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DRONE-BASED AIR PURIFICATION TECHNOLOGIES: MAPPING THE EVOLUTION OF AN EMERGING ENGINEERING

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Abstract - Air pollution represents a persistent global challenge that requires innovative, adaptive, and spatially flexible technological solutions. While conventional air purification systems are predominantly stationary and infrastructure dependent, recent advances in unmanned aerial systems have enabled the conceptual transition from atmospheric monitoring to active airborne remediation. The integration of ionization units, electrostatic particle collectors, and aerosol removal mechanisms into lightweight unmanned aerial platforms introduces a novel research frontier at the intersection of aerospace engineering and environmental technology. Despite growing experimental interest, the scientific landscape of drone assisted air purification remains fragmented and insufficiently synthesized. This study provides a systematic bibliometric analysis of research addressing the convergence between unmanned aerial vehicles and active air depollution processes. The Web of Science Core Collection database was selected to ensure methodological rigor and high quality peer reviewed sources. A structured Boolean search strategy was employed to capture terminology related to aerial systems and purification mechanisms, followed by document type and temporal filtering. The final dataset includes 92 research articles published between 2016 and 2026. The analysis reveals an accelerated growth phase after 2020, thematic concentration around electrostatic and ionization technologies, and a strong emphasis on aerodynamic optimization and energy efficiency constraints. The findings position drone based air remediation as a specialized yet expanding niche characterized by interdisciplinary convergence and high technical complexity, offering a structured foundation for future research and technological development.

Keywords: Unmanned aerial systems, Air purification, Electrostatic precipitation, Ionization, aerosol removal, Bibliometric analysis, Environmental engineering, UAV technology.

1. Introduction

Air pollution remains one of the central technological and environmental challenges of the twenty first century [1]. Accelerated urbanization, industrial intensification, and expanding mobility networks have generated elevated concentrations of particulate matter, nitrogen oxides, sulfur compounds, volatile organic compounds, and secondary aerosols in metropolitan regions [2]. These pollutants interact through complex chemical and physical mechanisms that influence atmospheric radiative balance, microclimatic behavior, and public health outcomes [3]. The cumulative impact of degraded air quality extends beyond clinical effects, shaping economic productivity, infrastructure resilience, and long term sustainability strategies [4–6]. Within this context, atmospheric remediation has become a strategic priority for both policymakers and engineering communities.

Traditional air purification technologies are predominantly stationary [7]. Industrial electrostatic precipitators, high efficiency particulate air filtration systems, catalytic converters, and centralized purification towers operate effectively within controlled environments or fixed emission points [8,9].

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Their performance depends on stable airflow regimes and continuous energy supply [10]. Urban atmospheres, however, are dynamic systems characterized by variable wind fields, vertical stratification, and spatially distributed emission sources [11]. Pollutants disperse across three dimensional domains, whereas stationary infrastructures remain geographically constrained [12]. This structural asymmetry has encouraged exploration of mobile remediation platforms capable of intervening directly within polluted air masses [11].

Concurrently, unmanned aerial systems have achieved significant technological maturity [13]. Advances in lightweight composite materials, battery energy density, electric propulsion, embedded control systems, and satellite navigation have enabled reliable autonomous flight across diverse operational contexts [14]. Initially oriented toward surveillance, mapping, and inspection, these platforms now support modular payload integration and precise maneuverability [15]. The transition from environmental monitoring toward active atmospheric intervention represents a logical extension of this technological evolution [16].

Air quality monitoring using aerial platforms is well established in environmental research [13]. Active air purification introduces a different operational paradigm centered on direct pollutant removal [17]. Ionization modules, electrostatic particle collectors, aerosol filtration systems, and hybrid depollution assemblies must be integrated within strict mass and energy constraints [18]. Ionization processes charge suspended particles to enhance electrostatic attraction or sedimentation [19]. Miniaturized electrostatic precipitators rely on high voltage electric fields to capture particulates on collector surfaces [7]. Mechanical filtration systems channel ambient air through high efficiency media mounted on aerial frames [10]. Each configuration requires careful optimization of aerodynamic stability, power consumption, and structural weight [20].

The interdisciplinary character of drone assisted air purification spans aerospace engineering, atmospheric physics, materials science, and power electronics [21]. Rotor induced airflow modifies particle trajectories and electric field distributions, influencing capture efficiency [19]. Lightweight dielectric materials must withstand high voltage differentials without compromising structural integrity. Energy management remains critical [22], since purification modules increase electrical demand and reduce flight endurance [23]. Computational modeling and controlled experimentation support the evaluation of these complex interactions [17].

Urban deployment scenarios illustrate the potential relevance of mobile purification systems [11]. Localized pollution hotspots near traffic corridors, industrial facilities, or construction sites could be addressed through adaptive aerial interventions guided by real time sensor networks [24]. Integration with digital communication infrastructures enables coordinated mission planning and spatial targeting [25]. Despite these technological prospects, the scientific literature remains relatively concentrated and dispersed across multiple disciplines, with limited synthesis of thematic evolution and research intensity.

A systematic bibliometric analysis provides a structured approach for mapping this emerging field. By identifying publications situated at the intersection of unmanned aerial platforms and active air remediation processes, it becomes possible to quantify growth patterns, characterize dominant research clusters, and evaluate developmental phases. The present study undertakes such an analysis using a rigorously defined search strategy within a high impact scientific database. The methodological framework guiding data retrieval, filtering criteria, and temporal selection is detailed in the following section.

2. Methodology

The research design for this study is grounded in a systematic bibliometric analysis aimed at mapping the landscape of drone-assisted air purification technologies. The Web of Science (WoS) Core Collection was selected as the primary data source to ensure the inclusion of high-impact research subjected to rigorous peer-review processes. To capture the intersection between aerial platforms and environmental remediation, a comprehensive search string was developed:

$$\begin{aligned} &TS = ((\text{"}unmanned\ aerial\text{"} \\ &OR\ \text{UAV} \\ &OR\ \text{drone*} \\ &OR\ \text{RPAS} \\ &OR\ \text{"}unmanned\ aircraft\text{"}) \\ &AND\ (\text{"}ioniz*\text{"} \\ &OR\ \text{air purif*} \\ &OR\ \text{depollution} \\ &OR\ \text{de-pollution} \\ &OR\ \text{aerosol removal} \\ &OR\ \text{particle collection} \\ &OR\ \text{"}electrostatic*\text{"})) \end{aligned} \quad (1)$$

where TS means Topic Search.

