

Energy-Efficient UAV-Enabled Systems for Sustainable Port Logistics: A Bibliometric and Systematic Review

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Abstract

Ports are critical nodes in global supply chains and increasingly depend on intelligent, energy-efficient, and autonomous technologies to improve operational performance and sustainability. Within this context, unmanned aerial vehicles (UAVs) are evolving from isolated aerial platforms into network-enabled systems capable of supporting sensing, communication, computation, and decision-support functions. This study examines the evolution of energy-efficient UAV-enabled systems for sustainable port logistics, with particular emphasis on autonomous system architectures, mobile edge computing, artificial intelligence, optimisation, and Internet of Things integration. Following PRISMA 2020 reporting guidelines, a bibliometric and systematic review was conducted based on a curated dataset of 49 peer-reviewed publications indexed in Scopus between 2001 and 2026. The analysis combines performance indicators with science mapping techniques, including bibliographic coupling and keyword co-occurrence, to identify research trends, influential contributions, and thematic structures. The results reveal a transition from fragmented exploratory studies to a rapidly expanding research field shaped by UAV-assisted edge computing, resource allocation, intelligent optimisation, and energy-aware system design. Four main thematic clusters are identified: UAV-assisted mobile edge computing and network optimisation; advanced optimisation and intelligent UAV systems; energy efficiency and resource allocation; and application-oriented developments and hardware innovations. The findings indicate that energy efficiency is the central design principle connecting UAV autonomy, system integration, and sustainability-oriented port logistics.



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1. Introduction

Recent advances in unmanned aerial vehicles (UAVs) have reinforced their role as energy-aware, autonomous, and intelligent electronic systems capable of integrating sensing, communication, computation, and decision-support functionalities. A recurring theme in the literature is the transition of UAVs from isolated operational tools to interconnected

components of broader cyber-physical systems, enabling real-time optimisation and adaptive system performance in dynamic environments [1,2].

Within this context, energy efficiency and resource management emerge as central design constraints in UAV-enabled systems. The limited onboard energy capacity requires the optimisation of multiple interdependent processes, including trajectory planning, communication, sensing, computation, and data transmission. This challenge becomes particularly relevant in data-intensive and latency-sensitive environments, where trade-offs between computational demand, communication performance, and energy consumption must be carefully balanced [3,4]. Consequently, optimisation techniques supported by artificial intelligence are increasingly adopted to enhance system-level efficiency, particularly in task allocation, communication scheduling, trajectory design, and adaptive control [2,5].

Simultaneously, the integration of UAVs within distributed computational architectures has gained significant attention. Mobile edge computing (MEC), in particular, enables UAVs to operate as aerial nodes within networked systems, supporting computation offloading, latency reduction, and real-time data processing in resource-constrained environments [4,5]. This architectural perspective reflects a broader shift towards energy-efficient, network-aware, and intelligent UAV systems capable of operating within complex and distributed infrastructures.

In parallel, application-oriented studies demonstrate the versatility of UAV-enabled systems in supporting sustainability-related functions, including environmental monitoring, carbon-emission monitoring, climate data acquisition, infrastructure inspection, and precision resource management [6,7]. These applications rely on the ability of UAVs to provide high-resolution and near-real-time data, thereby enhancing situational awareness and supporting informed decision-making in complex operational contexts.

Moreover, the literature indicates a growing convergence between UAV technologies and advanced computational paradigms, including autonomous control systems, secure communication protocols, digital twins, edge intelligence, and emerging computing architectures such as in-memory computing and distributed intelligence [8,9]. This trend reflects a broader transition towards scalable, adaptive, and resilient system architectures capable of operating under uncertainty while maintaining system reliability, computational efficiency, and data integrity.

Despite these advances, the research landscape remains fragmented across multiple disciplines, including robotics, communication systems, embedded electronics, environmental science, artificial intelligence, and logistics. Existing studies predominantly address isolated components, such as optimisation models, communication frameworks, sensing applications, or energy-efficient hardware, without systematically consolidating these elements into coherent UAV-enabled system architectures [10,11].

This fragmentation is particularly relevant in the context of maritime and port logistics environments. Ports are increasingly required to improve operational efficiency, environmental performance, safety, and digital integration, while managing complex flows of vessels, cargo, infrastructure, vehicles, and data. Although UAV technologies have been increasingly explored in areas such as monitoring, optimisation, communication, and environmental sensing, there is still limited synthesis of how these capabilities can be understood as part of integrated, energy-efficient, and intelligent systems for sustainable port logistics.

As a result, the literature lacks a structured understanding of how UAV-enabled technologies have evolved across interconnected dimensions of energy efficiency, autonomous system design, optimisation, edge computing, artificial intelligence, and sustainability-oriented applications. This gap is especially relevant for port logistics, where UAVs are not merely aerial platforms, but potential components of broader digital

infrastructures supporting real-time monitoring, decision support, risk reduction, and environmental management.

For port logistics, this research gap is not only conceptual but also operational. Port environments involve heterogeneous and interdependent activities, including vessel traffic, cargo handling, terminal yard operations, infrastructure inspection, environmental monitoring, safety control, and data exchange between multiple stakeholders. In these contexts, UAVs can only generate practical value when their sensing, communication, computation, and decision-support capabilities are connected to specific operational requirements. Therefore, the link between energy-efficient UAV-enabled systems and sustainable port logistics depends on understanding how technical developments such as mobile edge computing, artificial intelligence, optimisation, IoT integration, and autonomous control can support concrete port functions while reducing energy consumption, improving situational awareness, and strengthening environmental and operational performance.

To address this gap, this study provides a bibliometric and systematic review of energy-efficient UAV-enabled systems for sustainable port logistics. Unlike prior studies that examine isolated technological aspects, this work integrates multiple research streams, including mobile edge computing, artificial intelligence, optimisation techniques, IoT-enabled infrastructures, and sustainability-oriented applications, into a unified analytical framework.

Accordingly, this study addresses the following research question: How have UAV technologies evolved as energy-efficient, autonomous, and intelligent systems for sustainable port logistics, and what research trends and thematic structures define this field?

The main contribution of this study is threefold. First, it provides a structured overview of the temporal evolution, citation impact, and publication patterns of research on UAV-enabled systems. Second, it identifies the most influential contributions and thematic clusters shaping the field, with particular attention to energy efficiency, edge computing, optimisation, and intelligent system integration. Third, it discusses the implications of these developments for sustainable port logistics, highlighting current limitations and future research directions for integrated, energy-aware UAV-enabled architectures.

This article is structured as follows. Section 2 presents the materials and methods, detailing the systematic review procedures, the Scopus-based data collection process, and the bibliometric approach applied in the study. Section 3 reports the main results, including the analysis of scientific production, citation impact, influential contributions, geographical distribution, contributing authors, and thematic clusters. Section 4 discusses the findings, with particular emphasis on their implications for energy efficiency, autonomous UAV systems, intelligent infrastructures, and sustainable port logistics. Section 5 concludes the study by summarising the main findings, outlining limitations, and proposing directions for future research.

2. Materials and Methods

This study adopts a bibliometric and systematic literature review (SLR) approach to examine the evolution, intellectual structure, and thematic development of energy-efficient UAV-enabled systems for sustainable port logistics. The methodological design combines performance analysis and science mapping techniques, following established bibliometric procedures for identifying publication trends, influential contributions, conceptual structures, and emerging research themes [12–14].

The review was conducted using the Scopus database as the primary source of bibliographic records. Scopus was selected because of its broad coverage of peer-reviewed literature in engineering, computer science, electronics, transportation, environmental sciences, business, and applied technology fields [15,16]. This coverage is particularly relevant for the present study, given the interdisciplinary nature of UAV-enabled systems,

which combine autonomous platforms, energy efficiency, communication networks, mobile edge computing, artificial intelligence, digital transformation, and sustainability-oriented applications. The use of a single database also ensured consistency in metadata extraction, document classification, citation data processing, and bibliometric mapping. Nevertheless, the exclusion of other databases, such as Web of Science and IEEE Xplore, is acknowledged as a methodological limitation and is further discussed in the limitations section. This systematic review was conducted in accordance with the PRISMA 2020 reporting guidelines. The review protocol was not registered in PROSPERO or another public registry, as the study does not fall within the health or social care scope typically covered by PROSPERO and data extraction had already been completed at the time of manuscript preparation. No formal protocol was prepared prior to the review. The study selection process is reported through a PRISMA 2020 flow diagram, detailing the identification, screening, eligibility assessment, and inclusion process [17].

