Trends and Gaps in Environmental Impact of Last Mile Delivery using Unmanned Aerial Vehicles: A Bibliometric Analysis

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Abstract: Digitalization and sustainability currently represent two relevant topics in logistics, especially in last mile logistic (LML). From one side, the implementation of green last mile delivery solutions is becoming a popular topic due to the growing emphasis on sustainable and eco-friendly practices in the retail industry as well as logistics. On the other side, digitalization and smart technologies – like Unmanned aerial Vehicles (UAVs) for automatic delivery- represent a new research frontier also for their potential to minimize environmental impact and boost operational effectiveness of LML. Little attention has been given so far to the evaluation of the environmental impacts of these digital technologies in LML, as the focus is currently mostly on their performance. This paper presents a bibliometric analysis aiming at evaluating both economic and environmental sustainability of UAVs in LML, thus focusing on technical obstacles and positive contributions of these technologies in terms of e.g. consumer accessibility, cost reduction, and environmental sustainability. The analysis has been carried out on papers published in scientific databases between 2017 and 2024. The most relevant technical challenges associated with last mile UAV delivery have been identified considering the technological and environmental points of views. Furthermore, the analysis highlights the current research gaps and emphasizes the need for more comprehensive analysis and frameworks to address critical aspects of UAV delivery in LML, such as consumer accessibility, weather conditions, flight duration, and battery capacity.

Keywords: UAV delivery, Last mile logistics; Life cycle assessment, Environmental impact, Energy consumption, Sustainability, Emissions.

1. Introduction

The 21st century has witnessed an unprecedented surge in urbanization (United Nations, 2022), accompanied by a rapid proliferation of e-commerce platforms (InsightAce Analytic, 2024), radically reshaping the dynamics of modern society (Eurostat, 2023). As populations continue to gravitate towards urban centres in search of economic opportunities and a better quality of life, the demand for goods and services has increased, also driving the exponential growth of online retail transactions (Statista, 2023). While this digital revolution has enhanced convenience and accessibility for consumers, it has also catalysed a series of challenges, particularly in the field of urban logistics, especially in last mile logistics(LML), which often represents the most inefficient tier of a supply chain (Lauenstein & Schank, 2022; Olsson et al., 2019; Premkumar et al., 2021) from both an economic perspective (F. Li et al., 2021; Ranieri et al., 2018), and environmental one (Patella et al., 2020). Thus, inefficiencies in LML operations not only strain resources and increase operational costs (Kostrzewski et al., 2022), but also are contributing to increase emissions (Awwad et al., 2018), city congestion (Muriel et al., 2022), and energy waste. In this context, exploring new and more sustainable solutions is becoming imperative to mitigate environmental degradation and enhance operational efficiency. Recently, smart and digital technologies have been explored as new delivery methods in LML: the most promising is Unmanned aerial Vehicles (UAVs). The integration of UAVs into the urban logistics landscape represents a paradigm shift, offering numerous advantages over conventional delivery methods. UAVs, with their aerial capabilities and autonomous navigation systems, have the potential to bypass traffic congestion (Y. Li et al., 2022), reduce delivery times (Khanda et al., 2022), and minimize carbon emissions (Rodrigues et al., 2022), thus fostering a more sustainable and efficient delivery ecosystem. Additionally, UAVs can provide delivery in a cheaper way for remote areas, bridging the accessibility gap and improving the inclusivity of logistic services.

While the economic convenience has been analysed by several studies, the environmental impact of these delivery solutions has reached less attention due to several issues. This study provides a comprehensive bibliometric analysis of the existing literature on UAVs-based delivery systems by focusing on their environmental impact in

LML. The paper is organized as follows: in section 2 the adopted methodology is proposed; the bibliometric and the following network analysis are discussed in section 3 and 4 respectively.

2. Methodology

The present study focuses on the environmental impacts of the adoption of UAVs in LML through a bibliometric analysis, aiming at identifying trends and gaps in the literature regarding the methods of analysis, tools, variables, and boundary conditions involved. The bibliometric analysis is conducted using VosViewer software. This research includes journal articles, books, and conference papers in English, published in two scientific article databases: Scopus and Web of Science.

