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Reoccurrence of Dust Storms in South Asia and Their Implications for Vegetation Health

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ABSTRACT

Dust emission and accumulation have been continually increasing over the past several decades in South Asia. Dust storms, originating in western regions, regularly move across the Indian subcontinent and may reach parts of the Himalayas, including the Tibetan Plateau (TP). Their frequency has risen rapidly on the Indo-Gangetic Plains. Dust storms impact processes associated with atmospheric composition, radiative balance, precipitation, nutrient cycling, and vegetation sustainability. However, these effects have not yet been synthesized in the context of South Asia, which this study addresses. We investigate dust sources and the causes of dust storms in South Asia, their implications for the TP ecosystem, and how they impact vegetation health and sustainability. Indian dust storms originate from both, the local Thar Desert and distant deserts in the Middle East and Northeast Africa. Long-range dust transport has synergistic as well as antagonistic effects on vegetation health and ecosystem sustainability, while vegetation also acts as a trap for atmospheric dust, purifying polluted air. Soils in forest ecosystems may derive 4%–30% of their nutrient inputs, mainly phosphorus (P), from long-range transported dust. Dust-bound P can also be absorbed through foliar uptake of dust deposited on leaves. In simulation experiments, plants were able to increase their P content by 30%–37% through foliar uptake. However, dust deposition on leaves and its subsequent uptake can impair plant growth and biomass production by clogging stomata, modifying the leaf microenvironment, hindering transpiration and gas exchange, degrading chlorophyll, limiting photosynthesis, and reprogramming cellular metabolism. It is hypothesized that plant responses to dust may have an evolutionary basis. We conclude that dust can have mixed impacts on ecosystem functioning and highlight the urgent need for systematic and detailed investigations into its effects in a regional context.

1 | Introduction

Dust storms are common across many parts of the world, and their impacts have been steadily increasing (Choobari et al. 2014). Mainly originating in arid and semi-arid deserts, global dust fluxes are estimated to range between 1500 and 2600 Tg (teragrams) per year (Sharma and Kulshrestha 2017). Mineral dust affects various aspects of human health, air quality, soil formation and erosion, desertification, groundwater quality, crop growth, local and global climates, and ecosystem services (Appel et al. 1985; Chan et al. 1999; Tegen et al. 2002; Tong et al. 2017; Rodriguez-Caballero et al. 2022; Kok et al. 2023; Chappell et al. 2023; Pokharel and Pandey 2024). In addition, dust has a significant effect on radiative energy, leading to both warming and cooling effects in the atmosphere (Tegen and Lacis 1996; Huang et al. 2006a, 2006b; Forster et al. 2007; Demott et al. 2010). Dust

Summary

Atmospheric dust levels are steadily increasing. In South Asia, dust storms originating in the west affect the entire Indo-Gangetic Plains and can reach as far as the Tibetan Plateau (TP) and other parts of the Himalayas. These dust storms influence atmospheric composition and health, affect rainfall patterns, and alter soil nutrient composition essential for sustaining vegetation. In this paper, we explore the sources of dust, the causes of dust storms in South Asia, and their ecological implications, including for the TP. We explain how dust storms impact vegetation health and sustainability across the region. The Thar Desert, along with deserts in the Middle East and Northeast Africa, are the main dust sources. Long-distance dust transport has both beneficial and harmful effects on plant health. For example, plants help trap dust from the atmosphere and purify the air. Dust may also provide nutrient security for forest soils, and plants may even obtain some of the nutrients, such as phosphorus, from dust deposited on the surface of their leaves. However, this dust deposition also significantly impairs plant growth and biomass production by decreasing gas exchange, increasing tissue damage, and disrupting metabolism. Thus, dust can have both positive and negative effects on ecosystem functioning and may influence plant evolution.

- **Practitioner Points**
  - Systematic, long-term, and detailed investigations are urgently needed to understand the impact of dust on ecosystem functioning and vegetation health in South Asia.
  - A reliable early warning system for dust storm outbreaks, especially during the pre-monsoon season, is needed.
  - A long-term research program should be established to examine the impacts of dust storms on ecosystem functioning, develop bioengineering solutions to increase ecosystem resilience, and mitigate the challenges posed by such storms.
  - Improved management of land, soil, water bodies, and anthropogenic activities is urgently required to reduce desertification.

can also modify cloud properties, such as the number, concentration, and size of cloud droplets, which can lead to alterations in cloud albedo and longevity (Twomey et al. 1984; Albrecht 1989). Moreover, the temperature effects of dust may influence atmospheric stratification (Ackerman 1989; Hansen et al. 1997).

Aeolian dust production and transport vary greatly across time and space. Among different land types, deserts or barren lands are estimated to contribute the most to global dust emissions (~56%), followed by shrublands (31%), and grasslands (~12%), while croplands are relatively minor contributors (Chappell et al. 2023). In terms of emission intensity per unit area, the Horn of Africa is regarded as the largest dust source. From 2001 to 2020, the Middle East, North Africa, Australia, and East Asia were ranked chronologically as the most significant contributors (Chappell et al. 2023). Additional sources of dust emissions may remain uncharacterized, especially in areas where smooth land surfaces are not sealed by biogeochemical crusts and the soils remain potentially erodible (Vos et al. 2020).

Dust emission patterns reflect strong seasonality across both hemispheres (Harrison et al. 2021; Cowie et al. 2014; Chappell et al. 2023). Deserts in the Middle East and North Africa are the predominant emitters during the months of February and March. Emissions then shift to the deserts of East Asia from April to May, and back to the Middle East from June to August. Additionally, the East Asian and North American grasslands, as well as the North American shrublands, emit large amounts of dust in April and May. Between September and January, dust sources shift to the Southern Hemisphere, with Australian shrublands becoming the dominant emitters. In India, a peak in dust emission occurs between April and June. The country's northwestern region (latitude 23°3′ N to 30°12′; longitude 63°30′ and 70°18′ E) is home to the Thar Desert, which spans over 2.3 million square kilometers and is extending at a rate of 0.5 km per year. Desertification in India may be expanding eastward and southward (Pal et al. 2023; Chauhan 2003). Therefore, an increase in dust storm events in India is expected, and this source may have been underestimated in previous studies (Chappell et al. 2023). Indian dust storms are expected to impact the entirety of South Asia and may have far-reaching effects on the Himalayas, including the Tibetan ecosystems (Pokharel et al. 2020; Wang et al. 2021; Singh et al. 2022; Pokharel and Pandey 2024); however, these Indian dust storms remain under-researched.

The seasonal shift and formation of new dust sources are expected to alter dust-climate interactions and the source-sink relationship of dust with ecosystem services. For example, the mineral composition of dust from the deserts of the Middle East, the shrublands of Australia, and the grasslands and deserts of Asia differs significantly from that of North African dust (Journet et al. 2014; Chappell et al. 2023). However, the mineralogical contributions of dust from these various sources, and their seasonal variations, to ecosystem services and vegetation dynamics in South Asia remain poorly investigated. Research on dust emission (sources and mechanisms), sediment transport, and cycling could have far-reaching implications for nutrient fluxes, the mineralogical compositions of sinks, carbon cycling, food security, the management of degraded lands, and the achievement of sustainable development goals (Webb et al. 2017; Chappell et al. 2019; Chappell et al. 2023; Pokharel and Pandey 2024). Undoubtedly, the accumulation of particulate matter has complex effects on vegetation health and sustainability.

Dust contributes significantly to the nutrient budgets of ecosystems. For example, dust has been arriving in the Amazon for the past 7500 years, helping to alleviate phosphorus deficiencies in its forests (Evan et al. 2016; Nogueira et al. 2021). Although the Sahara Desert was previously thought to be the main source (Evan et al. 2016), recent studies suggest that diverse sources may contribute to the dust pool (Pokharel and Kaplan 2019; Nogueira et al. 2021). On the one hand, dust input can help offset nutrient depletion in tropical, arid, and semi-arid ecosystems (Pett-Ridge 2009; Arvin et al. 2017). On the other hand, dust storms may have adverse effects on plant biochemical processes, physiology, and morphology, as particulate matter can be absorbed through leaf surfaces (Soheili et al. 2023).