The search strategy was designed to retrieve studies addressing the intersection between UAV technologies, sustainable port logistics, environmental performance, operational efficiency, and digital transformation. The search was applied to titles, abstracts, and author keywords. The search string combined terms related to unmanned aerial vehicles, drones, autonomous aerial systems, port logistics, maritime logistics, port operations, terminal operations, sustainability, environmental impact, carbon emissions, decarbonisation, green logistics, energy efficiency, operational efficiency, performance, productivity, Industry 4.0, digital transformation, smart logistics, IoT, digital twins, and cyber-physical systems. The complete search string is presented below:

TITLE-ABS-KEY ("Unmanned Aerial Vehicle*" OR UAV OR UAS OR drone* OR "autonomous aerial system*" OR "aerial robotics") AND TITLE-ABS-KEY ("port logistics" OR "maritime logistics" OR port* OR harbor OR harbour OR "maritime transport" OR "shipping logistics" OR "smart port*" OR "port operation*" OR "terminal operation*") AND TITLE-ABS-KEY (sustainab* OR "environmental impact" OR "carbon emission*" OR decarbonization OR "green logistics" OR "energy efficiency") AND TITLE-ABS-KEY ("operational efficiency" OR performance OR productivity OR "Industry 4.0" OR "digital transformation" OR "smart logistics" OR "IoT" OR "Internet of Things" OR "digital twin*" OR "cyber-physical system*") AND (LIMIT-TO (LANGUAGE, "English")) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "cp")) AND (LIMIT-TO (SUBJAREA, "ENGI") OR LIMIT-TO (SUBJAREA, "COMP") OR LIMIT-TO (SUBJAREA, "SOCI") OR LIMIT-TO (SUBJAREA, "ENVI") OR LIMIT-TO (SUBJAREA, "BUSI") OR LIMIT-TO (SUBJAREA, "MULT") OR LIMIT-TO (SUBJAREA, "ECON")) AND (LIMIT-TO (SRCTYPE, "j") OR LIMIT-TO (SRCTYPE, "p")).

The updated search was conducted in Scopus on 26 May 2026. At the time of data extraction, the search returned 88 bibliographic records. The records were exported from Scopus in RIS format and screened to verify their relevance to the research scope. Because Scopus is a continuously updated database, subsequent replications of the same search string may retrieve additional records indexed after the extraction date. Therefore, the dataset used in this study reflects the bibliographic coverage available at the time of data collection.

The screening process considered the title, abstract, keywords, source type, and thematic alignment with the study objectives. Studies were retained when they addressed at least one of the following dimensions: UAV-enabled systems, energy efficiency, autonomous or intelligent system architectures, edge or distributed computing, optimisation, IoT-enabled infrastructures, sustainability-oriented monitoring, or logistics and port-related applications.

The inclusion criteria were defined as follows: peer-reviewed journal articles or conference papers indexed in Scopus; publications written in English; studies addressing UAVs, unmanned aerial systems, autonomous aerial systems, or drone-enabled technologies;

and studies with relevance to port logistics, maritime logistics, port operations, terminal operations, energy efficiency, sustainability, environmental performance, operational efficiency, digital transformation, smart logistics, IoT, digital twins, or cyber-physical systems. The exclusion criteria were review papers, editorials, book chapters, non-peer-reviewed documents, records without sufficient bibliographic information, studies outside the technological or application scope of the review, and studies without a clear connection to UAV-enabled sustainable port logistics.

No automation tools were used to exclude records. All screening and eligibility decisions were performed manually according to the predefined inclusion and exclusion criteria. The initial screening of titles, abstracts, and keywords was conducted by two authors, while the eligibility assessment of the retrieved reports was reviewed and validated by the full author team. Disagreements and borderline cases were discussed until consensus was reached. All 88 records were screened based on title, abstract, and keywords. At this stage, 25 records were excluded because they did not meet the thematic or methodological scope of the review. The remaining 63 reports were retrieved and assessed for eligibility. Following full-text eligibility assessment, 14 reports were excluded with reasons: outside the specific scope of UAV-enabled sustainable port logistics ($n = 6$), insufficient methodological or empirical relevance ($n = 3$), not focused on port, maritime logistics, or terminal management ($n = 2$), not eligible as an article or conference paper after manual verification ($n = 2$), and full text unavailable or insufficient information for extraction ($n = 1$). The final dataset consisted of 49 peer-reviewed publications published between 2001 and 2026.

To address the interdisciplinary nature of the dataset, the 49 included publications were classified according to their degree of connection with sustainable port logistics. Three analytical categories were considered: direct port and maritime logistics studies, transferable maritime or logistics-related studies, and technological foundation studies with port-logistics relevance. This classification was used to avoid treating all records as equivalent in terms of port specificity and to support a more critical interpretation of the results, as shown in Table 1.

Table 1. Classification of the included studies according to their connection with sustainable port logistics.

Analytical Category	Classification Criterion	Number of Studies	Examples from the Dataset	Role in the Review
Direct port and maritime logistics studies	Studies directly addressing ports, port infrastructure, land-side port operations, shipping, inland waterways, seaborne transport, maritime logistics, or port-related environmental monitoring	5	Port carbon-emission monitoring, inland ship MEC networks, shipping digitalisation, seaborne shipping sustainability, environmental impact in port infrastructures	Provide direct evidence on the relationship between UAV-enabled or digital technologies and port or maritime logistics contexts
Maritime, transport, environmental, infrastructure, or logistics-related transferable studies	Studies not exclusively focused on ports, but addressing maritime, transport, infrastructure, environmental monitoring, logistics, safety, or operational contexts with transferable relevance to port environments	9	Bulk handling systems, underwater communication, UAV-based air pollution monitoring, water-leak detection, drone delivery, disaster management, smart IoT environments	Support the interpretation of how UAV-enabled systems may be transferred to port logistics functions such as monitoring, inspection, safety, environmental control, and operational coordination

Table 1. Cont.

Analytical Category	Classification Criterion	Number of Studies	Examples from the Dataset	Role in the Review
Technological foundation studies with port-logistics relevance	Studies focused on UAV-enabled systems, energy efficiency, mobile edge computing, artificial intelligence, optimisation, communication networks, resource allocation, embedded systems, or energy-efficient hardware, without direct port application	35	UAV-assisted MEC, UAV trajectory planning, energy-aware resource allocation, edge computing, federated learning, UAV communication, autonomous navigation, energy-efficient onboard processing	Provide the technological basis for understanding how energy-efficient UAV-enabled architectures may support future sustainable port logistics applications

These publications formed the basis for the bibliometric and systematic analysis. The study selection process is summarised in Figure 1 using a PRISMA flow diagram [17]:

