in PM_{10} samples (sampling time: 48 h).

During the monsoon, daily mean $PM_{2.5}$ values in Mukteshwar were usually lower than the Indian air quality standard of 60 μg m^{-3} for 24-hour period (satisfactory level) [28]. Over Kolkata and Darjeeling, there was a negative association between wind speed, temperature, total PAHs, and solar radiation [96].

In November, meteorological and dynamical conditions caused the BL to be suppressed by 200–250 m over the western IGP and 250–350 m over the eastern and central IGP. Meteorology and regional-scale dynamics are thought to have been critical in the extensive buildup of $PM_{2.5}$ across the IGP, especially in December. Every year, such variations in the weather circumstances significantly reduce the ventilation across

the IGP (e.g., Fig. 7**)**. In the IGP region, aerosol-radiation exchanges are proposed to slow the formation of the BL by limiting the amount of solar radiation reaching the surface. This phenomenon can raise PM pollution [55].

The winter season tends to reduce the ventilation of aerosols due to low mixing, increasing $PM_{2.5}$. Aside from other factors, the elevated aerosol values during the pre-monsoon period were linked to BL conditions. Aerosol scavenging is caused by significant rains caused at minimal levels in the monsoon season. Similar to Nepalese Himalayan regions, shifts of moist and dry convection northern climate wet scavenging processes exhibited a low level of carbonaceous and ionic species in PM_{10} during monsoon, which slowly increased in post-monsoon and reached maximum in the pre-monsoon period [81]. Likewise, the levels of aerosols were greater in 2015 than in 2016, which could be attributed to the increased rainfall in 2016. Variations in mountain valley wind patterns could explain the daily variance of aerosols ($PM_{2.5}$ and PM_{10}) [50].

4 Salient features of pollution in Himalayan region

4.1 Cloud condensation nuclei

Atmospheric aerosols originating via various anthropogenic and natural sources considerably control the budget for radiation on the Earth via direct or indirect influence on the climate and the hydrological cycle [125, 126]. While aerosols directly impact the environment by absorbing and scattering terrestrial and solar radiations [127], they indirectly modify cloud-based microphysical and radiational properties and hence rainfall patterns by activating CNN [128]. The size and chemical composition of aerosols, as well as their effects, are closely linked [129][130], which are further amended with developments involving primary emissions, secondary production, and aerosol morphology [131-133]. Throughout recent years, forest fire incidents have continued to occur in the Himalayan foothills. Therefore, the quantification and prospective effects of generated BC aerosols are crucial. The impact of anthropogenic particulates, mainly of the absorbing type, has possible consequences for local and major weather patterns and extreme weather scenarios in the foothills of the Himalayas [134]. In addition, the radiative force of carbonated aerosols increases the heating of the atmosphere, which can lower the vertical temperature gradient, thus stabilizing the atmospheric spine and reducing rainfall [135]. Pollutants in the Himalayan valleys are transported at high altitudes by valley gusts triggered by the hot springs between the

mountain and valleys [136, 137]. These small convective events can carry contaminants to high levels of the atmosphere and even persist well above the border layer. Massive circulations could transfer these aerosols to nearby glaciers in the Himalayan region. Multiple research studies have shown that deposited BC aerosols on snow can melt glaciers by increasing the snow albedo feedback [38, 54].

Model and satellite observational studies demonstrate a 2.5 °C surplus heating of pre-monsoon aerosol across the Himalayan region in the last four decades [138]. Carbonated aerosols are possible climate-forcing factors and are largely below 2.5 μm in size. These particles are produced mainly by carbonate substances such as OC and EC [139, 140]. Fresh EC particulates are hydrophobic in nature and are hardly likely to function as CCNs under common atmospheric conditions because of non-significant hygroscopic growth [141]. However, rising primary emissions and bad weather conditions in the winter can improve the nucleation, aggregation, condensation, and aging process, leading to more significant carbonate aerosols [142].

Moreover, the river's valleys form deep narrow pockets suited to accumulate aerosols from the lowly IGP region, altering their spatial distribution throughout the medium mountainous region. This might significantly influence the orographic precipitation microphysics in this location by changing the CCN spectrum. It takes collisions between droplets and subsequent coalescence for cloud droplets to aggregate into larger raindrops, which starts the rain process [143, 144]. The increase in CCN concentration affected precipitation by delaying or inhibiting the microphysical process of cloud formation [145, 146]. To examine the indirect effect of the aerosol, it is necessary to directly measure the CCN spectrum, chemical composition, and aerosol size distribution [147].

Although little research has been done in Nepal, the majority of it has been confined to the highest elevations in terms of measuring the aerosol size distribution; At Shorong Base Camp (4900 m) [148] and Khumbu Valley (5079 m), researchers observed the aerosol diameter were between 10–700 nm [149]. Another study at different altitudes (1300-5000 m) suggested that winds may be responsible for transporting pollution from the valley to the ridge [150]. However, few scholars have explored the ridge-valley circulation to clarify the Kathmandu Valley's daily diurnal cycle of aerosols [151, 152]. Nevertheless, no previous ground studies were conducted to calculate the aerosol size distribution in lower elevation ridge-valley zones, where the IGP's aerosol haze could modify orographic precipitation.