Leaf properties and growth stages influence how plants interact with airborne particulate (Jiao et al. 2021; Soheili et al. 2023; Bridhikitti et al. 2024). Dust itself is an abiotic stress for plants (Soheili et al. 2023), but it can also transport organic matter, pathogenic spores, and other organisms, making its effects on vegetation health even more complex. In the following sections, we provide a synthesis of these aspects and examine how dust can amplify both abiotic and biotic stresses in plants.

In South Asia, the occurrence of dust storms rises steadily from March through June (Littmann and Steinriicke 1989; Chappell et al. 2023), with multiple events typically occurring during the pre-monsoon period of May to June (Dey et al. 2004; Sharma et al. 2012; Sharma and Kulshrestha 2017; Chappell et al. 2023). While westerly and southwesterly winds have generally been associated with the transport of dust over the Indo-Gangetic Plains (Sharma and Kulshrestha 2017), easterly winds are also believed to offer an alternate transport pathway (Banerjee et al. 2021). However, information on these dust storms is fragmented, and many events remain poorly documented, hindering systematic study.

Against this backdrop, a number of dust storms that occurred over the Indian subcontinent between 2003 and 2022 are cataloged here (Table 1). Information on these events was compiled from the scientific literature (Table 1A, which includes major dust storms in the region that have been investigated in detail) as well as from the open-source web portals (Table 1B). Event-specific data were gathered from both peer-reviewed literature and public sources (Table 1A,B). However, some storm events may have been omitted due to limited record availability and the absence of a centralized data system. This underscores the need for a comprehensive, large-scale database of dust storm events in the Indian subcontinent.

This study aims to enhance our understanding of the spatial and temporal patterns of dust storms in the northern plains of India, explore their sources and causes, and assess their ecological implications for vegetation, including forests, in the context of climate change. Long-range transported dust is shown to play a crucial role, yet remains significantly understudied in the South Asian context. Furthermore, we summarize the impacts of dust storms originating in India on the Tibetan Plateau (TP), particularly in relation to regional water security. It is also anticipated that this study will serve as a valuable resource for policymakers in developing scientific infrastructure to support dust storm research in the region, especially in light of ongoing climate change and concerns over vegetation sustainability.

2 | Dust Storm Events in the Indian Subcontinent

Dust storms in the Indian subcontinent are highly seasonal, occurring primarily during the pre-monsoon period. They are most common in the arid and semi-arid regions of Rajasthan, Haryana, Punjab, Delhi, the Gangetic Plains, the cold arid zones of Jammu and Kashmir, and can extend further into the central Himalayas (Middleton 1986; Sikka 1997; Ginoux et al. 2001; Tegen et al. 2002; Gautam et al. 2011; Singh et al. 2016; Sarkar et al. 2019; Chakravarty et al. 2021; Singh et al. 2022; Victor 2024; Jain et al. 2025). These storms can elevate dust loads by as much as 3–5 times above background levels (Jain et al. 2025). Dust storms have also been reported in Nepal, although they remain comparatively undocumented. For example, on March 28, 2016, a massive dust storm originating from the west struck the Kathmandu Valley with gusts reaching 22.8 m/s, causing significant damage.

Different parts of the Indian subcontinent, especially north and northwest India, experience dust storms of varying intensities, mainly during the pre-monsoon season (Table 1). Ganganagar (Rajasthan, India) has recorded the highest annual number of days with dust storms (17 days per year) in the Indian region, while Bikaner, Jodhpur, New Delhi, Kanpur, and Allahabad have historically experienced several dusty days annually (Singh 1971; Middleton 1986). Furthermore, some areas north of the Gangetic Delta reportedly experienced 3–4 dust storms per year (Singh 1971). However, the frequency of dust storms appears to have increased over the past 15 years. For example, in the northwestern Patiala region in India, six dust storms were recorded between April and June 2010 (Sharma et al. 2012). Similarly, at least five major dust storms were recorded between April and June 2015 (Sharma and Kulshrestha 2017), and in 2021, some areas in western India recorded 4–7 dust storms in the month of June alone. Moreover, at least one dust storm occurred each week in April of 2021, and at least three storms were recorded between the second and fourth weeks of March the same year. In 2019, India experienced at least 170 dusty days, while approximately 50 dust storms were recorded in 2018. A marked increase in the number of severe dust storms has also been observed, with 22 events between 2003 and 2017, compared to only nine between 1980 and 2003. A list of major dust storms in the Indian subcontinent during the period 2003–2022 is compiled in Table 1.

These dust storms are typically accompanied by gusty winds ranging from 10.3 m/s to over 20 m/s. They severely impair visibility, degrade air quality, and lead to significant accumulation of dust, increasing both, coarse and fine particulate matter in the ambient air. In earlier studies, dust storm frequency in northern India showed weak correlations with rainfall, wind speed, and wind erosion factors (Chepil et al. 1962). Later, occurrences were found to be positively associated with high temperatures (Littmann 1991). Recent events often involve strong surface winds, decreased maximum ambient temperatures, increased relative humidity, and in some cases, rainfall of varying intensity (Table 1).

Dust storms result in significant dust loading across the entire Indo-Gangetic Basin. For instance, during a 2018 storm, surface dust concentrations ranged from 0.32 to 0.64 mg m^{-3}, while values of aerosol optical depth (AOD) and aerosol index (AI) increased, altering the aerosol's optical, physical, and radiative properties (Tiwari et al. 2019). In another event, PM_{10} (particulate matter with a diameter of 10 micrometers or less) concentrations jumped to over 93.3 mg/m^3, AOD reached 1.46, and the Ångström exponent (AE) dropped to 0.29 (Taneja et al. 2020). During a 2010 storm, total dust emissions were estimated at 7.5 Tg, with dust loadings of 21,000 and 19,000 mg/m^2 in the boundary layer and free troposphere, respectively. Local

TABLE 1A | A catalogue of dust storm in India and Nepal. Information sourced from the scientific publications.

Date	Dust storm affected areas	Origin/cause	Air quality, dust related indices	Wind/Gust ($m\ s^{-1}$)	Damages	Precipitation (Yes/No)	Source
January 20–26, 2022	Indian subcontinent	Arabian Peninsula/ north-south cyclonic and anticyclonic circulation patterns generated by a sizable north-south pressure gradient	Poor; Exceeded the national tolerable level of 100 $\mu g\ m^{-3}$ (PM10), with peaks as high as 650 $\mu g\ m^{-3}$.	NA	NA	NA	Victor et al. (2024)
June 13–17, 2018	Central Himalaya	Arabian Desert, north-African eastern coasts, and Thar Desert/Low pressure system over northern India and prevalence of strong winds	Poor; AE 1.2 to 0.3 Dust loading 1.5 to 2.5 Tg; Cooling at the SRF and TOA but a significant heating of atmosphere (~0.21 K day^{-1} at Gandhi College and 0.72 K day^{-1} at Lumbini)	20	NA	NA	Singh et al. (2022)
June 14, 2018	Indian-Gangetic Basin	NA	320–640 $\mu g\ m^{-3}$ dust (Kanpur, UP). Atmospheric radiation 84 $W\ m^{-2}$. Heating 1.84 K day^{-1}	NA	NA	NA	Tiwari et al. (2019)
May 17, 2018	Rajasthan, Delhi, UP	Arabian Peninsula, northwestern Iran, Pakistan, Thar Desert	Poor; atmospheric radiation 124 $W\ m^{-2}$. Heating 2.69 K day^{-1}	NA	> 100 dead, many injured, trees uprooted, power outage, fire, damage to houses	NA	Tiwari et al. (2019)
May 12–16 2018	North Indian states (Haryana, Delhi, and Uttar Pradesh)	Thar Desert	Poor, PM_{10} 250.9 ± 108.3; $PM_{2.5}$ 91.6 ± 45 at Delhi; Dust loading 3.9 $g\ m^{-2}$; AOD > 2	Over Delhi 1.37 ± 0.6	NA	NA	Jain et al. (2025)
May 13, 2018	UP, Andhra Pradesh, West Bengal, and Delhi-NCR	NA	NA	NA	> 60 dead, > 83 injured	Yes	Sarkar et al. (2019)
May 12, 2018	UP, Delhi	NA	Poor	NA	> 30 dead	NA	Sarkar et al. (2019)
May 7–8, 2018	Northern India	NA	NA	NA	NA	Yes	Sarkar et al. (2019)
May 1–4, 2018	Indian-Gangetic Plain (IGP), Southern India,	Thar desert/upper-level jet stream, upper	AOD and dust CMD in the Thar Desert above 1 and 1.8 $g\ m^{-2}$	> 27.8	> 100 uprooted trees, toppled houses, blackout		Wang et al. (2021), Sarkar et al. (2019)

