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INTEGRATING URBAN AIR MOBILITY INTO COMMERCIAL AIRSPACE: A BIBLIOMETRIC REVIEW OF REGULATORY CHALLENGES

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ABSTRACT

Urban Air Mobility (UAM) has emerged as a transformative aviation concept with the potential to alleviate ground congestion losses and redefine passenger and cargo transportation within urban environments through the deployment of electric and autonomous aerial systems. However, the integration of UAM into commercial airspace remains significantly constrained by fragmented and underdeveloped regulatory frameworks. This research investigates the challenges and gaps associated with global UAM regulatory frameworks through a multi-phase methodological approach integrating PRISMA screening, bibliometric analysis, and hybrid deductive–inductive coded literature review. Bibliometric assessment conducted using VOSviewer identified thematic evolution, academic collaboration patterns, influential contributors, and citation relationships across the existing body of knowledge. The findings indicate that current research remains predominantly technology-oriented, with comparatively limited focus on regulatory frameworks. Coding literature review identified airspace management, infrastructure, vehicle certification, and societal acceptance as the most critical regulatory challenges, while legal liability and AI governance remain substantially underexplored. The study further highlights collaborative harmonisation among regulators, policymakers, and industry stakeholders as the most widely proposed mitigation strategy. Overall, the research establishes a significant gap between technological advancement and regulatory preparedness, thereby underscoring the necessity for globally coordinated, scalable, and adaptive regulatory frameworks to support safe and sustainable UAM integration.

Keywords: Urban Air Mobility, eVTOL, Regulatory Framework, Integration Challenges, Bibliometric Analysis, Commercial Airspace

1. Introduction

Urban Air Mobility (UAM) refers to the transportation of passengers or goods within urban metropolitan regions using aerial systems [1]. This is primarily enabled through hybrid or electric Vertical Take-Off and Landing (eVTOL) aircraft [2]. Although often used interchangeably with Advanced Air Mobility (AAM), UAM represents a subset of AAM and is specifically focused on short-range operations within urban environments [3]. According to European Union Aviation Safety Agency (EASA) [4], UAM is defined as a new, safe, secure and more sustainable air transport system for passengers and cargo in cities, enabled by advanced technologies and integrated into multimodal transportation networks, utilising both piloted and autonomous eVTOL aircraft.

While the concept of aerial personal transport dates back to the early 20th century, its first practical manifestation occurred during the 1950s and 1960s through scheduled helicopter services [3]. Interest in UAM resurged in the 2010s, driven by increasing demand for on-demand air mobility services and advances in aerospace innovations, including the introduction of eVTOL concept through a viral video showcasing the concept of single-person flight by the National Aeronautics and Space Administration (NASA) [1]. Since then, progress in battery technologies, distributed electric propulsion, and autonomous flight systems, combined with growing interest from major aerospace companies such as Airbus, Boeing, and Bell, has accelerated the development of various design forms including vectored thrust, wingless multicopters, rotorcraft and Lift + Cruise aerial vehicles [2]. Currently, leading industry players such as Joby Aviation, Archer, Volocopter, EHang, Wisk, and Lilium are actively working towards eVTOL certification, supported by investments from notable airlines and automotive manufacturers including United Airlines, Aston Martin, Porsche, Audi, General Motors, Hyundai, and Toyota among others [3].

Urban traffic congestion imposes significant economic and social costs in addition to carbon emissions and traffic related incidents as illustrated in Fig. 1. According to the latest Global Traffic Scorecard from INRIX, the United States alone experiences losses of approximately USD 85.8 billion and more than 49 hours of lost time per driver annually [5]. Moreover, the US Environmental Protection Agency [6] estimates an average passenger vehicle emits approximately 4.6 metric tons of carbon dioxide per year while the World Health Organization [7] reports that road accidents result in around 1.19 million fatalities each year, with a further 20 to 50 million people sustaining non-fatal injuries globally. Hence, traffic congestion is a social, economic and environmental dilemma for expanding urban environments worldwide.

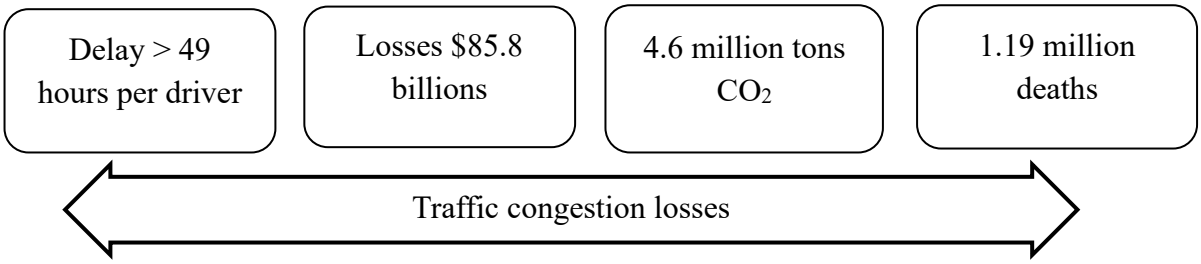


Fig. 1. The Urban Transportation Dilemma

UAM has been identified as a potential alternative to reduce ground congestion in urban areas by shifting a portion of travel demand from ground to air-based mobility, thereby enabling more efficient point-to-point transportation [8]. UAM is expected to transform urban mobility by reducing commute times through increased mobility, alleviating overburdened ground transport networks, improving environmental sustainability, and enhancing emergency response capabilities across healthcare, fire and law enforcement sectors**.** Consequently, UAM has the potential to support parcel delivery, shared mobility and critical services, forming a key component of the broader on-demand mobility ecosystem.

Based on the envisaged opportunities, market projections indicate strong growth potential. An optimistic estimate suggests that UAM could capture up to 20% of urban mobility market, resulting in a 46% reduction in driving time and a market value of US $1.5 trillion by 2040 [9]. However, a more conservative assessment by Cohen and Shaheen [3] estimates a total market value in the range of USD 74 - 641 billion by 2035. Notwithstanding, the realisation of these outcomes will depend on the successful integration of UAM into existing commercial airspace.

In line with EASA definition, UAM does not correspond to a standalone technology or a single platform or component, but rather to a highly coupled System of Systems (SoS). It consists of multiple interconnected subsystems, including air vehicles; infrastructure such as vertiports; communication and

cybersecurity systems; navigation and air traffic management; and the regulatory framework. These components operate independently but must function cohesively, as illustrated in Fig. 2.

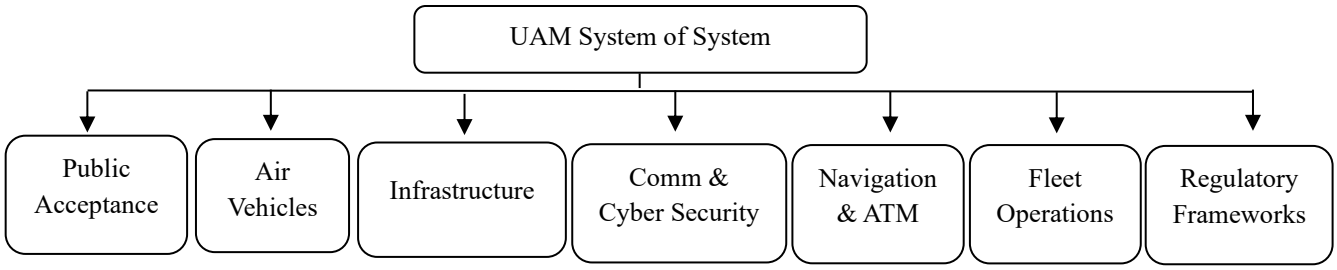


Fig. 2. Components of UAM SoS

As argued by Duraisamy, Natarajan and Sri Preethaa [10], the effectiveness of UAM operations depends on the emergent behaviour arising from interactions between these subsystems. Therefore, seamless interoperability among these evolving components is critical to maintaining an efficient and reliable mobility ecosystem. This creates an inherent problem, as addressing UAM implementation impediments necessitates a multidisciplinary approach that accounts for these interdependencies. Accordingly, the literature review focuses on the multidisciplinary challenges associated with the integration of UAM as a system of systems into commercial airspace, with particular emphasis on identifying gaps in the regulatory framework that necessitate further research.