Table 1 Search query applied to the two databases to obtain the articles to be analysed.

Database	Scopus	Web Of science
Research Query	TITLE-ABS-KEY ((("drone" OR "unmanned aerial vehicles" OR "UAVD")) AND ("last mile logistic" OR "urban logistic" OR "last mile delivery" OR "final mile"))	((TI=(("drone" OR "unmanned aerial vehicles" OR "uavs") AND ("last mile logistic" OR "urban logistic" OR "last mile delivery" OR "final mile"))) OR AB=((("drone" OR "unmanned aerial vehicles" OR "uavs") AND ("last mile logistic" OR "urban logistic" OR "last mile delivery" OR "final mile")))) OR AK=((("drone" OR "unmanned aerial vehicles" OR "uavs") AND ("last mile logistic" OR "urban logistic" OR "last mile delivery" OR "final mile")))
Analysed fields	Title, Abstract, Keywords	
Language	English	
Excluded study	Medical, chemistry, chemical engineering, biochemistry	
Time interval	No limits, only study from 2017 found	
Article type	Journal article, conference paper, review, Book Chapter	

The description of the research process followed, inclusion and exclusion criteria, are reported in Table 1 below. The authors chose few and not overly specific keywords to broadly analyse the literature and investigate the extent to which the theme of environmental sustainability is prevalent in current literature. The selected keywords are: "drone", "unmanned aerial vehicles", "UAV", "last mile logistic", "urban logistic", "last mile delivery", "final mile". Moreover, non-English articles and those within medical, chemistry, chemical engineering, biochemistry fields were excluded to refine the search. Only articles published between 2017 and May 2024 are analysed. The analysis included articles from scientific journals, conference papers, and book chapters.

From the application of search queries, 399 articles were initially obtained from Scopus and 173 from Web of Science, totalling 572. After setting the exclusion criteria described above and removing duplicates, the number decreased to 372 articles. From the articles selected, we applied filters embedded within the databases, based on the content of titles and abstracts, requiring that both contain keywords such as "energy," "consumption," "electricity," "emissions," "sustainability," and "emission reduction". The purpose of the filter applied in the last step is to eliminate articles that only address the introduction of UAVs in LML from a purely economic or performance perspective without delving into energy and environmental analysis. As a result, we obtained 119 articles eligible for further examination. The article selection process is summarized in Figure 1 below.

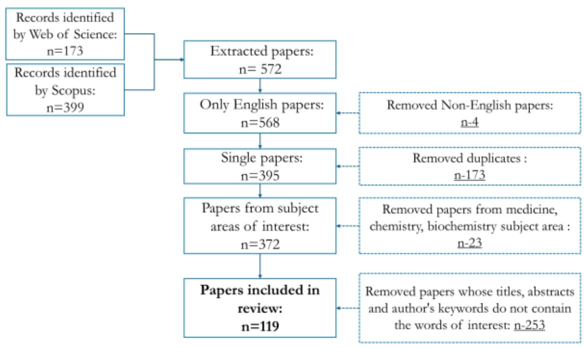

Figure 1 Selection process of papers to include in the analysis.

3. The Bibliometric analysis

The data presented in Figure 2 illustrates the distribution over time of the articles selected. A clear upward trajectory is evident in the number of publications from 2017 to 2023, signifying a growing interest in UAVs technology within academia and industry for the application in LML. The substantial increase observed in 2021 likely reflects the heightened focus on minimizing human contact and optimizing logistics during the COVID-19 pandemic, which spurred exploration of safer and more sustainable delivery alternatives. The data for 2024 reflects only the first two months of the year.

As illustrated in Figure 3, the distribution of research publications in our bibliographic analysis reveals a distinct focus on recent advancements. Articles, constituting 69 of the included works, suggest a strong emphasis on disseminating the latest research findings on the environmental and energetic impact of UAV delivery in LML. This prevalence of articles indicates a dynamic research landscape actively exploring various facets of this technology. In contrast, the presence of book chapters (9 papers) suggests a nascent body of established knowledge on the topic. The limited representation of data papers (2 papers) and reviews (1 paper) further reinforces the focus on recent research and the relative novelty of the field.