The structural justification for the selection of these specific terms and operators is detailed in Table 1.

Table 1. Search string components and technical justification

Sequence category	Search terms	Justification for selection
Aerial platform	unmanned aerial, UAV, drone*, RPAS, "*unmanned aircraft*"	Includes both common and regulatory terminology (RPAS = "Remotely Piloted Aircraft System", UAV = "Unmanned Aerial Vehicle") to capture engineering papers and legislative frameworks.
Active remediation	ioniz*, air purif*, depollution, "*de – pollution*"	Targets the specific mechanical or chemical processes of cleaning the air, distinguishing from simple monitoring.
Physical processes	aerosol removal, particle collection, "*electrostatic* * "	Captures the underlying physics of air treatment, such as electrostatic precipitation and the removal of particulate matter.
Boolean logic	*AND / OR Operators*	The OR operator expands the synonym reach within categories, while the AND operator ensures the intersection of drones and purification.

This systematic approach ensures that the retrieved literature is both relevant to the technological scope of the study and sufficiently broad to include various engineering solutions. By restricting the scope to "Article," the dataset was reduced to 102 results, thereby prioritizing original research contributions that establish new benchmarks for the State of the Art over secondary literature or conference abstracts.

The longitudinal distribution of these publications, as illustrated in Figure 1, reveals three distinct evolutionary phases. Between 1999 and 2015, the field remained in a conceptual state with sporadic yearly outputs. A transition period followed from 2016 to 2020, marked by a gradual increase in experimental validations. The most significant growth occurred between 2021 and 2026, reaching a historical peak of 17 articles in 2023. This recent surge indicates a maturing technological niche, though the consistently low volume of annual publications, which rarely exceeds 15 units, underscores that this remains an elite and underdeveloped area of aerospace engineering and environmental science.

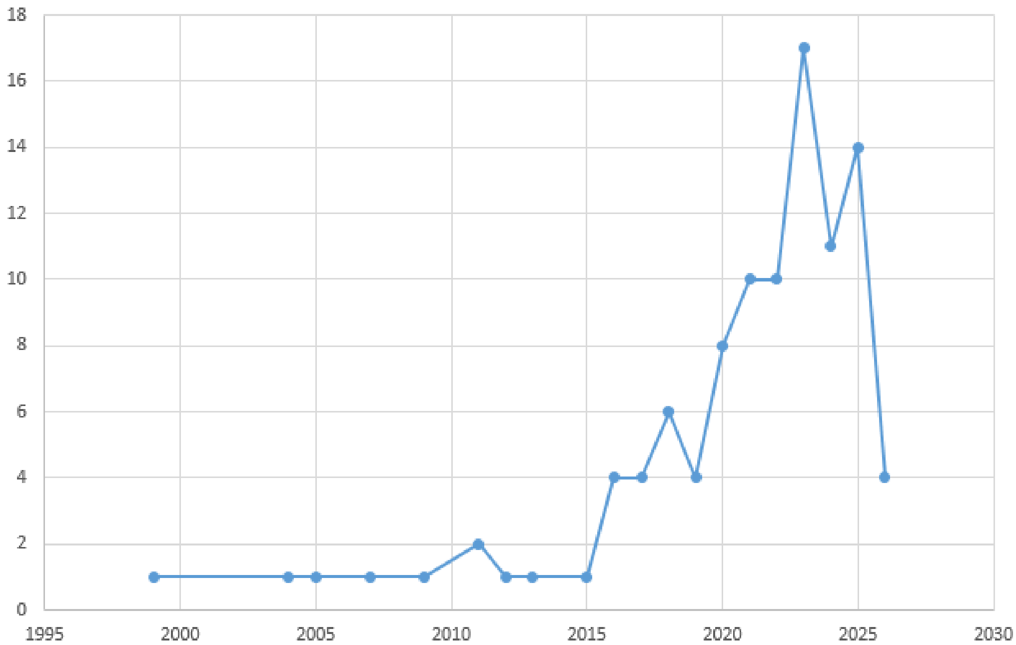

Figure 1: Annual scientific production in UAV-based air remediation (1999–2026)

To maintain a focus on contemporary innovations, the final sample was narrowed to 92 articles published within the last decade (2016–2026), a selection process formalized in Figure 2. The temporal scope was extended to include the current year (2026) to ensure the analysis captures the most recent advancements and validates the current trajectory of the field.