2. Literature Review

2.1 Challenges for UAM Integration in Commercial Airspace

A preliminary review of scholarly articles on UAM underscores technical vehicle design certification, infrastructure integration, cybersecurity and communication, and public acceptance including associated societal impact, as notable challenges constraining the proliferation of UAM. The foremost hurdle in UAM adoption concerns safety-optimized vehicle design, that is, ensuring that UAM does not pose a hazard to passengers, other airspace users or the public over which it operates. In addition, Pak et al. [11] identify energy constraints arising from battery degradation, noise reduction, and efficiency as key technological challenges. Although, the technical architecture of the UAM ecosystem is supported by innovations in electric propulsion systems, automation, and aerodynamics, which aim to overcome these challenges as argued by Sengupta et al. [12]. However, these novel designs require continuous adaptation of the regulatory framework to keep pace with technological advancement and ensure safety [11].

Ground infrastructure, including vertiports, battery-charging platforms, and maintenance docks, is considered essential for UAM integration [13]. As it is critical to ensure safe separation between UAM operations and existing air traffic, effective Air Traffic Management (ATM) represents another significant hurdle impeding safety and scalability [1]. Consequently, reliable Communication, Navigation and Surveillance (CNS) on board UAMs become pivotal, which is affected by cybersecurity vulnerabilities and High Intensity Radiated Fields (HIRF) [14], [15], [16]. Thus, infrastructure, communication and airspace management constitute interconnected obstacles that persist in absence of a unified regulatory framework within which local authorities play a crucial role as outlined by Barbano and Costa [17].

An EASA sponsored survey on societal acceptance of UAM in Europe [18], highlighted a strong linkage between public acceptance and perceived exposure to noise, safety, privacy, and environmental impacts. A recent survey based study utilizing Structural Equation Modelling (SEM) identified transparent safety regulations, competitive fares, and clear visibility of environmental benefits as core drivers of UAM adoption [19]. UAM offers promising benefits in lowering greenhouse gas emissions

and easing congestion in urban areas; however, the extent of these environmental advantages is largely contingent on the adoption of sustainable energy sources and the efficiency of operational systems [20]. Accordingly, urban planning regulations are fundamental in managing UAM's environmental impacts, ensuring alignment with existing urban infrastructure and fostering broader public acceptance of the UAM ecosystem.

2.2 Absence of Unified Regulatory Framework for UAM

The multidisciplinary technical and operational challenges outlined are closely linked to the absence of a comprehensive regulatory architecture. Although national and international aviation regulatory authorities such as the International Civil Aviation Organization (ICAO), Federal Aviation Administration (FAA), NASA, EASA, Civil Aviation Safety Authority in Australia (CASA), and Civil Aviation Administration of China (CAAC) have initiated structured research and regulatory development since 2018 to support the safe integration of UAM [8], [21], the lack of a standardised global regulatory framework continues to hinder large-scale adoption.

Airworthiness certification of eVTOLs, airspace management, noise control, and pilot licensing are the critical issues encapsulating the outstanding regulatory frameworks for UAM [22]. A fundamental challenge arises from the unconventional design of the UAM ecosystem, which does not align neatly with existing aviation categories. The eVTOL aircraft, for instance, cannot be fully classified as helicopters due to their fixed wings and forward flight capabilities, nor as conventional airplanes because of their vertical take-off and landing functionalities. To address this gap, the FAA has introduced a new power-lift category specifically for eVTOL aircraft [23]. While, this framework considers aspects such as distributed electric propulsion, high-voltage systems, and novel failure modes, it still lacks fully developed airworthiness standards tailored to these new configurations.

Beyond aircraft certification and vertiport regulations, pilot training and licensing frameworks must also evolve. Current airline training models are cost intensive and not well suited to eVTOL operations [24]. Furthermore, as UAM systems progress towards higher levels of autonomy, it remains unclear whether operator-based certification will replace traditional pilot licensing; regardless, all such frameworks will require rigorous validation. In addition, existing studies emphasise the necessity of establishing a clear and coherent legal framework for UAM certification and operations that align with urban planning and sustainability objectives. This includes revising noise regulations and incorporating community engagement to enhance public acceptance [20], [25].

Table 1. List of Deductive Codes based on Research Questions

Deductive Codes	Research Questions
RQ1	What is the academic trend towards emphasis on UAM regulations?
RQ2	How critical is the regulatory framework for widespread adoption of UAM?
RQ3	What are the major challenges to UAM integration?
RQ4	What solutions are proposed by the academic sources to the identified challenges?

Based on the literature review, it is evident that the absence of unified regulatory framework is a primary barrier constraining the widespread adoption of UAM (Table 1.). A preliminary analysis of Scopus trends further reinforces this gap: out of 2677 journal articles and conference papers published over the past two decades on UAM, fewer than 10% (148 publications) include "regulation" as a keyword. This highlights the need for a comprehensive study that not only identifies the challenges but also compares existing regulatory frameworks and critically evaluates their effectiveness in addressing these gaps. Consequently, as a prerequisite, it is imperative to systematically identify the gaps and challenges associated with the development of global UAM regulatory structures together with the proposed solutions.

3. Research Design

3.1 Multi-Phase Methodology

The research adopts a multi-phase methodological approach that integrates PRISMA methodology, publication trend analysis, bibliometric analysis and coding literature review to provide a solid foundation for identifying challenges and gaps within UAM regulatory frameworks as illustrated in Fig. 3. This combined approach aligns closely with the methodology adopted by Piven and Shvindina [26], where bibliometric analysis is integrated with content analysis to bridge quantitative data synthesis and qualitative interpretation, thereby enabling both quantitative and qualitative depth.

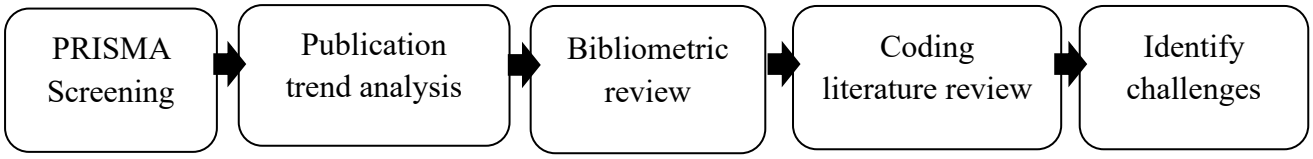


Fig. 3. Research design

The first step in literature review involves data collection. To ensure the reliability and validity of the findings, high-quality scholarly sources have been prioritized by utilizing the Scopus database, a premier index for peer-reviewed literature. While this focused scope reduces the total volume of data, it significantly strengthens the rigor and credibility of the research outcomes. The document selection process has been further refined using the PRISMA framework, which involved systematic identification based on keywords, screening via inclusion/exclusion criteria, and a rigorous quality assessment for eligibility evaluation.

To form basis for ascertaining academic focus on UAM regulations, a comprehensive trend analysis has been conducted to map chronological shifts and identify influential authors, countries, institutions, and funding sources. Subsequently, bibliometric analysis has been conducted using VOSviewer software (V1.6.20) to analyse the intellectual structure of the field. VOSviewer facilitates in revelation of research hotspot clusters, thematic evolution, academic collaborations and citation relationships through network, overlay, and density visualisations. Moreover, it also enables identification of influential articles and contributors including journals, authors, countries, and institutions. A primary advantage of VOSviewer is its ability to visually represent conceptual relationships, which is essential for understanding the multidisciplinary nature of UAM as a 'System of Systems'. As Piven and Shvindina [26] suggest, these tools uncover conceptual linkages and thematic clusters that offer deeper insights into complex research environments. Furthermore, to validate the results and mitigate potential variations arising from a targeted document set, a comparative analysis has been integrated.