The researcher measured the chemical and optical properties of aerosols from 1999 to 2000 at two Nepalese locations: Langtang (3920 m) and Nagarkot (2150 m) [153]. In 1999, there was a peak in the aerosol optical depth during the springtime that was greater than 1.0 at Nagarkot, Nepal. Another study reported monthly mean concentrations for OM from a one-year collection at the Godavari in Kathmandu Valley [104]. A total of 326 samples with 24-hour average concentration yielded an annual mean $PM_{2.5}$ concentration of 26 ± 19 μg m^{-3} in 2006. At the same time, average mass concentrations per 24 hours varied from a high of 120 ± 10 μg m^{-3} in the middle of January to a low of 0.8 μg m^{-3} in the middle of August. The fraction of soluble ionic species and their chemical composition provide CCN characteristics. Still, little is known about the aerosol size spectrum over these valleys from which CCN estimates can be inferred. Furthermore, because organic species predominate, the soluble organic fraction plays a crucial role in calculating the CCN spectrum appropriately.

4.2 Atmospheric Brown Clouds (Haze)

Increasing pollutant emissions connected with South-East Asian countries' fast-growing economies have gradually increased aerosol levels, with an observable positive trend over the previous three decades [138]. Satellite data indicate that light-absorbing ABCs (hazes) over India grow across the Thar desert and IGP, with a sharp boundary defined by the Himalayas, which function as a barrier and stretch thousands of kilometers [1, 154]. According to research, the high Himalayas are located in an area mainly undisturbed by Indian ABCs and dust layers initiated in central Asia [155]. However, the Cloud Aerosol Lidar and Infrared Pathfinder Satellite (CALIPSO) has adequately assessed the vertical extent of the Indian ABC only since April 2006, highlighting dense ABCs over northern India that can be 3-5 km thick [1].

Furthermore, valley winds in the Himalayan mountains can transfer aerosol-rich BL air to higher altitudes [150]. Analogous processes of vertical pollution transport on steep mountain slopes have already been identified in Europe [156]. The transport of optically active aerosol to the elevated Himalayan areas is concerning, as the region's glaciers have been receding with increasing melting rates since the 1820s [157], and are in danger of completely vanishing in the coming decades [158]. If the Himalayan glaciers continue to recede unchecked throughout this century, water scarcity will worsen in northern India, particularly during the dry season. Furthermore, India's reliance on freshwater supplies from the Himalayas is likely to grow in the future due

to rising water use for industrial and agricultural purposes, fueled by rapid economic expansion.

Moreover, the coarse and fine PM concentrations obtained from size distributions collected by online OPC (GRIMM 190) exhibited remarkable differences linked to changing wind systems and air masses. PM_1 levels, for example, can be as low as 1 μg m^{-3} in dry air from the Tibetan plateau and as high as 10 μg m^{-3} in humid air delivered from Nepal via upward winds [80]. Such significant changes in particulates imply that the Nepal Climate Observatory-Pyramid (NCO-P) site captured air masses from the middle and lower troposphere at the northern border of the Indian ABC, to study the vertical transport of particulates to the Himalayas and IGB.

Previous remote sensing data and in situ measurements show the upward transportation of aerosols from the lower Nepal provinces and upwind regions on the southern side of the higher Himalayas, representing the northern shore of the Indian ABC, has been affected. Sulfate levels at NCO-P are almost equivalent to values of other Himalayan stations and five to ten times smaller than in pollutant areas in the Indian subcontinent. Carbonated aerosols frequently have a sharper vertical gradient, especially during the dry season, with 2 times the magnitude variations between NCO-P in India's most polluted metropolitan areas. In NCO-P, the carbonaceous particulates levels are mainly regulated by a direct injection by the valley-breeze circulation of limited layer air upward. Mineral dust is a major part of PM_{10} in NCO-P, with an average seasonal value ranging from 0.5 to 10 μg cm^{-1}.

Moreover, even in remote Himalayan locales, Springtime PM concentrations exceed WHO air quality guidelines [47]. Recently WHO updated the recommended values of air pollutants which are stricter for general public health. According to the new guidelines for PM_{10} and $PM_{2.5}$, the recommended values are set to 15, 45, and 5, 15 μg m^{-3} for annual and 24-h maximum threshold levels of PM_{10} and $PM_{2.5,}$ respectively [159]. Based on 2 years of monitoring particulate's chemical composition, it is evident that a transit of anthropogenic aerosols constituting the Asian ABC is impacting the southern side of the high Himalayas [81]. During the last decade, PM_{10} studies in South and East Asia have shown that the values may range from a few tenths to hundreds of μg m^{-3} of air across large areas with significant light absorption components (iron oxides and BC). [125]. Such dense PM hazes substantially impact air quality and tropospheric temperature rate [1, 160].