(Continues)

TABLE 1A | (Continued)

Date	Dust storm affected areas	Origin/cause	Air quality, dust related indices	Wind/ Gust ($m\,s^{-1}$)	Damages	Precipitation (Yes/No)	Source
	the Bay of Bengal, and Tibetan Plateau	trough, the subtropical high			by damaged power lines and casualties		
May 2, 2018	Northwest India	Thar desert/Convective system	Over Delhi, PM_{10} prevailing 148 $\mu gm^{-3} > 350\ \mu g\,m^{-3}$, and peak 880 $\mu g\,m^{-3}$	7.2	> 100 casualties	No	Banarjee et al. (2021)
April 5–6, 2017	Jaipur (Rajasthan) Kanpur (UP)	Arabian Peninsula, Iran/Pakistan	PM_{10} 19.178 $mg\,m^{-3}$; $PM_{2.5}$ 6.249 $mg\,m^{-3}$	NA	NA	NA	Mishra (2018)
April 4, 20, and 30 and May 20 and 30, 2015	Bikaner, Jaipur, Hisar, Delhi, and Agra	North-west Africa and the Middle East	AE 0.40–0.03. Ca^{2+} the most dominating cation with flux in the range of 106.7 $mg\,m^{-2}day^{-1}$ at Bikaner to 7.4 $mg\,m^{-2}\,day^{-1}$ at Delhi. AOD > 2.0; Dust fall flux~8465 $mg\,m^{-2}\,day^{-1}$ in Bikaner.	NA	NA	NA	Sharma and Kulshrestha (2017)
May 30, 2014	New Delhi	Confluences of the outflow frontiers of two thunderstorms, low-level warm air from Middle East and extra-tropical dry cold air	PM_{10} (950 $\mu g\,m^{-3}$) $PM_{2.5}$ (550 $\mu g\,m^{-3}$); AOD 1.0, AE 0.5.	NA	NA	NA	Chakravarty et al. (2021)
March 19–23, 2012	Udaipur (Rajasthan), Patiala (Punjab)	Thar desert	$PM_{2.5} > 200\ mg\,m^{-3}$; PM_{10} 600 $mg\,m^{-3}$	NA	NA	NA	Yadav et al. (2017)
May 18, 2011	Jaipur	NA	9.15×10^4 (aerosol number conc.)	NA	NA	NA	Prakash et al. (2013)
June 1–3, 2010	Gangetic plains of India. Dust advected to Himalayan foothills causing possible impacts, such as atmospheric warming and glaciers melting	Thar desert/low pressure and strong surface winds	Aerosol radiative forcing (ARF) −50 to −100 and −25 $W\,m^{-2}$, SSA values 0.88 to 0.92	NA	NA	NA	Gharai et al. (2013), Kumar et al. (2015)

(Continues)

TABLE 1A | (Continued)

Date	Dust storm affected areas	Origin/cause	Air quality, dust related indices	Wind/ Gust ($m\,s^{-1}$)	Damages	Precipitation (Yes/No)	Source
May 26–28, 2010	Indian Gangetic Basin, transportation to Himalayan foothills	Thar Desert	Poor, vertical reach to the mid-troposphere	NA	NA	NA	Kumar et al. (2015)
April 28, 2010	Patiala, in the northwestern part of Indo-Gangetic Plains, India	Thar Desert	AOD 1.5; SSA 0.88 to 0.92; ARF at SRF and TOA~−50 to $-100\,W\,m^{-2}$ and from~−10 to $-25\,W\,m^{-2}$	NA	NA	NA	Sharma et al. (2012)
April 20–21, 2010	Northern and northwestern parts of India (Rajasthan, Haryana, Delhi, UP)	Western disturbance	Total dust emission 7.5Tg, total dust loadings 21,000–19,000 $mg\,m^{-2}$, AOD up to 2.1, AE −0.09	NA	NA	NA	Desouza et al. (2013), Kumar et al. (2015)
June 15 & 17, 2009	Jaisalmer (Rajasthan)	Thar Desert	PM_{10}-30% in the eroded aeolian mass on June 15	13.9-15.2/NA	1166, 466 $kg\,ha^{-1}$ total soil loss (15 and 17 June, respectively), 3 $kg\,ha^{-1}$ total SOC loss	NA	Santra et al. (2013), Santra et al. (2010)
June 12, 2006	Nainital	Thar Desert	Coarse & giant particles-$16.4 \times 10^6/m^3$, $7.9 \times 10^3/m^3$, respectively	7.6/NA	NA	NA	Hegde et al. (2007)
April 10–11, 2006	Hyderabad	Thar Desert	AOD 0.2 higher, AE decreased PM 1.0, 2.5, and 10 µm diameter were higher	NA	NA	NA	Badarinath et al. (2007)
May 12, 15, 18–20, 2004	Kanpur	Oman, southwest Asian basins, & Thar Desert	Warming and cooling effects in atmosphere	NA	NA	NA	Chinnam et al. (2006)
June 10 & 16 2003	New Delhi, Varanasi (UP)	Indian Gangetic Basin	Maximum aerosol index	NA	NA	NA	El-Askary et al. (2006)

TABLE 1B | A catalogue of dust storm in India and Nepal, collated from open sources like media and web portals.

Date	Dust storm affected areas	Origin/Cause	Air quality, dust related indices	Wind/ Gust ($m\,s^{-1}$)	Visibility (km)	Damages	Precipitation (Yes/No)
June 24, 2021	New Delhi	NA	Moderate	NA	NA	NA	NA
June 17, 2021	Phalodi, Rajasthan	NA	NA	NA	NA	NA	NA
June 10, 2021	Delhi	NA	NA	10/17.89			Yes
June 1, 2021	Rajasthan	Western disturbance, upper air cyclonic circulation	NA	5.4/10.3		NA	NA
May 30, 2021	Delhi	NA	NA	10.3/15.6	NA	NA	NA
May 22, 2021	Eastern & western districts, Rajasthan	Western disturbances	NA	5.4/10.3	NA	NA	NA
May 16, 2021	Surat, Gujrat	Tauktae Cyclone	NA	NA	NA	NA	Yes
April 27, 2021	Ahmedabad, Gujrat	Thar desert	NA	NA/11.11	NA	NA	NA
April 16, 2021	New Delhi	NA	AQI 252–238, poor	3.9/NA	3–0.5 km	1 death	Yes
April 14, 2021	Rajasthan	Western disturbances, upper air cyclonic circulation	NA	5.4/10.3	NA	NA	Yes
April 1, 2021	New Delhi	Cyclonic circulation	AQI 182, moderate	NA/11.1–13.9	NA	NA	NA
March 30, 2021	Most of the Indian Gangetic Plain	NA	Low	8.3–11.1/11.1	NA	NA	NA
March 23, 2021	Rajasthan	NA	NA	11.1–13.9/NA		Trees uprooted, power outages	Yes
March 12, 2021	Delhi	NA	NA	NA	NA	NA	Yes
June 10, 2020	Delhi	NA	NA	NA	NA	Tees uprooted, power outage	
May 10, 2020	Delhi-NCR, Chandigarh, Punjab	Western disturbance, cyclonic circulation	NA	NA/19.4	NA	NA	Yes
June 12, 2019	UP, Delhi	NA	NA	NA/8	NA	NA	Yes
June 7, 2019	NA	NA	NA	NA	NA	Trees uprooted, 26 killed, 57 injured, massive power outages	Yes
May 8, 2019	Delhi	Northwest India	Very poor	NA	NA		NA
May 2–3, 2018	Northern India	NA	NA	27.8/NA	NA	> 100 dead, > 100 injured	Yes
May 27, 2016	Northwestern India	Western disturbances	NA	NA	NA	NA	NA