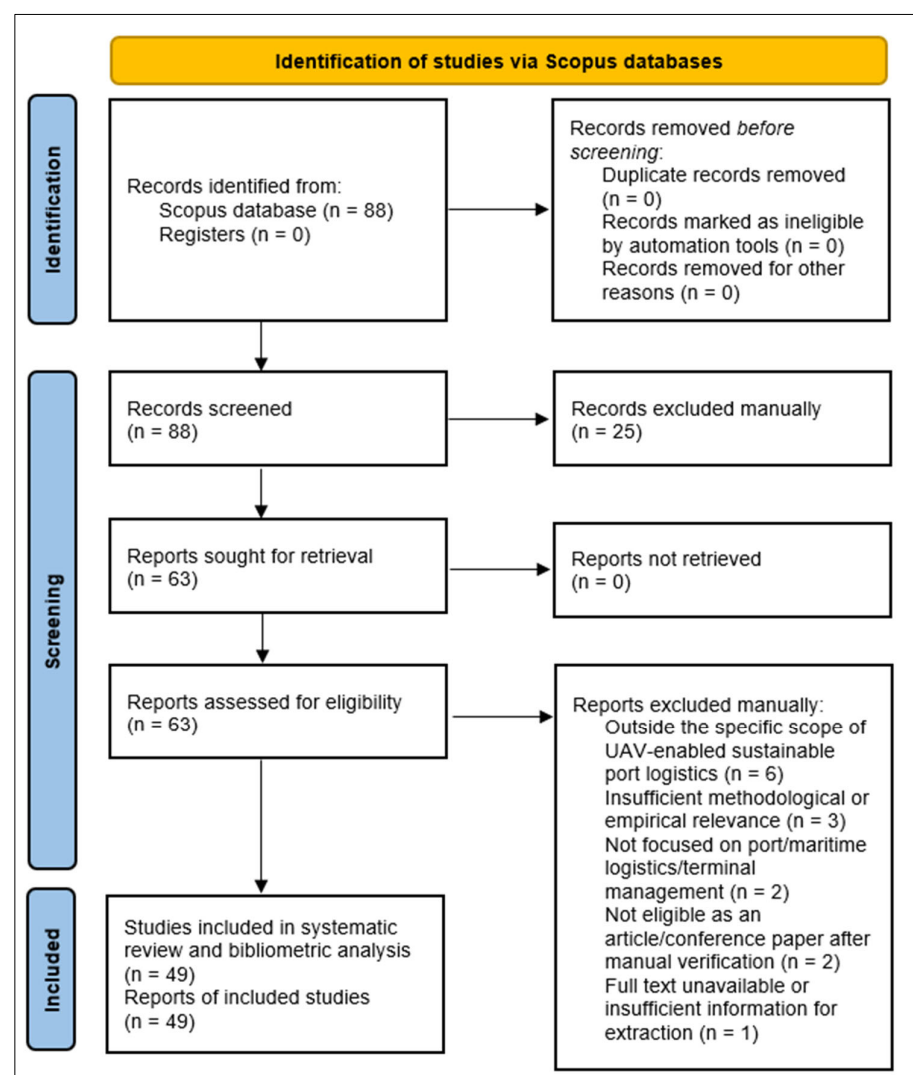


Figure 1. PRISMA 2020 flow diagram showing the identification, screening, eligibility assessment and inclusion process for the systematic review and bibliometric analysis.

Although the final dataset is relatively small, this is consistent with the emerging and interdisciplinary nature of the research field. UAV-enabled systems for sustainable port logistics remain a developing area, with relevant contributions dispersed across multiple domains, including electronics, communication systems, robotics, artificial intelligence, environmental monitoring, and logistics. Therefore, the dataset is appropriate for a structured bibliometric and systematic review aimed at identifying early patterns, thematic clusters, and research gaps.

The analytical procedure was organised into two complementary stages. For each included publication, bibliographic and thematic information was extracted and organised in a structured dataset. The extracted data were organised, manually checked, and analysed using Microsoft Excel for Microsoft 365 (Microsoft Corporation, Redmond, WA, USA). The extracted information included authors, year of publication, source title, publisher, country or affiliation information when available, citation count, document type, keywords, abstract content, technological focus, application domain, and relevance to sustainable port logistics. The extracted data supported both the descriptive bibliometric analysis and the qualitative interpretation of technological and application-oriented themes. This procedure allowed the review to combine quantitative indicators with a systematic reading of the selected publications.

First, a performance analysis was conducted to examine the temporal distribution of publications, citation impact, influential contributions, publication sources, publishers, countries, and authors. This stage provided a quantitative overview of the development and scholarly influence of the field.

Second, science mapping techniques were applied to explore the intellectual and conceptual structure of the dataset. Bibliographic coupling was used to identify groups of publications sharing common reference patterns, thereby revealing conceptual proximity between studies. Keyword co-occurrence analysis was also performed to map the semantic structure of the field and identify dominant and emerging research themes.

The bibliometric analysis was supported by VOSviewer version 1.6.20 (Centre for Science and Technology Studies, Leiden University, Leiden, The Netherlands) [13,14], which was used to generate network, overlay, and density visualisations. Network visualisation enabled the identification of thematic clusters; overlay visualisation supported the interpretation of temporal trends; and density visualisation highlighted areas of stronger research concentration. The interpretation of the results combined quantitative bibliometric indicators with qualitative reading of the selected publications, allowing the analysis to move beyond descriptive metrics and identify the main technological and application-oriented directions of the field.

Given the bibliometric and systematic review design of this study, no meta-analysis was performed. Therefore, no effect measures, statistical heterogeneity assessment, sensitivity analysis, reporting bias assessment, or certainty assessment were applied. Similarly, no risk-of-bias assessment of intervention effects was conducted, as the review does not evaluate clinical, experimental, or intervention-based outcomes. Instead, the analysis focused on bibliometric performance indicators, science mapping, and thematic synthesis of the selected literature.

Use of Generative Artificial Intelligence

During the preparation of this manuscript, ChatGPT, version GPT-5.5 (OpenAI, San Francisco, CA, USA), was used to support language refinement, preliminary organisation of analytical categories, and editorial consistency. The tool was not used to generate the dataset, conduct the Scopus search, select the publications, perform the bibliometric analysis, or independently interpret the results. All methodological decisions, data analy-

sis, interpretation, critical review, and final manuscript preparation were conducted and validated by the authors.

Overall, this methodological framework ensures a transparent and reproducible review process. By combining systematic screening, performance analysis, and science mapping, the study provides a structured basis for understanding how energy-efficient UAV-enabled systems have evolved and how they may support sustainable port logistics through autonomous, intelligent, and integrated technological architectures.

3. Results

The final dataset comprised 49 peer-reviewed publications indexed in Scopus and published between 2001 and 2026. These studies were analysed to identify publication trends, citation impact, influential contributions, publication sources, geographic distribution, contributing authors, and thematic structures. The findings are organised according to the main analytical dimensions of the study: temporal evolution of scientific production and citation impact, influential publications, publication sources and publisher-level distribution, geographical distribution, key contributing authors, bibliographic coupling, and keyword co-occurrence analysis.

The results are reported through a combination of descriptive indicators, tables, and science mapping visualisations. This structure enables the identification of publication patterns, citation dynamics, thematic clusters, and emerging research trends in energy-efficient UAV-enabled systems for sustainable port logistics. The interpretation remains focused on the evidence derived from the selected dataset and provides the empirical basis for the discussion presented in Section 4.

Before presenting the bibliometric and thematic results, the dataset should be interpreted according to the classification introduced in Table 1. The 49 included publications do not form a homogeneous set of direct port-logistics studies. Instead, they combine direct port and maritime logistics evidence, transferable studies from related maritime, transport, environmental, infrastructure, and logistics contexts, and technological foundation studies on UAV-enabled systems, energy efficiency, mobile edge computing, artificial intelligence, communication networks, resource allocation, and energy-efficient hardware. Therefore, the results are not interpreted as evidence that all identified technological developments have already been implemented in ports. Rather, they indicate how the knowledge base required for future energy-efficient UAV applications in port logistics is evolving across related research domains.

3.1. Temporal Evolution of Scientific Production and Citation Impact

Figure 2 presents the temporal evolution of scientific production and citation impact in the final dataset between 2001 and 2026. The figure combines the annual number of publications with the corresponding citation counts, allowing a comparative assessment of knowledge production and scholarly influence within the field.

The results indicate an uneven but clearly evolving trajectory. During the period between 2001 and 2018, scientific production remained limited and sporadic, with only isolated contributions and low citation impact. This pattern suggests that the field was still in an exploratory stage, with limited consolidation around UAV-enabled systems, energy efficiency, and sustainable logistics applications.

A more visible expansion can be observed from 2019 onwards. Between 2019 and 2023, the number of publications increased gradually, while citation impact became more concentrated. In particular, 2022 recorded the highest citation count, with 251 citations, followed by 2023, with 216 citations. This indicates that studies published during this period had a significant role in shaping the intellectual development of the field, especially

in areas related to UAV-assisted mobile edge computing, resource allocation, environmental monitoring, and intelligent system optimisation [4,18–20].

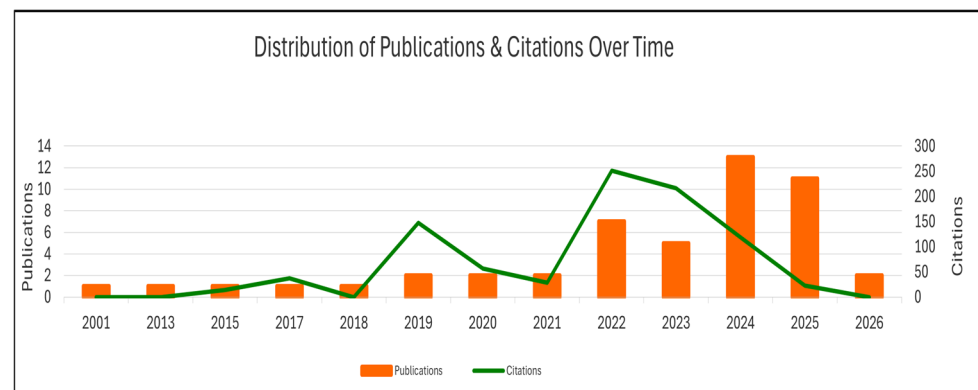


Figure 2. Annual scientific production and citation counts in the reviewed dataset from 2001 to 2026.