The aerosol concentration was increased in the existence of regional-scale haze in dry seasons [45]. During the studied period, the synoptic-scale winds and the diurnal profile of wind observed suggest that aerosols may be transported from the low terrain to the inner valleys of the central Himalayas throughout the day. A study conducted by Shrestha et al. gives new insights into the role of the mountain valley circulation in aerosol perspective and mass concentration across the central Himalayan range and documents the function of synoptic transport and climatic control (rainfall and haze events) in regulating the diurnal cycle amplitude and daily variability [45].

4.3 Dust event

Despite the susceptibility and heavy metal content dependence upon several temporal and spatial factors (precipitation, PM concentration, removal efficiency, wind deposition, etc.), a critical correlation entails that the former acts as an efficient proxy for metallic pollution. Anthropogenic pollution hotspots with high magnetic material inputs can be identified using magnetic susceptibility studies of leaf magnetic susceptibility. In brief, magnetic susceptibility is a material's response to a magnetic field. Magnetic susceptibility can monitor metals and or hydrocarbons in soils, sediments, dust, and fly ashes [161]. Magnetic susceptibility can also help define environmental pollution processes. Schädlich et al. [162] and Knab et al. [163] in Germany used conifer needle susceptibility as a pollution proxy in an industrial zone influenced by fly ash deposition and a relatively cleaner area in the black forest. Moreno et al. [164] used susceptibility and isothermal remanent magnetization (IRM) of dust-loaded deciduous tree leaves (Platanus sp. and Quercus Ilex) to map traffic emissions in Rome. Hanesch et al. [165] established the capacity of maple tree susceptibility and IRM to susceptibility ratio to monitor short-term (up to several months) dust deposition. Therefore, sensing-based monitoring technology is suggested as a cheap and speedy approach to measuring environmental contamination in metropolitan areas such as Kathmandu [161]. Despite the success of these procedures, there are no sampling or study standards [161]; thus, more studies require proper interpretation of findings and deduction of conclusion-based assessment, which may require more advanced and specified sampling and characterization approaches [166].

PM was mainly exceeded during the pre-monsoon season due to dust being transported from the Thar Desert and the Arabian Peninsula, separate from increased visitor activity. Moreover, organics and sulfate aerosols substantially improved during

the dust episode. Additionally, dust from the Thar Desert reaches the western and central Himalayas in the spring [167, 168].

In the pre-monsoon months, haze is denser as wind-blown desert dust contributes, much of which originates in the Thar Desert [154, 169]. In the Kathmandu valley, soil dust, including road dust, predominantly contributes up to 26 % of wintertime PM_{10} [170]. Overall, the emissions are generated from mixed PM sources, both local and remote, as studied in the Mahabaleshwar region (high-altitude location in the Western Ghats region in southwest India) [50]. Major sources of aerosol absorption (BC and dust) are in Asia, comprising anthropogenic emissions (biofuel, fossil fuel, and CRB) and natural dust aerosols from the desert. So, it is concluded that local industry, road emissions, dust from the desert, and long-range emissions enhanced PM concentration in the Himalayas region [48, 168, 170].

A brief detail of different natural and anthropogenic factors contributing to air pollution in the Himalayas region and IGP is given in Table 5 and Table 6. It can be perceived by comparing both tables that most of the pollution at IGP is due to local and anthropogenic sources. Particularly burring of crop residuals and biomass, formation of secondary pollutants, and monsoon influence are dominated in IGB than Himalayas region. In contrast at Himalayas region's primary and natural pollution sources also contributed substantially. Forest fires, dust, transboundary movement of pollutants from IGP, tourist activities, and wood burning are dominant pollutants sources in the Himalayas. At the same time, topography, monsoon, and unique wind patterns modulate pollution episodes. However, the comparative studies based on a simultaneous sampling of the Himalayas region and IGP are minimal; primarily, natural and anthropogenic sources contribute to total pollution, and it is difficult to distinguish them from PM arrived from long-distance transport. Thus, more ground-based sampling is needed to provide a comprehensive assessment and projection of pollution levels and consequences in the Himalayas region in the coming years.

5 Conclusion and Future Studies

Currently, the issue of air quality has become a focus for major cities with the rapid development of the economy and urbanization. Studies on PM have garnered great scientific attention due to the characteristics of air pollution and their significant health repercussions. In this review paper, the Himalayas region is selected as a study area to

analyze the sources and characteristics of PM. The spatial-temporal change of PM in the Himalayas region has its specific features, and the meteorological factors are essential factors that affect PM concentration. The topography, BB, airmass trajectories, and meteorological factors strongly correlate with the PM concentration variation and the resultant deterioration of air quality in this region. These factors are the leading cause of both PM concentrations ($PM_{2.5}$ and PM_{10}) in the Himalayas region, exceeding the WHO standard for annual and 24 h (mostly during post-monsoon days).