(Continues)

TABLE 1B | (Continued)

Date	Dust storm affected areas	Origin/Cause	Air quality, dust related indices	Wind/Gust ($m\ s^{-1}$)	Visibility (km)	Damages	Precipitation (Yes/No)
May 23, 2016	Western and northern India	NA	NA	10.7/14.3		Uprooted trees, 5 dead, power outage, damage to physical infrastructures	NA
March 28, 2016	Kathmandu (Nepal) and surrounding	NA	NA	NA/22.8	0.2 km	Injuries	NA
May 20, 2015	Rajasthan	Pressure gradient force	NA	NA	NA	Many injured	NA
April 18, 2014	UP	NA	NA	20.8/NA		Trees uprooted, 18 dead, power outages	NA

Abbreviations: AE, angstrom exponent; AOD, aerosol optical depth; AQI, air quality index; ARF, aerosol radiative forcing; CMD, dust column mass density; N/A, information not available; NCR, national capital region; SRF, surface; Tg, Teragram; TOA, top of the atmosphere; UP, Uttar Pradesh.

and regional AOD increased significantly to 2.1, while AE dropped to −0.09 (Kumar et al. 2014). Radiative forcing due to dust was estimated as $-2.9\ W/m^2$ at the top of the atmosphere, $5.1\ W/m^2$ within the atmosphere, and $-8.0\ W/m^2$ at the surface (Kumar et al. 2014).

An opposing viewpoint argues that high wind speeds during the storms may dilute and disperse atmospheric particles (Prakash et al. 2013), though supporting evidence for this claim is highly limited. On the contrary, extensive evidence indicates that dust storms often transport substantial amounts of particulate matter, contributing to large-scale accumulation across parts of the Indian subcontinent and reaching the central Himalayas (Yadav et al. 2017; Singh et al. 2022). A 70% increase in dust load, from 1.5 to 2.5 Tg, has been recorded, with only 50% attributed to the original source (the Thar Desert) and the remaining 50% from anthropogenic activities and pollutants (Singh et al. 2022). The mixing of anthropogenic pollutants with transported dust reduces incoming shortwave solar radiation reaching the ground (Chinnam et al. 2006; Singh et al. 2022). It is evident that aerosol indices vary depending on the intensity of dust storms (El-Askary et al. 2006).

The presence of elevated aerosol layers during storms may also influence the Indian summer monsoon by warming the mid to lower levels of the atmosphere (Tiwari et al. 2019). Observations of significant variation in single scattering albedo (SSA) during such storms suggest a strong absorption property in the aerosols (Taneja et al. 2020). Additionally, variations in radiative forcing at the surface, within the atmosphere, and at the top of the atmosphere have been frequently observed (Taneja et al. 2020; Kumar et al. 2015; Sharma et al. 2012). Radiative forcing may result in surface cooling at the top and warming effects in the inner surface of the atmosphere, creating thermal gradients that influence atmospheric dynamics, monsoon circulation, and the hydrological cycle across the Indian subcontinent, including the Himalayas (Tiwari et al. 2019; Kumar et al. 2015; Gautam et al. 2011).

3 | Origins of Dust Storms

The strongest dust storm in the Indian subcontinent in the past three decades, recorded in May 2018, originated over the Arabian Peninsula and reached the western and southwestern regions of India through long-range transport. A second segment of the storm evolved from the northwestern regions of Iran, Pakistan, and the Thar Desert (Sarkar et al. 2019). Other sources of dust storms affecting India include Oman and the basins of Southwest Asia (Chinnam et al. 2006). For many-years, the Thar Desert has been recognized as a major source of dust storms, with the eastward transport of dust being a common phenomenon (Santara et al. 2010; Hegde et al. 2007; Badarinath et al. 2007; Chinnam et al. 2006).

The Himalayas act as a barrier to the passage of dust storms, resulting in significant dust accumulation over their foothills and across the Gangetic Plains (Singh et al. 2004). Consequently, the Gangetic Plains experience the highest dust accumulation during the pre-monsoon season on an annual basis (Singh et al. 2004; Gautam et al. 2007). Dust storms originating in the Arabian Peninsula, Iran, and Pakistan move eastward due to strong northeasterly winds (Mishra 2018). Dust from Southwest Asia and Eastern Africa is typically transported to the Indo-Gangetic Plains by westerly winds (Sharma and Kulshrestha 2017). However, uncharacteristic easterly winds may offer an alternate pathway for dust transport into the region (Banerjee et al. 2021).

During eastward transport, dust can reach high altitudes, often extending into the mid-troposphere (Gharai et al. 2013). Convective dust storms that originate in the Thar Desert may be advected to northern and northwestern India by western disturbances, which facilitate the entry of foreign particles (Desouza et al. 2013; Singh et al. 2022). These storms generate strong uplift, which can carry the dust to higher altitudes and suppress precipitation by altering the physical properties of clouds (Desouza et al. 2013). Additionally, such uplifts may result from the generation of substantial turbulent kinetic energy during the interaction of strong wind shear with mixing planetary boundary layers (Pokharel et al. 2017a, 2017b; Pokharel and Kaplan 2019; Wang et al. 2021; Singh et al. 2022).

4 | Causes of Dust Storms

Dust storms are a climatic phenomenon often resulting from unstable atmospheric conditions during the summer. They occur when loose soil or sand interacts with strong westerly winds, which are generated by pressure gradient forces over a region. For example, a five-fold increase in $PM_{2.5}$ (fine particulate matter) was observed over the central Himalayan region during a dust storm caused by a low-pressure system over northern India, accompanied by strong winds of approximately 20 $m\,s^{-1}$ (Singh et al. 2022). The presence of low-pressure zones over the Indo-Gangetic Plains can generate high surface winds (Kumar et al. 2014, 2015). These winds reach their peak when intense land heating leads to convective low-pressure systems and the inflow of westerly and southwesterly winds (Littmann and Steinriicke 1989).

Nearly one-eighth of Indian's landmass is affected by wind erosion, with the Thar Desert accounting for a significant portion and frequently acting as the primary dust source. Dust deflation from the Thar Desert is also expected to play a vital role in regional climate change impacts (Santra et al. 2010). In addition to the Thar, other key sources of dust storms in the Indian subcontinent include the northwestern Arabian Desert and eastern Pakistan (Middleton 1986; Pease et al. 1998; Léon and Legrand 2003; Washington et al. 2003; Dey et al. 2004). Active western disturbances and cyclonic circulations associated with upper-air or low-pressure systems often give rise to dust storms that move eastward across the subcontinent (Figure 1). Strong dust-laden winds often blow over the northern Indian Plains as a result of pressure gradients associated with cyclonic circulation over the Thar Desert and adjacent regions of Pakistan.