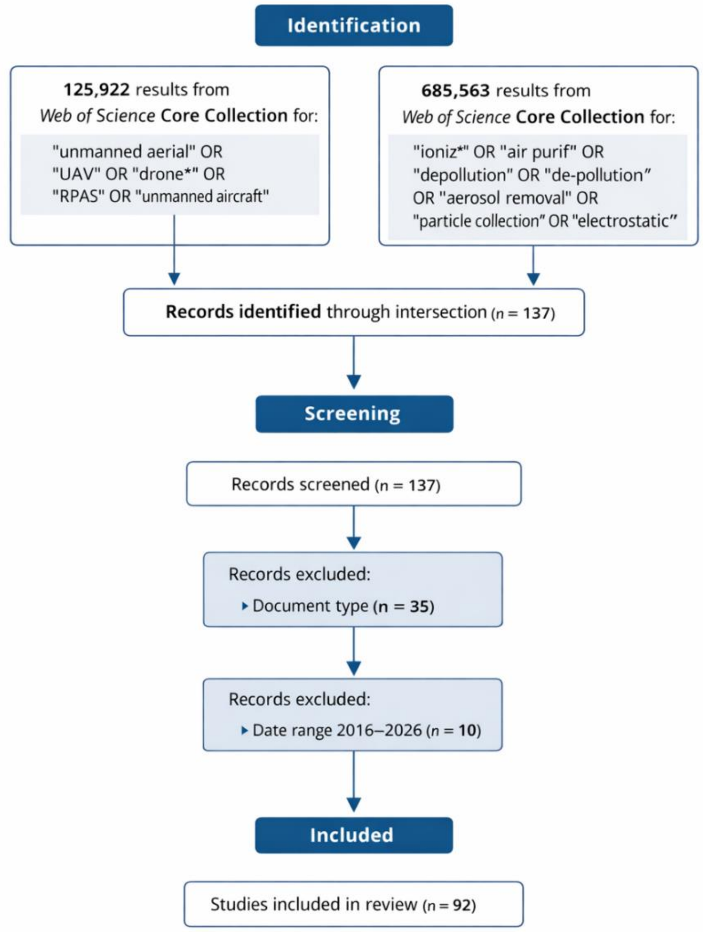

Figure 2: PRISMA Flow Diagram

To further investigate the intellectual structure and collaboration patterns within the field of drone-based air purification, additional bibliometric analyses were conducted using co-authorship and co-occurrence techniques. These analyses aimed to identify international collaboration networks and to map the conceptual organization of the research domain.

Four complementary analyses were performed: (1) co-authorship at country level, (2) co-occurrence of all keywords, (3) co-occurrence of author keywords, and (4) co-occurrence of Keywords Plus. For each analysis, specific threshold values were applied in order to ensure statistical relevance and to reduce noise generated by low-frequency items. The methodological configuration, including research questions, applied filters, and quantitative outcomes, is summarized in Table 2.

Table 2. Summary of bibliometric analyses performed

Analysis	Research question	Filter applied	Results (items meeting threshold / total)
Co-authorship – Countries	What is the international collaboration structure in the field?	Minimum number of documents per country = 1; Minimum number of citations per country = 5	28 / 35 countries meet the thresholds
Co-occurrence – All Keywords	What is the overall conceptual structure of the research domain?	Minimum number of occurrences of a keyword = 3	21 / 675 keywords meet the threshold
Co-occurrence – Author Keywords	What are the main thematic directions defined by authors?	Minimum number of occurrences of a keyword = 3	12 / 399 keywords meet the threshold
Co-occurrence – Keywords Plus	What additional themes emerge from bibliographic indexing?	Minimum number of occurrences of a keyword = 3	8 / 297 keywords meet the threshold

In the co-authorship analysis, countries were used as the unit of analysis to identify collaboration patterns and geographical distribution of research activity. The applied thresholds ensured that only countries with a minimum level of scientific contribution and impact were included in the network visualization.

The thematic structure of the field was examined through three distinct co-occurrence analyses. The all-keywords analysis provided a comprehensive overview of the conceptual landscape. The author-keywords analysis highlighted the core research directions explicitly emphasized by researchers, while the Keywords Plus analysis captured additional themes derived from citation-based indexing. The uniform occurrence threshold (≥3) across these analyses allowed for methodological consistency and comparability of results.

3. Results

The analysis of international collaboration through country co-authorship identifies the prominent geographic clusters driving innovation in drone-based air remediation. By applying a threshold of at least one document and five citations per country, 28 out of 35 countries were retained for the network mapping. The People's Republic of China emerges as the primary contributor with 32 documents and 619 citations, followed by the USA with 24 documents and 281 citations. These two nations exhibit the most significant influence, as evidenced by China's total link strength of 55, indicating a robust integration into global research efforts. Other established contributors include Singapore with 115 citations and England and Germany, both with 111 citations, despite having a lower volume of total documents. Notably, Cyprus demonstrates high impact efficiency, securing 167 citations from only two indexed papers. The initial network structure of these interactions is presented in Figure 3.

The network connectivity highlights distinct clusters of cooperation where the USA and China act as the main anchors for global knowledge exchange. European participation is characterized by high citation impact relative to document volume, with countries like Germany and England showing strong linkages within the international community. Smaller but highly specialized nodes, such as Cyprus and Singapore, maintain high total link strengths, suggesting that their research is central to the development of specific technical standards in the field. This distribution confirms that while the volume of research is concentrated in large economies, the intellectual influence is distributed across a diverse group of nations, each contributing specialized expertise to the evolving landscape of unmanned aerial depollution.

Figure 3: Network Visualization of co-authorship by countries

To maintain the chronological flow of the results, the temporal dimension (Figure 4) of the co-authorship network is assessed through an overlay visualization. This analysis identifies the periods during which specific nations integrated into the research landscape. While established nodes define the core of the network, recent years have seen the emergence of new participants that represent the current research frontier. Specifically, Singapore and Japan are identified as the most recent contributors to the field, as indicated by their yellow coding in the temporal map.

Despite their later entry, Singapore has already established a significant presence with 115 citations, suggesting that these newer nodes are producing high-impact research.

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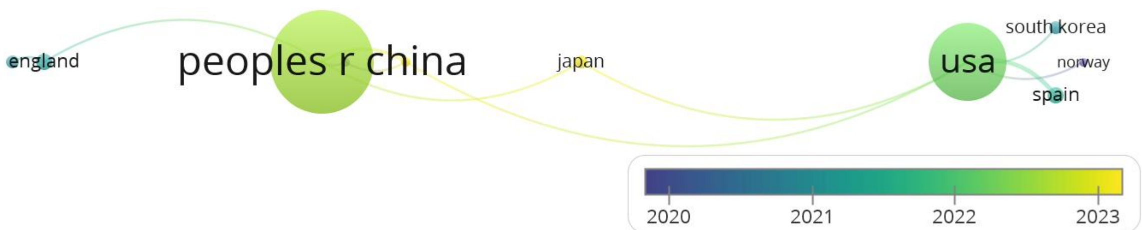

Figure 4: Overlay Visualization of national scientific contributions

The spatial intensity of the collaboration network is further defined by the density of the nodes, reflecting the concentration of scientific authority (Figure 5). As indicated by the bibliometric data, the People's Republic of China and the USA function as the primary anchors of the global research map, exhibiting the highest concentration of publications and citations. This density confirms that the foundational expertise remains centered within these two hubs.