From 2024 onwards, the dataset shows a clear increase in publication volume, with 13 publications in 2024 and 11 publications in 2025. However, citation counts decrease substantially in comparison with 2022 and 2023, with 119 citations in 2024 and 23 citations in 2025. This difference is consistent with the recency of these publications, which have had less time to accumulate citations. Therefore, the lower citation impact of the most recent publications should not be interpreted as lower relevance, but rather as a temporal limitation inherent to citation-based indicators.

Overall, the temporal distribution reveals a transition from a fragmented and low-volume research landscape to a rapidly expanding field. The citation peak observed in 2022 and 2023 suggests the presence of influential contributions related to edge-enabled UAV systems, energy-efficient resource management, and sustainability-oriented applications [18–21]. At the same time, the increase in publications from 2024 onwards indicates growing academic attention to autonomous, intelligent, and optimisation-driven UAV-enabled systems, although the long-term scholarly impact of these recent studies remains to be observed [1,2,22–24].

This temporal pattern suggests that the field is still in transition. Earlier contributions provided foundations in energy-efficient computation, sensing, and autonomous navigation [25–27]. More recent studies expand this basis towards UAV-assisted edge computing, resource management, intelligent system design, and sustainability-oriented applications [18,20,22,23]. For port logistics, this progression is relevant because UAV applications require the combination of aerial sensing, reliable communication, real-time processing, energy-aware operation, and decision support [6,11,21]. However, the results also show that direct application to port logistics remains recent. The publication trend should therefore be read as evidence of growing technological readiness and research convergence, not as evidence of widespread operational deployment in ports.

3.2. Most Influential Publications Based on Citation Impact

Table 2 presents the most influential publications in the dataset, ranked according to citation impact. The table includes studies that have contributed significantly to the development of research on UAV-enabled systems, energy efficiency, mobile edge computing, optimisation, environmental monitoring, and intelligent infrastructures. Publications with at least 10 citations are reported.

Table 2. Most influential publications in the dataset based on citation impact.

Authors	Year	Cited by
Suleiman A.; Zhang Z.; Carlone L.; Karaman S.; Sze V. [25].	2019	142
Ei N.N.; Alsenwi M.; Tun Y.K.; Han Z.; Hong C.S. [18]	2022	107
Oloruntobi O.; Mokhtar K.; Gohari A.; Asif S.; Chuah L.F. [21]	2023	91
Motlagh N.H.; Kortoci P.; Su X.; Loven L.; Hoel H.K.; Haugsvaer S.B.; Srivastava V.; Gulbrandsen C.F.; Nurmi P.; Tarkoma S. [19]	2023	82
Ai Q.; Qiao X.; Liao Y.; Yu Q. [4]	2022	57
Xiao Z.; Chen Y.; Jiang H.; Hu Z.; Lui J.C.S.; Min G.; Dustdar S. [20]	2022	46
Michailidis E.T.; Volakaki M.-G.; Miridakis N.I.; Vouyioukas D. [22]	2024	40
Suleiman A.; Chen Y.-H.; Emer J.; Sze V. [26]	2017	37
Gul O.M.; Erkmén A.M. [27]	2020	32
Wang W.; Lv Z.; Lu X.; Zhang Y.; Xiao L. [28]	2021	28
Musci M.A.; Persello C.; Lingua A.M. [29]	2020	25
Ebrahimi Z.; Zaid M.; Wijtvliet M.; Kumar A. [30]	2023	22
Ibraiwish H.; Eltokhey M.W.; Alouini M.-S. [2]	2024	20
Krapez J.-C.; Muñoz J.S.; Mazel C.; Chatelard C.; Déliot P.; Frédéric Y.-M.; Barillot P.; Hélias F.; Polo J.B.; Olichon V.; Serra G.; Brignolles C.; Carvalho A.; Carreira D.; Oliveira A.; Alves E.; Fortunato A.B.; Azevedo A.; Benetazzo P.; Bertoni A.; Goff I.L. [31]	2022	18
Li J.; Shi Y.; Dai C.; Yi C.; Yang Y.; Zhai X.; Zhu K. [23]	2025	16
Al-Naeem M.; Hafizur Rahman M.M.; Banerjee A.; Sufian A. [32]	2023	14
Haidar A.; Tomov S.; Luszczek P.; Dongarra J. [33]	2015	14
Jamshed M.A.; Ayaz F.; Kaushik A.; Fischione C.; Ur-Rehman M. [24]	2024	12
Putra R.V.W.; Marchisio A.; Shafique M. [1]	2024	11
Liu W.; Sun X. [34]	2022	11

The citation distribution reveals a strong concentration of scholarly influence in a limited number of publications, particularly those published between 2019 and 2023. This pattern is consistent with the temporal results presented in Section 3.1, where the highest citation impact was observed in 2022 and 2023.

The most cited contribution is the study by Suleiman et al. [25], which focuses on an energy-efficient visual-inertial odometry accelerator for autonomous navigation in nano-drones. This work is particularly relevant because it addresses the relationship between onboard computation, energy consumption, and autonomous navigation, which represents a foundational challenge for energy-constrained UAV systems.

A second group of highly cited studies is associated with UAV-assisted mobile edge computing, resource allocation, and communication efficiency. Ei et al. [18] examine energy-efficient resource allocation in multi-UAV-assisted edge computing systems, while Ai et al. [4] address joint optimisation of communication and computation resources in wireless inland ship MEC networks. Xiao et al. [20] also contribute to this stream by reviewing resource management challenges in UAV-assisted MEC systems. Together, these studies indicate the growing relevance of UAVs as aerial nodes within distributed and edge-enabled computational infrastructures.

Another important group of publications relates to sustainability-oriented and environmental applications. Motlagh et al. [19] provide a survey of UAV-based air pollution monitoring, while Oloruntobi et al. [21] examine the sustainable transition of the seaborne shipping industry. These studies extend the relevance of UAV-enabled systems beyond technical optimisation by connecting aerial sensing, environmental monitoring, and sustainability challenges in maritime and logistics contexts.

The dataset also includes influential studies on intelligent optimisation, secure computation, and AI-enabled UAV systems. Michailidis et al. [22] address secure computation efficiency in UAV-enabled RIS-assisted MEC-IoT networks, while Ibraiwish et al. [2] inves-

tigate energy-efficient UAV deployment using particle swarm optimisation. More recent contributions, such as Li et al. [23], explore learning-based stochastic games for trajectory and task offloading optimisation in space and aerial edge computing, indicating the emergence of advanced learning-based approaches in the field.

Overall, the most influential publications indicate that the intellectual structure of the field is shaped by four main technological directions: energy-efficient UAV hardware and onboard processing, UAV-assisted edge computing and resource allocation, AI-driven optimisation, and sustainability-oriented sensing and monitoring. These directions provide the basis for the thematic cluster analysis developed in the subsequent sections.

From a port-logistics perspective, the highly cited publications should be interpreted with caution. Their influence does not necessarily derive from direct application to ports, but from their contribution to the technical foundations of energy-efficient UAV systems. Studies on onboard processing and autonomous navigation support UAV endurance, real-time sensing, and inspection capability [25,26]. Contributions on UAV-assisted mobile edge computing, resource allocation, secure computation, and task offloading explain how UAVs may operate as networked components of distributed digital infrastructures [18,20,22,23]. Other studies connect these foundations to environmental monitoring, maritime sustainability, shipping digitalisation, and port carbon-emission monitoring [6,11,19,21]. Thus, citation impact should be read as evidence of the knowledge base supporting future UAV integration in port logistics, rather than as direct evidence of mature port adoption.