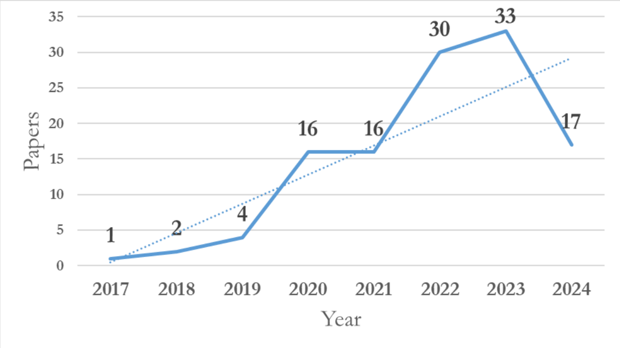

Figure 2 Papers distribution in the analysed time period.

Data papers, crucial for replicating and building upon existing research, are scarce. Similarly, the lack of review papers highlights the need for synthesizing the existing knowledge base, identifying research gaps, and providing comprehensive analysis to guide future works. This observed distribution underscores the opportunity for further research efforts: while the abundance of articles signifies a rapidly evolving field with a focus on recent advancements, there's a need for consolidating and synthesizing existing knowledge. Future research could address this gap by focusing on data-driven analysis and comprehensive reviews to build upon the current foundation of research articles.

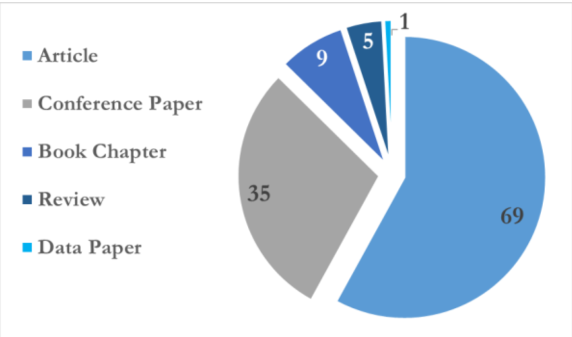

Figure 3 Cluster of paper types outlined form the analysis.

The distribution of subject areas shown in Figure 4 offers valuable insights into the multifaceted nature of research surrounding UAV delivery in LML. Computer Science (70 papers) and Engineering (64 papers) emerge as the leading subject areas. This dominance reflects the crucial role of these disciplines in developing and optimizing UAV technology for last mile delivery. Research in computer science likely focuses on algorithms for efficient route planning (Cherif et al., 2023), obstacle avoidance, and safe autonomous flight (Wang et al., 2019). Engineering research, on the other hand, might delve into UAV design, propulsion systems (ElSayed & Mohamed, 2020), and robust navigation technologies suitable for diverse environments (Bányai, 2022). The inclusion of Social Sciences (36 papers) highlights the importance of understanding societal perspectives on UAV delivery. This research could explore public perception, concerns regarding privacy (Tu & Piramuthu, 2023) and noise (X. Ren & Cheng, 2020). Additionally, it might address regulatory frameworks needed for safe and responsible UAV integration into urban airspace (Elsayed & Mohamed, 2020). The presence of Mathematics (29 papers) and Decision Sciences (28 papers) indicates a focus on quantitative analysis and optimization techniques. Mathematical models could be used to optimize flight paths (Shao et al., 2022), battery life (X. X. Ren et al., 2023), and payload capacity (Rabta et al., 2018), while decision science research could explore the economic (Kostrzewski et al., 2022) feasibility and strategic (Nur et al., 2020) decision-making processes associated with UAV delivery adoption. The inclusion of Energy (17 papers) and Environmental Science (16 papers) underscores a growing concern for the environmental impact of UAV delivery. Research in these areas might assess energy consumption of UAVs (Golinska-Dawson & Sethanan, 2023), and strategies to minimize the environmental footprint (Babjak & Yung, 2024; Figliozzi, 2017; Jiang et al., 2019) of this technology. Finally, the presence of Business, Management, and Accounting (12 papers) highlights the importance of exploring the business case for UAV delivery. This research could analyse return on investment, warehouse layout optimization, and performance metrics to evaluate the economic viability of UAV delivery for different companies and industries.