Figure 5: Density Visualization of global research output

Moving to the conceptual mapping of the field, the second stage of the bibliometric investigation involves a co-occurrence analysis of all keywords. This analysis identifies the primary thematic pillars by evaluating terms that appear at least three times. Out of the 675 keywords identified in the research corpus, 21 terms met this threshold, forming the structural basis for the network visualization.

The resulting network illustrates how technical engineering parameters intersect with operational aerial platforms. As shown in Figure 4, the keywords are organized into four distinct clusters that reflect different dimensions of the research. Cluster 1 includes terms focused on the mechanics of application, such as "deposition," "nozzle," "electrostatic spraying," and "performance". Cluster 2 links operational platforms like "aircraft" and "drones" with physical processes such as "corona discharge" and "discharge". Cluster 3 covers broader concepts including "UAV," "exposure," and "radiation," while Cluster 4 is concentrated on systemic integration, featuring "design," "droplet deposition," and "system".

The connectivity within this map (Figure 6) highlights "UAV" and "design" as high-frequency nodes, with "UAV" appearing 9 times and "design" appearing 8 times. The strength of the links between "design," "UAV," and "deposition" indicates that the core of the current literature is focused on the architectural optimization of drones for particle dispersal. Furthermore, terms like "plant protection" maintain a strong link strength of 10, suggesting that the technological roots of this field are closely tied to precision agriculture techniques that are now being adapted for air remediation tasks. This thematic distribution confirms a highly specialized research environment where mechanical performance and system design are the primary drivers of scientific discourse.

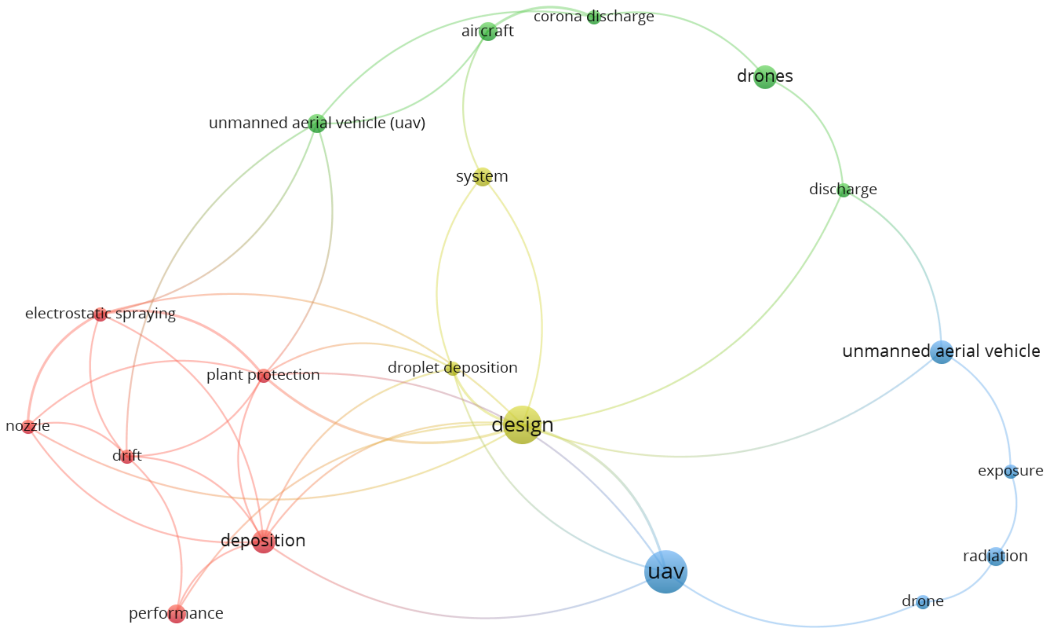

Figure 6: Network Visualization of keywords (All Keywords)

The temporal and structural evolution of these keywords is further clarified by analyzing their distribution within the research timeline. The overlay visualization identifies specific technical parameters as the most recent focal points of scientific inquiry. Terms such as "design," "nozzle," "droplet deposition," and "discharge" are highlighted in yellow, signaling their status as contemporary research frontiers. This shift indicates that the academic community has moved beyond general concepts toward the engineering of specialized hardware for active air remediation

The density distribution (Figure 7) of the keyword network provides a complementary perspective by highlighting the most established and central themes. The highest concentration of research activity is centered on "design" and "UAV," which represent the most prominent hubs in the current conceptual map. This intensity suggests that these two areas form the intellectual foundation of the entire field, around which all other technical parameters gravitate. While the overlay highlights the novelty of specific components like nozzles, the density visualization confirms that the overall success of the domain remains anchored in the structural optimization and functional integration of these aerial systems. This dual perspective ensures a comprehensive understanding of both the foundational pillars and the emerging innovations in drone-based depollution.

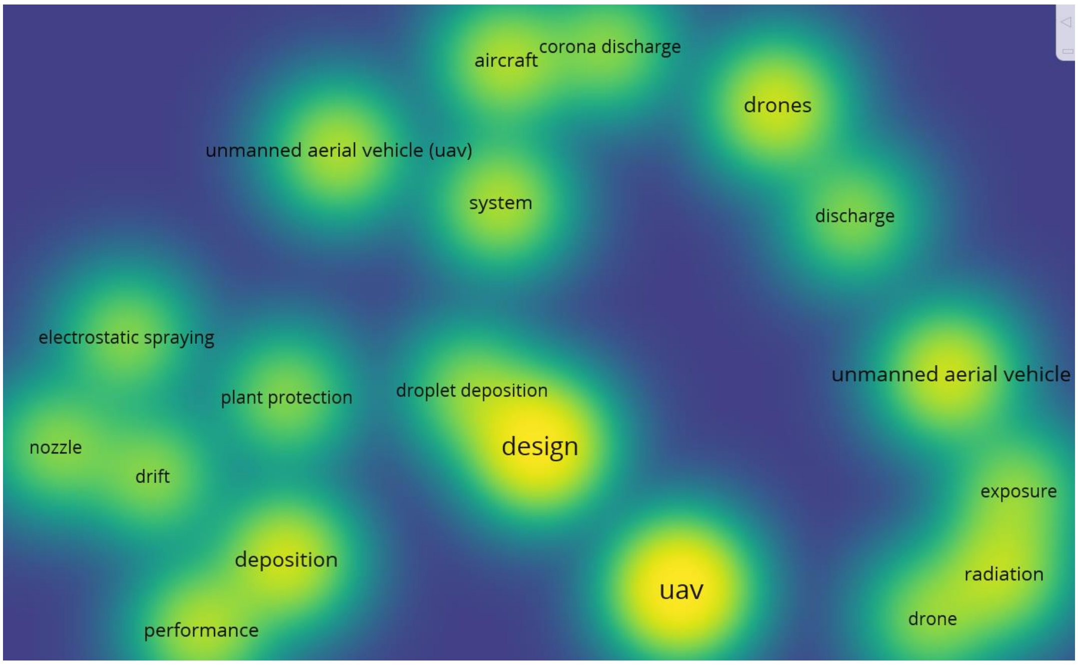

Figure 7: Density Visualization of research focus (All Keywords)

The third stage of the bibliometric investigation examines the co-occurrence of Author Keywords, with a minimum threshold of three occurrences per term. From a total of 399 distinct author-defined keywords identified in the dataset, only 12 met this inclusion criterion. This sharp reduction confirms a high degree of thematic dispersion at the micro-level of researcher-defined terminology, while simultaneously highlighting a compact conceptual core shared across the field.

The network visualization generated in VOSviewer (Figure 8) reveals three clearly delimited clusters, each representing a specific conceptual orientation within drone-based air remediation research. The structural configuration of the map indicates moderate network density, with several high-centrality nodes acting as bridges between otherwise specialized subdomains.

The first cluster is centered on "UAV", which records the highest number of occurrences (8) and a total link strength of 3. This node is directly connected to "drone," "droplet deposition," and "radiation," forming a technically oriented subgroup that emphasizes operational performance and physical interaction mechanisms. The presence of "droplet deposition" within this cluster suggests that a significant portion of the literature originates from precision spraying and aerial dispersion research, which is now being extended toward pollutant removal applications. The inclusion of "radiation" indicates that electrostatic or ionization-based charging mechanisms are conceptually integrated with UAV platform studies, reinforcing the interdisciplinary character of the field.

The second cluster groups together "aircraft," "corona discharge," and "drones." Here, "corona discharge" exhibits a relatively high total link strength (4), equal to that of "unmanned aerial vehicle (UAV)" and second only to "plant protection" (5). This cluster reflects the electrical engineering dimension of airborne purification systems. Corona discharge represents the fundamental physical principle underlying ionization and electrostatic particle charging, and its close proximity to "aircraft" and "drones" demonstrates that authors frequently conceptualize purification technologies through the lens of high-voltage discharge integration into aerial platforms. The dual presence of both "drones" and "aircraft" suggests terminological variability rather than conceptual divergence, indicating that researchers employ both general aviation terminology and UAV-specific nomenclature.

The third cluster is organized around "electrostatic spraying," "plant protection," and "unmanned aerial vehicle (UAV)." Among all author keywords, "plant protection" displays the highest total link strength (5), confirming that agricultural spraying technologies constitute an important technological precursor to airborne depollution systems. The strong association between "electrostatic spraying" and "unmanned aerial vehicle (UAV)" highlights the transfer of mature crop-dusting electrostatic techniques into experimental atmospheric remediation applications. This cluster underscores the evolutionary pathway of the field: rather than emerging independently within environmental engineering, drone-based air purification appears to inherit technical frameworks from precision agriculture and aerial application science.

Overall, the connectivity pattern displayed in Figure 9 indicates that the author-keyword network is structured around three dominant technological pillars: (1) UAV platform engineering and dispersion mechanics, (2) high-voltage ionization and corona-based charging processes, and (3) electrostatic spraying technologies rooted in plant protection systems.

The relatively balanced distribution of link strengths across clusters suggests that no single subdomain monopolizes the discourse; instead, the field evolves through cross-disciplinary integration.

Importantly, the modest number of high-frequency author keywords (12 out of 399) demonstrates that the research area remains terminologically heterogeneous and technically specialized. Authors tend to define their contributions through niche engineering descriptors, while only a limited set of shared terms achieves recurrent usage across publications. This pattern is characteristic of emerging technological domains in which conceptual consolidation is still underway.The analysis of terminology strategically chosen by authors provides a specific perspective on research niches. In Figure 8, the network of author keywords exposes direct correlations between structural design (continuum robots) and kinematic control requirements.

Figure 8: Network Visualization of technical correlations (Author Keywords)

The temporal distribution of author keywords, illustrated in the overlay visualization (Figure 9), identifies a clear transition from established aerial applications to specialized air treatment mechanisms. The color-coded gradient reveals a three-stage thematic development between 2021 and 2026, marking the field's evolution from general platform integration to the detailed engineering of physicochemical processes.

Initial research, appearing in darker hues (2021.0–2021.5), focused on foundational platforms and existing dispersal methods, with terms such as "aircraft", "unmanned aerial vehicle (UAV)", and "electrostatic spraying". This distribution indicates that the field's technical origins are rooted in adapting precision agricultural spraying and general aviation frameworks for environmental remediation tasks. A transition phase followed around 2022.0, where the emergence of "plant protection" and "radiation" signified a period of hybridization, applying established crop-dusting techniques to explore broader atmospheric particle behavior.

The current research frontier, highlighted in yellow (2022.5–2023.0+), is dominated by specialized terms such as "corona discharge" and "droplet deposition". The recent prominence of corona discharge is particularly significant, as it marks a move toward active air ionization and the optimization of electrical capture efficiency. This progression confirms that the academic discourse has moved beyond general system design toward the specific mechanical and electrical challenges of active air remediation.

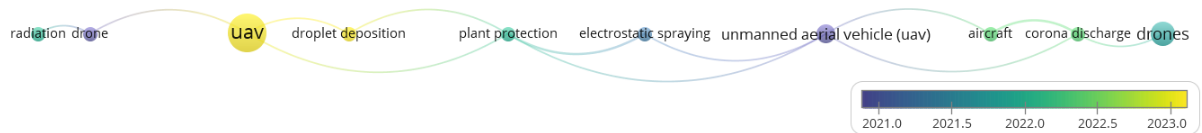

Figure 9: Overlay Visualization of specialized research frontiers (Author Keywords)

The fourth stage of the bibliometric investigation shifts the focus toward Keywords Plus co-occurrence. Unlike author-selected terms, these keywords are automatically generated by the Web of Science algorithms based on the titles of cited references, providing an objective perspective on the theoretical foundations and interdisciplinary connections of the field. Out of the 297 identified terms, only 8 reached the minimum threshold of 3 occurrences, reflecting a significant thematic concentration on applied engineering and systematic performance.

This analysis organizes the literature into two primary clusters, as illustrated in the network visualization in Figure 10.

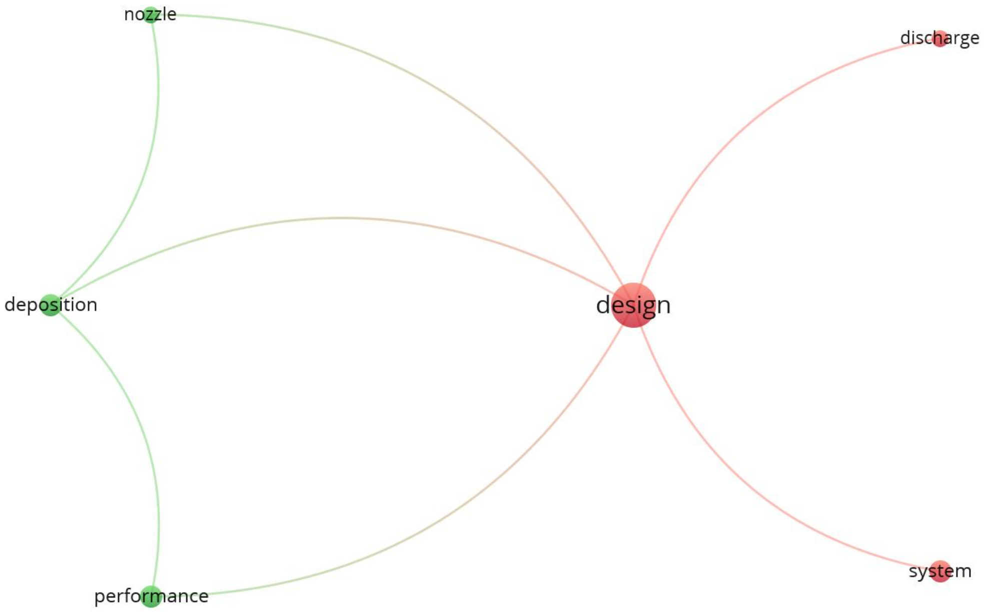

Figure 10: Network Visualization of bibliographic indexing (Keywords Plus)

The first cluster (Cluster 1) centers on structural and operational parameters, including terms such as "design", "discharge", and "system". Within this group, the node "design" exhibits the highest frequency (8 occurrences) and a total link strength of 5, consolidating its role as the central pivot in current research architecture. The strong links between design and system suggest that the structural optimization of aerial platforms is intrinsically linked to the functional integration of purification modules.

The second cluster (Cluster 2) highlights the mechanical dimension and efficiency evaluation, defined by terms such as "deposition", "nozzle", and "performance". The interconnections among these terms emphasize the importance of specific hardware components—such as spray nozzles—in determining the final yield of the depollution process. Although terms like "exposure" and "finite-element" are part of the filtered dataset, they present a total link strength of zero, indicating specialized methodological niches that use numerical modeling for exposure risk assessment but remain relatively isolated from the broader technical discourse.

The earliest research phase, indicated by purple and dark blue tones (circa 2021.0), is defined by terms such as "system". This suggests that during the field's inception, the primary focus was on the overarching integration of components into a functional aerial unit. As the literature matured toward 2022.0 (green tones), terms like "performance", "deposition", and "discharge" gained prominence. This period represents a shift toward characterizing the operational output and physical behavior of air purification payloads, moving from "what the system is" to "how the system functions".

The current research frontier, highlighted in yellow (2023.0–2024.0), is anchored by the node "design" and supported by "nozzle".

The overall structure of the Keywords Plus network confirms that the intellectual core of the domain is sustained by a dependency between aeronautical design optimization and the mechanical performance of dispersal systems. The high link strength of "deposition" (3) relative to "performance" (2) indicates that the success of drone-based technologies is primarily evaluated through the precision with which purification agents or electrical charges interact with polluted air masses. This bibliometric perspective highlights a clear transition toward a mature engineering discipline, where design rigor and flow control are essential for active remediation efficiency.

The temporal dimension of the bibliographic indexing, represented through the Keywords Plus overlay visualization, highlights a clear shift in research focus as the domain transitioned from general system conceptualization toward architectural optimization and mechanical refinement. The color-coded gradient identifies a chronological progression where foundational systemic concerns have given way to more recent, specialized engineering parameters.

The late emergence of "design" as a high-frequency, recent term indicates that the scientific community is now revisiting structural frameworks to optimize them specifically for air remediation tasks rather than relying on adapted agricultural models.

Furthermore, the recent focus on "nozzle" engineering underscores a trend toward miniaturization and the technical refinement of the physical interface between the drone and the atmosphere. Overall, this temporal evolution demonstrates that drone-based air purification is moving toward a stage of high-fidelity engineering, where structural design and precision components are the primary drivers of innovation.

4. Discussion

4.1 Analysis of Co-authorship by Countries

The co-authorship network at country level reveals a geographically concentrated yet structurally interconnected research landscape. The People's Republic of China and the United States dominate the field in both publication volume and citation impact, functioning as central hubs within the global collaboration graph. China's high total link strength indicates an extensive pattern of international partnerships, suggesting that its research institutions operate as integrative platforms for cross-border technological exchange. The United States demonstrates a similar anchoring role, with strong citation performance and wide collaborative reach. This dual-core configuration reflects broader trends in aerospace engineering and environmental technology, where large research infrastructures and sustained funding programs enable rapid prototyping, experimental validation, and system integration. The prominence of these two nations positions them as agenda-setting actors whose methodological choices and technological orientations influence subsequent developments across the network.

Beyond these two principal nodes, the European contribution is characterized by high citation efficiency relative to document volume. Countries such as Germany and England display moderate publication counts paired with strong citation metrics, indicating focused research efforts with substantial influence. Cyprus presents a particularly interesting case, achieving a high citation count from a small number of publications. This pattern suggests the presence of highly specialized research groups producing technically sophisticated contributions that resonate internationally. Singapore's relatively recent entry into the field, combined with strong citation performance, highlights the emergence of agile research ecosystems capable of rapid integration into advanced engineering domains. The temporal overlay further confirms a gradual expansion of participation after 2020, reflecting growing global awareness of adaptive air remediation technologies.

The structural configuration of the collaboration network indicates a core–periphery dynamic. Established economies form the dense center of interactions, while smaller or newer participants connect through strategic partnerships rather than autonomous clusters. Such a configuration is typical of emerging interdisciplinary domains that require access to advanced laboratories, high-voltage testing facilities, aerodynamic simulation platforms, and environmental measurement infrastructure. The distributed yet interconnected pattern suggests that the field benefits from knowledge circulation rather than isolated national trajectories. Overall, the co-authorship analysis portrays drone-based air purification as an internationally collaborative niche, anchored by technologically mature nations and progressively expanded through specialized contributions from smaller research communities.

4.2 Analysis of Co-occurrence by All Keywords

The co-occurrence analysis of all keywords provides insight into the conceptual architecture of the field. With only 21 out of 675 keywords surpassing the occurrence threshold, the domain displays a compact thematic nucleus surrounded by a wide dispersion of low-frequency descriptors. The central position of terms such as "UAV" and "design" indicates that the literature converges around platform engineering and system configuration. This emphasis reflects the engineering-driven nature of the domain, where structural optimization, aerodynamic performance, and payload integration determine operational feasibility. The linkage between "UAV," "design," and "deposition" demonstrates that air purification research builds upon dispersion mechanics originally developed in agricultural and spraying applications. The recurrence of terms like "electrostatic spraying," "nozzle," and "corona discharge" highlights the translation of electrohydrodynamic principles into airborne remediation contexts.

Cluster differentiation within the network further clarifies the domain's internal structure. One cluster concentrates on mechanical performance parameters, including droplet behavior and deposition efficiency. Another integrates aerial platforms with electrical discharge processes, reflecting the intersection between aeronautical engineering and high-voltage physics. A third cluster connects exposure and radiation-related concepts with UAV operations, suggesting attention to particle interaction dynamics and environmental effects. The fourth cluster emphasizes systemic integration, reinforcing the notion that successful implementation depends on coordinated hardware and software architectures. This multi-cluster arrangement illustrates a domain shaped by technical convergence rather than disciplinary isolation.

The temporal overlay reveals a progressive refinement of thematic focus. Earlier studies concentrated on general UAV deployment and spraying technologies, while recent contributions emphasize specialized hardware components and discharge optimization. The prominence of "design" in recent years signals a phase of architectural reconsideration, where researchers revisit platform geometry, airflow management, and energy allocation to accommodate purification modules. This transition from general application to component-level engineering suggests a trajectory toward increased technical specificity. The density visualization confirms that UAV platform optimization remains the gravitational center of the field, around which electrostatic and deposition processes are organized. Collectively, the all-keyword analysis portrays a research domain that has evolved from adaptation of existing aerial spraying systems toward purpose-built airborne depollution architectures.

4.3 Analysis of Co-occurrence by Author Keyword

The author-keyword network offers a micro-level perspective on how researchers conceptualize their own contributions. The limited number of recurring terms indicates terminological heterogeneity, a common feature of technologically emerging domains. Authors frequently adopt specialized descriptors aligned with their disciplinary backgrounds, whether in electrical engineering, fluid dynamics, materials science, or environmental modeling. Despite this dispersion, three thematic cores are clearly identifiable: UAV platform engineering, high-voltage ionization processes, and electrostatic spraying technologies derived from plant protection systems. The centrality of “UAV” and “plant protection” reflects the historical pathway through which airborne purification concepts have developed, drawing from established agricultural dispersion methods.

The presence of “corona discharge” as a highly connected node underscores the importance of electrical particle charging as a foundational mechanism. Its strong linkage to aerial platform terminology suggests that researchers approach purification through the integration of electrostatic capture systems into flight-capable structures. The association between “droplet deposition” and UAV-related terms indicates that airflow dynamics and particle trajectory control remain key design considerations. This cluster configuration demonstrates that active air remediation is treated as a coupling problem between charged particle physics and rotor-induced aerodynamics. The moderate network density reflects a balanced distribution of influence among subdomains, with no single theme overshadowing others.

The temporal overlay reveals a clear evolution in author emphasis. Earlier phases emphasized platform adaptation and electrostatic spraying borrowed from agriculture. Subsequent work introduced radiation and discharge-related terminology, indicating increasing engagement with ionization physics. The most recent period highlights corona discharge and deposition optimization as leading topics, pointing toward advanced electrical and mechanical integration challenges. This progression illustrates conceptual maturation, where the field transitions from adapting existing technologies to addressing specialized performance constraints. The author-keyword analysis therefore captures the intellectual self-definition of the community as it consolidates around shared engineering problems while maintaining interdisciplinary diversity.