Accordingly, articles selected through well-defined PRISMA methodology were analysed using hybrid deductive-inductive coding literature review to determine regulations criticality, identify the gaps, and proposed solutions for UAM regulatory frameworks within the existing body of knowledge. The obtained results have been critically analysed and augmented with bibliometric and publication trend analysis to enable synthesis of critical literature review. Summarising, this multi-phase approach ensures quantitative rigor through bibliometric and publication trend analysis, qualitative depth through coding literature review, and practical relevance through PRISMA screening and comparative evaluations.

3.2 Data Collection using PRISMA Framework

Collection of quality scholarly articles is a pre-requisite for conduct of bibliometric analysis. Accordingly, organized data has been collected in sequential steps using the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) technique as it provides a comprehensive, evidence-based framework to enhance the transparency, completeness, and reproducibility of systematic review [27]. Notwithstanding, collection of high-quality research articles is contingent on formulation of an effective search string based on the right keywords. Broader keywords may provide a wide range of sources; however, they introduce unrelated publications. On the other hand, concise terms pose a risk of exclusion of valuable research. Thus, there is a need to balance comprehensiveness with precision. Accordingly, various factors were considered including use of Field Codes, Boolean Operators and Wildcards to finalize search string for this analysis as listed in Table 2.

Table 2. Details of Search Query for Database

Parameter	Description
Keywords	UAM, Urban Air Mobility, AAM, Advance Air Mobility, UAV, eVTOL, Airtaxi, drone, taxi-drone, PAV, Personal Air Vehicle, Regulations, Regulatory Framework, Integration
Field Codes	TITLE-ABS-KEY (Article title, Abstract, and keywords)
Boolean Operators	Used operators such as AND, OR
Wildcards	Used wildcard symbol '?' for alternate spellings (e.g., "Regulat?" for regulation(s), regulatory etc.)
Search String	TITLE-ABS-KEY (UAM OR "Urban Air Mobility" OR AAM OR "Advance? Air Mobility" OR eVTOL OR airtaxi OR drone OR taxi-drone OR PAV OR "Personal Air Vehicle") AND ("Regulat?" OR (Regulatory AND Framework) OR "Integrat?")

In addition, establishment of search scope is critical to limit the results from vast field of knowledge. Given its strong reputation for indexing peer-reviewed scientific literature, Scopus database has been selected for data collection with publication type restricted to research or review articles and conference proceedings published in English language over last twenty (20) years. To streamline the search process in compliance with search scope, Inclusion/ Exclusion Criteria (IC/EC) has been formulated as per Table 3.

Table 3. Inclusion/ Exclusion Criteria

I/E	Criteria	Description
IC1	Subject Area	Subject areas to include Engineering, Computer Science, Social Sciences, Environmental Sciences, and Energy.
IC2	Language	The papers published in English language only
IC3	Type	Must be a research or review article or from a conference proceeding only
IC4	Timeframe	Sources must be within the 2007–2026 window unless historically essential
EC1	Influence	Research articles having less than 2 citations are excluded
EC2	Access	Full text of papers not accessible
EC3	Relevance	The papers not related to UAM or Regulatory Framework

3.3 Data Screening and Analysis Process

A semi-automated approach was adopted for the screening of collected data using the PRISMA methodology. The identification phase served as an initial filtering stage for scanning the extensive Scopus database to retrieve materials containing key terms and concepts relevant to the research domain of 'Urban Air Mobility' together with 'Regulatory Frameworks' or 'integration'.

During the screening phase, both automated and manual filtering methods were utilised. Automated screening was conducted using the inclusion criteria. Of the 384 documents identified during the initial phase, 105 documents were excluded through automated inclusion filters, comprising 61 exclusions under IC1 (subject area criteria), 7 under IC2 (language criteria), 32 under IC3 (document type criteria), and 5 under IC4 (timeframe criteria). Automation process enabled rapid identification and filtering of potentially relevant studies from a large dataset.

Subsequently, manual screening of the remaining 279 documents resulted in the exclusion of an additional 141 sources following application of the exclusion criteria. This included 120 exclusions under EC1 (influence criteria), 4 under EC2 (access criteria), and 17 under EC3 (relevance criteria). The procedures adopted for each manual screening stage warrant brief explanation. EC1 was implemented by exporting bibliometric data from Scopus into Microsoft Excel and applying citation based filters to exclude all sources with fewer than two citations. Thereafter, the remaining 159 documents were individually assessed for full-text accessibility, which identified 78 documents with open access, 71 with limited access through the university library system, and 6 available through Google Scholar. Consequently, only four documents were determined to be non-compliant with EC2. Finally, to verify relevance under EC3, the titles of the remaining 155 documents were manually reviewed, resulting in exclusion of 17 additional documents and reducing the number of eligible sources to 138 for further analysis. The bibliometric data associated with these documents was subsequently filtered in Microsoft Excel for bibliometric analysis using VOSviewer.

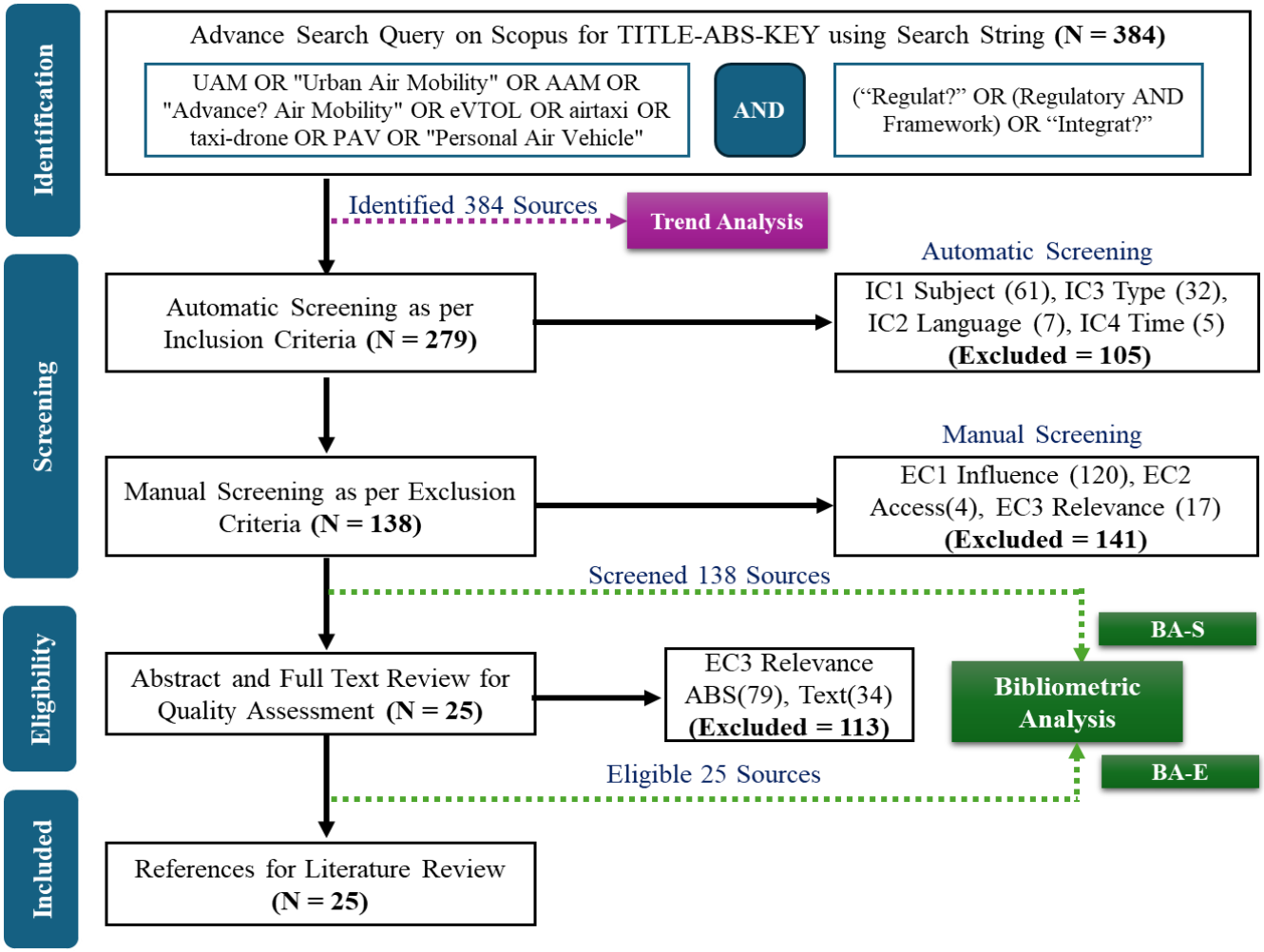


Fig. 4. PRISMA Flow Diagram for Bibliometric Analysis and Literature Review

During the eligibility phase, quality assessment was conducted through manual refinement, resulting in exclusion of an additional 113 papers. This included exclusion of 79 papers based on abstract review, while 34 documents were excluded following full-text assessment. Consequently, 25 articles were selected for comparative bibliometric analysis and coded literature review, as these studies provided substantial empirical grounding for the investigation of regulatory challenges associated with UAM integration into commercial airspace (Fig. 4.).

4. Publication Trend Analysis

Publication trend analysis undertaken using Scopus data of 384 documents identified through advance search with selected search string. Temporal distribution of published documents presented in Fig. 5. indicates an exponential rise in academic interest into Urban Air Mobility particularly since 2022.

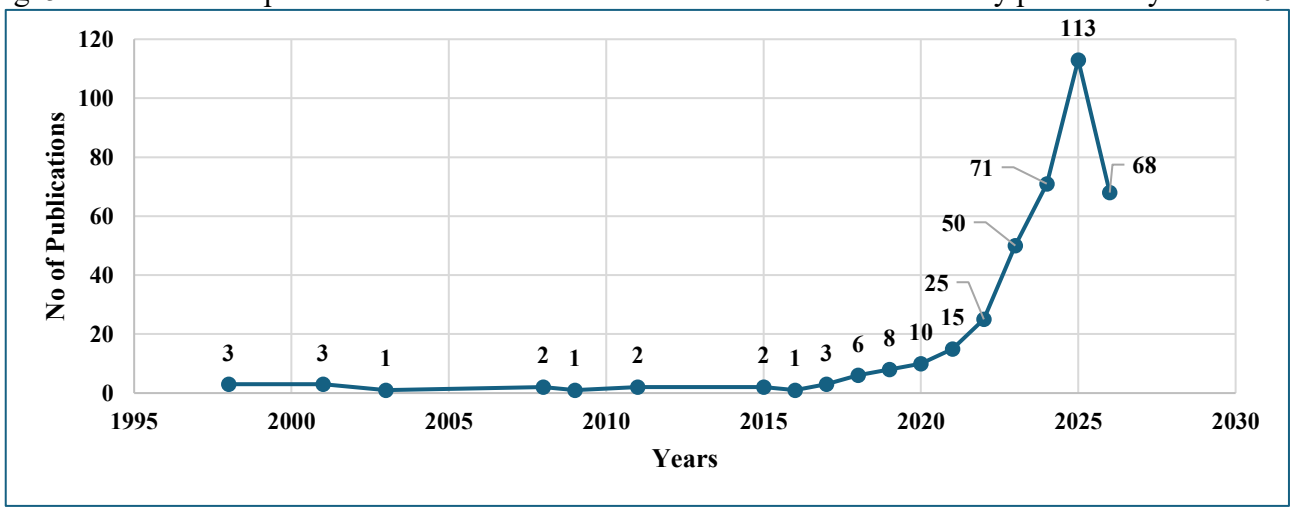


Fig. 5. Temporal Distribution of Published Documents

This upsurge is attributed to advances in energy density, increased focus on sustainability goals, and investment from leading airlines and automotive manufacturers for prototypes development [28].

5. Bibliometric Analysis

The bibliometric analysis was conducted in two stages using the screened and eligible sources presented in Fig. 4. This approach enabled broad coverage of the literature through analysis of 138 screened papers (BA-S), while the comparative bibliometric assessment of the 25 eligible sources (BA-E) provided further refinement and validation of the findings. The analysis generated key insights, including the identification of relationships among research themes within the existing body of knowledge using co-occurrence analysis for thematic mapping and thematic evolution. Furthermore, co-authorship analysis utilising citation metrics enabled identification of academic collaboration patterns, including the most influential countries, authors, and publication sources within the domain.

In addition, bibliographic coupling analysis based on citation metrics identified citation relationships and highlighted most influential research institutes and significant studies over time. The overlay visualisation feature in VOSviewer enabled mapping of academic collaborative linkages and research evolution by countries and institutes providing a global perspective. Collectively, these analyses facilitated in identification of academic trend with regards to the emphasis on UAM regulations while examining the current extent of international collaboration and the broader body of knowledge.

Co-occurrence analysis conducted using keywords occurrence strength together with publication year to identify thematic mapping and evolution trends (Fig. 6.).

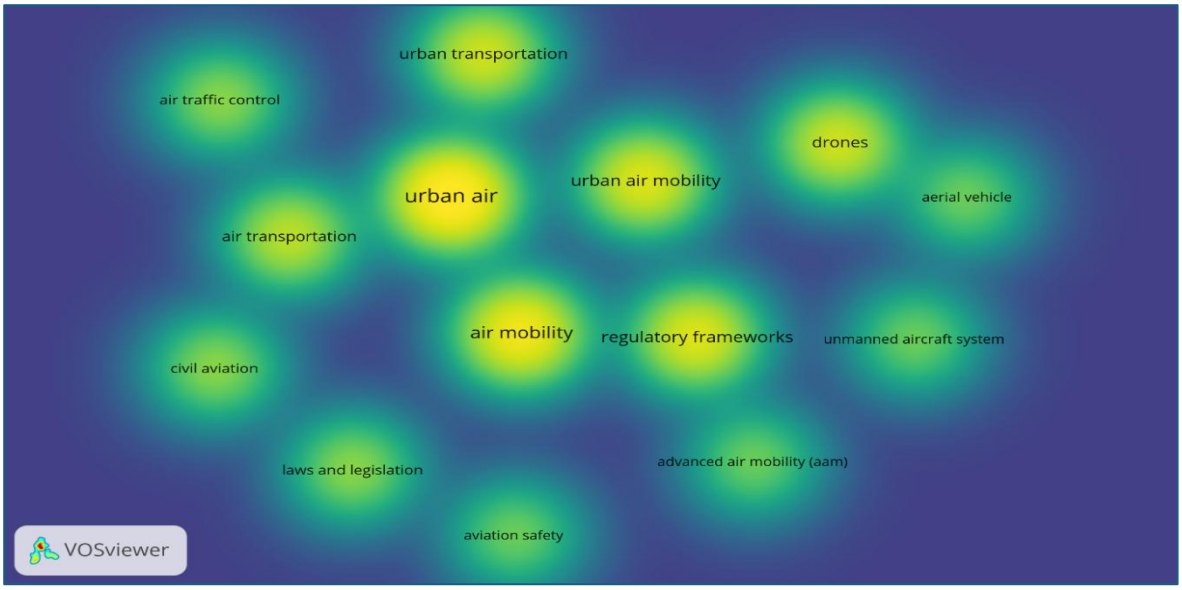


Fig. 6. Research Hotspots based on Keywords

The density visualization of co-occurrence analysis revealed research hotspots with "urban air", "air mobility", "urban air mobility" and "air transportation" identified among the most prominent research areas. The comparative assessment validated the identified themes and additionally highlighted "regulatory framework" and "aviation safety" as recurrent themes. The network diagram highlighted that the regulatory framework maintained linkages with all major research hotspots. Nevertheless, critical review of link strength and total link strength using density visualisation demonstrated that, despite maintaining strong connections with other themes, regulatory framework has relatively weaker total link strength than themes such as Air Navigation and Air Traffic Control. The findings underscore the identified research gap, whereby the broader literature provides comparatively limited focus on regulatory frameworks. These findings are further validated by keyword citation analysis, as the overlay plot developed using keyword occurrence strength and average citation scores highlights significantly limited emphasis on regulatory framework within the UAM domain as shown in Fig. 7.

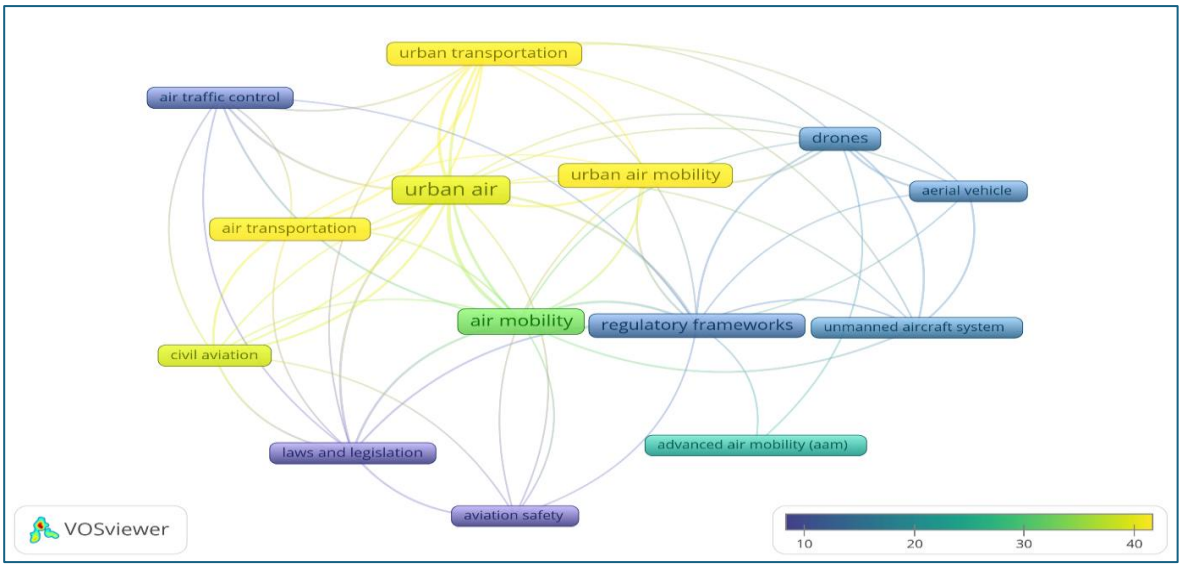


Fig. 7. Thematic Mapping with Keyword and Average Citation Scores

Overlay plots generated using keyword occurrence strength and average publication year indicates that research trends have primarily focused on Air Mobility and Air Traffic Control since 2022, whereas research specifically addressing regulatory frameworks and legislation emerged more prominently in 2023 as illustrated in Fig. 8. The analysis further highlights a recent shift in academic interest toward aviation safety.

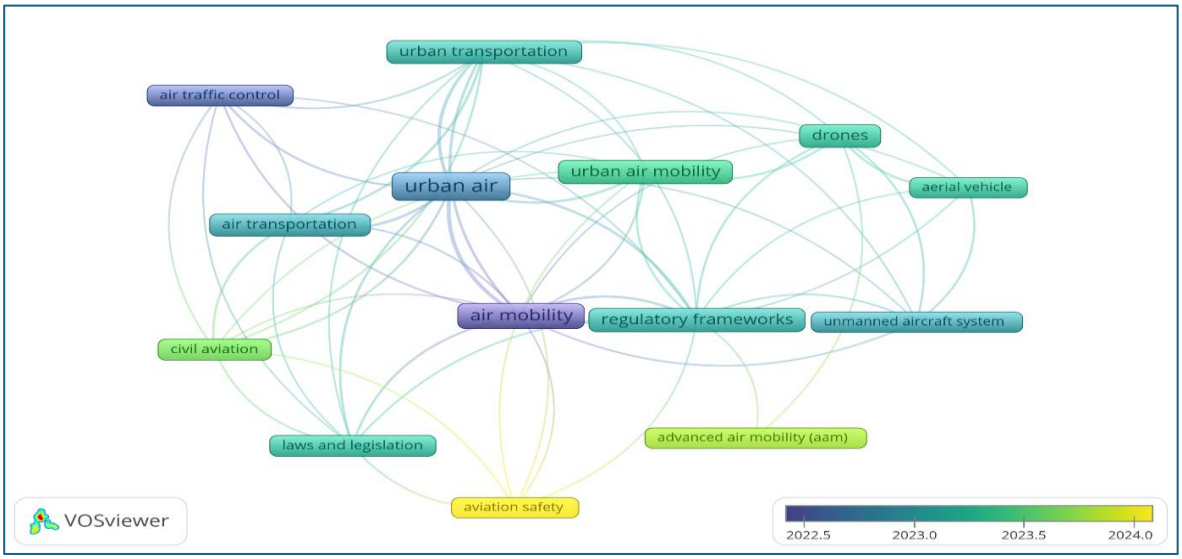


Fig. 8. Thematic Evolution with Keyword and Average Publication Year

Co-authorship analysis conducted using total citation count as the primary measurement metric to identify academic collaborations among leading countries, authors, and publication sources.
Density visualisation based on citation counts revealed the USA and Germany as the most influential countries within the UAM domain, followed by China and Spain. Furthermore, overlay visualisation based on citation strength and average publication year as illustrated in Fig. 9., highlights collaborative UAM research conducted by Germany and the USA since 2023, while the UAE, Australia, and South Korea have recently commenced research activity in the domain. Comparative assessment additionally identifies Poland and Sweden as countries that commenced focused research within UAM regulatory domains since 2022.

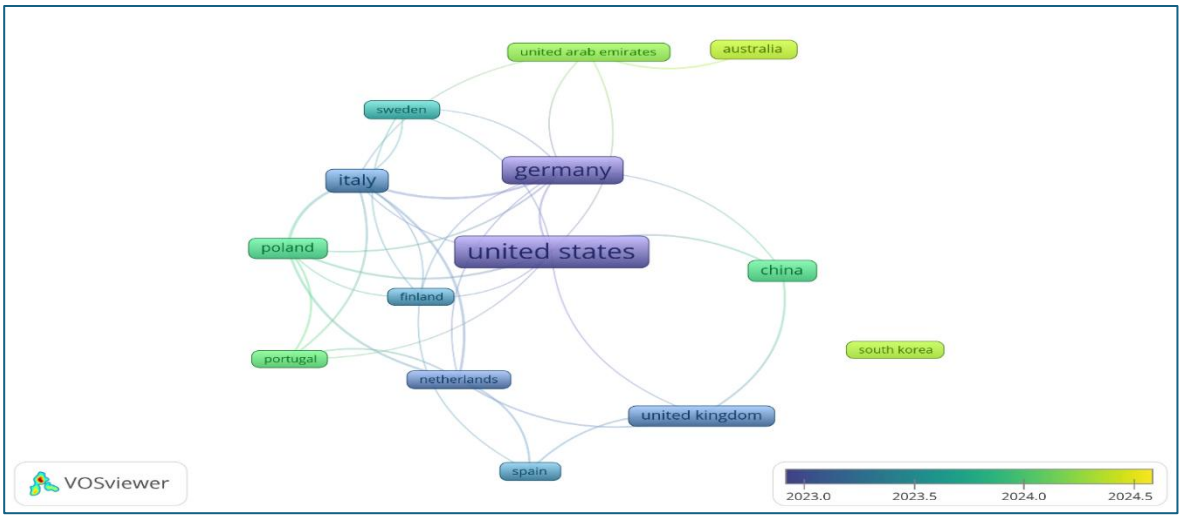


Fig. 9. Academic Collaboration Evolution Among Countries

Overlay visualisation based on link strength and average citation score depicts Di Vito, V. and Torens, C. as the most collaborative authors based on link strength, Conversely, average citation scores identify Schweiger, K. and Preis, L. as the most influential authors within the broader UAM domain while comparative assessment highlights Pons-Prats, J. and Goodrich, K.H. as influential contributors within the UAM regulatory framework domain based on strong citation performance. Overlay visualisation based on citation strength, link strength, and average publication year identifies AIAA Scitech Forums and Progress in Aerospace Sciences among the earliest influential publication sources, while Drones and Sustainability have become influential publication venues in more recent years. Comparative assessment additionally identifies Transport Research Part E: Logistics and Transportation Review as an early influential source contributing to UAM regulatory framework research.

Bibliographic coupling analysis conducted using total citation count as the filtering criterion identified citation relationships among influential institutes and research articles.

Overlay visualisation based on citation counts and average publication year highlights strong linkages between NASA research centres in the USA and German Aerospace Center DLR in Germany since 2021, while the University of Aeronautics and Astronautics in China has emerged as a moderately influential institution in recent years. Comparative assessment additionally identifies collaborative relationships among institutes from the USA, Europe, and Australia as illustrated in Fig. 10.

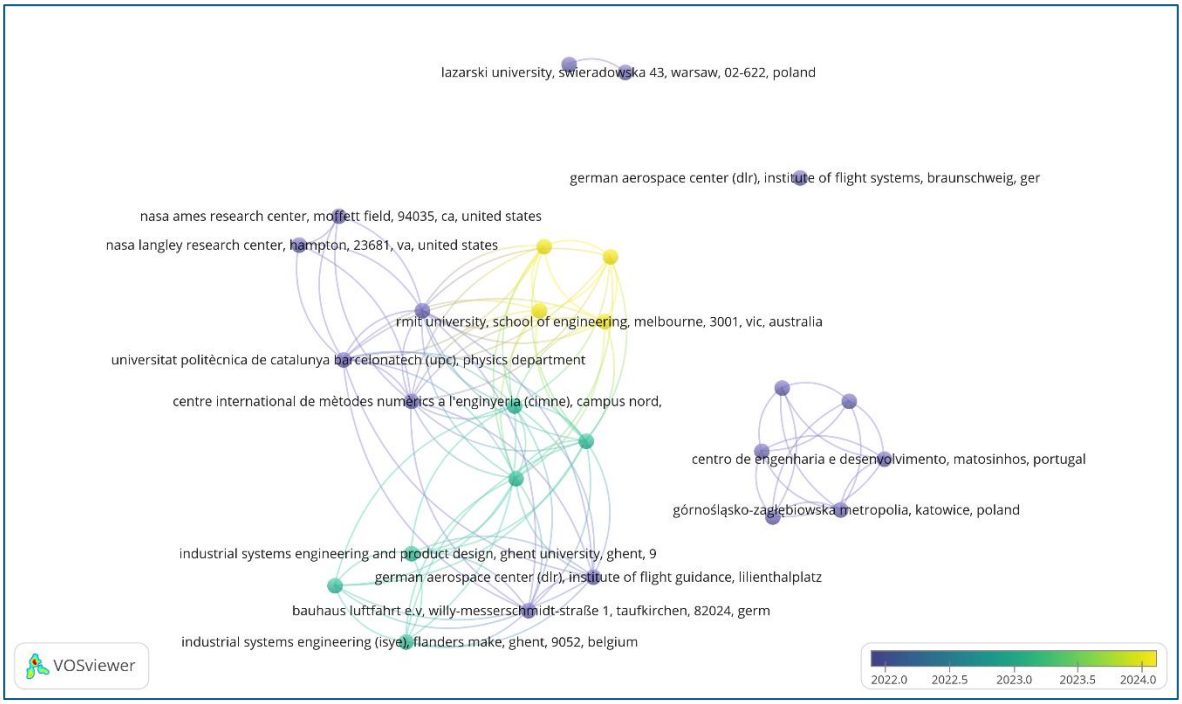


Fig. 10. Citation Relationship among Institutes with Average Publication Year

Overlay visualisation based on linkage strength and average publication year as illustrated in Fig. 11. highlights the paper by Raghunatha, A., having strong bibliographic coupling alongside studies by Pons-Prats, J. and Koumoutsidi, A. The analysis further identifies the conference paper by Vascik, P.D. as one of the earliest influential documents in the field, dating back to 2018. Comparative assessment remains consistent with the findings.

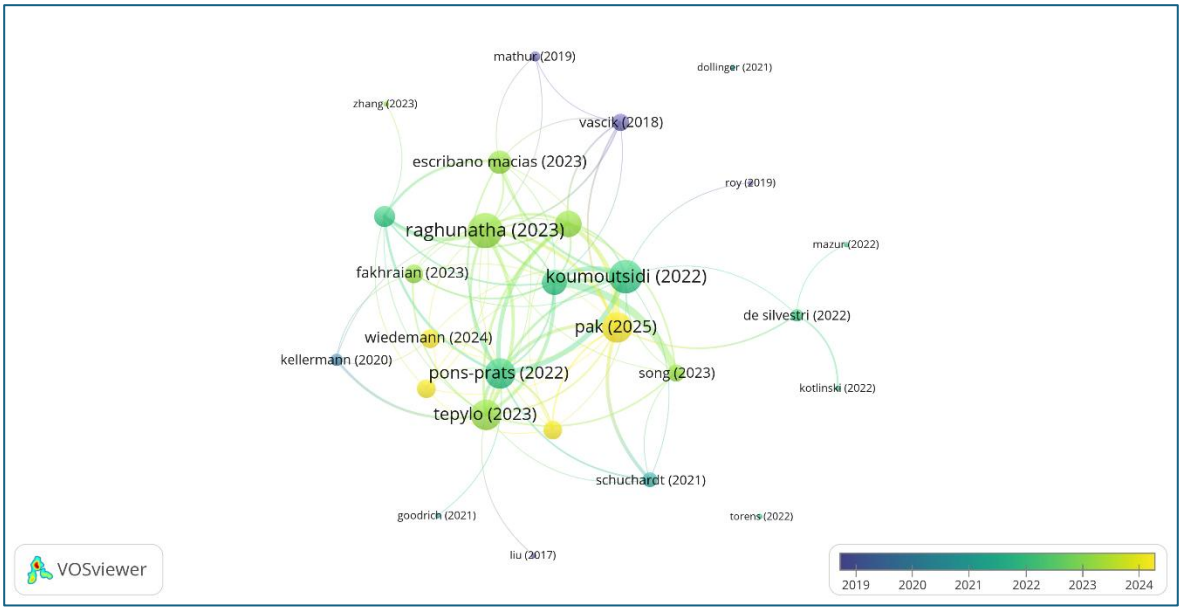


Fig. 11. Citation Relationship among Papers with Linkage Strength

6. Coding Literature Review

A coding literature review is a systematic method of analysing academic literature through the assignment of codes to key concepts and themes identified across multiple sources. It bridges qualitative and quantitative approaches by enabling categorisation and analysis of recurring patterns across the reviewed articles, thereby improving critical assessment in addressing specific research questions [30]. For this research, a hybrid deductive-inductive coding approach has been adopted, which is particularly suitable for UAM research due to the fragmented and evolving nature of the regulatory literature. While deductive coding enables alignment with predefined research objectives, inductive coding facilitates the identification of emergent regulatory challenges beyond initially anticipated categories.

Table 4. List of Inductive Codes based on Regulatory Framework Challenges

Inductive Code	Challenge/ Domains within Regulatory Frameworks
C1	Airworthiness Certification (eVTOL Vehicles/ Batteries/ Propulsion etc.)
C2	Airspace Management & Integration (ATM/ UTM etc.)
C3	Infrastructure (Vertiports etc.)
C4	Communication, Navigation, Surveillance (CNS) and Cybersecurity
C5	Operations (Flight Rules/ Weather etc.) and Pilots Licensing
C6	Operator Approvals (AOC/MRO etc.) and Safety (SMS)
C7	Social Acceptance (Privacy etc.) and Environment (Noise/ Emission)
C8	Legal and Liability Concerns for unmanned, autonomous, and AI based systems

Subsequently, domain specific challenges identified during the literature review were systematically deconstructed and assigned inductive codes (C1-C8) as per Table 4. Frequency scores associated with these domains were evaluated to identify the most extensively researched challenges, while gaps were determined based on challenges receiving a coverage score of less than 60% across the reviewed literature. As coding literature review addresses RQ2 to RQ4, the comprehensive matrix covering methodology, findings, and detailed response to research questions while the summarized results are presented in Table 5 (Appendix A).

Table 5: Coded Literature Review Summary for Research Questions

ID	Source	RQ2 Criticality	RQ3 Major Challenges	RQ4 Solution Provided
S1	Raghunatha et al. (2023) [31]	Yes	**C1, C2, C3, C4, C5, C6, C7**	Yes
S2	Wiedemann et al. (2024) [32]	Yes	**C1, C2, C3, C5, C6**	Yes
S3	Vidovic et al. (2024) [33]	Yes	**C1, C2, C3, C4, C7**	Yes
S4	Shi Y. (2024) [34]	Yes	**C5, C8**	Yes
S5	Goodrich and Theodore (2021) [35]	Yes	**C1, C2, C3, C4, C5, C6, C7, C8**	Yes
S6	Hoopes and Takahashi (2023) [36]	Yes	**C1, C2, C5**	Yes
S7	Tripaldi et al. (2025) [37]	Yes	**C1, C2, C3, C7**	No
S8	Chaisit et al. (2024) [38]	Yes	**C1, C3, C7**	No
S9	Torens et al. (2022) [39]	No	**C8**	Yes
S10	Barbano and Costa (2023) [17]	Yes	**C2, C3**	Yes
S11	Madi and Madi (2024) [40]	Yes	**C8**	Yes
S12	Hijazeen et al. (2025) [41]	Yes	**C3, C5**	Yes
S13	Pons-Prats et al. (2022) [42]	Yes	**C1, C2, C3, C4, C7, C8**	Yes
S14	Agustinho and de Mattos Bento (2022) [43]	Yes	**C2, C3, C4, C6**	Yes
S15	Mazur et al. (2022) [22]	Yes	**C1, C2, C3, C4, C5, C7**	Yes
S16	Farooqui (2025) [44]	Yes	**C2, C3, C7**	Yes
S17	Castro and Garcia (2021) [45]	Yes	**C2, C4, C5, C6, C7**	No
S18	Trimarchi A. (2023) [46]	Yes	**C2, C3, C7, C8**	Yes
S19	Fakhraian et al. (2023) [47]	Yes	**C1, C2, C6**	No
S20	Van Huis (2023) [48]	Yes	**C1, C2, C3, C5, C6, C7**	Yes
S21	Kramar et al. (2021) [49]	Yes	**C2, C7**	Yes
S22	Li et al. (2025) [8]	Yes	**C2, C3, C5**	No
S23	Schweiger and Preis (2022) [50]	Yes	**C2, C3, C4, C6, C7**	Yes
S24	Wild G. (2024) [51]	Yes	**C1, C2, C3, C4, C5, C6, C7, C8**	Yes
S25	Kotlinski et al. (2022) [52]	Yes	**C2, C8**	Yes

7. Results and Discussion

As per publication trend and bibliometric analysis, UAM research demonstrates rapid technological advancement in recent times, however, research on regulatory frameworks remains comparatively fragmented, reactive, geographically concentrated, and underdeveloped relative to operational and engineering domains. The comparatively weak total link strength associated with regulatory frameworks suggests that governance related studies remain secondary to technology oriented UAM research. This imbalance may impede practical implementation, as operational scalability within commercial airspace fundamentally depends upon regulatory harmonisation and certification pathways. The delayed emergence of regulatory framework research after 2023 indicates that the regulations are evolving reactively in response to accelerating technological development. Such lag between innovation and regulation has historically contributed to implementation bottlenecks in aviation industry.

The dominance of the USA and Germany through strong institutional influence of NASA and DLR respectively, signifies the concentration of aerospace industrial capability, research funding, and institutional maturity within advanced aviation economies. Conversely, the limited representation of developing nations highlights potential asymmetries in future participation within globally harmonised UAM ecosystems. Moreover, such concentration may unintentionally bias regulatory development

toward western operational models that may not fully account for differing urban, infrastructural, and governance conditions globally. Notwithstanding, it may be highlighted that the comparative bibliometric methodology utilised in preceding analyses improved analytical robustness by balancing broad thematic coverage with topic specific validation. However, overreliance on citation metric inherently favours established research institutions, potentially underrepresenting emerging regulatory studies within rapidly evolving UAM domains. Consequently, the research gap identified during the preliminary literature review is validated through trend and bibliometric analyses, thereby justifying increased scholarly attention toward regulatory framework development within the UAM domain.

The coded literature review summary indicates more than 90% of the reviewed documents identifying regulatory frameworks as an essential element for ensuring safe, reliable and scalable adoption of UAM. However, critical analysis highlights that this finding is based on dataset filtered through the PRISMA screening process, which is inherently influenced by documents specifically related to regulatory frameworks. It is important to note that, despite the inclusion of 34 additional sources filtered during the quality assessment stage based on full text review, only 15% of UAM related publications (59 out of 384 documents) focus on regulatory frameworks, thereby indicating comparatively limited research attention within the domain. This argument is further supported by the thematic mapping analysis highlighting significantly lower emphasis on regulatory framework development compared with the technical and technological aspects of UAM. Such underrepresentation of regulatory research may create a disconnect between technological readiness and operational deployment.

The criticality of domain specific gaps within UAM regulatory frameworks was determined by mapping the coverage of inductively coded challenges against the reviewed literature. Based on the scoring criteria, airspace management, infrastructure requirements, public acceptance, and vehicle certification were identified as the most critical domains, with more than 60% of scholars highlighting them as key challenges. Table 6 further identifies cybersecurity, operator and pilot licensing, safety governance, and liability concerns associated with autonomous systems as notable gaps within existing UAM regulatory frameworks. The uneven distribution of research attention across regulatory domains suggests that immediate operational barriers currently receive greater academic prioritisation than long-term governance complexities, such as AI accountability and automated decision-making liability.

Table 6. Coverage Scores for Regulatory Challenges

Code	Key Challenges	Coverage Score (%age)
C1	Airworthiness Certification	62%
C2	Airspace Management	86%
C3	Infrastructure	74%
C4	CNS & Cybersecurity	44%
C5	Operations and Pilot Licensing	52%
C6	Operator and Safety	50%
C7	Social Acceptance	68%
C8	Legal and Liability Concerns	32%

Critical evaluation highlights airspace management as the most extensively researched topic, with almost all scholars acknowledging it as the primary obstacle restricting UAM adoption. The overwhelming focus on airspace management reflects the foundational dependency of UAM operations on safe integration within already congested low-altitude urban airspace. This further indicates that scholars largely perceive traffic integration as the principal operational bottleneck preceding wider commercial scalability. Consequently, regulatory authorities worldwide are actively developing mitigation strategies in the form of U-Space initiatives in Europe and UTM systems in the USA.

Conversely, granular investigation indicates that legal and liability concerns remain the most underrepresented challenge among the selected sources, with fewer than one-third identifying them as a major issue. Interrogation of this comparatively limited focus highlights a potentially significant regulatory lag, particularly considering the rapid advancement of autonomous and AI-enabled systems. The absence of mature liability and accountability frameworks may ultimately constrain commercial deployment despite technological readiness and operational necessity.

Frequency analysis of Table 5 indicates that approximately 80% of the selected sources propose regulatory framework solutions to address the identified challenges. The summarises the generalised solutions proposed by each author, it does not explicitly associate individual studies with specific regulatory challenges. To systematically address this limitation, Table 7 maps each challenge to its corresponding sources and key solution features, thereby providing a clearer overview of current academic approaches toward mitigating the identified barriers.