For future studies, several improvements and extensions are feasible, i.e., a more dependable automated weather station (AWS) should be installed for further research of the interplay between meteorological and pollution concentration characteristics. Continuous air pollution measurements would enable annual and seasonal variation studies all year round. The regional emission inventory created at the national and continental level versus the local bottom-up inventory and the pollutant emissions from small, open burning that are not detected by satellites is significantly uncertain. Continuous air quality monitoring stations in Lumbini, Nepal, and the neighboring IGP regions are undoubtedly required to monitor long-term air quality [109].

In addition, open flames impose further repercussions on land, land use, and biodiversity on atmospheric pollution [168, 171]. The region has frequent forest fire incidents throughout the pre-monsoon period and could offer the ideal opportunity to examine their footprint on the air quality and investigate sources of diagnostic ratios [30, 172]. Reducing BB emissions can significantly enhance the air quality in the IGP area during the post-monsoon [55, 57] but would have a minor impact in winter. In the stagnant air circumstances of winter, a far more aggressive decrease of anthropogenic emissions over a greater area of IGP is required to minimize the $PM_{2.5}$ enhancement produced by the region's meteorology and dynamics. Furthermore, this review magnifies the possibility of further analyzing health risks due to changes in aerosol constituents emanating from diverse BB and anthropogenic sources and the influence of overall PM [173].

The air quality after the monsoon period of IGP is much more susceptible to meteorological and the amount of residue consumed in NW India than to the timing of residue burning changes. Therefore, it is essential to study further and begin rapid efforts to offer farmers inexpensive and sustainable alternative solutions to residue consumption to accelerate its effective ban, which is critical in reducing the intensity of the IGP air pollution episodes following the monsoon. Moreover, the people living in

those urban areas inhale an extremely bad atmosphere, particularly in the non-rainy season. Thus, the current scenario calls on policymakers to take preventive action in good time to control such a harsher pollution scenario, especially in winter. An integrative approach based on collaboration among companies, government, and academia can improve PM_{10} and $PM_{2.5}$ pollution monitoring, management, and mitigation in the Himalayas mountainous region.

Secondary organic particle identification is problematic due to the use of surrogate measurement standards to evaluate SOA tracers. The development of standards that allow for unequivocal chemical identification advances in ambient measurements of SOA tracers and error reduction should all be included to better understand the abundance of SOA. Additional sources of uncertainty include differences in laboratory experiments compared to the atmosphere and potential differences in tracer-to-OC ratios for SOA produced in different parts of the world. Strong actinic flux and low air pressure at high elevations, such as in the Himalayas, may enable unique SOA formation methods. The fluctuation in tracer-to-OC ratios owing to location, season, and meteorological circumstances should be considered when determining the amount of SOA in ambient atmospheres [99].

Overall, post-monsoon IGP air quality was much more responsive to weather and the amount of residue burned in NW India's fields than to timing differences in residue burning. We need immediate action to provide farmers with cost-efficient and long-term alternatives to residue burning to accelerate its effective restriction, which is crucial for reducing the severity of post-monsoon IGP air pollution occurrences [57]. Meteorological parameters are variably associated with different size fractions of PM, such as Gupta and coworkers [42] reported that air temperature was better correlated with $PM_{2.5}$ than PM_{10}. At the same time, relative humidity and rainfall were better correlated with PM_{10} than $PM_{2.5}$. However, more investigations are required to determine the effects of regional climate on PM pollution, particularly long-distance transportation of PM with varying meteorological characteristics.

Recently, the investigation came to a clear conclusion on the lack of a substantial relationship between satellite-measured AOD and ground-observed PM, as well as emphasizing the significance of taking meteorology into account when estimating PM in Bangladesh; however, it is difficult to derive a conclusion based on a single study; thus more studies are required [42]. Anthropogenic pollution hotspots with high magnetic material inputs can be identified using magnetic susceptibility studies of leaf

magnetic susceptibility. Due to the significant correlation between exposure and heavy metals associated with urbanization, vulnerability can be utilized as a proxy for metallic pollution [161, 174].

As a result, in areas such as Kathmandu, where traffic-related problems are increasing, susceptibility-based biomonitoring techniques for temporal (short-term) and spatial assessment of pollution should be investigated. This method can be used to conduct detailed monitoring of exceptionally contaminated areas, provided that the susceptibility is calibrated with the metal content of the most prevalent tree type available.

Overall, findings based on ground data indicate that annual mean $PM_{2.5}$ and PM_{10} concentrations are significantly higher than health standards in many areas of IGP; for example, in Dhaka, $PM_{2.5}$ and PM_{10} concentrations are approximately 1.2–1.75 times higher than the BNAQS across all monitoring locations; as a result, people living in urban areas are inhaling extremely unhealthy air. In Dhaka, where heart disease is thought to be on the rise, the negative effects of such poor air quality have already been noticed, with a 12% (RR: 1.12; 95% CI: 1.01-1.23) increase in cardiovascular emergency room visits as a result of an increase of 103 μg m^{-3} (interquartile range change) in $PM_{2.5}$ [175].