From an operational port perspective, the integration of berth allocation, quay crane assignment, and preventive maintenance activities also illustrates the need for coordinated decision-support approaches [35]. In addition to citation impact, the dataset also reveals a clear conceptual and technological progression over time. While the most cited publications identify the contributions with greater scholarly influence, the chronological organisation of the studies helps to clarify how the field evolved from foundational computational efficiency towards autonomous, intelligent, and energy-aware UAV-enabled systems. Table 3 summarises this evolution by grouping the publications into four main periods according to their dominant focus, key technologies, research characteristics, and representative references.

Table 3. Conceptual and Technological Evolution of UAV-Enabled Systems in the Dataset.

Period	Dominant Focus	Key Technologies	Research Characteristics	References (IEEE)
2001–2015	Foundational computational efficiency and energy optimisation	HPC, GPGPU, embedded systems	Early studies focused on energy consumption and computational performance, with limited direct application to UAV systems Emergence of UAVs as energy-constrained platforms;	[33,36,37]
2017–2020	Integration of UAVs and energy efficiency	Embedded vision, VIO, sensor networks	emphasis on onboard processing and energy optimisation Consolidation of UAVs as network nodes; strong integration with edge computing and communication systems	[25–27,29,38,39]
2021–2023	Connected and intelligent systems	IoT, MEC, digital twins, UAV networks	Rapid expansion of the field; emphasis on autonomy, distributed intelligence, and multi-objective optimisation, with still-maturing citation impact	[4,7,10,18–21,28,30–32,34,40,41]
2024–2026	Autonomous and optimisation-driven systems	AI, DRL, federated learning, neuromorphic computing, SAGIN		[1,2,6,8,22–24,42–44]

The results presented in Table 3 indicate that the earliest period, between 2001 and 2015, was mainly associated with foundational computational efficiency and energy optimisation.

These studies focused on high-performance computing, embedded systems, and energy-performance trade-offs, with limited direct application to UAV-enabled systems.

From 2017 to 2020, the field began to incorporate UAVs more explicitly as energy-constrained autonomous platforms. Research during this period focused on embedded vision, onboard processing, autonomous navigation, sensor networks, and energy-efficient data collection. These contributions established important technological foundations for UAV systems operating under limited onboard energy capacity.

Between 2021 and 2023, the dataset shows a transition towards connected and intelligent UAV-enabled systems. During this period, UAVs were increasingly addressed as components of broader networked infrastructures, including Internet of Things, mobile edge computing, digital twins, and UAV communication networks. This stage reflects a stronger emphasis on computation offloading, resource allocation, system integration, and sustainability-oriented monitoring.

The most recent period, from 2024 to 2026, is characterised by the expansion of autonomous and optimisation-driven systems. The studies in this group place greater emphasis on artificial intelligence, deep reinforcement learning, federated learning, neuro-morphic computing, space-air-ground integrated networks, and multi-objective optimisation. Although many of these contributions are still recent and have not yet accumulated substantial citation impact, they indicate a clear movement towards adaptive, distributed, and energy-aware UAV-enabled architectures.

Overall, Table 3 complements the citation-based analysis by showing that the field has evolved through successive technological stages. The progression moves from computational efficiency and embedded systems towards UAV autonomy, network integration, intelligent optimisation, and sustainability-oriented applications. This temporal pattern provides an important basis for interpreting the thematic clusters and keyword co-occurrence structures presented in the following sections.

For port logistics, this progression has two implications. First, the literature is developing technical components that may support future UAV applications, including onboard energy efficiency, autonomous navigation, communication reliability, computation offloading, and resource management [18,20,22,23,25]. Second, the port-logistics dimension remains less mature than the underlying technological domains. Although recent studies address port carbon-emission monitoring, shipping digitalisation, and maritime sustainability [6,11,21], integrated UAV architectures validated in port operations remain limited. This reinforces the interpretation of the dataset as an emerging knowledge base, rather than as evidence of consolidated port implementation.

3.3. Publication Sources and Publisher-Level Distribution

Table 4 presents the distribution of scientific output across the publication sources represented in the final dataset. The results show a highly dispersed publication pattern, with most journals and conference proceedings contributing only one document. This dispersion indicates that research on energy-efficient UAV-enabled systems for sustainable port logistics is not yet concentrated around a limited group of specialised publication venues.

This fragmentation is consistent with the interdisciplinary nature of the field. The selected publications are distributed across areas such as electronics, communication systems, robotics, artificial intelligence, environmental monitoring, transportation, maritime systems, and logistics. As a result, UAV-enabled systems are addressed from different disciplinary perspectives, ranging from low-power hardware and autonomous navigation to mobile edge computing, sensing applications, and sustainability-oriented monitoring.

Although the distribution by publication source does not reveal a single dominant journal or conference, it confirms that the field remains in a developing stage. The absence

of a consolidated core set of publication venues suggests that the topic is still emerging at the intersection of several research communities. This is particularly relevant for sustainable port logistics, where UAV-related research remains connected to broader technological domains rather than being fully established as a specialised subfield.

Table 4. Distribution of scientific output across publication sources.

Source (Journal/Conference)	Number of Documents	Number of Citations
IEEE Open Journal of the Communications Society	2	28
IEEE Transactions on Vehicular Technology	2	23
IEEE Journal of Solid-State Circuits	1	142
IEEE Transactions on Intelligent Transportation Systems	1	107
Cleaner Engineering and Technology	1	91
IEEE Internet of Things Journal	1	82
IEEE Transactions on Green Communications and Networking	1	57
Wireless Networks	1	46
IEEE Transactions on Communications	1	40
IEEE ISCAS	1	37
Sensors (Switzerland)	1	32
Intelligent and Converged Networks	1	28
ISPRS Archives	1	25
IEEE TCAD	1	22

Given this dispersion, a publisher-level analysis was conducted to identify whether clearer concentration patterns emerge when publications are grouped under major editorial platforms. Table 5 presents the distribution of scientific output and citation impact by publisher for the 47 publications with identifiable publisher information.

Table 5. Distribution of scientific output and citation impact by publisher.

Publisher	Number of Documents	Number of Citations
Institute of Electrical and Electronics Engineers Inc.	28	616
Elsevier	6	101
Multidisciplinary Digital Publishing Institute (MDPI)	6	75
Springer	1	46
International Society for Photogrammetry and Remote Sensing	1	25
Frontiers Media SA	1	11
INFORMS Inst.for Operations Res. and the Management Sciences	1	11
Budapest University of Technology and Economics	1	6
Korean Society for Aeronautical and Space Sciences	1	3
University of Buckingham Press	1	0

Note: Publisher information was not specified for two of the 49 publications; therefore, Table 5 reports the distribution of the 47 records with identifiable publisher information.

The results indicate that IEEE, MDPI, and Elsevier are the main publishers represented in the dataset. IEEE has the highest number of documents and citations, reflecting its strong presence in technical areas such as communication systems, mobile edge computing, resource allocation, embedded electronics, intelligent control, and UAV-enabled network optimisation. This pattern is consistent with the technological orientation of several influential studies in the dataset, particularly those addressing UAV-assisted MEC, energy-efficient resource allocation, and computation offloading [4,18,20,22,28].

MDPI also appears as a relevant publisher in the dataset, with contributions associated with application-oriented and sustainability-related themes. These include studies on UAV-enabled sensing, environmental monitoring, smart port applications, energy-aware systems, and applied technological solutions [6,27,31,32]. This indicates that MDPI publications within the dataset tend to connect UAV technologies with operational, environmental, and sustainability-oriented contexts.

Elsevier contributes a smaller but significant group of publications, with studies addressing broader system-level and interdisciplinary perspectives, including digital twins, maritime digitalisation, collaborative UAV services, and sustainable transitions in maritime and logistics systems [5,21,43]. These contributions complement the more technically focused IEEE stream by emphasising integration, applied system architectures, and sectoral transformation.

Overall, the publisher-level distribution shows that the field is structured around complementary publication channels. IEEE concentrates much of the technical and engineering-oriented research, MDPI contributes to application-driven and sustainability-related developments, and Elsevier supports broader interdisciplinary and system-level approaches. These patterns reinforce the view that energy-efficient UAV-enabled systems remain an interdisciplinary research area, combining technical design, intelligent optimisation, digital infrastructure, and sustainability-oriented applications.