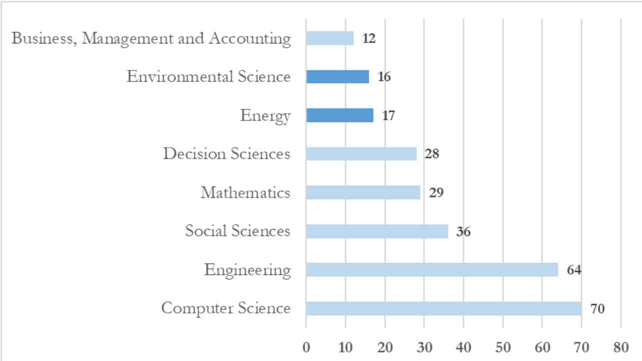

Figure 4 Most widespread subject areas among the selected articles.

Considering the productivity of the authors within present analysis, Figure reveals an interesting trend, in fact several authors stand out for their significant contributions. Five authors (Bruni M.E., Khodaparasti S., Li X., Liu X., and Xu J.) have each published four papers within the dataset. This suggests they are actively engaged in this field and likely shaping the current research landscape. Analysing the research areas of these authors highlights the presence of themes common to all of them: computer science, decision sciences, and engineering. This reinforces the multidisciplinary nature of UAV delivery research, where technical expertise converges with optimization strategies and considerations for societal impact.

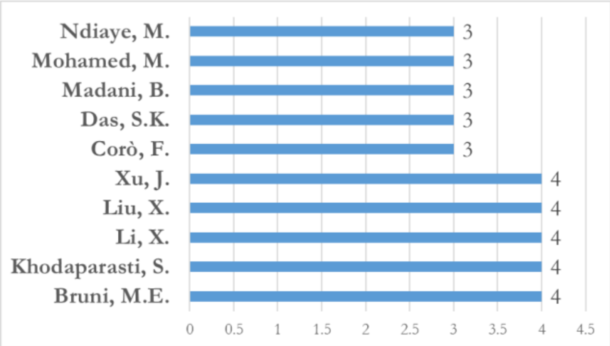

Figure 5 Classification of authors with at least 3 publications.

The analysis of subject areas (Figure 4) and journal classification with at least 2 publications (Table 2) offers insights into the research landscape of UAV delivery in LML. The prominence of Transportation Research Part D (8 papers) aligns with the presence of Social Sciences (36 papers) and Environmental Science as subject areas. This highlights research exploring the social and environmental implications of UAV delivery, perfectly aligned with a journal focused on the interaction between transportation and the environment. Similarly, the presence of Energies (5 papers) as a top journal aligns with the subject area of Energy. This reinforces the focus on understanding and minimizing the energy consumption of UAVs in LML.

Table 2 Classification of journal with at least 2 publications.

Sustainability Switzerland	8
Transportation Research Part C Emerging Technologies	8
Drones	6
Energies	4
Transportation Research Part D Transport And Environment	4
Computers And Industrial Engineering	3
IEEE Access	3
Lecture Notes In Computer Science Including Subseries Lecture Notes In Artificial Intelligence And Lecture Notes In Bioinformatics	3
Lecture Notes In Networks And Systems	3
ACM International Conference Proceeding Series	2

Furthermore, the presence of the journal UAVs (6 papers) aligns with the high presence of Engineering and Computer Science, 64 and 70 occurrences respectively within subject areas. This reinforces the focus on developing and optimizing UAV technology for efficient and environmentally conscious operations. Journals like Transportation Research Part C explore the integration of UAVs into existing transportation systems, potentially aligning with research that have Decision Sciences and Mathematics as subject areas. These subject areas could contribute to optimizing UAV delivery routes and resource allocation within transportation networks. Overall, the combined analysis reveals a multidisciplinary research effort focused on the environmental and technological aspects of UAV delivery.