Worldwide, poor air quality has been associated with a decline in life expectancy [176-178]. With more than 80 million children in Bangladesh [179], the majority of the population is likely to be affected by diseases induced directly or indirectly by air pollution. In agreement with Moniruzzaman et al. [180], this review has shown that the rapid urbanization of IGP major cities substantially impacts the severity of air pollution. As a result, government officials must act quickly to avoid a worsening pollution problem in the Himalayas region, especially during the post-monsoon and winter seasons. As a result, policymakers must pay strict attention to taking preventive measures as quickly as possible to halt the worsening pollution situation in the Himalaya region, particularly during the post-monsoon and winter seasons.

Acknowledgments

Corresponding author is thankful for Postdoctoral Research Fellowship awarded by the Chinese government at Hainan University, Hainan, Haikou, China. This work is supported by research grant from the Alexander von Humboldt Foundation of Germany and is gratefully acknowledged.

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Tables

Table 1 A comparison of ambient particulate matter bound water soluble inorganic ionic species in the Himalayas region and IGP areas in $\mu g\ m^{-3}$

Location specialty	Location	Sampling time	Pollutant type	NH_4^+	K^+	Ca^{2+}	SO_2^{4-}	NO_3^-	REF
Mountain stations (above sea level height in meter)	Dhulikhel 1,550	5 May to 25 May 2009	$PM_{2.5}$	0.02	0.37	0.37	0.02		[45]
	Besisahar 2,493	28 May to 6 June 2009	$PM_{2.5}$	0.014	0.36	0.36	0.014		
	Climate Observatory-Pyramid P, Nepal 5,079	Pre-monsoon	PM_{10}	0.52	0.12	0.34	1.48	1.48	[81]
		Monsoon	PM_{10}	0.00	0.05	0.00	0.50	0.37	
		Post-monsoon	PM_{10}	0.08	0.02	0.01	0.50	0.00	
		dry season	PM_{10}	0.14	0.02	0.10	0.22	0.08	
	Phortse, Nepal 4,450	Pre-monsoon	PM_8	1.6	0.50	0.19	0.94	1.5	[181]
		Monsoon	PM_8	0.26	0.15	0.03	0.17	0.34	
		Post-monsoon	PM_8	0.19	0.05	0.02	0.10	0.09	
		dry season	PM_8	0.15	0.07	0.05	0.18	0.23	
	Langtang, Nepal 3,920	Pre-monsoon	$PM_{2.5}$	0.54	0.20	0.66	1.4	0.78	[153]
		Monsoon	$PM_{2.5}$	0.08	0.01	0.10	0.20	0.09	
		Post-monsoon	$PM_{2.5}$	0.15	0.02	0.03	0.27	0.04	
	Nagarkot, Nepal 2,150	Pre-monsoon	$PM_{2.5}$	1.5	0.62	0.31	3.8	1.2	[153]
		Monsoon	$PM_{2.5}$	0.25	0.04	0.07	0.80	0.08	
		Post-monsoon	$PM_{2.5}$	1.20	0.28	0.05	2.5	0.80	
	Jiri, Nepal 2,150	pre-monsoon	PM_8	0.38	0.26	0.28	0.48	0.46	[181]
		monsoon	PM_8	0.14	0.08	0.02	0.12	0.02	
		post-monsoon	PM_8	0.20	0.10	0.04	0.20	0.06	
		dry season	PM_8	0.62	0.21	0.11	0.48	0.86	
	Rongbuk Glacier, China 6,500	monsoon	TSP		0.02	0.04	0.41	0.14	[182]
	Manora Peak, India 6,500	dry season	TSP	0.52	0.23	0.75	2.6	0.5	[183]
	Mt. Abu, west India 6,500	monsoon	TSP		0.13	2.4	2.7	0.43	[184]
		out of monsoon	TSP	0.37	0.2	1.7	2.6	0.74	
IGB urban location impacting air quality of Himalayan region	Hisar (urban, north-west India)	dry season	TSP	6.3	2.4	3.5	13	13	[185]
	Ahmedabad (urban, west India)	monsoon		0.05	0.2	2.5	3.1	0.94	[186]
		Post-monsoon		0.48	0.76	3.0	4.5	2.1	
	urban and rural sites in south India	monsoon	TSP, PM_{10}	0.2	0.6		3.9	1.8	[187, 188]
		Post-monsoon		1–2	0.4–1	0.6–4	3–10	1–4	
	Dhaka (Bangladesh)	dry season	TSP	1.9	1.6	6.8	11	3.6	[189]
	INDOEX campaign (north Indian Ocean)	pre-monsoon	$PM_{1.3}$	1.8	0.34		5.6	0.16	[190]

Table 2 A comparison of ambient particulate matter (absolute/average values) in the Himalayas region and IGP areas