From an interpretative perspective, the dispersion of publication sources and the concentration of contributions across IEEE, MDPI, and Elsevier suggest that the field is shaped by complementary but still partially disconnected research communities. IEEE publications mainly support the technical foundations of the field, particularly in mobile edge computing, resource allocation, communication networks, secure computation, and energy-aware system design [4,18,20,22]. MDPI publications contribute more strongly to application-oriented and sustainability-related themes, including UAV-enabled sensing, environmental monitoring, smart port applications, and energy-aware applied systems [6,27,31,32]. Elsevier publications provide broader system-level and interdisciplinary perspectives, especially in maritime digitalisation, digital twins, collaborative UAV services, and sustainable shipping transitions [5,21,43]. This pattern indicates that the field has not yet converged into a specialised port-logistics research domain, but is developing through interaction between engineering research, sustainability applications, and maritime digital transformation studies.

3.4. Geographical Distribution of Research Contributions

In addition to publication sources and publishers, the dataset also reveals an uneven geographical distribution of research contributions. Table 6 presents the countries with the highest number of publications and their corresponding citation impact.

The results show that China is the most productive country in the dataset, with 10 documents and 91 citations. This indicates a strong research presence in areas related to UAV-enabled systems, intelligent transportation, energy-efficient infrastructures, optimisation, and networked technologies. The prominence of China is consistent with the technical orientation of several studies in the dataset, particularly those addressing communication systems, resource allocation, digital infrastructures, and AI-enabled optimisation.

A second group of countries includes Finland, the United States, the United Kingdom, the Netherlands, and Pakistan, each contributing three documents. Among these, Finland presents a particularly high citation impact, with 82 citations from three documents. This suggests that Finnish contributions in the dataset have achieved significant scholarly visibility, especially in areas related to UAV-based sensing, environmental monitoring, and IoT-enabled applications [19].

Table 6. Countries with the highest publication output and corresponding citation impact in the reviewed dataset.

Country	Number of Documents	Total Citations
China	10	91
Finland	3	82
United States	3	48
United Kingdom	3	48
Netherlands	3	9
Pakistan	3	8
Saudi Arabia	2	34
India	2	14
Turkey	2	5
Canada	2	2

The United States and the United Kingdom also show relevant citation impact, with 48 citations each. Their contributions reflect the broader international engagement with UAV-enabled technologies, including autonomous systems, embedded computing, communication networks, and sustainability-oriented applications. The Netherlands and Pakistan appear with lower citation counts, indicating more limited scholarly impact within the selected dataset, although their presence confirms the geographically dispersed character of the field.

Other countries, including Saudi Arabia, India, Turkey, and Canada, contribute smaller publication volumes. Saudi Arabia shows a relatively high citation impact in comparison with its number of documents, which may be associated with technically focused studies on energy-efficient UAV deployment, communication systems, and optimisation [2]. India, Turkey, and Canada contribute to the diversification of the dataset, although with more modest citation levels.

Overall, the geographical distribution indicates that research on energy-efficient UAV-enabled systems is globally dispersed but asymmetrically distributed. China appears as the most productive contributor, while Finland shows strong citation performance relative to publication volume. The results suggest that the field is shaped by contributions from different regional research ecosystems, reflecting its interdisciplinary nature and its relevance to electronics, autonomous systems, communication networks, environmental monitoring, and logistics applications.

From a port-logistics perspective, the geographical distribution suggests that the field is still driven more by technological research capacity than by direct port-sector implementation. Countries with higher publication volume or citation impact appear mainly in connection with communication systems, UAV-enabled system design, environmental monitoring, and intelligent infrastructures. However, the dataset does not yet show a clear concentration of empirical studies conducted in major port regions or terminal environments. This matters because port applications depend on operational conditions such as vessel traffic, cargo flows, infrastructure constraints, safety requirements, regulation, and environmental monitoring needs. Future case-based studies across different port contexts would help clarify how the technological advances identified in the dataset can be transferred to port logistics practice.

3.5. Analysis of Key Contributing Authors

Table 7 presents the key contributing authors identified in the dataset, considering both citation impact and repeated authorship. Authors with at least 10 citations are reported, except for repeated authorship cases, which are included to show emerging continuity in the field. The results indicate a fragmented authorship structure, in which scholarly

influence is concentrated in a limited number of high-impact publications rather than in sustained multi-paper authorship trajectories.

Table 7. Authors with the highest citation impact and repeated authorship in the reviewed dataset.

Authors	Number of Documents	Number of Citations
Suleiman A.; Zhang Z.; Carlone L.; Karaman S.; Sze V. [25]	1	142
Oloruntobi O.; Mokhtar K.; Gohari A.; Asif S.; Chuah L.F. [21]	1	91
Motlagh N.H.; Kortoci P.; Su X.; Loven L.; Hoel H.K.; Haugsvaer S.B.; Srivastava V.; Gulbrandsen C.F.; Nurmi P.; Tarkoma S. [19]	1	82
Ai Q.; Qiao X.; Liao Y.; Yu Q. [4]	1	57
Xiao Z.; Chen Y.; Jiang H.; Hu Z.; Lui J.C.S.; Min G.; Dustdar S. [20]	1	46
Michailidis E.T.; Volakaki M.-G.; Miridakis N.I.; Vouyioukas D. [22]	1	40
Suleiman A.; Chen Y.-H.; Emer J.; Sze V. [26]	1	37
Gul O.M. [3,27]	2	34
Gul O.M.; Erkmén A.M. [27]	1	32
Wang W.; Lv Z.; Lu X.; Zhang Y.; Xiao L. [28]	1	28
Musci M.A.; Persello C.; Lingua A.M. [29]	1	25
Ebrahimi Z.; Zaid M.; Wijtvliet M.; Kumar A. [30]	1	22
Ibraiwish H.; Eltokhey M.W.; Alouini M.-S. [2]	1	20
Krapez J.-C.; Muñoz J.S.; Mazel C.; Chatelard C.; Déliot P.; Frédéric Y.-M.; Barillot P.; Hélias F.; Polo J.B.; Olichon V.; Serra G.; Brignolles C.; Carvalho A.; Carreira D.; Oliveira A.; Alves E.; Fortunato A.B.; Azevedo A.; Benetazzo P.; Bertoni A.; Goff I.L. [31]	1	18
Li J.; Shi Y.; Dai C.; Yi C.; Yang Y.; Zhai X.; Zhu K. [23]	1	16
Al-Naeem M.; Hafizur Rahman M.M.; Banerjee A.; Sufian A. [32]	1	14
Haidar A.; Tomov S.; Luszczek P.; Dongarra J. [33]	1	14
Liu W.; Sun X. [34]	1	11
Putra R.V.W.; Marchisio A.; Shafique M. [1]	1	11
Qadir M.A.; Naeem M.; Ejaz W. [5,45]	2	7

Note: The aggregated row for Gul O.M. [3,27] indicates repeated authorship across two publications, whereas the separate row for Gul O.M. and Erkmén A.M. [27] reports the authorship and citation impact of the individual co-authored publication.

The most influential contribution in the dataset is associated with Suleiman et al. [25], whose work on an energy-efficient visual-inertial odometry accelerator for autonomous navigation in nano-drones has achieved the highest citation impact. This study is particularly relevant because it addresses a central technological challenge in UAV-enabled systems: the balance between onboard computational capacity, energy consumption, and autonomous navigation performance.

A second group of influential contributions includes studies that expand UAV research towards environmental monitoring, maritime sustainability, and intelligent system integration. Motlagh et al. [19] provide an important contribution to UAV-based air pollution monitoring, while Oloruntobi et al. [21] address the sustainable transition of the seaborne shipping industry. Although these studies differ in scope, both contribute to the broader understanding of how UAV-enabled and digital technologies can support sustainability-oriented applications.

Another relevant set of authors contributes to the development of UAV-assisted mobile edge computing, communication efficiency, and resource allocation. Ai et al. [4], Xiao et al. [20], Ei et al. [18], and Michailidis et al. [22] are representative of this stream, with studies focused on computation offloading, energy-efficient resource management, secure computation, and UAV-enabled MEC-IoT networks. These contributions reinforce the importance of UAVs as components of distributed, energy-aware, and intelligent infrastructures.

The dataset also includes authors whose work is associated with optimisation-based and AI-enabled UAV systems. Ibraiwish et al. [2] address energy-efficient UAV deployment using particle swarm optimisation, while Li et al. [23] explore learning-based stochastic game approaches for trajectory and task offloading optimisation. These studies indicate a growing methodological orientation towards adaptive optimisation, intelligent control, and learning-based decision-making in UAV-enabled systems.