Considering the geographic distribution of articles (Figure), China and United States lead in the number of publications on the subject, followed by Italy. This may indicate strong interest and active research within these countries on how UAVs can be used to optimize delivery operations and reduce environmental impact in the context of LML. The numbers may also reflect the size of the academic and research community, the availability of research funding, or the priority given to this specific area of study in each country. Indeed, China is a global leader in the use and development of UAV technology for delivery purposes. For example, JD.com, a Chinese e-commerce giant, has initiated UAV delivery operations in various Chinese provinces (Meng et al., 2023). In the United States, companies like Amazon and Google's Wing project are actively exploring UAV delivery (Prathibha Rajashekhar, 2023). In Italy, research on UAVs is promoted by both academic institutions and private companies. For instance, Politecnico di Milano has conducted studies on the use of UAVs in urban logistics, as cited by (Borghetti et al., 2022). Companies like Poste Italiane have begun experimenting with UAV delivery in collaboration with Leonardo, an Italian company leader in high technology in defence, aerospace, and security, for the delivery of mail and packages in some remote areas (Corriere Adriatico, 2023). This global interest in UAV technology in LML signals a broader trend towards innovative, sustainable, and efficient delivery methods. Academic efforts, as well as public-private partnerships, are crucial for advancing UAV applications, addressing challenges such as safety, regulatory compliance, and public acceptance, and contributing to the reduction of carbon emissions in the supply chain.

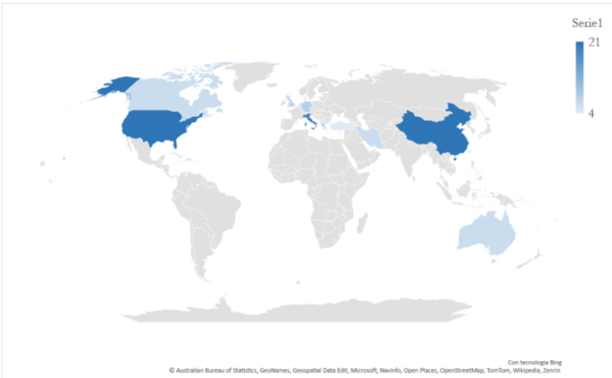

Figure 6 Geographical distribution of papers.

4. Network Analysis

A network analysis was also performed on the articles selected, starting from the analysis of the cooperation among researchers, with a focus on the most prevalent form of collaboration, namely co-authorship. To achieve this objective, the open-source text-mining tool 'VOSviewer' was employed to develop bibliometric maps. VOSviewer assesses the frequency of publications where two or more authors appear together; a higher count of co-authored articles indicates a greater level of cooperation between the respective authors. Given the relatively modest size of the reviewed article database, the 'full counting' method was selected, with a minimum requirement of three documents authored by an individual. Consequently, out of 378 authors, 9 meet the specified criteria. Based on the obtained results, five clusters are proposed:

- Cluster 1 (3 items): Liu Xiao, Li Xuejun, Xu Jia.
- Cluster 2 (3 items): Corò Federico, Pinotti Cristina M.
- Cluster 3 (2 items): Bruni Maria Elena, Khodaparasti Sara.
- Cluster 4 (1 item): Mohamed Moataz.
- Cluster 5 (1 item): Madani Batool M.

While the first three cluster exhibit stable cooperation, both the remaining clusters consist of a single author, meaning that the researcher has one-time collaborations with different authors. Notably, there is a lack of connection between the clusters, indicating limited collaboration among them in this field.

The following step of the network analysis focused on the co-occurrences among the keywords of the articles under review. All types of keywords were considered, employing the full counting method, and selecting keywords with at least 8 occurrences. Three clusters were created, and the network is illustrated in **Errore. L'origine riferimento non è stata trovata.**.

