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A Review of Literature on Coronal Ion Discharge from High-Voltage Power Lines

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Abstract**—***Corona discharge is a localized electrical ionization phenomenon that occurs around high-voltage power transmission lines when the electric field intensity exceeds the dielectric strength of air without causing complete breakdown. This review examines the mechanisms of corona ion generation, their chemical composition, environmental dispersion, interactions with atmospheric aerosols, and potential health implications. The literature indicates that corona onset is influenced by conductor geometry, surface condition, operating voltage, and atmospheric factors such as humidity, temperature, and air pressure. Corona discharge produces large concentrations of positive and negative ions, primarily hydrated molecular clusters, which readily attach to airborne aerosol particles. Studies show that corona-generated ions can modify local atmospheric electrical conditions by creating space charges that alter natural electric field distributions. Their dispersion is strongly affected by meteorological conditions, particularly wind speed, wind direction, rainfall, and atmospheric electric field variations. The attachment of ions to aerosols may produce predominantly unipolar charge distributions, potentially enhancing particle transport and deposition within the human respiratory system. Although the physical and chemical processes associated with corona discharge are well documented, uncertainties remain regarding its long-term environmental and health effects. Most existing evidence is based on laboratory studies, numerical simulations, and short-term field measurements, while comprehensive epidemiological investigations are limited. The review concludes that corona ion discharge is a multidisciplinary issue involving electrical engineering, atmospheric science, and environmental physics. Further research is required to clarify long-term exposure effects and support the development of evidence-based guidelines for managing potential environmental and health risks associated with high-voltage transmission systems.*

Keywords**—** *Corona discharge, corona ions, high-voltage power lines, atmospheric aerosols, environmental impact.*

I. Introduction

A. Background to the Study

Electrical energy transmission is an essential component of modern society, enabling the transfer of electricity from generating stations to distribution networks and consumers over long distances. High-voltage power transmission lines (HVPLs) are designed to minimize resistive I^2R losses by transmitting electricity at elevated voltages, often ranging from 132 kV to over 765 kV depending on the transmission network. These systems consist of metallic conductors suspended above the ground by towers and insulator assemblies. Although highly efficient for energy transport, the operation of HVPLs is associated with several environmental and atmospheric phenomena, one of the most prominent being corona discharge (Zobaa *et al*., 2025).

Corona discharge is a localized electrical breakdown of air that occurs when the electric field intensity around a conductor exceeds the dielectric strength of the surrounding air without causing a complete electrical breakdown between phases. Under such conditions, air molecules within the high-field zone become ionized, producing large quantities of positively and negatively charged ions known as corona ions (Peek, 1920). The phenomenon is particularly pronounced around conductors operating at extra-high voltages (EHV) and ultra-high voltages (UHV), especially where conductor surfaces contain structural irregularities or macro-defects such as scratches, contamination, dust deposits, or water droplets (Maruvada, 2000).

The generation of corona ions has attracted considerable scientific attention because of its implications for atmospheric electricity, environmental quality, and public health. Corona ions modify the natural atmospheric electrical environment by introducing significant space charges into the air surrounding transmission lines. These charges can alter the Earth's naturally occurring direct current (DC) electric field, which under fair-weather conditions typically averages approximately 100 V/m to 150 V/m, directed downward toward the Earth's surface (Zhang *et al*., 2026). The resulting electrical disturbances can extend considerable distances downwind from transmission corridors, depending on meteorological conditions and line design characteristics.

Furthermore, corona-generated ions rapidly interact with atmospheric aerosol particles. These interactions influence the electrical properties of airborne pollutants and may affect their transport, deposition, and inhalation characteristics (Matthew *et al*., 2023). Consequently, understanding the mechanisms of corona ion generation and dispersion has become increasingly important across environmental physics, electrical engineering, and public health research.

B. Literature Review

Research on corona discharge from power transmission lines spans several decades and encompasses investigations into electrical phenomena, atmospheric chemistry, aerosol physics, and biological effects. Early foundational work by Peek (1920) established the theoretical basis for corona inception and introduced empirical methods for estimating corona onset conditions on high-voltage conductors.