Dust storms are also driven by intense heat in the northern parts of the subcontinent. The Indo-Gangetic Plains frequently experience heatwaves during late spring and early summer due to the prolonged periods of clear sky, uninterrupted solar radiation, and sustained low wind speeds. These conditions are

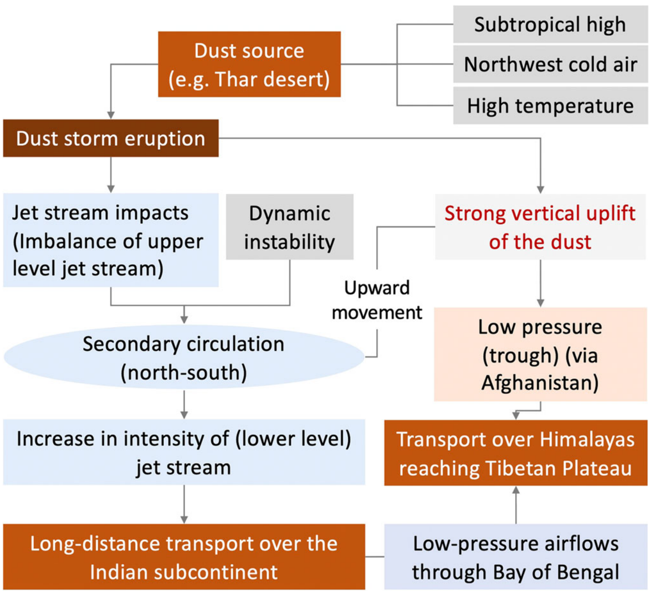

FIGURE 1 | A schematic representation of the long-distance transport of dust reaching forests across the Indian subcontinent, the Himalayan foothills, and the Tibetan Plateau.

disrupted by the intrusion of dry, dust-laden winds from the west and northwest, which culminate in dust storm events. Severe dust storms can also result from the interaction of two thunderstorm outflows. The downdraughts from these systems deflate the hot, loose surface soil, and their convergence with large-scale circulations of low-level warm air from the Middle East and extra-tropical cold, dry air intensifies dust uplift (Chakravarty et al. 2021).

Originating in western regions such as the Thar and Arabian deserts, these storms, under favorable meteorological conditions, can uplift dust to significant altitudes in the upper atmospheric layers and deposit large quantities across the Indian subcontinent, including the Himalayan foothills (Figure 1). Furthermore, dust storms originating in the Thar Desert and lifted vertically into the atmosphere may be transported to the TP via low-pressure airflows through Afghanistan, the Indo-Gangetic Plains, and the Bay of Bengal (Figure 1; Wang et al. 2021).

5 | Implications of Dust Storms for the Tibetan Plateau

Dust storms in the region not only affect the northern plains and Himalayan foothills of the Indian subcontinent but also have far-reaching impacts across the TP, which lies at an elevation of ≥ 4000 m above sea level (Pokharel and Pandey 2024). Dust originating from the Indian subcontinent and the Arabian Peninsula is deposited on the southern parts of the TP, especially during the pre-monsoon season (Middleton 1986; Lau et al. 2006). In addition, the TP receives dust from local sources and other deserts, including the Taklimakan, Gobi, Gurbantunggut, Kumtag, and Qaidam (Pokharel and Pandey 2024).

Dust intrusion into the TP influences atmospheric circulation, accelerates atmospheric heating, and reduces snow albedo

(Shichang et al. 2000; Lau et al. 2006, 2010; Xu et al. 2009). Dust deposition contributes to increased aridity and desertification in the TP by affecting cloud formation, altering precipitation patterns, enhancing atmospheric warming and circulation, disrupting radiative energy balance, causing biodiversity loss, degrading freshwater systems, and altering water quality (Pokharel and Pandey 2024). The impacts on fresh water resources, like rivers, are especially daunting, as dust accumulation accelerates snowmelt, glacier retreat, ice cover reduction, and wetland degradation. Some studies suggest that dust may also have certain beneficial effects on the TP, particularly by promoting cloud development. Dust particles can serve as nuclei for cloud condensation, extend cloud longevity, enhance convective cloud formation, and promote precipitation (Huang et al. 2006a, 2006b; Wang et al. 2010; Liu et al. 2019). In contrast, negative correlations between precipitation and dust concentrations have also been documented on the TP (Han et al. 2009).

Dust from northern India contributes to atmoshperic warming by heating the air over the southern TP (Lau et al. 2006; Meehl et al. 2008; Lau and Kim 2018). This leads to the so-called 'heat pump effect', which impacts precipitation patterns and intensifies the Indian monsoon. Moreover, the arrival of dust in the TP is accompanied by a variety of components, such as black carbon, salts, fly ash, microbes (including pathogens), and other contaminants, that influence the biogeochemical cycles of glacial ecosystems (Hu et al. 2020; Dong et al. 2020). Transported dust can also supplement the cryosphere with iron and other trace metals, alter the chemical composition of meltwater, and influence the region's nutrient supply (Li et al. 2019; Dong et al. 2020). Dust deposition on snow and glaciers in the southeastern parts of the TP lowers surface albedo, warming the glacier surfaces compared to clean snow (Zhang et al. 2017; Ji 2016; Qu et al. 2014). This dust-induced warming is also accelerating snowmelt in the western TP. Furthermore, dust affects various aspects of snow dynamics, including snow quantity, duration of coverage, melt rate, and the timing of glacier retreat (Wang et al. 2021; Zhang et al. 2018; Kang et al. 2010; Xu et al. 2009; Yao et al. 2012; Cheng and Wu 2007; Ménégoz et al. 2014; Xu et al. 2017). Collectively, dust deposition has a significant impact on the TP's hydrological system and biogeochemical cycles (Liu and Yanai 2002; Dong et al. 2020). Any substantial alteration to the TP's hydrological stability caused by dust is likely to have far-reaching consequences, as it would affect downstream river basins of the Indian subcontinent - the regions that support extensive forest cover.

It is clear that dust has multifaceted implications for environmental health. However, its ecological impacts on vegetation in South Asia have received limited attention, which we address in the following section.

6 | Implications of Dust Storms for Vegetation Health and Sustainability

The interactions between dust (transported from distant deserts) and vegetation within ecosystems are complex and multilayered (Figure 2). Vegetation acts as a huge sink for atmospheric dust remediation, playing a key role in air purification. On the one hand, dust-vegetation interactions can be synergistic, as transported dust contributes to the nutrient budgets of plants. On the other hand, these interactions can be antagonistic, with dust acting as a stressor on the ecosystem. We begin by examining how vegetation functions as a dust sink and helps in remediation of the polluted air.

6.1 | Vegetation as a Dust Trap

One study estimated that forest vegetation covering an area of 30 km^2 could remove at least 418 tons of dust from the

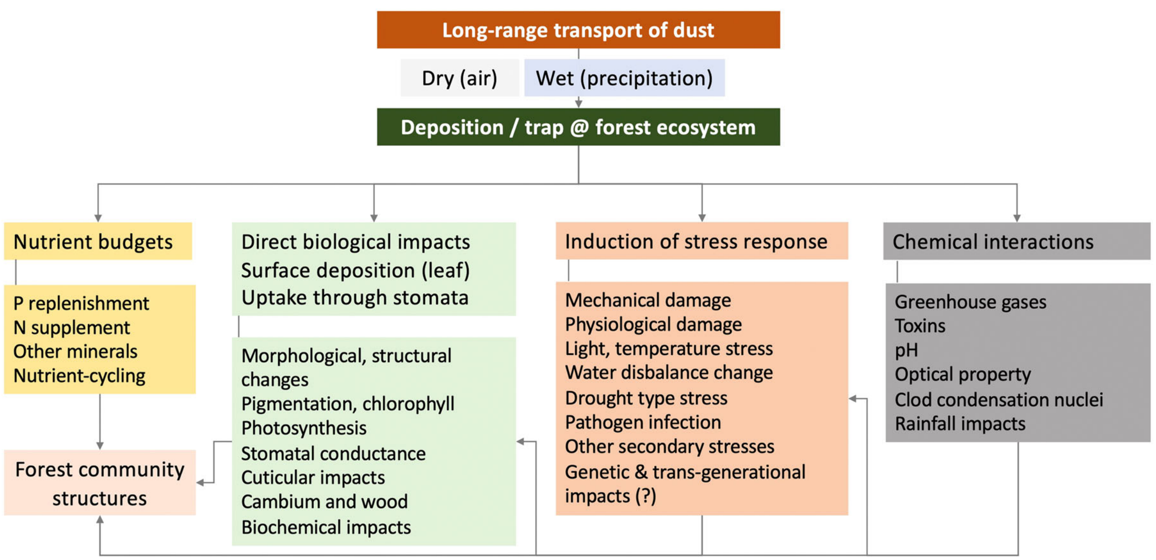

FIGURE 2 | A summary of the ecological impacts of dust on vegetation health and sustainability. Long-distance dust may be deposited either dry (from the air) or wet (via precipitation) onto tree surfaces. The complex, multi-layered effects of these depositions include both beneficial contributions to plant growth and harmful consequences. Environmental, morphological, physiological, and biochemical impacts of dust on vegetation have been relatively well studied, whereas dust-induced genetic and transgenerational effects remain comparatively underexplored. Collectively, these impacts influence vegetation community structure.

atmosphere, thereby helping reduce air pollution in urban areas (Uni and Katra 2017). Forest trees are estimated to have the capacity to capture between 0.95 and 5.197 $g\,m^{-2}$ of dust (Bridhikitti et al. 2024). The removal of dust by forests occurs primarily through the adhesion of particulate matter to leaf surfaces, followed by absorption into plant tissues (Wei et al. 2021; Bridhikitti et al. 2024). Dust may be deposited from the atmosphere either as dry fallout or through wet deposition via precipitation.

Among forest types, coniferous forests are considered the most efficient in removing dust, followed by evergreen and deciduous forests (Han et al. 2020; Bridhikitti et al. 2024). The effectiveness of dust removal is influenced by species composition, surface roughness, and local meteorological conditions. Several factors, such as leaf surface area, surface texture, waxiness, texture, trichome density, and stomatal frequency, contribute to a tree's dust trapping capacity (Yoon et al. 2009; Ram et al. 2014, 2015; Bridhikitti et al. 2024). For example, species with stellate, multi-radiate, and densely packed trichomes are capable of retaining large quantities of dust (Moradi et al. 2017). Canopy size and airflow rates also directly impact the amount of dust removed (Fowler et al. 1989).

In deciduous forests, leaf traits associated with effective dust collection include large size, leathery or thick textures, membrane-like thin textures, the presence of trichomes, and a short, dense indumentum on the upper or lower surfaces (Bridhikitti et al. 2024). Conversely, species with hairless leaf surfaces, small leaf sizes, or chartaceous (papery) leaf textures exhibit poor dust-trapping capacity (Bridhikitti et al. 2024). These features have direct implications for species selection in afforestation programs aimed at curbing desertification and reducing the spread of dust storms in the arid and semi-arid regions of the Indian subcontinent.

6.2 | Dust Chemical Composition

It is now well established that desert dust significantly influences phosphorus (P) cycling in arid and semi-arid terrestrial ecosystems by contributing relatively larger amounts of P than those derived from local soil sources (Okin et al. 2004; Arvin et al. 2017). Similarly, in tropical regions, dust inputs can offset nutrient depletion caused by soil weathering (Pett-Ridge 2009; Arvin et al. 2017). Major storms in the Indo-Gangetic Plains gather dust from a variety of sources, which include local origins in the arid Thar Desert and distant deserts in the Middle East, Arabian Peninsula, and Northeast Africa (Sharma and Kulshrestha 2017).

Sharma and Kulshrestha (2017) analyzed the chemical composition of several major dust storms over the northern plains of India. Their analysis revealed that calcium (Ca^{2+}), derived from crustal sources, was the dominant cation, with concentrations of 106.7 $mg\,m^{-2}\,day^{-1}$ near the source. This concentration consistently decreased eastward, dropping to 7.4 mg $mg\,m^{-2}\,day^{-1}$. Furthermore, sodium (Na^{+}) and chloride (Cl^{-}), contributed by the Arabian Sea, were also abundant, although their concentrations declined as the dust storm advanced inland. The most dominant anions found in major Indian cities during dust storms were sulfate (SO_4^{2-}) and nitrate (NO_3^{-}), primarily originating from anthropogenic emissions (Sharma and Kulshrestha 2017).

The southwestern coast of India receives aeolian dust from the Arabian Peninsula and Northeast African. The mineral dust in this region varies in concentration from 60 to 132 $\mu g\,m^{-3}$ and contains variable amounts of clay minerals along with high concentrations of iron (Fe), sourced from Northeast Africa, ranging between 3.4% to 6.5% (Kumar et al. 2020; Singh et al. 2023). Other major elements in the dust include Ca and magnesium (Mg). Additionally, mineral dust may contain trace metals such as manganese (Mn), cobalt (Co), nickel (Ni), copper (Cu), and cadmium (Cd), which can influence plant growth and physiological functioning (Singhal et al. 2023).

Dust storms also contribute micronutrients, mainly iron, to oceanic primary productivity (Kumar et al. 2020; Singh et al. 2023). While the role of dust-derived Fe in terrestrial ecosystems, such as the forests of South Asia, remains understudied, it is highly likely to be significant.

6.3 | Dust Contributions to Nutrient Budgets

The contribution of desert dust to the nutrient budgets of forest ecosystems, particularly as a source of essential elements such as phosphorus and nitrogen, has been an active area of global research (Stoorvogel et al. 1997; Weiss et al. 2002, Cusack et al. 2016; Ramaswamy et al. 2017). For example, Gross et al. (2016) estimated that 10%–29% of the phosphorus in a tropical rain forest in Panama is derived from long-distance transport of dust from the Saharan desert. Dust is also believed to carry rock-derived nutrients, including nitrogen, from arid regions to humid tropical forests (Mulitza et al. 2010; Prospero and Lamb 2003; Cusack et al. 2016). In European forests located below 52° N latitude, dust may account for up to 30% of total nutrient inputs, including various silicate and non-silicate minerals (Lequy et al. 2012). Europe receives dust from both, long-distance Saharan transport and local soil erosion (Lequy et al. 2012).

In a noteworthy study, Arvin et al. (2017) analyzed global dust patterns to estimate their contribution to nutrient supply in montane ecosystems under conditions of slow soil erosion. They used a dust supply index (DSI; the ratio of dust inputs to total chemical and physical outputs from erosion) and neodymium isotopes (Nd) as tracers for mineral phosphorus. The authors proposed that DSI offers a conservative estimate of dust-derived P relative to bedrock sources. Their results indicated that, on average, $77\% \pm 6\%$ of Nd in slow-eroding montane soils originated from dust. Furthermore, they estimated that $88\% \pm 7\%$ of Nd in pine needles was dust-derived, with $> 99\%$ of P in pine needles coming from dust at sites in Sierra Navada, California (Arvin et al. 2017). If validated by future independent studies across multiple locations, these findings imply a far-reaching contribution of dust to soil and vegetation nutrient budgets. It is evident that dust inputs form a substantial fraction of total soil inputs in slowly eroding landscapes (Hahm et al. 2014; Arvin et al. 2017). However, less is known about the reverse scenario of thin and rapidly eroding soils like those in the Himalayas that are nevertheless receiving constantly increasing amounts of dust (Singh et al. 2022).