In terms of publication volume, Gul [3,27] and Qadir, Naeem and Ejaz [5,45] appear among the few authors with more than one document in the dataset. Gul's contributions are related to UAV-driven and energy-aware data collection in robotic wireless sensor networks, while Qadir, Naeem and Ejaz contribute to digital twin-assisted and federated learning-enabled communication systems. Although the number of repeated authors remains limited, these cases suggest the emergence of more continuous research lines in energy-efficient UAV systems and intelligent networked infrastructures.

Overall, the author-level analysis confirms that the field is still developing and has not yet consolidated around a small group of highly prolific researchers. Instead, the intellectual influence of the field is mainly shaped by technically specialised and highly cited individual contributions. This pattern is consistent with an emerging interdisciplinary research area in which advances are driven by contributions from electronics, communication systems, artificial intelligence, environmental monitoring, and logistics-related applications.

From the perspective of port logistics, this fragmented authorship structure suggests that the field has not yet developed a stable research community specifically dedicated to UAV applications in ports. Instead, the knowledge base is being formed through contributions from adjacent domains, including electronics, communication systems, mobile edge computing, artificial intelligence, autonomous navigation, environmental monitoring, and maritime digitalisation. This reinforces the interdisciplinary character of the topic, while also indicating the need for stronger collaboration between UAV technology researchers, port authorities, terminal operators, logistics scholars, environmental specialists, and digital infrastructure experts.

3.6. Bibliographic Coupling and Thematic Clusters

The bibliographic coupling analysis provides insights into the intellectual structure of the dataset by identifying relationships among publications that share common references. This approach is particularly useful for examining emerging and interdisciplinary research fields, as it reveals conceptual proximity between studies even when direct citation links or co-authorship relationships are limited.

Figure 3 presents the bibliographic coupling network generated from the final dataset. In this network, publications are grouped according to shared reference patterns, allowing the identification of thematic clusters related to energy-efficient UAV-enabled systems, mobile edge computing, optimisation, intelligent infrastructures, and application-oriented developments.

The network indicates that the field is organised around several interconnected but distinguishable research streams. These streams reflect different technological priorities, including UAV-assisted edge computing, resource allocation, autonomous optimisation, secure communication, sensing applications, and energy-efficient hardware. The position and connectivity of the clusters suggest that the field is still developing, with some areas showing strong internal coherence and others emerging more recently.

Figure 4 presents the overlay visualisation of the bibliographic coupling network. The colour gradient represents the temporal distribution of publications, allowing the identification of older and more recent contributions within the network.

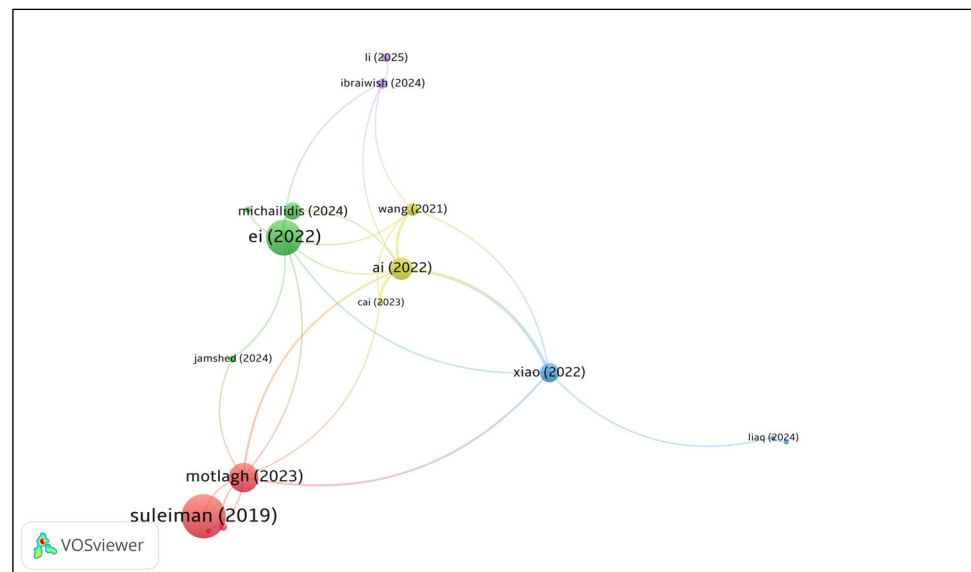


Figure 3. Bibliographic coupling network showing thematic clusters. Node colours indicate the thematic clusters, node size is proportional to citation impact, and link thickness represents the strength of bibliographic coupling between publications. Labels identify the first author and publication year of the mapped studies; the corresponding references are [2,4,18–20,22–25,28,41,45]. Visualisation generated using VOSviewer version 1.6.20.

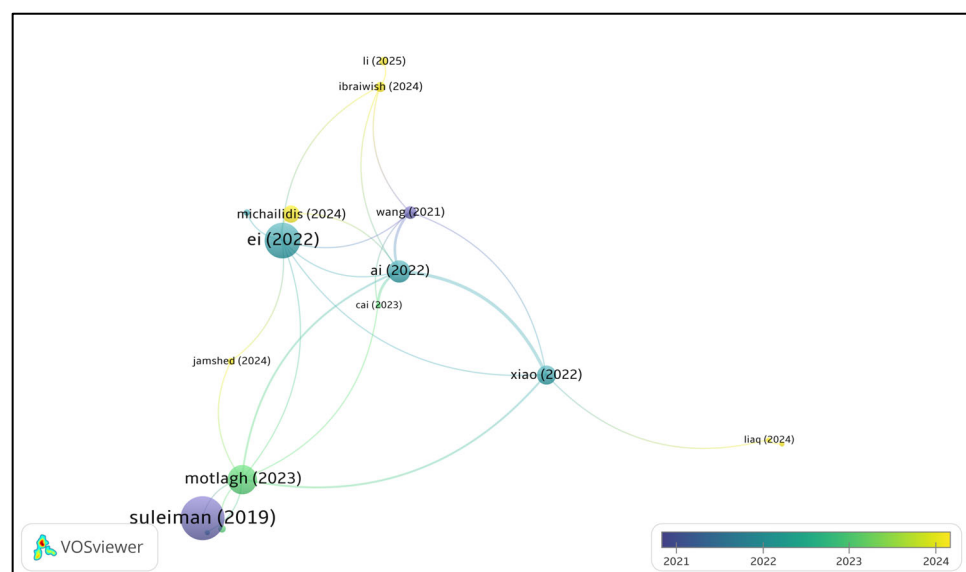


Figure 4. Overlay visualisation of the bibliographic coupling network. Node colour represents the average publication year according to the scale, node size is proportional to citation count, and link thickness indicates the strength of bibliographic coupling between publications. Labels identify the first author and publication year of the mapped studies; the corresponding references are [2,4,18–20,22–25,28,41,45]. Visualisation generated using VOSviewer version 1.6.20.

The overlay visualisation shows a temporal progression from earlier studies focused on hardware efficiency, onboard processing, and foundational UAV technologies towards more recent studies centred on artificial intelligence, learning-based optimisation, mobile edge computing, and distributed UAV-enabled infrastructures. This pattern is consistent with the chronological evolution presented in Table 3.

Figure 5 presents the density visualisation of the bibliographic coupling network. Areas with higher density indicate greater concentration of publications and stronger thematic proximity.