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Subsequent investigations provided comprehensive analyses of corona performance in transmission systems, demonstrating how conductor geometry, surface conditions, and environmental variables influence ion production rates (Jordi-Roger & Manuel, 2025).

Studies have consistently shown that corona ions are generated when the macroscopic electric field at the conductor surface exceeds a critical threshold known as the corona onset field. This threshold varies according to conductor diameter, conductor bundle configuration, air density, humidity, and atmospheric pressure (Maruvada, 2000; Jordi-Roger & Manuel, 2025). Once generated, the ions rapidly migrate away from the conductor under the influence of the local electric field and ambient wind forces.

Atmospheric studies have demonstrated that free ions survive only briefly before attaching to suspended aerosol particles. Nishida *et al*. (2025) reported that ion-aerosol attachment processes significantly alter the charge distribution of atmospheric particles. Under natural conditions, aerosols exhibit a bipolar charge distribution in which positive and negative charges occur in an approximate Boltzmann equilibrium. However, in the vicinity of HVPLs, corona ions convert this balanced distribution into a predominantly unipolar charge environment (Matthew *et al*., 2023).

Pablo *et al*. (2022) proposed that the unipolar charging of pollutant aerosols could increase their deposition velocity within the human respiratory tract following inhalation. This hypothesis stimulated considerable interest in the potential health implications of corona ion exposure. Later investigations by J-Fatokun *et al*. (2010) confirmed that overhead transmission lines can significantly influence local electric field conditions and ambient particle charging characteristics. Their findings demonstrated measurable increases in space charge density and modifications to atmospheric electrical properties near transmission corridors.

Research has also focused on the chemical composition of corona-generated ions. Studies conducted by Skalný *et al*. (2006), Sabo *et al*. (2012), and Manninen *et al*. (2011) revealed that corona ions comprise complex clusters of hydrated molecules whose composition depends strongly on ambient atmospheric conditions. Positive ions are typically dominated by protonated water clusters, whereas negative ions often consist of carbonate, nitrate, and oxygen-containing species (Asakawa & Hiraoka, 2023).

Recent investigations have expanded our understanding of corona behavior under varying meteorological and electrical conditions. Zhang *et al*. (2026) demonstrated that background electric field variations associated with thunderstorms and atmospheric disturbances can significantly influence corona initiation and development. Such findings suggest that corona activity is not solely determined by transmission line characteristics but also by dynamic atmospheric state variables.

Even though there is a lot of information about the physical processes of corona discharge, there are still unknowns about the consequences of long-term exposure on human populations. Existing studies have largely focused on laboratory experiments, numerical simulations, and short-term field measurements, while comprehensive epidemiological investigations remain relatively limited (Atepa *et al*., 2024).

C. Statement of the Problem

The widespread deployment of high-voltage transmission networks has resulted in increasing human exposure to environments influenced by corona ion generation. Although corona discharge is a well-established electrical phenomenon, concerns persist regarding its downstream environmental and health implications. Corona ions alter the Earth's natural atmospheric electrical environment by generating substantial space charges that modify local electric field profiles (Li & Lin, 2019).

More importantly, corona ions readily attach to airborne particulate matter ($PM_{2.5}$ and PM_{10},) including pollutants originating from industrial emissions, vehicular exhaust, agricultural activities, and domestic combustion sources. This charging process may increase the probability of particle deposition within the respiratory system due to enhanced electrostatic attraction between charged particles and lung mucosal tissues (Fews *et al*., 1999). Such effects may be particularly significant for vulnerable populations including children, the elderly, and individuals with pre-existing chronic respiratory disorders.

Meteorological phenomena further complicate the situation. Variations in relative humidity, wind speed, atmospheric pressure, rainfall, and thunderstorm activity can substantially alter corona generation rates and ion dispersion patterns (J-Fatokun *et al*., 2010; Zhang *et al*., 2026). Consequently, predicting spatial exposure levels and assessing associated risks remains challenging.