Site	Altitude (m)	Duration	PM_{10} (μg m^{-3}) Avg ± SD	$PM_{2.5}$ (μg m^{-3}) Avg ± SD	REF
Kathmandu, Nepal	1,400	Dec 21, 2012, and Jan 3, 2013	132.0±00	-	[170]
		Feb 13 and 21, 2013	121.77	-	
Delhi, India	225	Mar-May,2012	-	82.3 ± 50.5	[191]
Kathmandu	1400		169 ± 113 (01 Feb,2012-31Jan,2014)	195 ± 83 (17 days)	[40]
Delhi, India	225	Jan–Dec 2008	163± 63	-	[46]
Gul Pahari	256	-_	114 ± 67	-	[46]
Mohali, India	316	May, 2012	276.0 ± 220.2	104.0 ±80.3	[191, 192]
Chitwan, Nepal	415	Feb-May 2016	156.4 ±68.2	95.9 ± 49.0	[44]
Lumbini, Nepal	492	Apr–Jun 2013	128.8 ± 91.9	53.1 ± 35.1	[124]
Mahabaleshwar	1348	2015-2016	36.93±00	31 ± 16.3	[50]
Shadnagar, India	1450	Mar-May, 2014	35.8±00	14.1	[193]
Darjeeling	2200	Mar 2016	29.5±00	19.6	[19]
Mahabaleshwar	1348	June 2012 to May 2013	37.79±00	26	[18]
Srinagar, Kashmir Himalaya	1585	2013–2017	135 ± 112	87 ± 93	[194]
Nearby villages, Chitwan Bode Nepal	415	Apr-May,2016	160.0 ± 31.6	-	[105]

Table 3 A comparison of ambient particulate matter bound carbonaceous species (absolute/ range values) at the Himalaya region and IGP areas

Location	Sampling Time	Pollutant type	Sampling Duration	OC Avg/Range (min–mix) in	EC Avg/Range (min–mix) in	REF
1,550			May 2009 (12 h Avg)			
Besisahar 2,500	Pre-monsoon	$PM_{2.5}$	28 May to 6 June 2009 (21 h Avg)	10.18	1.10	
Climate Observatory-Pyramid P, Nepal 5,079	Pre-monsoon	PM_{10}	Feb 2004 to May 2008 (99 samples with 48h continuous sampling to varied day and night samples)	2.4	0.5	[81]
	Monsoon	PM_{10}		0.9	0.1	
	Post-monsoon	PM_{10}		1.4	0.1	
	dry season	PM_{10}		1.2	0.1	
Langtang, Nepal 3,920	Pre-monsoon	$PM_{2.5}$	Dec 1998 to Oct 2000 (48h continuous sampling)	3.4	0.5	[153]
	Monsoon	$PM_{2.5}$		0.8	0.2	
	Post-monsoon	$PM_{2.5}$		1.8	0.5	
Nagarkot, Nepal 2,150	Pre-monsoon	$PM_{2.5}$	Dec 1998 to Oct 2000 (48h continuous sampling)	14	1.5	[153]
	Monsoon	$PM_{2.5}$		2.0	0.5	
	post-monsoon	$PM_{2.5}$		6.3	1.0	
Lhasa, China 3,600	Winter	PM_{10}	2006 (24h Avg)	35	6	[183]
	Spring	PM_{10}		19	2.5	
	Summer	PM_{10}		17	3	
	Autumn	PM_{10}		18	4	
Manora Peak, India 1,950	pre-monsoon	TSP	Feb 2005–Nov 2006 (every 2nd week, 37 samples; 24h avg)	~ 10	1.5	[184]
	monsoon	TSP		2–6	0.3–0.4	
	post-monsoon	TSP		6–11	0.9–1.3	
Mt. Abu, west India 1,680	Pre-monsoon	TSP	May 2005–Feb 2006 (one sample per week, 41 samples; 24h avg)	3.5	0.1	[184]
	monsoon	TSP		2.2	0.2	
	post-monsoon	TSP		4.9	0.7	
	dry season	TSP		3.6	0.8	
Dhaka 4 sites (megacity, Bangladesh)	dry season	TSP	March–April 2001 (day Avg, 8am to 7pm)	46	22	[189]
INDOEX campaign (north Indian Ocean)	dry season	PM_1 to PM_3	February–March 1999 (C-130 aircraft used for 10x samples)	3.2	4.9	[190]
Bay of Bengal	dry season	TSP	19 March–11 April 2006 (24x samples; 24h Avg)	0.3–5.5	0.1–0.7	[195]
Lumbini, in southern Nepal Semi-urban	Pre-monsoon	$PM_{2.5}$, PM_{10}. PM_1	2 Apr–10 May 2013 2–13 Jun 2013 (5min sample interval)	-	4.9 (0.3–29.9)	[124]
Kathmandu, Nepal Urban	Pre-monsoon	PM_{10} – PM_1	Feb 2013–Jan 2014 (1h Avg)	-	14.5	[40]
	Monsoon				6.3	
	Post-monsoon				6.2	
	Winter				18.3	
Climate Observatory-Pyramid P, Nepal 5,079	Pre-monsoon	-	Mar 2006–Dec 2010 (30min Avg)	-	1.0	[9]
	Monsoon				0.4	
	Post-monsoon				0.3	
	Winter				0.4	
Delhi, India Megacity	Pre-monsoon (night)	PM_{10} - $PM_{2.5}$	Jan - Dec 2012 (45x night samples; 5min temporal resolution)	24.6	3.4	[191]
	Monsoon (night)			26.4	3.7	
	Post-monsoon (night)			46.5	8.3	
	Winter (night)			46.2	7.2	
Delhi, India Megacity	Pre-monsoon (day)	PM_{10} - $PM_{2.5}$	Jan - Dec 2012 (45x diurnal	30.3	8.5	[191]