Table 7. Mapping Solutions to Identified Challenges

Challenges	No of Sources	Proposed Solution
C1: Airworthiness Certification	7	Standardized regulations for vehicles certification through collaboration* (S3, S15, S24); Evaluate Dubai/ Singapore's policies to determine pathway (S2); UML Framework (S5); Clear definition for eVTOL variations and use (S6); Mandatory ICM systems (S20)
C2: Airspace Management	13	Standardized rules for safe interface with manned airspace through collaboration* (S6, S13, S15, S18, S20, S21, S23, S24); Local and regional capacity-building for airspace planning (S1); UML Framework (S5); Layered governance structure with flexibility for local authorities (S10); Helicopter regulations (S14); PansaUTM (S25)
C3: Infrastructure	10	Standardized worldwide regulations via collaboration* (S12, S13, S15, S18, S24); Evaluate Dubai/ Singapore's policies to determine pathway (S2, S16); UML Framework (S5); Layered governance structure with flexibility for local authorities (S10); EU UAM roadmap (S23)
C4: CNS & Cybersecurity	6	Standardized CNS regulations through collaborations* (S15, S23, S24); Adoption of direct prevention and strong encryption protocols (S3); UML Framework (S5); Helicopter regulations (S14)
C5: Operations and Pilot Licensing	7	Harmonized operational rules for safe airspace through collaboration* (S6, S15, S24); Evaluate Dubai/ Singapore's policies to determine pathway (S2); Develop less stringent regulations for reduced training cost (S4); UML Framework (S5).
C6: Operator and Safety	7	Standardized regulations for Operator's licensing through collaboration* (S3, S23, S24); Clear structures with roles and responsibilities (S1, S20); Evaluate Dubai/ Singapore's policies to determine pathway (S2); UML Framework (S5)
C7: Social Acceptance	9	Standardized regulations through collaboration* (S15, S18, S21, S24); Setting up a carbon budget for AAM (S1); Enforce clear privacy policies and reduced noise pollution (S3, S20); UML Framework (S5); EU UAM roadmap (S23)
C8: Legal and Liability Concerns	7	Standardized regulations through collaboration* (S18, S24); UML Framework (S5); EASA AI Roadmap and CoDANN for AI/ ML adoption (S9), Dubai's Law for UAM regulations (S11); Anticipated regulations for autonomous UAM (S13); Sector-specific legal framework for automation liability (S25).

*Collaboration refers to coordination among regulators, support agencies, policy makers and industry.

Comprehensive synthesis of Table 7 reveals that the formulation of standardised rules and regulations through coordinated collaboration among regulators (ICAO, EASA, FAA, CASA, and CAAC), support agencies (NASA, SAE International, and Eurocontrol), policymakers, and industry

stakeholders, represents the most frequently cited solution within the literature. Although collaborative harmonisation is consistently proposed as the preferred strategy, practical implementation remains challenging due to differences in national regulatory structures, urban density, political priorities, and governance systems across jurisdictions. Similarly, several sources recommend adoption of the Dubai regulatory framework and associated policies to accelerate UAM integration. However, such approaches may not be readily transferable to decentralised democratic systems, as regulatory models developed within highly centralised governance environments, such as Dubai and China, operate under significantly different legislative structures involving reduced stakeholder complexity and faster regulatory implementation pathways.

Furthermore, while adaptation of existing helicopter regulations, as proposed by Agustinho and de Mattos Bento [43], offers a pragmatic short-term pathway for initial UAM deployment, such legacy frameworks may prove insufficient to address emerging challenges associated with autonomous operations, AI-driven decision-making, and high-density urban traffic ecosystems. Among the proposed approaches, analytical appraisal indicates that the NASA UML framework [35] appears comparatively comprehensive due to its integrated treatment of operational scalability, autonomy progression, certification pathways, and infrastructure coordination encompassing all identified challenges.

Critical comparison of the proposed solutions further reinforces the uneven distribution of research attention, indicating that many existing approaches remain transitional and operationally focused, with comparatively limited emphasis on long-term regulatory harmonisation for autonomous and AI-enabled UAM ecosystems.

Conclusion

This research investigated the role of regulatory frameworks in the integration of UAM into commercial airspace through a structured methodology comprising of PRISMA screening, bibliometric analysis, and a hybrid deductive–inductive coded literature review. The findings provide clear evidence that regulatory frameworks constitute a critical enabler of safe, reliable, and scalable UAM deployment with more than 90% of the reviewed literature identified regulatory frameworks as essential for UAM integration. However, bibliometric analysis revealed that regulatory research remains significantly underrepresented as compared to technological and operational aspects, highlighting a notable gap within the existing body of knowledge.

The coded literature review identified airspace management, infrastructure development, public acceptance, and airworthiness certification as the most critical challenges. Legal liability, autonomous system governance, and AI-related accountability were found to be comparatively underexplored despite their growing importance for future operations. These findings indicate an imbalance in current research priorities, with greater emphasis on immediate operational challenges than on long-term requirements. The literature demonstrated broad consensus on collaborative development of standardised regulations through coordination among regulators, policymakers, support agencies, and industry stakeholders for mitigating identified challenges. Notwithstanding, future research through comparative analysis of global regulatory frameworks is critical to evaluate the effectiveness of existing regulatory approaches in mitigating highlighted challenges, and identification of harmonisation opportunities and barriers, enabling formulation of evidence-based recommendations to support UAM integration into commercial airspace.

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Appendix A: Coded Coverage Chart of Regulatory Challenges

ID	Source	C1	C2	C3	C4	C5	C6	C7	C8
S1	Raghunatha et al. (2023)	✓	✓	✓	✓	✓	✓	✓	
S2	Wiedemann et al. (2024)	✓	✓	✓		✓	✓	~	
S3	Vidovic et al. (2024)	✓	✓	✓	✓		~	✓	
S4	Shi Y. (2024)					✓			✓
S5	Goodrich and Theodore (2021)	✓	✓	✓	✓	✓	✓	✓	✓
S6	Hoopes and Takahashi (2023)	✓	✓			✓			
S7	Tripaldi et al. (2025)	✓	✓	✓				✓	
S8	Chaisit et al. (2024)	✓	~	✓		~	~	✓	
S9	Torens et al. (2022)								✓
S10	Barbano and Costa (2023)	~	✓	✓				~	
S11	Madi and Madi (2024)	~	~	~					✓
S12	Hijazeen et al. (2025)	~	~	✓		✓	~	~	
S13	Pons-Prats et al. (2022)	✓	✓	✓	✓	~	~	✓	✓
S14	Agustinho and Bento (2022)	~	✓	✓	✓	~	✓	~	
S15	Mazur et al. (2022)	✓	✓	✓	✓	✓	~	✓	
S16	Farooqui (2025)		✓	✓	~			✓	
S17	Castro and Garcia (2021)		✓		✓	✓	✓	✓	
S18	Trimarchi A. (2023)		✓	✓				✓	✓
S19	Fakhraian et al. (2023)	✓	✓	~	~		✓	~	
S20	Van Huis (2023)	✓	✓	✓		✓	✓	✓	
S21	Kramar et al. (2021)	~	✓	~		~	~	✓	
S22	Li et al. (2025)	~	✓	✓	~	✓	~	~	
S23	Schweiger and Preis (2022)		✓	✓	✓		✓	✓	
S24	Wild G. (2024)	✓	✓	✓	✓	✓	✓	✓	✓
S25	Kotlinski et al. (2022)	~	✓		~				✓
	Total Score (out of 25)	**15.5**	**21.5**	**18.5**	**11**	**13**	**12.5**	**17**	**8**
	Total Score (%)	**62%**	**86%**	**74%**	**44%**	**52%**	**50%**	**68%**	**32%**
	Legend / Coverage Status (Score)	**~ Partially Covered (0.5)**			**✓ Covered (1.0)**		**Empty-Not Covered (0)**		