Despite these concerns, significant gaps remain in understanding the long-term consequences of chronic exposure to corona-generated ions and unipolarly charged aerosols. There is, therefore, a pressing need for a systematic, comprehensive review of current knowledge regarding corona ion production, chemical characteristics, environmental transport, and potential public health impacts.

D. Justification of the Study

Understanding corona ion generation is critical from both engineering optimization and public health standpoints. From an engineering perspective, corona discharge contributes to continuous active power losses, audible noise, electromagnetic interference (EMI), and degradation of transmission system insulation performance (Maruvada, 2000). Accurate prediction of corona onset conditions enables design engineers to optimize conductor selection, grouping, and bundles to minimize these undesirable operational losses.

From an environmental perspective, corona-generated ions significantly influence atmospheric electrical processes and aerosol dynamics. The ability of these ions to modify particle charging characteristics affects pollutant transport and deposition velocities, with direct implications for local air quality management (Samah *et al*., 2024). Additionally, changes in local atmospheric electric fields may influence various environmental processes, including particle coagulation rates and micro-scale atmospheric chemistry.

The study is further justified by continuing public concern regarding possible health risks associated with living near transmission corridors. Although existing evidence remains inconclusive, several researchers have suggested plausible bio-physical mechanisms through which corona-generated ions may increase respiratory exposure to ambient airborne pollutants (Fews *et al*., 1999; Atepa *et al*., 2024). A comprehensive understanding of these mechanisms is essential for developing evidence-based regulatory guidelines and public health safety margins.

Furthermore, advances in atmospheric monitoring technologies and numerical computational fluid dynamics (CFD) modeling techniques now provide opportunities for more accurate assessment of corona ion behavior under real-world conditions. A detailed review of current literature is therefore necessary to synthesize these findings, identify existing knowledge gaps, and define future research priorities.

E. Aim and Objectives

Aim

The primary aim of this study is to critically review and synthesize existing literature concerning the generation mechanisms, chemical composition, environmental transport, aerosol interactions, and potential health impacts of corona ion discharge from high-voltage power transmission lines.

Objectives

The specific objectives are to:

1. Examine the physical and electrostatic principles governing corona discharge and ion production around high-voltage conductors.
2. Analyze the chemical composition, charge characteristics, and mobility spectra of corona-generated cluster ions.
3. Investigate the environmental transport, boundary layer dispersion, and spatial distribution of corona ions under varying meteorological conditions.
4. Evaluate the microphysical interactions between corona ions and atmospheric aerosols.
5. Assess current toxicological and epidemiological evidence regarding potential human health effects associated with exposure to corona-generated ions and unipolarly charged particles.
6. Identify critical gaps in existing scientific knowledge and recommend strategic directions for future research.

II. Mechanisms of Ion Production and Physical Characteristics

Corona discharge is fundamentally an ionization process that occurs when the localized electric field intensity surrounding a conductor exceeds the dielectric strength of the air without causing complete electrical breakdown between phases. This phenomenon is particularly important in high-voltage transmission systems where electric field gradients near conductor surfaces may become sufficiently large to initiate Townsend avalanche ionization of atmospheric gases (Peek, 1920; Maruvada, 2000).

The onset of corona discharge depends primarily on the electric field strength at the conductor surface. According to Peek (1920), corona begins when the surface electric field exceeds a critical value known as the corona onset field. This threshold is influenced by several factors, including conductor radius, conductor surface condition, atmospheric pressure, air density, temperature, and relative humidity. Larger conductors generally exhibit lower surface electric field intensities for a given operating voltage and therefore possess higher corona inception voltages compared with smaller, single conductors.

The macroscopic corona onset condition is commonly estimated using Peek's empirical formula:

$$E_c = m_0 \delta E_0 \left(1 + \frac{0.301}{\sqrt{r\delta}}\right)$$

Where:

- E_c is the critical macroscopic electric field for corona inception (kV/cm),
- m_0 is the conductor surface irregularity factor ($m_0 \leq 1$),
- δ is the relative air density correction factor,
- E_0 is the reference breakdown strength of air under standard temperature and pressure (STP, typically taken as 30 kV/cm peak or 21.2 kV/cm rms), and
- r is the outer radius of the conductor (cm) (Peek, 1920).