Table 4 Major sources contributing to fine and coarse particulate matter in air

Source Type	Source inventories	Size category of PM
Natural and primary	Soil and road dust (mineral particulates)	mainly coarse
	Sea-salt	Coarse
	Dust from a volcanic eruption	Coarse
	Organic particulates (marine and continental)	Coarse
Natural and secondary	Sulfates from volcanic SO_2	Fine
	Nitrates from NOx (lightning, soil microbes)	Fine
	OM from biogenic gases	mainly coarse
	Sulfates from biogenic gases (mainly DMS)	Fine
Anthropogenic and primary	Dust from fossil fuel burning, cement	coarse and fine
	manufacturing, metallurgy, waste incineration	Fine
	Soot (black carbon) from fossil fuels (coal and oil).	Fine
	Soot from biomass combustion (forest and savanna fires, agricultural burning, and fuel wood).	Fine
	Biomass burning (without soot).	Fine
Anthropogenic and secondary	Sulfates form SO_2 (mainly from coal and oil burning)	Fine
	Nitrates from NO_x (fossil fuel and biomass combustion)	mainly coarse
	OM from gases of anthropogenic	Fine

Table 5 Insight into the salient feature that contributes to shaping the ambient air quality at Himalayan and high-altitude sites

Location	Study time	Sampling	Pollution characteristics and major identified factors affecting Air quality	REF
Mukteshwar and Gual Pahari (Foothills of the Indian Himalayas)	2006–2010 (Mukteshwar) 2008 and 2009 (Gual Pahari)	PM_{10} and $PM_{2.5}$: Real-time beta attenuation particulate monitors (FH 62 I-R).	Monsoon: the Thar Desert influenced aerosol concentrations during the early monsoon; Dust events: increased coarse mode $PM_{2.5-10}$ percentages in both sites more dominantly in Mukteshwar.	[28]
Himalayas region	2005 8 Aug-31 Oct	$PM_{2.5}$ (sampler information not available)	Biogenic SOA: the range of biogenic SOA such as isoprene, monoterpenes and monoterpenes in organic carbon fraction of PM2.5 were 2–19%, 1–5% and 1–4%. Increased levels of isoprene derivatives in the Himalayan aerosol show biogenic SOA as a major source of organic carbon.	[99]
High-altitude Himalayan station in Nepal (5079 m asl)	2006	PM_{10}: high-volume system with DIGITEL PM_{10} pre-separator DPM. (FR:1 $m^3\ h^{-1}$)	Mineral dust: formed 50% of total PM; Monsoon: regulated dry and moist convection and wet scavenging processes; Valley breeze: facilitated PM transport and changed the chemical composition of PM; Asian brown cloud: carried Impact on glaciers	[81]
Kathmandu Valley and small town of Besisahar (Nepal)	May-June 2009 (pre-monsoon season)	$PM_{2.5}$: Scanning Mobility Particle Sizer (SMPS, 14–340 nm)	The mountain valley wind mechanisms: influence the diurnal cycle of aerosol size distribution; Synoptic scale haze: intensify pollution level; Regional scale pollutant transport: pollution transfer from the low-lying IGP and the formation of south-westerlies during the pre-monsoon season; Monsoon season: remove a large percentage of ambient PM pollution; Local emissions	[45]
Semi urban location in Garhwal Himalayas	Jan to Dec 2017	$PM_{2.5}$: low volume particulate sampler (APM550, MFC) (FR:16.7 LPM)	Winter and monsoon: fewer forest fires/biomass burning occurred during the monsoon season, lowering OC/EC concentrations; Wet scavenging: monsoon washout ambient PM; Local emission: pollution from autos and biomass outnumbers long-distance travel; Boundary layer dynamics: traps pollutants and inversion layer prevent dispersion.	[39]
Mukteshwar –a rural Himalayan Mountain terrain	Dec 2005-Dec 2008	PM_{10} and $PM_{2.5}$: Real-time PM monitors (FH 62 I-R) (FR:1 $m^3\ h^{-1}$)	Monsoon: July and August are the monsoon months with the lowest average readings.	[47]
Southern Nepal	2016	PM_{10}, $PM_{2.5}$, PM_1: Environmental Dust Monitor (EDM 180)	Forest fires: Forest fires add PM in the pre-monsoon season, making it an ideal location to examine their impact on air quality and develop source-specific diagnostic ratios.	[44]
Western Himalayan region Himachal Pradesh	2011–2015	PM_{10} (sampler information not available)	Winter: Solid waste burning; Monsoon: Alter PM_{10} level; Dust: dust from a nearby unpaved road, and long-range traffic pollution; Long-range transported pollution: Himachal Pradesh, pollution from local industry and traffic, as well as pollutants from long-distance transportation, increased PM_{10} concentrations; Complex hilly terrain: Influence wind circulation and trap pollutants.	[48]
Brahmaputra Valley	June 2013–May 2014	BC: Magee Scientific Aethalometer model AE31 (FR:4 LPM)	Transportation from the deserts of West Asia and the IGB: Extra transit from west Asian deserts and the IGB; Particles of sea salt coming from the Bay of Bengal: cause greater coarse particle levels in the pre-monsoon season.	[49]
Darjeeling (India) High altitude Himalayan Station	Oct. 2015–May 2016	PM_{10}: High volume samplers (FR:1 $m^3\ min^{-1}$)	Monsoon and winter: Post-monsoon observed highest PAH loading while Pre-monsoon PAH concentrations were lowest; High solar radiative fluxes: In post-monsoon and pre-monsoon, solar radiation modulates PAH burden.	[197]
Mahabaleshwar Hill station in India (1200 m asl)	Mar 2015–Feb 2017	PM_{10} and $PM_{2.5}$: GRIMM Environmental Dust Monitor (EDM 180) FR: 1.2 LPM ±3%	Seasonality: PM_{10} peaked in the pre-monsoon and $PM_{2.5}$ peaked in the winter while both were lowest in the summertime; Planetary boundary layer and mountain valley winds: Changes in mountain valley winds and local sources were connected to diurnal oscillations in PM; Local sources; Dust from the Arabian Peninsula and the Thar Desert and Tourist activities; Dust storms: Significantly increased organics and sulfate particles.	[50]