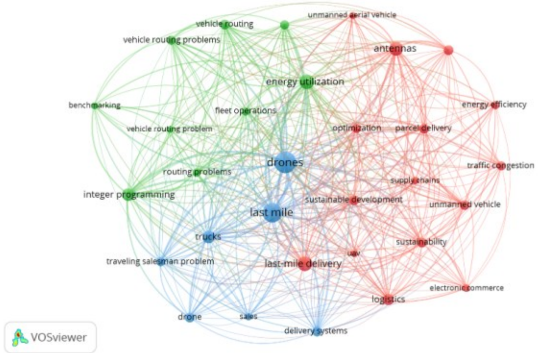

Figure 7 Key-words co-occurrence network.

Analysing Cluster 1 and 3 and the connections between them, a focus about Delivery optimization stands out. These clusters combine items related to delivery systems (trucks, drones), last mile delivery, parcel delivery, logistics, and optimization techniques (routing problems, traveling salesman problem, integer programming) suggesting a focus on optimizing delivery routes and strategies for various delivery methods (trucks-drones combination) in the context of LML. Cluster 2 encompasses terms related to fleet operations management, vehicle routing problems, benchmarking, and energy efficiency/consumption. This cluster highlights the importance of managing delivery fleets for efficiency, including energy usage and route planning.

Therefore, analyzing the connections between these three clusters, two key areas of interest can be defined:

1. Delivery Optimization: Optimizing delivery routes and strategies for various delivery methods (trucks, drones) in the context of LML. Techniques like routing problems and optimization algorithms are employed for efficient delivery planning.
2. Fleet Management and Efficiency: Highlighting the importance of managing delivery fleets for efficiency, including aspects like vehicle routing, energy usage, and benchmarking performance against industry standards.

Finally, the corpus of titles and abstracts were analysed to examine how the most recurring words appear among the articles within this corpus. For this analysis, the full counting method was employed, considering only words that were repeated at least 15 times. Terms deemed by the authors to be uninteresting or too vague were manually excluded (namely: application, approach, challenge, city, number, paper, recent year, research, result, solution, term, and work). From this analysis, the four clusters shown in Figure 8 were obtained.

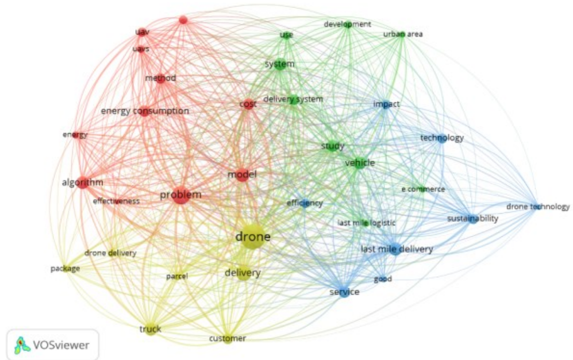

Figure 81 Network of the most common terms between titles and abstracts.

Cluster 1 (in red) predominantly focuses on the technical and operational aspects of unmanned aerial vehicles (UAVs). Keywords such as "algorithm," "method," and "model" indicate a strong emphasis on the computational and methodological frameworks used in UAV research. The presence of terms like "cost," "effectiveness," and "energy consumption" suggests an interest in the efficiency and economic viability of UAV systems. This cluster highlights the core technological innovations and challenges faced in UAV deployment. The second cluster (in green) centres around the application of UAVs in delivery and logistics, particularly in urban settings. Keywords such as "delivery systems," "last mile logistic," and "urban area" indicate a focus on the integration of UAVs into the existing logistics infrastructure. The term "e-commerce" underscores the growing importance of UAVs in modern retail and consumer delivery services. This cluster reflects research aimed at optimizing the use of UAVs to enhance delivery efficiency and system development. Cluster three (in blue) merges technological advancements with their practical impacts and sustainability. Keywords like "drone technology," "efficiency," and "sustainability" suggest an exploration of how UAVs can be leveraged to improve service delivery while minimizing environmental impact. The inclusion of "last mile delivery" indicates a focus on the final segment of the delivery process, which is crucial for overall logistics efficiency. This cluster encapsulates research that balances technological progress with service quality and sustainability concerns. The fourth cluster (in yellow) is oriented towards the end-user experience and the practical aspects of UAV delivery. Keywords such as "customer," "delivery," and "drone delivery" highlight the consumer-facing side of UAV applications. Terms like "package," "parcel," and "truck" indicate an interest in the operational logistics of integrating UAVs with traditional delivery methods. This cluster reflects research on improving customer satisfaction and streamlining the delivery process through the use of UAVs. Analysing **Errore. L'origine riferimento non è stata trovata.** there are notable connections between clusters, particularly between Cluster 1 and Cluster 3, where technological and methodological innovations intersect with practical applications and sustainability considerations. For example, advancements in algorithms and models (Cluster 1) directly influence the efficiency and impact of UAV technology (Cluster 3). Finally, each cluster exhibits strong internal cohesion, with tightly connected keywords reflecting focused research areas. For instance, Cluster 2's emphasis on urban logistics and e-commerce underscores a concentrated effort to address specific challenges in LML using UAVs.