This equation illustrates the significant influence of conductor geometry and atmospheric density on corona formation.

Surface imperfections play a major role in local field enhancement. Scratches, dust deposits, corrosion, insect contamination, and water droplets create localized regions of increased curvature that concentrate electric field lines, increasing the local field intensity far beyond the calculated average surface value (Maruvada, 2000). During rainy weather, suspended water droplets deform into Taylor cones under electrostatic forces, acting as miniature conductive protrusions that significantly lower the corona inception threshold and result in elevated ion production rates.

In alternating current (AC) transmission systems, corona generation exhibits dynamic, bipolar characteristics. During the positive half-cycle of the applied voltage wave, free electrons are accelerated toward the conductor, creating a positive space charge cloud of ionized air molecules through impact ionization. Conversely, during the negative half-cycle, electrons are emitted and accelerated away from the conductor surface, generating negative space charge clouds via electron attachment processes involving highly electronegative oxygen and other atmospheric constituents (Chang *et al*., 1995). Consequently, both positive and negative ion populations are alternately generated throughout each AC cycle.

Corona ionization zones are capable of producing extremely high concentrations of charge carriers. Experimental investigations have demonstrated that unipolar corona ionizers operating at relatively modest voltages can generate local ion concentrations exceeding 10^{14} ions/m^3 (Intra *et al*., 2020). Around commercial transmission lines operating at hundreds of kilovolts, substantial space charge clouds develop and extend considerable distances from the conductor paths depending on prevailing meteorological conditions.

The transport and electrical mobility of corona ions are governed by their net electrical charge, molecular mass, and collision frequencies with surrounding neutral air molecules. Newly generated ions possess high initial electrical mobility

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and respond rapidly to the alternating electric field. However, their free lifetime as pristine molecular ions is typically brief because they undergo fast thermodynamic hydration reactions and rapidly attach to background aerosol particles suspended in the troposphere (Samah *et al*., 2024). This ion-aerosol interaction significantly changes the environmental behavior and atmospheric residence time of corona-generated charges.

III. Chemical Composition and Mobility Spectra of Corona Ions

The chemical composition of corona-generated ions is determined by the composition of the background atmosphere and the ultra-fast ion-molecule reactions that occur immediately downstream of the ionization zone. Corona discharge initiates a complex sequence of chemical pathways involving nitrogen, oxygen, water vapor, carbon dioxide, ozone, and trace atmospheric constituents (Shahin, 1965; Skalný *et al*., 2006).

Positive corona ions in ambient air are dominated by hydrated proton clusters. Chemical ionization studies have shown that the hydronium ion (H_3O^+) serves as the core thermodynamic nucleus around which water molecules cluster to form stable species represented by the general formula:

$$H_3O^+ (H_2O)_n$$

Where the hydration number (n) depends strongly on ambient relative humidity and absolute temperature (Shahin, 1965; Manninen *et al*., 2011). Under conditions of elevated moisture content, larger, heavier hydrated clusters become thermodynamically favored.

Additional positive ion species arise when trace chemical contaminants are present in the air mass. Ammonia (NH_3), for example, readily participates in ion-molecule exchange reactions due to its high proton affinity, producing ammonium ion clusters (NH4), while volatile organic compounds (VOCs) may contribute to the formation of more complex, heavy ionic clusters (Sabo et al., 2012). These reactions demonstrate that corona ion composition is highly sensitive to local, anthropogenic atmospheric chemistry.

Negative corona ions exhibit even greater chemical diversity and complexity. Initial electron attachment reactions with gaseous O2 produce unstable oxygen-based radical ions, which subsequently undergo rapid charge-exchange reactions with carbon dioxide (CO2), nitrogen oxides (NOx), and water vapor. As a result, carbonate ions (CO3-), nitrate ions (NO3-), and their respective hydrated forms frequently dominate the steady-state negative ion population in ambient air (Skalný et al., 2006). The co-generation of ground-level ozone (O3) during corona discharge further influences negative ion chemistry by promoting secondary oxidation and chemical transformation pathways.

Differential mobility measurements of corona-generated ion spectra indicate that these cluster ions are extremely small. Manninen et al. (2011) reported that positive cluster ions generally possess mobility diameters smaller than 1.7 nm, while negative cluster ions are typically smaller than 1.6 nm. These precise dimensions place them structurally within the category of molecular cluster ions rather than condensed aerosol particles.

Ion mobility spectra provide critical data regarding the transport dynamics of corona plumes. Because electrical mobility (K) is inversely related to the structural mass and collision cross-section of the ion cluster, smaller clusters exhibit high mobilities and respond instantaneously to local voltage gradients. These high electrical mobilities enable corona-generated ions to migrate efficiently away from transmission conductors into the space-charge boundary layer before eventually attaching to larger atmospheric aerosol particles (Manninen *et al*., 2011).

The detailed characterization of corona ion composition and mobility is critical because these fundamental properties dictate how charges interact with ambient particulate matter, alter macro-scale atmospheric electrical properties, and contribute to human exposure downwind. Variations in ion chemistry also directly modify the field and diffusion charging efficiencies of ambient aerosols.

IV. Environmental Dispersion and Meteorological Influence

Once ejected from the active ionization volume around high-voltage conductors, corona ions are transported through the planetary boundary layer via a combined mechanism of electrostatic drift, turbulent diffusion, and convective bulk meteorological transport. The resulting spatial and temporal distribution of these ions determines the downwind footprint of environmental exposure and the magnitude of local atmospheric electrical anomalies.

Ambient wind is the dominant physical factor controlling the advective dispersion of corona ion plumes. Investigations by Matthews and Henshaw (2010) demonstrated that downwind ion concentrations are heavily dependent on cross-line wind speed and direction vector fields. Under calm conditions (wind speed < 1 m/s), ions are confined close to the transmission corridor due to rapid recombination and ground capture. Conversely, moderate winds transport space charge clouds substantial distances downwind. Ground-level ion concentrations often increase with wind speed up to an optimum range of approximately 3–5 m/s due to efficient mechanical extraction, beyond which mechanical dilution and dispersion dominate, reducing peak concentrations (J-Fatokun et al., 2010).

The absolute concentration of unattached cluster ions decreases with increasing radial distance from the transmission centerline. However, this spatial decay profile is highly asymmetric because wind direction vectors and localized terrain macro-topography create preferential transport pathways. River valleys, dense vegetation barriers, and urban structural canopies can significantly modify mechanical wind fields, leading to localized pockets of enhanced space-charge accumulation (Matthews & Henshaw, 2010).

Corona-generated space charges significantly modify the local atmospheric electric field profile. Fews et al. (2002) observed that space charge emitted from operating high-voltage power lines can alter the baseline fair-weather electric fields over lateral distances extending hundreds of meters from transmission corridors. In some conditions, high unipolar ion concentrations can completely reverse the polarity of the

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natural atmospheric electric field, generating localized vertical potential gradients that differ significantly from background reference values.

Meteorological state variables such as relative humidity, ambient temperature, precipitation, and barometric pressure also influence ion survival and transport. Elevated relative humidity shifts the molecular cluster distribution toward higher hydration states, reducing average electrical mobility (Manninen et al., 2011). Active rainfall drastically increases corona activity by creating pendant water drops on conductor surfaces that function as continuous micro-protrusions for corona initiation (Maruvada, 2000). Temperature and barometric pressure govern the relative air density correction factor (δ), shifting the Peek's formula onset threshold (Ec) on a seasonal or diurnal basis.

Thunderstorm environments represent highly transient, coupled conditions for corona activity. Numerical modeling by Zhang et al. (2026) demonstrated that large background electric field variations associated with convective cell development can alter corona inception and avalanche evolution. Residual space charge layers generated from preceding lightning steps or corona bursts can form shielding fields, which either delay or accelerate subsequent discharge cycles, dramatically modifying the net space charge output rate.

The combined interaction of high-voltage electrostatic fields and dynamic atmospheric boundary layer transport produces a highly stochastic environmental profile around transmission corridors. Consequently, ion concentrations exhibit substantial temporal and spatial variability, making deterministic exposure modeling a challenging task.

V. Interaction with Aerosols and Health Implications

One of the most critical environmental and biophysical consequences of corona discharge from high-voltage power transmission lines is the microphysical interaction between corona-generated cluster ions and background atmospheric aerosol particles. Tropospheric aerosols consist of solid or liquid particulate matter suspended in the air matrix, originating from natural processes (e.g., mineral dust, sea spray) and anthropogenic activities (e.g., industrial emissions, heavy-vehicle diesel exhaust, biomass burning, and residential combustion) (Onaiwu & Ayidu, 2025). Because free corona cluster ions possess high electrical mobility, they rapidly undergo collisions with and attach to these airborne particles, modifying their net surface charge properties.

The physical kinetics of ion-aerosol attachment are governed by two distinct mechanisms: diffusion charging (where random thermal motion drives ion-particle collisions) and field charging (where ions drift along external electric field lines to intercept particle cross-sections). According to Nishida *et al.* (2025), free atmospheric cluster ions attach to background aerosols within brief transport timescales, rapidly altering the baseline steady-state charge distribution of the local aerosol population. Under background tropospheric conditions, aerosols typically exhibit a balanced, bipolar charge distribution close to Boltzmann equilibrium. However, in plumes influenced by high-voltage lines, the massive injection of highly mobile unipolar ions creates a severe charge asymmetry, converting the background distribution into a highly unipolar charge state (Fews et al., 1999).

The ultimate charging efficiency of ambient aerosols depends on the local ion number density (Ni), average particle mobility diameter (Dp), hydrodynamic residence time within the plume, and local aerodynamic turbulence levels. Fine and ultrafine particles (Dp < 100 nm) require fewer individual ion collisions to achieve a significant charge-to-mass ratio, whereas larger accumulation-mode particles (Dp > 1.0 µm) can accumulate dozens of elementary charges under dense space-charge field conditions (Intra et al., 2020). Consequently, transmission corridors act as regional electro-physical forcing zones where ambient particulate matter acquires charge characteristics completely different from unaffected control environments.

The high-efficiency charging of atmospheric pollutants has direct implications for particle transport, drift velocities, and deposition profiles. Charged aerosols experience localized image-charge and Coulombic forces that can accelerate their deposition onto surrounding environmental surfaces, including vegetation and residential structures. In the context of human exposure physics, this mechanism is highly relevant because inhaled particles experience enhanced electrostatic attraction toward the grounded, moist mucosal surfaces of the human respiratory tract, potentially increasing their deposition fraction (Fews et al., 1999).

Fews et al. (1999) proposed that corona-generated ions could enhance the deposition efficiency of hazardous ambient aerosols within the tracheobronchial and alveolar regions of the lung via electrostatic image forces. This biophysical mechanism does not imply that the corona cluster ions themselves possess direct chemical toxicity; rather, it indicates that corona discharge operates as an environmental modifier that can increase the baseline internal dose of hazardous airborne co-pollutants already present in the local air mass. Criteria air pollutants, such as fine combustion soot, toxic heavy metal fractions, and industrial acidic aerosols, may therefore exhibit enhanced localized deposition when subjected to corona-induced charging.

The potential public health risks of this process have generated significant scientific debate. Increased internal deposition of fine ($PM_{2.5}$) and ultrafine ($PM_{0.1}$) particulate matter within the respiratory system is epidemiologically linked to systemic inflammation, oxidative stress, and adverse cardiovascular and respiratory clinical outcomes. Consequently, any regional physical mechanism capable of increasing particle deposition fraction warrants systematic scientific evaluation (Atepa *et al*., 2024). Vulnerable sub-populations, including children, elderly individuals with reduced lung clearance, and patients with pre-existing asthma or chronic obstructive pulmonary disease (COPD), may be at elevated risk.