Table 6 Insight into salient features that contribute to shaping the ambient air quality in IGP areas

Location	Study time	Sampling specification	Pollution characteristics and major identified factors affecting Air quality	REF
Kolkata	Oct 2015–May 2016	PM_{10}: High volume samplers (FR:1 m^3 min^{-1})	Pre-monsoon: Pre-monsoon PAH concentrations were lowest; Winter: PAH loading was highest than in other seasons; The boundary layer dynamics: shallower boundary layer enhanced PAH concentrations; High solar radiative fluxes: High solar radiative fluxes accelerated PAH photo-degradation, reducing PAH loading during the pre-monsoon	[197]
Lumbini (Southern Nepal)	Pre-monsoon Apr -June 2013	PM_1, $PM_{2.5,}$ and PM_{10}: Grimm EDM 164	Agro-residue burning: Agro-residue burning and regional woodland fires combined with climatic circumstances supportive of pollution transport to Lumbini; Ganges Valley, other parts of India and Nepal, contributed the most significant contribution to pollution concentration; Fossil fuel combustion: accounting for more than half of the ambient BC concentration.	[124]
Northern India	Post-monsoon 2003-2018	$PM_{2.5}$: satellite data	Indian CRB timing intensified post-monsoon pollution load	[57]
Kanpur is an industrial city in North India	Apr 2007 through Feb.2008	PM_{10}: Partisol® Model 2300 4–channel speciation samplers. FR:16.5 (LPM)	Post-monsoon winter: contribution of SOC to PM mass increased from 5% during post-monsoon to 16% during winter at residential sites and from 2 % during post-monsoon to 7% during winter at traffic sites.	[74]
Gual Pahari	Jan–Dec 2008	PM_{10}: APM 541 sampler BC: Aethalometer (AE33)	Monsoon, winter, and summer: SIs peaked in the post-rainy/winter seasons.	[46]
Chhattisgarh, (Mahanadi riverside basin of Rajim), India	July 2012–June 2013	$PM_{2.5–10}$, $PM_{2.5}$ and PM_1: nine-stage cascade impactor sampler (TE 20-800, USA)	In situ burning of rice crop residues: During the summer months of May and June, the bulk concentration of particulate matter increases abruptly; Biomass burning activities at a rural site in eastern central India: Substantial positive correlations found among particles in fine size bins (0.43-2.5 μm) during winter and summer.	[198]

Highlights

- Characteristics of PM pollution in the Himalayas region are discussed.
- As a distant source, CRB in IGP contributes substantially to PM pollution in the Himalayas.
- PM pollution at high-altitude locations in the Himalayas is increasing.
- The unique topography and local weather dynamics intensify pollution in the Himalayas.
- Increasing black carbon in the Himalayas jeopardizes the monsoon and hydrological cycle.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: