

Dust Aerosols and Climate Change in Northeastern Nigeria: A Systematic Review of Sources, Climatic Effects, Feedbacks and Adaptation Options

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ABSTRACT

Northeastern Nigeria sits squarely within the Sudano-Sahelian ecological zone one of sub-Saharan Africa's most climate-stressed environments. Year after year, communities across the region face the combined pressures of advancing desertification, recurrent Harmattan dust incursions, prolonged drought, and steadily declining agricultural output. The dust driving much of this crisis does not simply pass through: it arrives from the Sahara Desert, the Bodélé Depression, the shrinking Lake Chad Basin, overgrazed rangelands, and farmlands emptied by conflict, and it reshapes the radiation budget, disrupts cloud formation, suppresses rainfall, and feeds back into the very land degradation that produced it. We synthesised evidence from 50 verified studies across six interconnected themes: dust source identification and transport dynamics; radiative forcing and temperature modulation; dust–rainfall and monsoon interactions; land use, desertification, and dust–climate feedbacks; health, air quality, and socio-economic effects; and methodological advances. The findings are sobering but also instructive. Bodélé dust still dominates during peak Harmattan. At the same time, local sources tied to Lake Chad's loss of more than 90% of its surface area since the 1960s, overgrazing, and conflict-driven farmland abandonment are growing in importance and, critically, are amenable to management. Dust aerosols cut surface solar radiation by 30–40%, impose surface radiative forcing near 35 W m^{-2} , cool the daytime surface by $1.2 - 1.8 \text{ }^\circ\text{C}$, and warm the lower troposphere at $0.5 - 1.2 \text{ Kday}^{-1}$. These changes tip the atmosphere toward greater stability, suppress convective rainfall, and push monsoon onset back by one to two weeks delays that, for rain-fed smallholder farmers, can determine whether a growing season is viable or not. Running beneath all of this is a self-reinforcing feedback loop in which degraded land, elevated dust loading, reduced rainfall, drying soils, and further vegetation loss sustain and amplify one another. We identify the near-total absence of ground-based observational infrastructure as the single most limiting factor in the evidence base. The paper closes by setting out practical priorities: regional dust monitoring, early-warning systems, landscape restoration, high-resolution modelling, and the formal integration of dust into Nigeria's climate governance architecture.

Keywords: Dust aerosols; Harmattan; climate change; northeastern Nigeria; radiative forcing; West African Monsoon; desertification; aerosol optical depth

INTRODUCTION

Mineral dust aerosols are among the most abundant natural particles in the global atmosphere, yet their role in shaping regional climate receives far less attention than greenhouse gases, even though the physical consequences are substantial and, in some regions, immediate (Knippertz & Todd, 2012; Kok et al., 2017). Dust originates in arid and semi-arid landscapes wherever wind stress overrides the cohesive resistance of loose surface soils. Once it's in the air, it travels across local, regional, and even intercontinental scales — interacting with the climate system in two broad ways. Direct effects involve the scattering and absorption of solar and terrestrial radiation. Indirect effects work through cloud microphysics, precipitation dynamics, and the surface energy balance (Marticorena & Bergametti, 1995; Solmon et al., 2008).

Few places make this clearer than the West African Sahel. The Sahara is the world's single largest mineral dust source, and the Bodélé Depression in northern Chad ranks among the most consistently active aeolian emission zones on Earth. Dust lifts off there on roughly 100 days each year, propelled by the Bodélé Low-Level Jet (Washington & Todd, 2005; Washington et al., 2006; Todd et al., 2007). Come November, the Harmattan picks up these plumes and sweeps them southwestward across West Africa. Northeastern Nigeria lies directly in that path (Engelstaedter et al., 2006; Mbourou et al., 1997). The effects are tangible: thick brown haze settles over Maiduguri and Damaturu for weeks, solar irradiance drops sharply, and the convective activity that rain-fed farming depends on gets pushed back or suppressed altogether (Balarabe et al., 2016; Ogunjobi et al., 2004).

The northeastern zone takes in six states — Borno, Yobe, Adamawa, Bauchi, Gombe, and Taraba — stretching across roughly 272,395 km² of the environmentally fragile Sudano-Sahelian transition. The region has been dealing with multiple overlapping crises simultaneously. Lake Chad has shed more than 90% of its surface area since the 1960s, leaving behind vast expanses of fine, wind-susceptible lacustrine sediment (Pham-Duc et al., 2020, 2022). Years of conflict have emptied and stripped entire farming landscapes. Overgrazing and deforestation have removed what vegetative protection once existed (Nwilo et al., 2020; Brandt et al., 2017). Against a background of already heavy Saharan and Bodélé dust loading, these changes have produced a dust–climate system of unusual severity (Prospero et al., 2002; Gao et al., 2025).

What makes dust so central to this picture is the role it plays on both sides of the environmental equation. It's both a consequence of land degradation and an amplifier of it. Bare land emits more dust. More dust in the column warms the troposphere, stabilises the atmosphere, and reduces rainfall. Less rainfall dries soils and weakens vegetation. Weaker vegetation exposes still more bare soil. That cycle, already measured and documented, is accelerating (Cowie et al., 2013; N'Datchoh et al., 2018; Balkanski et al., 2021).

The research literature on this topic has grown, but it remains spread across disciplines — atmospheric physics, agroclimatology, public health, remote sensing, land-use science — and no previous synthesis has pulled it together through a physically grounded framework. This review does that for the period 2016–2025, and it draws out conclusions intended to be genuinely useful for both researchers and decision-makers.

Review Objectives

This review pursues six specific objectives:

1. Identify the principal sources and seasonal transport pathways of dust aerosols affecting northeastern Nigeria.
2. Examine how dust modifies the regional radiation balance, surface temperature, and atmospheric thermal structure.
3. Assess the mechanisms and magnitude of dust-related rainfall suppression and West African Monsoon disruption.
4. Analyse the interactions and feedbacks between land degradation, desertification, and dust–climate dynamics.
5. Consider the health, agricultural, gendered, and socio-economic dimensions of dust–climate impacts.
6. Identify knowledge gaps and propose evidence-based adaptation and policy actions suited to the region.

STUDY AREA AND METHODOLOGY

Study Area

The six states of northeastern Nigeria run from the Sahel savanna in the far north — where Borno and Yobe share their border with the Lake Chad Basin — southward through Guinea Sudan savanna into the wetter woodlands of Adamawa and Taraba. The geography of the review area, including state boundaries, major cities, the Lake Chad Basin, and dominant dust transport pathways, is shown in Figure 1.

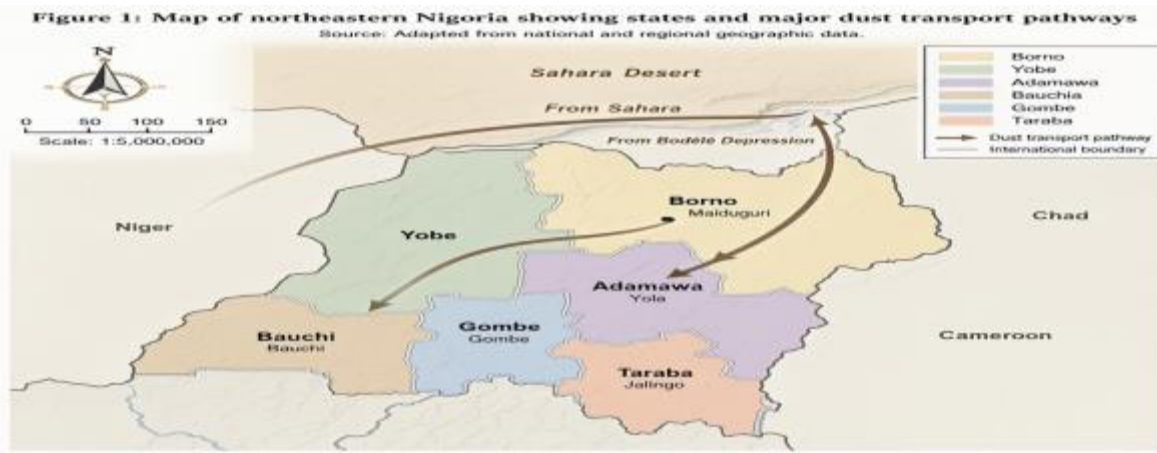


Figure 1: Map of northeastern Nigeria showing Borno, Yobe, Adamawa, Bauchi, Gombe and Taraba States, Lake Chad and major dust transport pathways from the Sahara and Bodélé Depression.

Figure 1 is the Map of northeastern Nigeria showing the six states covered in this review (Borno, Yobe, Adamawa, Bauchi, Gombe, and Taraba), the Lake Chad Basin with approximate current and historical shorelines, major cities including Maiduguri, Damaturu, Yola, Bauchi, Gombe, and Jalingo, and the dominant northeasterly Harmattan dust transport pathways from the Sahara Desert and Bodélé Depression. State boundaries, a north arrow, and scale bar are included. The figure illustrates the three-tier source structure: (a) transboundary long-range input from the Sahara and Bodélé; (b) regional contribution from the shrinking Lake Chad; and (c) local sources from degraded rangelands and conflict-abandoned farmlands.

Moving from north to south, annual rainfall climbs steeply: below 400 mm yr⁻¹ in northern Borno, rising to above 1,000 mm yr⁻¹ in parts of Adamawa and Taraba (Nicholson, 2013; Akinsanola & Ogunjobi, 2017). Temperatures are high and consistent year-round, with pronounced diurnal swings and a sharp seasonal break between the June–September rains and the dry, dusty October–May period.

The Harmattan sits at the heart of that dry season. Northeasterly trade winds lift and carry dust from the Sahara and Bodélé at transport altitudes of 1,000–3,000 m (Washington et al., 2006; Todd et al., 2007). The heaviest aerosol loading concentrates in the northern states, thinning out toward the south — but even Adamawa and Taraba show measurable dust impacts at peak (Anuforum et al., 2007).

That dust arrives in three nested tiers. Long-range transboundary inputs from the Sahara and Bodélé dominate during the core Harmattan months (Engelstaedter et al., 2006; Prospero et al., 2002). At a regional scale, the retreating Lake Chad contributes growing quantities of fine lacustrine sediment (Pham-Duc et al., 2022). And at the local scale, bare cropland, overgrazed pasture, deforested hillsides, unpaved roads, and abandoned farmland are all contributing meaningfully to the regional dust burden (Nwilo et al., 2020; Brandt et al., 2017).

Literature Search Strategy and Screening

We searched systematically for studies published between January 2016 and December 2025 across seven platforms: Scopus, Web of Science, Google Scholar, African Journals Online, ResearchGate, relevant journal websites, and Nigerian university repositories. The Boolean search string applied was:

("dust aerosol" OR "mineral dust" OR "Harmattan dust" OR "Saharan dust" OR "PM10" OR "PM2.5" OR "aerosol optical depth" OR "AOD") AND ("climate change" OR "climate variability" OR "radiative forcing" OR "rainfall" OR "precipitation" OR "temperature" OR "monsoon" OR "desertification" OR "land degradation") AND ("northeastern Nigeria" OR "Borno" OR "Yobe" OR "Adamawa" OR "Bauchi" OR "Gombe" OR "Taraba" OR "Lake Chad Basin" OR "Sahel Nigeria")

The search and screening process followed PRISMA 2020 guidance. The full four-stage workflow is summarised in Figure 2. Fifty studies satisfied all inclusion criteria and form the evidence base for this synthesis.

PRISMA Flow Diagram

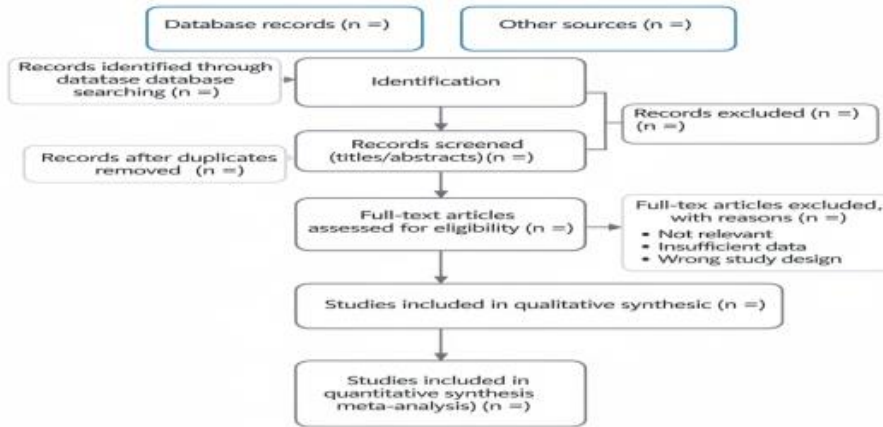


Figure 2: PRISMA flow chart showing literature search, screening and final selection of reviewed studies.

Figure 2 is PRISMA 2020 flow diagram of the systematic literature search and screening process. Stage 1 shows identification of records from seven academic databases and repositories. Stage 2 shows screening for geographical relevance to northeastern Nigeria, the Nigerian Sahel, or the Lake Chad Basin. Stage 3 shows eligibility assessment based on quantitative dust–climate data, climate-relevant variables, and peer-review status. Stage 4 shows final inclusion of 50 verified studies. The number of records identified, duplicates removed, records screened, records excluded (with reasons), and studies included are indicated at each stage.

Inclusion and Exclusion Criteria

We included articles published within the 2016–2025 window that focused on dust aerosols or related atmospheric particulates, addressed at least one climate-relevant variable (radiation, temperature, precipitation, atmospheric dynamics, land degradation, or drought), and held clear relevance to northeastern Nigeria, the broader Nigerian Sahel, or the Lake Chad Basin. Peer review was mandatory.

We excluded articles focused exclusively on indoor air pollution without a climate link, studies from unrelated regions without clear transferability, non-peer-reviewed material, and items that substantially duplicated findings already captured elsewhere in the corpus.

Note on framework sources: Several foundational references published before 2016 including Marticorena & Bergametti (1995), Holben et al. (1998), and Washington & Todd (2005) are cited as framework sources to contextualise the governing equations and regional background. They are not counted among the 50 reviewed studies, and this distinction is maintained throughout.

Data Extraction and Thematic Classification

For each retained study we recorded: authors, year, geographic focus, methodology, dust variable examined, climate or environmental outcome measured, principal findings, quantified impacts, and stated limitations. Studies were then assigned to one of six thematic categories. The full distribution is shown in Table 1.

Table 1. Thematic classification of the 50 reviewed studies.

Theme	Focus	Number of studies
A. Dust sources and transport	Source identification, trajectory analysis, seasonal dynamics	10
B. Radiative forcing and temperature	AOD, radiation balance, surface and atmospheric temperature	9

C. Dust–rainfall and monsoon	Convection, cloud microphysics, West African Monsoon modulation	8
D. Land use, desertification, and feedbacks	Land degradation, vegetation, soil moisture, feedback dynamics	9
E. Health, air quality, and socio-economics	PM exposure, respiratory illness, crop yields, gender, economics	7
F. Methodological advances	Remote sensing, modelling, machine learning, ground validation	7
Total		50

Environmental Physics Framework

When you strip away the complexity, dust–climate interaction is a problem in atmospheric and environmental physics. To make sense of the large and varied body of evidence we reviewed, we anchored our synthesis to a set of governing equations drawn from radiative transfer theory, aerosol microphysics, aeolian transport, boundary-layer thermodynamics, and land-surface energy balance. These equations were not solved numerically in this review. Their purpose was interpretive: to give us a consistent physical reference frame for testing whether reported values from different studies made sense in relation to each other, and for identifying where magnitudes were physically implausible and warranted closer scrutiny. Each symbol is defined at first use and listed in the Nomenclature table above.

Aerosol Optical Depth and Radiative Attenuation

Aerosol optical depth (AOD), τ_λ , is the most widely reported column-integrated measure of aerosol loading. For a vertical atmospheric column extending from the surface to altitude z , AOD at wavelength λ is expressed through the Beer–Bouguer–Lambert law (Holben et al., 1998; Tanré et al., 1997):

$$\tau_\lambda = \int_0^z \beta_{\text{ext}}(\lambda, z') dz' \quad (1)$$

where τ_λ is the aerosol optical depth at wavelength λ (dimensionless), $\beta_{\text{ext}}(\lambda, z')$ is the volume extinction coefficient at wavelength λ and altitude z' (m^{-1}), and z is the column height (m).

The extinction coefficient is the sum of scattering and absorption components:

$$\beta_{\text{ext}} = \beta_{\text{sca}} + \beta_{\text{abs}} \quad (2)$$

where β_{sca} is the volume scattering coefficient (m^{-1}) and β_{abs} is the volume absorption coefficient (m^{-1}).

The attenuation of downwelling solar irradiance through the aerosol column follows as:

$$I_\lambda = I_{0,\lambda} \exp[-\tau_\lambda m(\theta)] \quad (3)$$

where I_λ is the surface downwelling spectral irradiance ($\text{W m}^{-2} \text{nm}^{-1}$), $I_{0,\lambda}$ is the top-of-atmosphere spectral irradiance ($\text{W m}^{-2} \text{nm}^{-1}$), $m(\theta)$ is the relative optical air mass (dimensionless), and θ is the solar zenith angle.

Ångström Exponent and Particle-Size Discrimination

The spectral dependence of AOD is described using the Ångström exponent α , which helps discriminate coarse-mode mineral dust from fine-mode anthropogenic aerosol (Balarabe et al., 2016; Ashpole & Washington, 2012):

$$\tau_{\lambda} = \tau_{\lambda_0} \left(\frac{\lambda}{\lambda_0} \right)^{-\alpha} \quad (4)$$

where τ_{λ_0} is the AOD at reference wavelength λ_0 (typically 500 nm) and α is the Ångström exponent (dimensionless). Values of $\alpha < 0.5$ indicate coarse-mode mineral aerosol dominance, characteristic of Harmattan dust over the region (Ogunjobi et al., 2004; Anuforom et al., 2007).

Direct Radiative Forcing

Dust direct radiative forcing, ΔF , is defined as the difference in net radiative flux at a given atmospheric level between aerosol-laden and aerosol-free conditions (Saidou Chaibou et al., 2020; Kok et al., 2017):

$$\Delta F = (F^{\downarrow} - F^{\uparrow})_{\text{aerosol}} - (F^{\downarrow} - F^{\uparrow})_{\text{aerosol-free}} \quad (5)$$

where ΔF is the direct radiative forcing (W m^{-2}), F^{\downarrow} is the downwelling broadband radiative flux (W m^{-2}), and F^{\uparrow} is the upwelling broadband radiative flux (W m^{-2}).

The atmospheric component of radiative forcing, which drives dust-induced tropospheric heating, is obtained as the difference between top-of-atmosphere (TOA) and surface (SFC) forcing:

$$\Delta F_{\text{ATM}} = \Delta F_{\text{TOA}} - \Delta F_{\text{SFC}} \quad (6)$$

where ΔF_{ATM} , ΔF_{TOA} , and ΔF_{SFC} are the atmospheric, top-of-atmosphere, and surface components of radiative forcing, respectively (W m^{-2}).

Atmospheric Heating Rate

Absorbing dust aerosols heat the atmospheric column through the vertical divergence of net radiative flux. The radiative heating rate follows from the first law of thermodynamics applied to a unit air mass (Saidou Chaibou et al., 2020):

$$\frac{\partial T}{\partial t} |_{\text{rad}} = - \frac{g}{c_p} \frac{\partial F_{\text{net}}}{\partial p} \quad (7)$$

where $(\partial T / \partial t)_{\text{rad}}$ is the radiative heating rate (K s^{-1}), $g = 9.81 \text{ m s}^{-2}$ is gravitational acceleration, $c_p = 1005 \text{ J kg}^{-1} \text{ K}^{-1}$ is the specific heat capacity of dry air at constant pressure, F_{net} is the net radiative flux (W m^{-2}), and p is atmospheric pressure (Pa). The negative sign follows the standard meteorological convention in which pressure decreases with altitude; Equation (7) is used qualitatively to interpret lower-tropospheric heating from absorbing dust layers.

Single Scattering Albedo

The single scattering albedo, ω_0 , determines the relative contributions of scattering and absorption to total extinction (Evan et al., 2014; Kok et al., 2017):

$$\omega_0 = \frac{\beta_{\text{sca}}}{\beta_{\text{sca}} + \beta_{\text{abs}}} \quad (8)$$

where ω_0 is dimensionless and bounded between 0 and 1. Values close to 1 indicate strongly scattering aerosols, while lower values indicate stronger absorption. For Saharan and Bodélé-sourced dust, ω_0 at 550 nm commonly lies in the range 0.85–0.92 (Evan et al., 2016).

Static Stability and Convective Inhibition

Dust-induced surface cooling and lower-tropospheric heating increase atmospheric stability. Static stability is represented using the Brunt–Väisälä frequency, N (N'Datchoh et al., 2018):

$$N^2 = \frac{g}{\theta} \frac{\partial \theta}{\partial z} \quad (9)$$

where N is the Brunt–Väisälä frequency (s^{-1}), θ is the potential temperature (K), and z is altitude (m). A positive value of N^2 confirms a statically stable atmospheric layer.

The energy barrier that must be overcome to initiate deep convection is quantified by convective inhibition (CIN):

$$CIN = - \int_{z_s}^{z_{LFC}} g \frac{T_{v,p} - T_{v,e}}{T_{v,e}} dz \quad (10)$$

where CIN is in $J\ kg^{-1}$, z_s is surface altitude (m), z_{LFC} is the level of free convection (m), $T_{v,p}$ is the virtual temperature of the rising air parcel (K), and $T_{v,e}$ is the virtual temperature of the environment (K).

Aerosol–Cloud Microphysics (Twomey Effect)

Where mineral dust acts as cloud condensation nuclei (CCN), cloud droplet number concentration N_d responds to CCN concentration through an empirical power-law relationship (Solmon et al., 2008):

$$N_d = c (N_{CCN})^k \quad (11)$$

where N_d is cloud droplet number concentration (cm^{-3}), N_{CCN} is activated CCN concentration (cm^{-3}), and c and k are empirically derived constants.

For fixed cloud liquid water content L , an increase in N_d reduces the mean effective droplet radius:

$$r_{eff} \propto \left(\frac{L}{N_d} \right)^{1/3} \quad (12)$$

where r_{eff} is the effective droplet radius (μm) and L is cloud liquid water content ($g\ m^{-3}$). Increased CCN loading therefore produces more numerous but smaller droplets, reducing coalescence efficiency and suppressing precipitation.

Dust Emission Flux

Vertical dust emission flux from bare or weakly vegetated surfaces is governed by surface friction velocity, following the Marticorena–Bergametti framework (Marticorena & Bergametti, 1995; Laurent et al., 2008):

$$F_d = C \frac{\rho_a u_*^3}{g} \left(1 - \frac{u_{*t}}{u_*} \right) \left(1 + \frac{u_{*t}}{u_*} \right)^2 u_* > u_{*t} \quad (13)$$

$$F_d = 0, \text{ for } u_* \leq u_{*t} \quad (14)$$

where F_d is the vertical dust emission flux ($kg\ m^{-2}\ s^{-1}$), C is a soil-dependent empirical constant (dimensionless), ρ_a is air density ($kg\ m^{-3}$), u_* is the surface friction velocity ($m\ s^{-1}$), u_{*t} is the threshold friction velocity for particle entrainment ($m\ s^{-1}$), and g is gravitational acceleration. Loss of vegetation cover lowers u_{*t} , making dust emission possible under weaker wind conditions the physical core of the land-degradation dust feedback discussed throughout this paper.

Horizontal Saltation Flux

The horizontal saltation mass flux, Q , which provides the mechanical energy to mobilise finer dust particles into suspension, is expressed as:

$$Q = \frac{\rho_a}{g} u_*^3 \left(1 - \frac{u_{*t}}{u_*}\right) \left(1 + \frac{u_{*t}}{u_*}\right)^2 \quad (15)$$

where Q is the horizontal saltation mass flux ($\text{kg m}^{-1} \text{s}^{-1}$).

Aerosol Transport and Deposition

Atmospheric transport, mixing, and removal of dust are described by the Eulerian mass conservation equation (Knippertz & Todd, 2012):

$$\frac{\partial C}{\partial t} + \nabla \cdot (\mathbf{u} C) = \nabla \cdot (K \nabla C) + E - D - S \quad (16)$$

where C is atmospheric dust mass concentration (kg m^{-3}), \mathbf{u} is the three-dimensional wind vector (m s^{-1}), K is the turbulent diffusion tensor ($\text{m}^2 \text{s}^{-1}$), E is the emission source term ($\text{kg m}^{-3} \text{s}^{-1}$), D is the dry deposition sink ($\text{kg m}^{-3} \text{s}^{-1}$), and S is the wet scavenging sink ($\text{kg m}^{-3} \text{s}^{-1}$).

The dry deposition flux at the surface is given by:

$$F_{\text{dep}} = v_d C \quad (17)$$

where F_{dep} is the dry deposition flux ($\text{kg m}^{-2} \text{s}^{-1}$) and v_d is the deposition velocity (m s^{-1}).

Surface Energy Balance under Dust Loading

Dust modifies the land-surface energy balance by attenuating incoming shortwave radiation. The surface energy balance is expressed as (Saidou Chaibou et al., 2020; Slingo et al., 2006):

$$R_n = (1 - \alpha_s) S_{\text{dust}}^{\downarrow} + L^{\downarrow} - L^{\uparrow} = H + LE + G \quad (18)$$

where R_n is net all-wave radiation at the surface (W m^{-2}), α_s is surface albedo (dimensionless), $S_{\text{dust}}^{\downarrow}$ is dust-attenuated downwelling shortwave irradiance (W m^{-2}), L^{\downarrow} is downwelling longwave irradiance (W m^{-2}), L^{\uparrow} is upwelling longwave irradiance (W m^{-2}), H is sensible heat flux (W m^{-2}), LE is latent heat flux (W m^{-2}), and G is ground heat flux (W m^{-2}).

Soil Moisture Dynamics

The temporal evolution of rooting-zone volumetric soil moisture, θ_s , is described by the simplified water-balance equation:

$$\frac{d\theta_s}{dt} = \frac{1}{\rho_w z_r} (P - ET - R_o - D_r) \quad (19)$$

where θ_s is volumetric soil moisture content ($\text{m}^3 \text{m}^{-3}$), ρ_w is the density of water (1000 kg m^{-3}), z_r is effective rooting depth (m), P is precipitation rate ($\text{kg m}^{-2} \text{s}^{-1}$), ET is evapotranspiration rate ($\text{kg m}^{-2} \text{s}^{-1}$), R_o is surface runoff ($\text{kg m}^{-2} \text{s}^{-1}$), and D_r is deep drainage ($\text{kg m}^{-2} \text{s}^{-1}$). Dust-driven reductions in P through the stability and microphysical pathways of Equations (9) – (12) combined with altered surface energetics from Equation (18), suppress θ_s and amplify vegetation stress, closing the feedback loop described in Section 3.5.

Synthesis-Level Use of the Equations

The equations in this section served as interpretive tools rather than as a numerical modelling system. Each governing relation provided a physical reference frame against which we assessed the quantitative results of the reviewed studies for internal consistency, cross-study comparability, and physical plausibility. For example, reported surface radiative forcing of approximately -35 W m^{-2} and top-of-atmosphere forcing of approximately -12 W m^{-2} imply atmospheric absorption of roughly $+23 \text{ W m}^{-2}$ through Equation (7). This is consistent with

reported lower-tropospheric heating rates of $0.5 - 1.2\text{K day}^{-1}$ through Equation (8) (Saidou Chaibou et al., 2020). Similarly, the emission relationship in Equation (14) explains why observed vegetation loss in Borno, Yobe, and Adamawa can increase dust emission without any corresponding increase in regional wind speed. Where reported magnitudes diverged substantially from the physically expected range, those studies were flagged in the synthesis as warranting closer methodological scrutiny.

RESULTS AND DISCUSSION

Overview of the Reviewed Literature

Research on dust aerosols and climate change in northeastern Nigeria has grown considerably since 2016, advancing in both quantity and methodological sophistication. The early literature mostly took a descriptive approach, characterising dust haze events and using satellite data to estimate aerosol loading (Balarabe et al., 2016; Ogunjobi et al., 2004). By the early 2020s, something of a shift had occurred. More recent work connects aerosol dynamics to land-surface processes, hydrology, agriculture, and human health in ways that earlier studies hadn't attempted (Heinold et al., 2013; Balkanski et al., 2021; Wane et al., 2025).

Throughout this literature, satellite remote sensing has carried most of the weight MODIS AOD products, CALIPSO vertical profiling, Landsat land-use analyses (Tanré et al., 1997; Ginoux et al., 2012). Ground-based measurements, by contrast, are thin. AERONET sun photometers, PM samplers, and radiosondes remain scarce, which is partly a product of the enormous logistical and security challenges of sustained fieldwork in Borno and Yobe (Holben et al., 1998). In our assessment, this gap in ground-truth data is the most consequential limitation in the current evidence base a point we revisit in Section 3.8. The distribution of research methods across the reviewed studies appears in Table 2.

Table 2. Principal methods used in the reviewed studies, with representative references.

Method	Description	Representative studies
Satellite remote sensing	MODIS AOD, CALIPSO, CERES, Landsat	Tanré et al. (1997); Ginoux et al. (2012); Balarabe et al. (2016)
Ground-based observation	AERONET, PM sensors, radiometers	Holben et al. (1998); Anuforum et al. (2007)
Trajectory and dispersion modelling	HYSPLIT, Lagrangian back-trajectories	Todd et al. (2007); Washington et al. (2006)
Chemical transport / regional modelling	WRF-Chem, convection-permitting simulation	Heinold et al. (2013); Laurent et al. (2008)
Climate model projections	CMIP5/CMIP6, coupled GCM scenarios	Balkanski et al. (2021); Kok et al. (2017); Wane et al. (2025)
Statistical trend analysis	Mann–Kendall, correlation, regression	Akinsanola & Ogunjobi (2017); Nicholson (2013)

Dust Sources, Transport Pathways, and Seasonal Dynamics

Pinpointing where northeastern Nigeria's dust actually comes from has attracted sustained research effort, and the picture that emerges is more nuanced than a simple "Bodélé sends dust south" account would suggest. The view that the Bodélé Depression supplies the lion's share of regional aerosol burden during Harmattan is well-supported satellite source activation maps, backward-trajectory analyses, and dedicated field campaigns all point the same direction (Washington et al., 2006; Todd et al., 2007; Prospero et al., 2002). Dust driven off the

Depression by the Bodélé Low-Level Jet typically reaches Borno and Yobe within two to three days, arriving at altitudes of 1,000–3,000 m in winds averaging 10–15 m s⁻¹ (Engelstaedter et al., 2006; Todd et al., 2007).

What has shifted over the review period is the weight now given to local and regional sources. Lake Chad's retreat has uncovered enormous areas of fine-grained lacustrine sediment that is extraordinarily susceptible to wind entrainment a dust source that simply did not exist at this scale two generations ago (Pham-Duc et al., 2020, 2022; Gao et al., 2025). Land-cover analyses show that overgrazing, deforestation, and conflict-driven farmland abandonment have substantially increased bare-soil exposure across Borno, Yobe, and Adamawa (Nwilo et al., 2020; Brandt et al., 2017). From a physics perspective, this matters because the erodibility of any surface is governed by the threshold friction velocity u_{*t} in Equation (14). As vegetation thins out, u_{*t} drops, and the same wind that previously moved nothing can now mobilise large quantities of dust (Cowie et al., 2013). The principal findings on sources and transport are consolidated in Table 3.

Table 3. Summary of dust source and transport findings.

Source / Process	Principal finding
Bodélé Depression	Dominant long-range source during peak Harmattan; dust arrives within 2–3 days at 1,000–3,000 m altitude (Todd et al., 2007; Washington et al., 2006)
Sahara Desert	Major transboundary contributor throughout the dry season (Engelstaedter et al., 2006; Prospero et al., 2002)
Lake Chad Basin	Rapidly expanding local source; >90% lake-area loss since the 1960s exposes fine lacustrine sediment (Pham-Duc et al., 2020, 2022; Gao et al., 2025)
Degraded rangelands and abandoned farmlands	Growing local sources linked to overgrazing and conflict-driven displacement (Nwilo et al., 2020; Brandt et al., 2017; Cowie et al., 2013)
Seasonal pattern	Maximum aerosol loading November–March; southward attenuation but measurable even in sub-humid southern states (Anuforom et al., 2007; Mbourou et al., 1997)

The management implications of this are worth flagging directly. Most policy conversations about Sahelian dust orbit around the Bodélé and Sahara — sources over which no single country has meaningful leverage. The local component is a different story. It's controllable, at least in principle, through land management, surface stabilisation, and rangeland rehabilitation.

Radiative Effects and Temperature Modulation

Dust's radiative effects over northeastern Nigeria operate simultaneously at the surface and higher up in the atmosphere, and they pull in opposite directions which is part of what makes the climate response so disruptive.

Following Equations (1) and (4), dust increases column AOD and attenuates incoming shortwave radiation. Across the reviewed literature, peak Harmattan events reduce surface solar radiation by approximately 30–40% (Kok et al., 2017; Balarabe et al., 2016). Regional Sahelian studies report surface radiative forcing near -35 W m^{-2} and top-of-atmosphere forcing near -12 W m^{-2} during heavy dust events (Solmon et al., 2008; Knippertz & Todd, 2012). Applying Equation (7) to those numbers gives an implied atmospheric absorption of roughly $+23 \text{ W m}^{-2}$, consistent with Saidou Chaibou et al. (2020). At the surface, that translates to a daytime cooling of about 1.2–1.8 °C (Kok et al., 2017) modest in absolute terms but consequential when propagated through the surface energy balance of Equation (19), where it suppresses evapotranspiration and reduces water availability for crops.

Meanwhile, aloft, iron-oxide-bearing dust and particles mixed with black carbon absorb solar energy. Through Equation (8), this warms the lower troposphere at rates of approximately $0.5 - 1.2 \text{ K day}^{-1}$ (N'Datchoh et al., 2018; Balkanski et al., 2021). The single scattering albedo governing this process [Eq. (9)] typically sits between

0.85 and 0.92 at 550 nm for Saharan and Bodélé dust (Evan et al., 2016). The key consequence of this dual structure surface cooling below, tropospheric warming above is an increase in atmospheric stability as captured by Equation (10). Greater stability resists the upward motion required to initiate convective clouds, and that suppression of convection is the bridge between dust's radiative physics and its hydrological impacts.

Dust also squeezes the diurnal temperature range, dampening afternoon highs while longwave trapping keeps night-time temperatures slightly elevated. Observed reductions are roughly 2–3 °C during Harmattan episodes (Mbourou et al., 1997; Anuforom et al., 2007). Over a growing season, that thermal dampening may affect crop development and pest dynamics in ways the literature hasn't yet fully explored. The full picture is in Table 4.

Table 4. Radiative and temperature effects of dust aerosols over northeastern Nigeria.

Effect	Reported magnitude	Key references
Reduction in surface solar radiation	30–40%	Kok et al. (2017); Balarabe et al. (2016)
Surface radiative forcing	$\approx -35 \text{ W m}^{-2}$	Solmon et al. (2008); Knippertz & Todd (2012)
Top-of-atmosphere forcing	$\approx -12 \text{ W m}^{-2}$	Solmon et al. (2008)
Implied atmospheric absorption [Eq. (7)]	$\approx +23 \text{ W m}^{-2}$	Saidou Chaibou et al. (2020)
Daytime surface cooling	1.2–1.8 °C	Kok et al. (2017)
Lower-tropospheric heating rate [Eq. (8)]	0.5–1.2 K day ⁻¹	N'Datchoh et al. (2018); Balkanski et al. (2021)
Reduction in diurnal temperature range	2–3 °C	Mbourou et al. (1997); Anuforom et al. (2007)

Dust–Rainfall Interactions and West African Monsoon Modulation

Dust and rainfall are connected through three interacting mechanisms that together produce a persistent, season-long suppression of convective precipitation the kind of rainfall this region's farming communities depend on.

The thermodynamic mechanism is the most straightforward. Cooling the surface and warming the lower troposphere simultaneously strengthens convective inhibition through Equations (9) and (10). The energy barrier to deep convection rises. The atmosphere becomes more reluctant to overturn. Modelling and observational work reports convective rainfall reductions of 12–18% under heavy dust loading (Solmon et al., 2008; Bercos-Hickey et al., 2020). In a zone where annual totals are already below 600 mm across much of Borno and Yobe, reductions of that scale are not just statistically significant they're agricultural emergencies.

The microphysical mechanism compounds the problem. Dust acting as CCN drives up droplet number concentration [Eq. (11)] and simultaneously drives down mean droplet radius [Eq. (12)]. Clouds end up with more, smaller droplets that don't coalesce readily into rain. Rainfall efficiency drops by roughly 8 – 10% (N'Datchoh et al., 2018).

Then there's the circulation effect. Absorbing dust warms the mid-troposphere across the broader Sahel, modifying the temperature gradient that sustains the African Easterly Jet and weakening the wave activity that organises deep convection (Bercos-Hickey et al., 2020; Balkanski et al., 2021). When climate models include more physically realistic dust behaviour, they simulate a stronger African monsoon a clear indicator of how central this process is (Balkanski et al., 2021).

Pulling these mechanisms together, the reviewed literature points to early-season rainfall reductions of up to 20 mm per event and a monsoon onset delay of one to two weeks in high-dust years (N'Datchoh et al., 2018; Nicholson, 2013). A two-week delay in planting-season onset is not a minor inconvenience for a smallholder with no irrigation backup. Looking further ahead, coupled climate projections suggest dust–climate interactions, amplified by greenhouse warming, will raise the probability of renewed Sahelian drying through mid-century under SSP2-4.5 to SSP5-8.5 pathways though the exact magnitude varies across models (Wane et al., 2025; Balkanski et al., 2021). Table 5 summarises these findings.

Table 5. Dust–rainfall and monsoon interaction findings.

Process	Climate effect	Key references
Surface cooling + tropospheric warming	Increased stability; enhanced CIN [Eqs. (10) – (11)]	Bercos-Hickey et al. (2020); Solmon et al. (2008)
Suppressed vertical motion	Reduced initiation of convective rainfall	Solmon et al. (2008)
Cloud microphysical modification [Eqs. (12) – (13)]	Rainfall efficiency reduced by 8–10%	N'Datchoh et al. (2018)
AEJ modification and moisture-transport disruption	Reduced inland monsoon penetration	Bercos-Hickey et al. (2020); Balkanski et al. (2021)
High-dust years	Monsoon onset delayed by 1–2 weeks	N'Datchoh et al. (2018); Nicholson (2013)
Future projection (SSP2-4.5 to SSP5-8.5)	Heightened Sahelian drying risk by mid-century	Wane et al. (2025); Balkanski et al. (2021)

Land Use, Desertification, and Dust–Climate Feedbacks

If there is one finding that runs consistently through the entire review period, it's this: the dust–land degradation feedback is real, it's physically grounded, and it's getting worse. It's not a complicating factor sitting on the margins of the story it's the story.

The mechanism works as follows. When vegetation is lost through overgrazing, deforestation, crop abandonment, or forced displacement u_{*t} in Equation (13) falls. Wind that previously couldn't move any sediment can now lift dust. The resulting airborne loading suppresses rainfall [as described in Section 3.4], and the modified surface energy balance [Eq. (18)] and soil-water budget [Eq. (19)] reduce rooting-zone soil moisture by an estimated 15–20% in highly exposed areas (Nwilo et al., 2020). Lower soil moisture makes revegetation harder. Bare ground is exposed for the next event. The cycle continues.

Land-cover studies confirm that degradation across the Nigerian Sahel and Lake Chad Basin has materially expanded active dust source areas since 2000 (Nwilo et al., 2020; Brandt et al., 2017). Lake Chad's ongoing contraction adds an independently important source of fine aeolian material (Pham-Duc et al., 2022; Gao et al., 2025). Where dust settles on surviving vegetation, it reduces photosynthetic activity and adds to the stress on communities that are already struggling.

Conflict deserves more attention than it has received in the atmospheric science literature. The insecurity that has persisted across Borno, Yobe, and Adamawa has triggered large-scale farmland abandonment. Abandoned farmland doesn't stay intact — it loses its canopy, its roots decay, and it becomes a locally important dust source (Nwilo et al., 2020). Security, environmental governance, and climate adaptation are not separate problems here. They're the same problem. Table 6 maps the feedback pathways.

Table 6. Dust–climate feedback pathways in northeastern Nigeria.