Despite the physical and theoretical plausibility of this electro-statically enhanced pollutant deposition model, direct epidemiological evidence linking proximate HVPL corona exposure to increased clinical disease incidence remains limited and non-conclusive. Most published studies rely heavily on stylized laboratory exposure chambers, numerical

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flow models, and short-term field campaigns rather than longitudinal, large-cohort epidemiological designs (Atepa et al., 2024). As a result, considerable scientific uncertainty remains regarding the absolute magnitude of health risks attributable to chronic exposure to corona-modified aerosols.

An additional environmental factor is the concurrent production of ozone (O3) and reactive nitrogen/oxygen species (RNS/ROS) within the corona plasma volume. Corona processes generate trace quantities of ozone through the dissociation and subsequent recombination of triplet ground-state oxygen molecules (O2) (Bocci, 2010). Although net chemical concentrations produced by modern transmission line designs are generally low and remain well below ambient air quality standards under normal conditions, corona-induced chemical synthesis can influence micro-scale boundary layer oxidation chemistry.

From a classical power engineering perspective, corona discharge represents a continuous source of non-recoverable active energy loss. The continuous generation, acceleration, and drift of space charges require continuous electrical power from the grid, resulting in corona power losses (Pc) that can escalate from fractions of a watt to hundreds of watts per meter of transmission line during severe foul weather (Enesi et al., 2013). While a large fraction of these generated space charges undergo fast recombination or are collected by overhead shield wires and grounded towers, significant quantities escape into the lower boundary layer, where they remain available to modify ambient aerosol populations.

Overall, the interfacial coupling between corona cluster ions and atmospheric aerosols represents a critical link connecting high-voltage transmission grid operations to regional air quality and public health physics. While fundamental physical laws support the concepts of aerosol charging and electrostatic deposition enhancement, further research is required to determine the exact extent to which these microscopic shifts result in measurable, clinical public health outcomes.

VI. Discussion

The comprehensive literature reviewed demonstrates that corona discharge from high-voltage power transmission lines is a highly coupled phenomenon that spans electrical engineering, atmospheric boundary layer physics, aerosol physical chemistry, and environmental epidemiology. While corona discharge has historically been evaluated almost exclusively within power systems engineering to optimize grid efficiency and minimize radio interference, contemporary research underscores its broader environmental footprint.

A primary finding synthesized from the literature is that the inception, scaling, and time-resolved intensity of corona ion plumes are highly non-linear functions of conductor surface micro-geometry and dynamic atmospheric conditions. Variables such as conductor bundling configurations, operational surface roughness (m0), transient relative humidity, and local air density collectively determine the operational margin to the Peek's law threshold (Maruvada, 2000; Riba et al., 2018; Lesuanu & Peace, 2025). These coupled dependencies highlight the value of continuing to refine high-voltage line design parameters to proactively suppress corona formation.

The reviewed literature consistently demonstrates that corona space charge plumes act as a major local modifier of the atmospheric electrical environment. The injection of unipolar space charge clouds modifies the potential gradient profile, extending the physical footprint of the transmission line's electrostatic influence hundreds of meters laterally downwind into residential zones (Fews et al., 2002). This capacity to modify the ambient atmospheric electric field highlights how high-voltage grid infrastructure interfaces with planetary electrical processes.

Another critical insight involves the transformation of aerosol physical properties via unipolar ion attachment. The rapid collision kinetics between highly mobile cluster ions and suspended particulate matter disrupt the baseline bipolar Boltzmann equilibrium, driving local aerosols into heavily asymmetric unipolar charge states (Fews et al., 1999; Hoppel & Frick, 1986). While the fundamental physical mechanisms of diffusion and field charging are well-established in aerosol science, substantial uncertainty persists regarding the long-term biological significance of inhaling unipolarly charged particles versus neutral counterparts.

Meteorological variations introduce a high degree of stochastic uncertainty throughout the reviewed literature. Wind velocity and directional vector fields dictate the advective transport, plume dispersion, and downwind dilution patterns of the space charge layer (Matthews & Henshaw, 2010). Extreme meteorological events, such as active precipitation and thunderstorms, present a complex scenario: rainfall elevates ion generation rates via droplet deformation, while thunderstorm electric fields create complex feedback loops with the transmission line's local field profile (Zhang et al., 2026). Consequently, human exposure profiles are highly variable in both space and time, presenting a major barrier to generalized, deterministic risk assessments.