The impacts of dust on forest health, sustainability, and productivity have been extensively studied in the context of African dust storms originating in the Sahara and affecting the Amazon rainforest (Koren et al. 2006; Bristow et al. 2010; Evan et al. 2016; Nogueira et al. 2021). Similar effects on forest ecosystems in the Indian subcontinent are now starting to emerge. For instance, significant amounts of dust-derived mineral nutrients have been detected in southwest monsoon rains in India (Ramaswamy et al. 2017). Large quantities of desert dust are transported over the Indian Peninsula, with sizeable portions (annual average of 20.7 g m^{-2}) being wet-deposited in the Western Ghats and serving as a source of nutrients for the region's highly sensitive ecosystem (Ramaswamy et al. 2017). This mineral dust, from the Nubian Desert (Northeast Africa) and the Arabian Peninsula, is crustal in nature and contains $\geq 58\%$ SiO_2 and $\geq 18\%$ Al_2O_3 (Ramaswamy et al. 2017). It also contain major cations such as Na^+, K^+, Mg^{2+}, and Ca^{2+}, and anions such as Cl^-, NO_3^-, SO_4^{2-}, and PO_4^-. The rainforests of the Western Ghats derive approximately 4% of their total P requirements from this mineral dust source (Ramaswamy et al. 2017). The region receives dust-derived particulate P at rates equivalent to 16.6 mg P m^{-2} per year (or 166 g P ha^{-1}), nearly an order of magnitude higher than the P input from Saharan dust to the Amazon rainforest (estimated at 7–39 g P ha^{-1}) (Ramaswamy et al. 2017). Additionally, the Western Ghats receive dissolved P and N at rates of approximately 100 g P ha^{-1} and 6,463 g N ha^{-1} per year, respectively (Ramaswamy et al. 2017).

Thus, dust helps to maintain forest soil fertility and compensates for hydrological P losses on a decadal timescale (Ramaswamy et al. 2017). By replenishing nutrients such as P and N, dust may support plant growth and enhance ecosystem productivity, including in the forests of India. However, an investigation by Tandule et al. (2022) reports a recent decline in dust deposition along India's western coast- the dust that had historically arrived from the Middle East and Africa. Such reductions may have profound impacts on the productivity of oceanic and terrestrial ecosystems (Tandule et al. 2022). Shifts in global dust emission and deposition patterns are expected to alter ecosystem nutrient budgets. For instance, the removal of biocrusts is expected to increase the dust emissions, thereby changing deposition dynamics and potentially influencing P equilibrium in rainforests (Rodriguez-Caballero et al. 2022). Nevertheless, while dust supplies essential nutrients, its particulate matter, once deposited on plant surfaces and eventually absorbed, can adversely affect plant functioning and physiology.

6.4 | Impact of Dust on Plant Functioning

A study conducted in Central and East Asia (mid-latitude regions) found that dust storm frequency was negatively correlated with vegetation condition and positively correlated with aridity (Park et al. 2020). In India, drifting sand has created vegetation gaps in the Aravalli Hills, which has further increased the risk of intensified dust storms and the expansion of the Thar Desert. Continuous exposure of forests to dust may disrupt physiological processes, ultimately leading to accelerated forest degradation (Moradi et al. 2017). For instance, persistent dust accumulation on leaf surfaces can reduce gaseous exchange, impair stomatal functioning, and strongly inhibit photosynthesis (Moradi et al. 2017; Meravi et al. 2021). Dust-covered leaves absorb more solar radiation, and raise internal leaf temperatures—an effect more pronounced with fine dust than with coarse particles, with temperature increases reported to be up to 10 times greater (Molnár et al. 2020; Durand et al. 2021). When dust load effects were evaluated on leaf traits (leaf area, specific leaf area, relative water content, leaf N and P content, chlorophyll content, stomatal conductance, photosynthetic rate, and intrinsic water-use efficiency) in four roadside tree species in India, sites with lower dust loads exhibited significantly higher values across these leaf attributes (Chaturvedi et al. 2013).

In a decade-long study across arid and semi-arid regions of Asia, including the Indus Plains, Jiao et al. (2021) established a direct inverse relationship between AOD and normalized difference vegetation index (NDVI). Particulate matter interferes with climatic factors and suppresses vegetation activity by reducing surface solar radiation (SSR), altering photosynthetically active radiation (PAR), and modifying surface air temperature and precipitation patterns (Jiao et al. 2021). Increased aerosol concentrations suppressed vegetation growth during early and middle developmental stages, although some positive effects were observed in later stages (Figure 3; Jiao et al. 2021; Soheili et al. 2023). This pattern is likely due to dust's differential impacts on leaf morphology and anatomy. Young leaves with softer tissues are more susceptible to negative impacts of dust than mature ones (Soheili et al. 2023).

Dust also affects plant respiration and can cause mechanical damage to leaves (Farmer 1993). Micro-wounds created by such damage can facilitate microbial colonization (Pradhan et al. 2020; Pradhan et al. 2023). The cumulative stress from dust deposition resembles drought stress (Soheili et al. 2023). The final impact of dust on plant growth appears to be related to the quantity of dust deposited on the abaxial (lower) and adaxial (upper) surfaces of mature leaves. When small amounts of dust accumulate only on the upper surface, gas exchange via the lower surface may remain unaffected (Li et al. 2019). However, particulate matter ≤ 2.5 μM can easily enter the leaf via stomata, clog the stomatal pores, degrade chloroplast, reduce carotenoids, and cause necrosis and chlorosis (Moradi et al. 2017; Roushani Nia et al. 2018; Lin et al. 2021). These effects are more pronounced in seedlings and young plants (Moradi et al. 2017; Soheili et al. 2023).

Dust uptake also alters plant biochemical composition; carbohydrate levels may increase, while starch and protein content

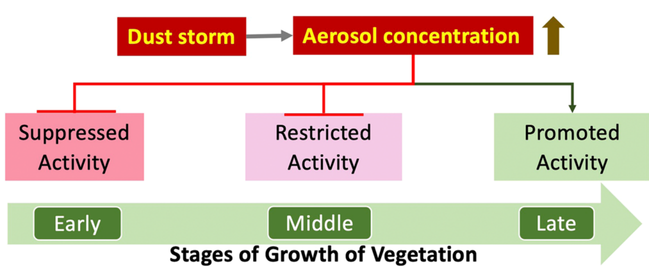

FIGURE 3 | Impacts of dust on vegetation activity at different stages of growth. During early stages, dust negatively affects vegetation processes, while some recovery or adaptation may occur at later stages.

may decrease (Sett 2017; Soheili et al. 2023). Reduced photosynthetic rates can affect cambial activity and influence wood properties (Clark et al. 2021). Overall, dust uptake impairs transpiration, gas exchange, and photosynthetic machinery, induces oxidative stress, and alters both primary and secondary metabolism, thereby affecting plant growth and productivity (Figure 4).

An intriguing possibility of foliar uptake of P from dust has also been proposed, especially for plants growing in soils where P availability is limited (Gross et al. 2021; Starr et al. 2023). Ecosystems on young soils are often N-limited, but as soils age geologically and P inputs from weathering decline, they transition to P-limited systems (Menge et al. 2012). Under such conditions, atmospheric P inputs, such as those from dust deposition, become highly important (Menge et al. 2012). Plants growing continuously in P-deficient soils may favor a direct foliar uptake of P from dust deposited on their leaves (Gross et al. 2021; Starr et al. 2023). It has even been hypothesized that in certain forest species, foliar uptake can entirely bypass soil-mediated P absorption, and thus sustain P budgets essential for tree growth and productivity (Starr et al. 2023). This phenomenon has also been proposed for crop species such as wheat and chickpea (Gross et al. 2021). In simulation studies mimicking natural dust depositions, 30%–37% of sparingly soluble dust-P was acquired by foliar uptake (Gross et al. 2021; Starr et al. 2023). However, the same studies reported reductions in photosynthesis by 17%–30% and declines in biomass by 17%–58% due to dust deposition.