5. Discussion

The present analysis reveals a dynamic field with a focus on optimizing UAV delivery for efficiency and sustainability. The research areas explored in selected papers further highlight the multifaceted nature of UAV delivery, encompassing technical challenges, environmental considerations, and real-world implementation issues. The increase of publications from 2017 to 2023 underscores the growing academic and industry interest in leveraging UAVs for efficient and environmentally friendly delivery solutions. The bibliometric analysis highlights the interdisciplinary nature of this research, with significant contributions from computer science and engineering, focusing on route optimization, autonomous navigation, and UAV design. Furthermore, the inclusion of social sciences in this body of work reflects a recognition of the societal implications of UAV delivery, such as privacy concerns and regulatory challenges. The findings suggest that while technological advancements are pivotal, the successful deployment of UAVs in urban logistics hinges on addressing environmental and societal factors. The clusters identified in the keyword analysis—ranging from technical methodologies to practical applications and consumer-facing aspects—demonstrate the broad scope of research aimed at optimizing delivery systems while minimizing ecological impact. This holistic approach is essential for developing sustainable LML solutions that not only enhance efficiency but also align with broader environmental goals. Notably, the leading research contributions from China and the United States highlight the global momentum towards innovative delivery methods, driven by significant investments in technology and public-private partnerships. These efforts are pivotal in overcoming barriers such as regulatory compliance and public acceptance, thereby paving the way for widespread adoption of UAV technology in logistics. Despite these advancements, the potential environmental benefits and drawbacks of UAVs in LML require a more detailed examination. UAVs can significantly reduce greenhouse gas emissions and traffic congestion compared to traditional delivery methods. However, issues such as energy consumption, battery disposal, and noise pollution present challenges that need further exploration. Future research should investigate these environmental impacts in greater depth to provide a balanced understanding of UAV deployment. As the field continues to evolve, future research should focus on synthesizing existing knowledge, addressing data gaps, and exploring new avenues for integrating UAVs into the complex urban logistics network. Specifically, there is a need for studies that incorporate content analysis and a broader range of sources, including industry reports and practical applications, to gain a more comprehensive understanding of UAV delivery systems. Moreover, recommendations for future research include examining the lifecycle environmental impacts of UAVs, exploring alternative energy sources, and developing frameworks for regulatory and public acceptance.

This study faces several limitations. Firstly, the bibliometric analysis focuses on quantitative metrics such as publication counts and keyword frequencies but does not analyse the actual content of the papers. This approach can overlook nuanced insights and the depth of research findings. Additionally, the study primarily examines academic publications, potentially missing valuable information from industry reports and practical applications that are not covered in scholarly literature. These limitations suggest the need for future research to incorporate content analysis and a broader range of sources to gain a more comprehensive understanding of UAV delivery systems.

6. Conclusions

In conclusion, the integration of UAVs in LML represents a dynamic and rapidly evolving field characterized by significant technological advancements and interdisciplinary research efforts. The upward trend in academic publications reflects the growing recognition of UAVs as a viable solution for enhancing delivery efficiency and sustainability. However, the successful implementation of UAV delivery systems requires addressing environmental concerns, societal impacts, and regulatory hurdles. Continued research and collaboration between academia, industry, and policymakers are essential to fully realize the potential of UAVs in transforming LML and achieving sustainable urban delivery solutions.

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