There has also been considerable analytical advancement in determining the chemical identities of corona ions, according to the literature. The deployment of high-resolution mass spectrometry and modern ion mobility spectrometers has allowed researchers to map out specific hydrated cluster channels, such as H3O+(H2O)n and CO3-(H2O)n, clarifying the micro-chemical pathways occurring immediately outside the plasma volume (Manninen et al., 2011; Skalný et al., 2006). Ion-pollutant interactions are better described by kinetic models thanks to these data.

Despite these physical insights, major knowledge gaps remain unaddressed. The current body of literature is heavily weighted toward short-term localized field monitoring campaigns, laboratory chamber simulations, and idealized numerical modeling, with a noticeable deficiency in robust, multi-year epidemiological cohorts tracking populations residing near major transmission corridors (Atepa et al., 2024). This empirical gap represents a weak link in the literature, given that public health concerns remain a primary driver of research funding in this area.

Furthermore, the clinical significance of electro-statically enhanced deposition remains open to question. While the physical models demonstrating increased lung deposition

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fractions due to image forces are theoretically sound and validated in stylized airway replicas, direct confirmation of increased morbidity or mortality in exposed human cohorts is still lacking (Fews et al., 1999). Future research must cross traditional disciplinary boundaries by pairing real-time atmospheric particle tracking with toxicological models and longitudinal health registries to provide definitive risk characterization.

Ultimately, the literature indicates that corona ion discharge cannot be solved by a single discipline. It requires an integrated approach that merges electrical power engineering, micro-meteorology, aerosol physics, and environmental health science to fully map out and mitigate its environmental impacts.

VII. Conclusion

Corona discharge remains an important environmental and operational factor in high-voltage and ultra-high-voltage power transmission systems. The event begins when local macroscopic electric field gradients near the conductor surface surpass the surrounding air's dielectric ionization threshold, producing substantial downwind flows of positive and negative space charge. The onset, scaling, and temporal intensity of these corona plumes are governed by conductor geometry, bundle configurations, operational surface conditions, and local meteorological state variables.

This comprehensive review highlights that corona-generated ions are not simple, isolated charges; rather, they rapidly organize into complex hydrated molecular cluster ions whose precise chemical composition is modulated by ambient tropospheric chemistry and anthropogenic trace contaminants. Possessing high electrical mobilities, these clusters readily undergo charge transfer and attachment kinetics with ambient aerosol particles ($PM_{2.5}$ and PM_{10}), disrupting the natural bipolar Boltzmann charge equilibrium and generating extensive downwind zones of highly unipolar aerosol systems.

Meteorological boundary layer dynamics exert a dominant control over the environmental transport, advection, and ground-level footprint of these corona plumes. Wind vectors, relative humidity, precipitation, and macro-scale thunderstorm fields govern both the physical emission rate and the spatial dispersion of the space charge layer, introducing significant temporal and spatial stochasticity into exposure profiles.

A primary environmental health concern identified in contemporary literature is the biophysical model of electrostatically enhanced deposition of hazardous ambient air pollutants within the human respiratory tract. While theoretical frameworks and laboratory models confirm that unipolar charging increases particle deposition fractions via electrostatic image forces on lung airway surfaces, definitive epidemiological links to clinical disease outcomes in exposed populations remain sparse due to a lack of long-term, large-cohort epidemiological studies.

In conclusion, corona ion discharge from high-voltage transmission networks represents a complex, multidisciplinary problem positioned at the intersection of electrical power grid optimization, atmospheric physics, aerosol dynamics, and environmental epidemiology. While substantial progress has been made in characterizing the plasma physics of ion production and the chemistry of molecular clusters, focused research is needed to bridge the gap between physical models and long-term biological outcomes. Future research initiatives should prioritize long-term, continuous field monitoring arrays, advanced computational fluid dynamics (CFD) boundary layer modeling, and structured epidemiological studies. These efforts will help resolve current scientific uncertainties and establish robust, evidence-based safety guidelines for managing high-voltage transmission infrastructure.

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