The capacity for foliar dust uptake may have an evolutionary basis. Plant species that evolved in regions far from desert sources, such as maize, showed only marginal responses to dust application, whereas those from dust-rich environments may have developed specialized mechanisms to utilize P from dust deposited on their leaves (Gross et al. 2021; Starr et al. 2023). These findings suggest the existence of an alternate P uptake pathway that could benefit trees in P-limited ecosystems. Foliar uptake is an important physiological process even in tropical rainforests—not only for the epiphytic species that rely entirely on atmospheric inputs for water and nutrients, but also for canopy trees (Yang et al. 2024). Thus, widespread foliar uptake of P may be an important strategy for ensuring nutrient supply in ecosystems with limited soil-derived P (Menge et al. 2012; Gross et al. 2021; Starr et al. 2023). Ensuring an optimal P supply is critical for maintaining the competitive ability and Darwinian fitness of plant communities in resource-stressed ecosystems (Pradhan et al. 2023).

Moreover, dust may also alter forest community structure, particularly affecting epiphytic lichens and Sphagnum mosses (Farmer 1993). Severe dust storms can damage tree crowns and result in tree mortality, which in turn reduces forest productivity (Clark et al. 2021). The nature of tree species (and associated traits) also influence susceptibility to dust-related stress. For example, broadleaf evergreen species are more vulnerable to drought and temperature stress (Lopez-Iglesias et al. 2014). However, broadleaf evergreen species tend to have lower stomatal conductance and may better tolerate oxidative stress compared to deciduous species (Calatayud et al. 2010; Soheili et al. 2023).

In addition to nutrient delivery, dust may affect greenhouse gas emissions (e.g., N_2O) and interact with CO_2 fertilization processes (Cusack et al. 2016). During long-distance transport, the physicochemical properties of dust particles can change due to coagulation with other atmospheric substances, heterogeneous chemical reactions with trace gases, and in-cloud processing (Maring et al. 2003; Valle-Di'az et al. 2016; Rodriguez-Caballero et al. 2022). As dust ages and mixes with other aerosols, its optical properties and its ability to act as cloud condensation nuclei are also modified (Rosenfeld et al. 2001; Haywood et al. 2008; Valle-Di'az et al. 2016), potentially impacting rainfall patterns and thus forest ecosystems. A contrasting trend has also been reported in the Indian subcontinent: over the past two decades, summer monsoon rainfall and circulation strength have revived. This has resulted in a significant increase in vegetation greening and a consequential decline in the abundance of dust over northwestern India (Jin and Wang 2018).

In summary, dust has mixed effects on forest health, productivity, and sustainability (Figure 2). It significantly contributes to forest nutrient budgets and helps in safeguarding them by complementing inputs from weathered soils. At the same time, dust can negatively impact forest health and sustainability in several ways (Figures 2–4). While the impacts of African dust from the Sahara on tropical forests have been relatively well studied, far less is known about the ecological effects of dust

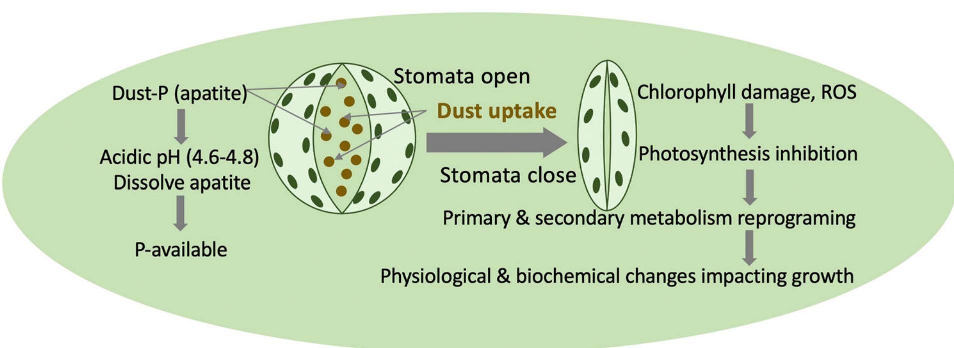

FIGURE 4 | Schematic representation of the effects of dust uptake on leaf physiology and foliar phosphorus (P) supply. Apatite, the most abundant phosphate in mineral dust, dissolves under acidic conditions. Leaf exudates may help create favorable conditions for converting unavailable dust-bound P into a bioavailable form.

originating from the Thar Desert on the vegetation health in the Indian subcontinent.

Many studies have been conducted in India on the effects of industrial dust pollution on vegetation health (Prusty et al. 2005; Pandey et al. 2008; Singh et al. 2021), yet the compounded effects of industrial pollution and dust storms remain underexplored. This is notable given that pollutants from anthropogenic sources often undergo turbulent mixing with the mineral dust from deserts during storms across the Indo-Gangetic Plains and the central Himalayas (Singh et al. 2022). These interactions can amplify impacts, such as increased particulate concentrations, degraded air quality, and altered radiative balance and heat fluxes (Chakravarty et al. 2021; Singh et al. 2022), all of which may have profound biological and ecological consequences.

Furthermore, results from studies on other dust types cannot be fully extrapolated to sand dust storms due to differences in physiochemical composition of the particulate matter in different types of dust, tree species diversity, dust-holding capacity of various tree species, tree community structures (forest vs. roadside trees), physiological parameters, and meteorological contexts. Thus, further research is urgently needed to better understand the impacts of dust storms on ecosystem functioning in South Asia.

7 | Conclusions and Recommendations

Research on dust storms and their implications for vegetation health in the Indian subcontinent is hindered by the lack of systematic scientific documentation. Although a few dust storms have been studied in detail (Prasad et al. 2007; Prasad and Singh 2007; Singh et al. 2005; Srivastava et al. 2010, 2011; Saha et al. 2022; Jain et al. 2025), comprehensive, long-term investigations into their effects on forest ecosystem functioning in the eastern Indian subcontinent are still lacking.

Factors such as climate change, land degradation, increasing aridity, recurrent wildfires, and inadequate management practices exacerbate the impact of dust storms, especially those originating in the Thar and Arabian deserts. There is a need to establish a reliable early warning system for dust storm outbreaks, especially during the pre-monsoon season. The region would also benefit from continuous monitoring systems and the implementation of bio-engineering programs that could study the ecological impact of dust storms, devise resilience-enhancing mechanisms, and mitigate their consequences. These efforts should be accompanied by improved management of land, soil, water resources, and anthropogenic activities to curb desertification.

It is now well established that dust concentrations over the Indian subcontinent have increased steadily over the past four decades (Nazish Khan and Sajid Akhter 2022). Furthermore, the long-range transport of dust from the Thar Desert and the West Asian/Arabian deserts to the eastern Himalayas, including regions of India, Nepal, and the TP, is well documented (Gautam et al. 2009; Carrico et al. 2003; Chatterjee et al. 2012; Wang et al. 2021; Pokharel and Pandey 2024). Consequently, their potential impacts on the health and sustainability of the vegetation in the ecosystems across these regions can be reasonably hypothesized and should be prioritized for further research.

Author Contributions

Shree P. Pandey: conceptualization, investigation, funding acquisition, writing – original draft, writing – review andediting, visualization. **Ashok Kumar Pokharel:** investigation, writing – original draft, writing – review and editing, visualization, validation. **Zechen Peng:** writing – review and editing.

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Ethics Statement

The authors have nothing to report.

Consent

This review has not included any human participants or animals or specific datasets like sequences that require a specific submission.

Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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