Pathway	Effect	Key references
Land degradation → dust emission [Eq. (14)]	Reduced vegetation lowers u^* , raising F_d	Cowie et al. (2013); Marticorena & Bergametti (1995)
Lake Chad shrinkage → source expansion	Exposed lacustrine sediments increase local dust loading	Pham-Duc et al. (2020, 2022); Gao et al. (2025)
Dust → rainfall suppression [Eqs. (9) – (12)]	Enhanced stability reduces convective rainfall	Solmon et al. (2008); N'Datchoh et al. (2018)
Rainfall decline → soil moisture loss [Eq. (19)]	Soil moisture falls by 15–20% in high-exposure areas	Nwilo et al. (2020)
Soil moisture loss → vegetation failure	More bare land; intensified wind erosion risk	Nwilo et al. (2020); Brandt et al. (2017)
Conflict → land abandonment	New dust hotspots in insecurity-affected zones	Nwilo et al. (2020)

Health, Air Quality, and Socio-Economic Effects

Dust doesn't stay in the upper atmosphere. It comes down, it stays near ground level during stable conditions, and it gets breathed. During Harmattan, PM_{10} and $PM_{2.5}$ concentrations rise sharply and frequently breach health-protective thresholds for extended stretches of time (Bauer et al., 2019). Clinical data from the region and continent-wide assessments show increased presentations of asthma, acute bronchitis, respiratory infections, and a range of cardiorespiratory conditions. Children, elderly people, and those with underlying illness carry the largest burden. Continental-scale modelling specifically attributes a substantial portion of Africa's outdoor air-pollution health burden to mineral dust (Bauer et al., 2019). How those risks compound when dust and heat stress hit simultaneously a combination that will become more common under warming remains an important gap.

The economic costs spread wide: crop-yield losses, healthcare expenditure, reduced labour productivity during haze episodes, infrastructure abrasion, and impaired transport visibility. Regional agricultural projections consistently identify climate-driven yield pressure across West Africa, with dust-related rainfall suppression as a contributing mechanism (Sultan & Gaetani, 2016). Specific cost figures in the grey literature should be treated cautiously — they're often illustrative rather than rigorously derived.

These burdens don't fall equally between men and women. Women in northeastern Nigeria's agrarian communities carry primary responsibility for food production, water collection, fuel gathering, and food processing. All of those roles are directly and materially disrupted by dust-related climate impacts. Female-headed households are further disadvantaged by reduced access to irrigation, credit, improved seed, and extension services, leaving them with fewer options for adapting. This dimension of the problem has received far less research attention than its practical importance warrants.

On the more hopeful side: land restoration delivers clear co-benefits. Agroforestry systems, shelterbelts, controlled grazing regimes, and rangeland revegetation all simultaneously reduce local dust emission, improve soil-moisture retention, moderate local temperatures, and support agricultural productivity (Brandt et al., 2017; IPCC, 2022). These are scalable interventions with well-documented track records in the Sahel.

Methodological Advances and the 2025 Extension

The methods used to study dust and climate in this region have evolved substantially over the review period. The early literature leaned heavily on satellite-based AOD characterisation. More recent work has brought

regional atmospheric modelling, convection-permitting dust-emission simulation, and coupled land–atmosphere frameworks into the picture (Heinold et al., 2013; Laurent et al., 2008; Balkanski et al., 2021). Work published through the 2025 cut-off extends that trajectory further: new analyses of aerosol-type anomalies and their connections to pre-monsoon precipitation trends over Nigeria (Onyejuruwa et al., 2025), a four-decade spatiotemporal reanalysis of African aerosol trends using MERRA-2 (Omokpariola, 2025), a reassessment of drought risk trajectories in the western Sahel (Wane et al., 2025), and a specific investigation of toxic dust emissions from drought-exposed lake beds a hazard directly relevant to Lake Chad's continued recession (Gao et al., 2025).

Limitations of the Evidence Base and of This Review

Several real limitations constrain the conclusions that can be drawn here. The most significant is the near-total absence of sustained ground-based observational infrastructure. With so few continuously operating aerosol measurement stations in the region, satellite retrievals go largely unvalidated and process-level understanding remains constrained (Holben et al., 1998). Even satellite data carry their own limitations: AOD retrievals over bright desert surfaces using Deep Blue and comparable algorithms can be unreliable across the steep surface-albedo gradients characteristic of the Sahel (Ginoux et al., 2012; Tanré et al., 1997). Attributing specific rainfall changes cleanly to dust as distinct from sea-surface-temperature variability, vegetation feedbacks, and greenhouse forcing is genuinely difficult, and quantitative estimates from individual studies should be read as indicative rather than definitive (Balkanski et al., 2021; Wane et al., 2025). This review has its own limits too. It drew only on English-language peer-reviewed sources, and the tendency for statistically significant or novel results to be published ahead of null findings may have introduced bias. Several quantitative claims encountered in the regional grey literature could not be verified independently, and they were either excluded or clearly qualified where they appear.

A Conceptual Model of the Dust–Climate Feedback Loop

All of the mechanisms described above converge on a single, overarching conclusion: dust aerosols in northeastern Nigeria are not simply a hazard blown in from somewhere else. They are an active node in a coupled human–environment system and one that is, in part, driven by human decisions about land use and governance.

The core feedback loop is depicted in Fig. 3 and can be expressed as a causal chain:

Land degradation → reduced threshold friction velocity u_{*t} [Eq. (14)] → increased dust emission F_d → higher aerosol optical depth τ_λ [Eq. (1)] → attenuated surface solar irradiance [Eq. (3)] → lower-tropospheric heating [Eq. (7)] → increased static stability [Eq. (9)] → strengthened convective inhibition [Eq. (10)] → suppressed convective rainfall → reduced rooting-zone soil moisture [Eq. (19)] → vegetation failure → further land degradation.

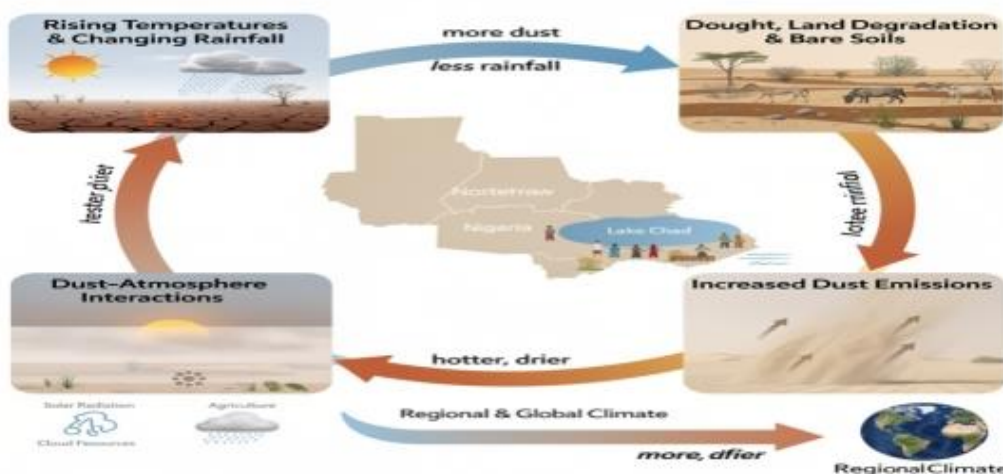


Figure 3: Conceptual model of the dust-climate feedback loop in northeastern Nigeria.

Figure 3 is a Conceptual model of the dust–climate feedback loop in northeastern Nigeria. The circular diagram shows the self-reinforcing cycle linking land degradation through each physical process step to vegetation failure and back to further degradation. Governing equation numbers are indicated at each node for direct cross-reference with Section 2.5. External amplifiers (a) Lake Chad contraction adding fine lacustrine sediment; (b) conflict-driven farmland abandonment creating new bare-soil source areas; and (c) background regional warming desiccating soils are shown as labelled external arrows entering the loop.