4.4 Analysis of Co-occurrence by Keywords Plus

Keywords Plus analysis provides an externally generated view of the domain’s theoretical foundations. The limited number of high-frequency indexing terms suggests that the literature is tightly clustered around applied engineering concerns. The prominence of “design,” “system,” and “discharge” indicates that bibliographic indexing recognizes structural configuration and electrical processes as the backbone of the field. The association between “deposition,” “nozzle,” and “performance” reinforces the operational orientation of the research, where measurable outcomes such as capture efficiency and flow distribution guide evaluation. This indexing pattern aligns with the empirical nature of drone-based purification studies, which frequently rely on experimental setups and performance metrics.

The separation of clusters within the Keywords Plus network reflects complementary engineering dimensions. One cluster centers on architectural system integration, while the other focuses on mechanical and fluidic parameters. The relatively isolated position of terms like “finite-element” suggests that advanced numerical modeling exists within the field yet remains peripheral compared to experimental design studies. This configuration indicates that while computational tools support development, the primary momentum derives from prototype testing and hardware optimization. The overlay visualization further demonstrates a chronological shift from system-level conceptualization toward detailed design refinement.

The recent prominence of “design” and “nozzle” in the temporal mapping signals a phase of engineering consolidation. Researchers appear increasingly attentive to micro-scale interfaces between drone and atmosphere, optimizing droplet formation, electric field geometry, and airflow modulation. This emphasis suggests that performance improvements are pursued through precision component engineering rather than broad conceptual restructuring. The Keywords Plus perspective thus corroborates findings from author-defined terminology, confirming that the field’s intellectual trajectory is directed toward structural optimization and component-level enhancement.

4.5 Domain Maturity Synthesis

Synthesizing the bibliometric evidence, drone-based air purification can be characterized as a specialized emerging engineering niche undergoing structured consolidation. The steady growth in publications after 2020 indicates accelerated engagement, while the limited annual volume reflects a focused and technically demanding domain. The co-authorship network demonstrates international integration anchored by technologically advanced nations, with smaller countries contributing targeted expertise. Conceptually, the keyword analyses reveal a compact core organized around UAV design, electrostatic discharge, and deposition mechanics. Such thematic concentration suggests increasing alignment around shared engineering objectives.

The evolutionary trajectory observed across temporal overlays indicates a shift from adaptation of agricultural spraying systems toward dedicated atmospheric remediation architectures. Early work relied heavily on established dispersion technologies, whereas recent studies prioritize high-voltage ionization efficiency, aerodynamic coupling, and structural refinement. This progression signals movement toward greater technological autonomy and specialization.

At the same time, the limited consolidation of terminology suggests that conceptual standardization remains in development. The field exhibits characteristics of a growth-stage technological domain: expanding publication activity, emerging collaboration networks, and progressive focus on component-level optimization.

The convergence of aerospace engineering, environmental science, and electrostatic physics positions the domain within a complex interdisciplinary framework. Such convergence fosters innovation yet requires harmonization of standards, metrics, and testing protocols.

The density of central nodes around design and UAV integration confirms that system architecture constitutes the intellectual anchor of the field. Overall, the maturity profile suggests an expanding research community building upon inherited technologies while gradually establishing its own methodological identity.

5. Future Research Directions

Future research is likely to focus on enhancing energy efficiency and flight endurance under purification load conditions.

The integration of high-voltage ionization modules imposes significant electrical demand, which directly affects operational range [26]. Advances in battery technology [27], lightweight dielectric materials [28], and power management algorithms could extend mission duration and enable sustained urban deployment. Hybrid propulsion systems and modular payload architectures may further support adaptability across diverse environmental scenarios. Research into aerodynamic optimization of rotor wash patterns could improve particle capture efficiency by directing airflow through electrostatic fields with greater precision.

Another promising direction concerns real-time adaptive control informed by atmospheric sensing. Coupling purification drones with distributed sensor networks could enable dynamic targeting of pollution hotspots [29]. Machine learning algorithms may optimize flight paths, discharge intensity, and airflow modulation based on environmental feedback. Such integration would transform drones from isolated devices into components of coordinated urban air management systems. Standardized performance metrics and validation protocols would support comparability across experimental platforms and accelerate technological diffusion [13].

Long-term development may also explore swarm-based remediation strategies, where multiple UAVs operate cooperatively to treat localized air masses. Coordinated swarms could distribute electrical fields or filtration units across three-dimensional volumes, increasing spatial coverage [30]. Research into inter-drone communication, collision avoidance, and collective energy management would underpin such systems. Environmental impact assessments and regulatory frameworks will play an important role in guiding safe deployment within populated areas. Through these avenues, the field can evolve toward scalable, adaptive, and context-sensitive air purification infrastructures.

6. Conclusions

The bibliometric analysis demonstrates that drone-based air purification represents a technologically sophisticated and internationally collaborative research niche. Publication growth after 2020 reflects heightened attention to adaptive environmental remediation, while collaboration networks highlight the leadership of China and the United States alongside impactful contributions from Europe and Asia. Conceptual mapping reveals a compact thematic core centered on UAV design, electrostatic discharge, and deposition mechanics. Temporal patterns illustrate a progression from adaptation of agricultural spraying systems toward specialized atmospheric purification architectures.

The field exhibits features of structured expansion, characterized by interdisciplinary convergence and increasing component-level refinement. Although annual publication counts remain moderate, citation performance and thematic consolidation suggest strong intellectual momentum. Continued advancement will depend on improvements in energy efficiency, aerodynamic coupling, and system integration. As technological maturity increases, drone-based air purification may contribute to flexible and spatially targeted environmental management strategies, complementing stationary infrastructure and supporting sustainable urban development.

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