Three external forces amplify this loop without being part of it: Lake Chad's ongoing contraction, the insecurity that keeps farmland bare and unmanaged, and background regional warming that progressively desiccates soils and weakens plant cover (Pham-Duc et al., 2022; Nwilo et al., 2020; Wane et al., 2025). Addressing climate vulnerability in this region means engaging the full feedback system not its components in isolation.

The major quantitative effects across all thematic domains are brought together in Fig. 4.

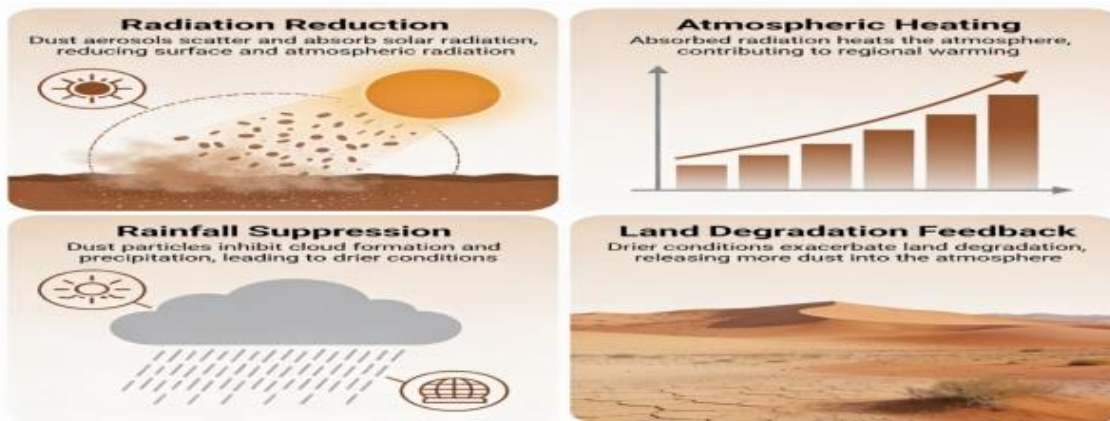


Figure 4: Summary of major climatic effects of dust aerosols: radiation reduction, atmospheric heating, rainfall suppression and land degradation feedback.

Figure 4. is a Summary of the major climatic effects of dust aerosols in northeastern Nigeria across four interconnected domains. Panel (a): radiation dust reduces surface solar radiation by 30 – 40% during peak Harmattan, with surface radiative forcing near 35 W m^{-2} and atmospheric absorption near $+23 \text{ W m}^{-2}$ [Equations (1) – (6); Tables 3 – 4]. Panel (b): temperature daytime surface cooling of $1.2\text{--}1.8 \text{ }^\circ\text{C}$ and lower-tropospheric heating at $0.5\text{--}1.2 \text{ Kday}^{-1}$ [Equations (7) – (8); Table 4]. Panel (c): rainfall and monsoon rainfall efficiency reduced by 8–10%; early-season rainfall reduced by up to 20 mm per event; monsoon onset delayed by 1–2 weeks in high-dust years [Equations (9) – (12); Table 5]. Panel (d): land feedback the self-reinforcing desertification–dust loop mediated by soil moisture and vegetation dynamics [Equations (13) – (19); Table 6]. All quantitative values are drawn directly from the reviewed studies.

CONCLUSION

This review confirms that dust aerosols are major climate-forcing agents in northeastern Nigeria, operating through interconnected physical pathways that, taken together, constitute a system rather than a collection of isolated effects. The central finding is not any single number not the 35 W m^{-2} surface forcing or the two-week monsoon delay but the structural character of the problem: a feedback in which degraded land, elevated dust loading, suppressed rainfall, and failing vegetation reinforce one another.

Two things stand out. The first is the degree of vulnerability. Because farming here is overwhelmingly rain-fed, and because the population is already among Africa's most climate-exposed, the rainfall suppression and growing-season disruption documented in this review translate almost directly into food insecurity, ill health, and economic loss. Women and displaced communities carry the heaviest share. The second is a reason for qualified optimism. The same evidence that shows how serious the problem is also shows where it's tractable. The local component of dust emission is growing, and unlike the Saharan and Bodélé sources, it responds to

land management, surface stabilisation, and restoration. The distinction between what is controllable and what is not should shape where resources and research attention go.

What's now needed is less a further demonstration that dust matters this synthesis has done that and more the investment in observational infrastructure, modelling capacity, and governance architecture to actually manage it. Where that investment is made at the right scale and grounded in an understanding of the system as a whole, the deteriorating trajectory described in this review need not be the only possible future.

RECOMMENDATIONS

The following actions follow directly from the synthesised evidence, grouped by domain.

A. Monitoring and Early Warning

1. Establish a regional dust-monitoring network across all six states, combining AERONET-standard sun photometers, low-cost validated PM sensors, radiometers, and automated weather stations at a density adequate for satellite validation (Holben et al., 1998; Onyejuruwa et al., 2025).
2. Develop an operational dust early-warning system linked to the Nigerian Meteorological Agency, agricultural services, and public-health infrastructure capable of providing actionable lead time before severe Harmattan episodes.

B. Land Restoration and Surface Stabilisation

3. Implement large-scale restoration on the most erodable surfaces degraded rangelands, Lake Chad margins, and conflict-abandoned farmland using agroforestry, shelterbelts, contour bunding, controlled grazing, and drought-resistant revegetation, with explicit monitoring of dust-emission outcomes (Brandt et al., 2017; Cowie et al., 2013).

C. Governance and Transboundary Cooperation

4. Strengthen environmental governance through the Lake Chad Basin Commission, with dedicated programmes to stabilise exposed lacustrine sediments and coordinate transboundary land and water management across member states (Pham-Duc et al., 2022).

D. Scientific and Modelling Capacity

5. Advance regional climate modelling using locally calibrated dust-emission inventories and higher-resolution simulations suited to the distinctive properties of Lake Chad sediments and degraded rangeland soils (Balkanski et al., 2021; Marticorena & Bergametti, 1995).
6. Build sustained interdisciplinary research capacity within Nigerian universities, linking atmospheric physics, agronomy, epidemiology, geography, conflict studies, and policy analysis (Onyejuruwa et al., 2025; Omokpariola, 2025).

E. Policy Integration

7. Formally embed dust management within Nigeria's National Adaptation Plan, Nationally Determined Contribution, and Great Green Wall commitments, treating dust explicitly as a climate-forcing agent — not merely an air-quality nuisance (IPCC, 2022).

F. Equity and Inclusion

8. Design and adequately resource gender-sensitive adaptation programmes that specifically address the compounded vulnerabilities of women farmers, female-headed households, and displaced rural communities, who face greater exposure and fewer resources for response (Sultan & Gaetani, 2016).

Conflict of Interest

The authors declare no conflict of interest.

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