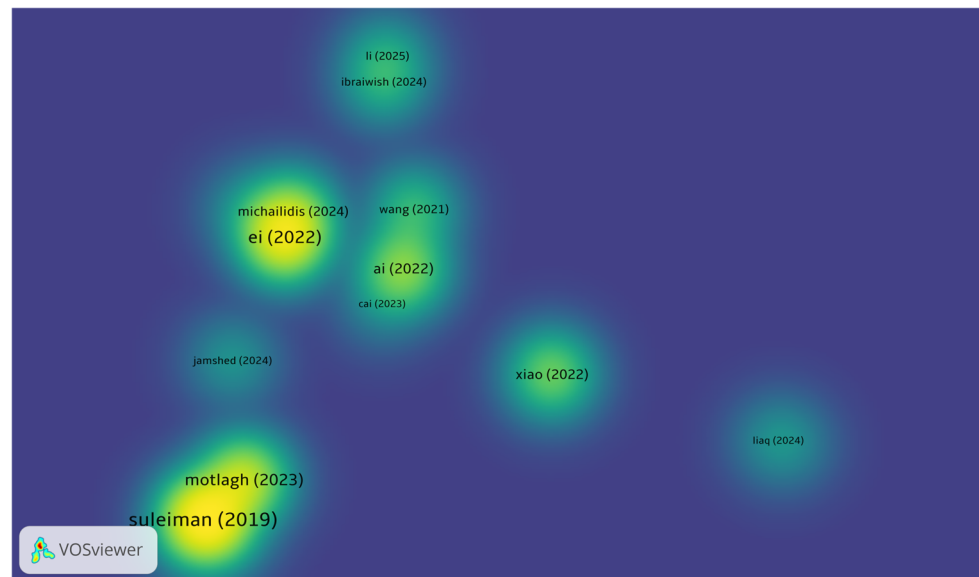


Figure 5. Density visualisation of the bibliographic coupling network. Colours range from blue, indicating lower publication density, through green to yellow, indicating higher concentration and weight of closely related publications. Labels identify the first author and publication year of the mapped studies; the corresponding references are [2,4,18–20,22–25,28,41,45]. Visualisation generated using VOSviewer version 1.6.20.

The density visualisation confirms that energy efficiency, UAV-assisted mobile edge computing, and resource allocation represent central areas of concentration in the dataset. At the same time, less dense regions indicate emerging research fronts, especially those associated with advanced optimisation, space-air-ground integrated networks, distributed intelligence, and sustainability-oriented applications.

Based on the bibliographic coupling network and the qualitative reading of the publications included in each group, four main thematic clusters were identified: UAV-assisted MEC and network optimisation; advanced optimisation and intelligent UAV systems; energy efficiency and resource allocation in UAV-MEC systems; and applications and energy-efficient hardware. These clusters are presented below.

Taken together, the four clusters should be interpreted as complementary technological layers rather than as evidence of consolidated port deployment. Cluster 1 relates to network connectivity and mobile edge computing; Cluster 2 to adaptive planning and intelligent UAV systems; Cluster 3 to energy efficiency, resource allocation, and secure computation; and Cluster 4 to sensing applications and energy-efficient onboard hardware. For port logistics, these streams indicate capabilities that may be relevant to inspection, environmental monitoring, safety-related observation, and operational decision support. However, the dataset shows that direct validation in port and terminal contexts remains limited.

3.6.1. Cluster 1: UAV-Assisted MEC and Network Optimisation

Cluster 1 includes studies focused on the integration of UAVs and unmanned systems within mobile edge computing and network optimisation architectures. The main contributions in this cluster address communication efficiency, computation offloading, resource management, and energy-aware operation in distributed network environments.

Ai et al. [4] propose a joint optimisation framework for communication and computation resources in IRS-aided wireless inland ship MEC networks. Although the study is centred on inland ship communication systems, it is relevant to the present analysis because it addresses the integration of computation, communication, and energy efficiency in maritime-related distributed infrastructures.

Xiao et al. [20] examine resource management in UAV-assisted MEC systems, identifying key challenges related to task offloading, computing resource allocation, energy consumption, and latency. Wang et al. [28] contribute to this cluster by proposing a distributed reinforcement learning framework for energy-efficient UAV relay under jamming conditions. Together, these studies indicate the importance of UAVs as networked aerial nodes capable of supporting computation and communication functions in complex environments.

From a temporal perspective, this cluster is concentrated mainly between 2021 and 2022. This suggests a consolidation phase in which UAV-assisted MEC and network optimisation became central themes in the development of energy-efficient UAV-enabled systems.

For port logistics, Cluster 1 is relevant because it addresses low-latency data exchange, distributed processing, and communication reliability. These capabilities may support UAV applications in which aerial data need to be processed close to the operational environment, such as inspection, monitoring, safety observation, or emergency-related assessment. In this sense, computation offloading and network management are not only technical concerns, but possible requirements for integrating UAVs into port digital infrastructures [4,18,20]. Nevertheless, the studies in this cluster remain predominantly technical and model-oriented, so their contribution should be interpreted as architectural support for future port applications rather than as evidence of mature deployment.

3.6.2. Cluster 2: Advanced Optimisation and Intelligent UAV Systems

Cluster 2 represents a more recent research stream focused on advanced optimisation and intelligent UAV-enabled systems. The studies in this cluster are associated with learning-based methods, multi-objective optimisation, trajectory design, task offloading, and adaptive decision-making in complex networked environments.

Ibraiwish et al. [2] investigate energy-efficient UAV deployment using particle swarm optimisation, with attention to positioning and system efficiency in UAV-enabled communication scenarios. Li et al. [23] propose a learning-based stochastic game for energy-efficient optimisation of UAV trajectory and task offloading in space and aerial edge computing environments. These contributions illustrate the increasing use of intelligent optimisation methods to address the interdependence between mobility, computation, communication, and energy consumption.

Temporally, this cluster is mainly positioned between 2024 and 2025, which indicates its emerging character. Its lower density and more peripheral position in the network suggest that these approaches are still being consolidated within the broader research structure. However, the cluster points to an important future direction in which UAV-enabled systems are increasingly shaped by adaptive, learning-based, and distributed optimisation methods.

From the perspective of sustainable port logistics, Cluster 2 is relevant because UAV operations may require adaptive planning under changing operational and environmental conditions. Port settings involve constraints such as vessel movements, restricted areas, weather variability, communication limitations, safety rules, and limited battery capacity. The methods represented in this cluster may support trajectory planning, mission scheduling, task allocation, computation offloading, and energy-aware routing [2,23,24]. However, the evidence remains mainly associated with modelling and algorithmic development. Therefore, this cluster points to future intelligent UAV architectures, while also showing the need for validation in operational port and terminal settings.

3.6.3. Cluster 3: Energy Efficiency and Resource Allocation in UAV-MEC Systems

Cluster 3 focuses on energy efficiency and resource allocation in UAV-assisted mobile edge computing and IoT-enabled infrastructures. This cluster is closely connected to Cluster 1,

but its emphasis is more specifically placed on the optimisation of energy consumption, computation efficiency, secure offloading, and latency-sensitive system performance.

Ei et al. [18] examine energy-efficient resource allocation in multi-UAV-assisted two-stage edge computing for beyond 5G networks. Their work addresses the challenge of minimising energy consumption while satisfying computational and communication constraints. Michailidis et al. [22] investigate secure computation efficiency in UAV-enabled RIS-assisted MEC-IoT networks, incorporating security concerns, computation offloading, and optimisation in the presence of aerial and ground eavesdroppers.

The studies in this cluster demonstrate that energy efficiency is not an isolated design parameter, but a system-level constraint that interacts with latency, computation, communication, security, and resource allocation. The temporal distribution from 2022 to 2024 suggests sustained research interest and gradual maturation of this stream.

For port logistics, Cluster 3 is relevant because UAV missions may depend on the balance between flight endurance, sensing quality, communication reliability, data processing, and cybersecurity. These requirements are particularly important when UAVs are considered for inspection, environmental monitoring, safety observation, or emergency-related tasks. The studies in this cluster suggest that UAV-assisted MEC can support these requirements through computation offloading, energy-aware resource management, latency reduction, and secure data processing [18,20,22]. However, the application of these approaches to port logistics remains underexplored, particularly regarding mission planning, integration with port digital platforms, cybersecurity governance, and operational validation.

3.6.4. Cluster 4: Applications and Energy-Efficient Hardware

Cluster 4 brings together application-oriented and hardware-related contributions. This cluster includes studies addressing UAV-based sensing, environmental monitoring, energy-efficient onboard processing, and embedded electronic architectures.

Suleiman et al. [25] present an energy-efficient visual-inertial odometry accelerator for autonomous navigation in nano-drones. This contribution is relevant because it addresses the hardware-level constraints of UAV autonomy, particularly the trade-off between computational performance and energy consumption. Motlagh et al. [19] provide a survey of UAV-based air pollution monitoring, highlighting the role of UAVs in environmental sensing and sustainability-oriented applications.

This cluster spans a broader temporal range, from 2019 to 2023, and combines foundational technological developments with application-oriented research. Its density indicates strong scholarly relevance, although its connectivity with the optimisation and MEC-focused clusters is more limited. This suggests that hardware and application-oriented research remains influential, but still partially separated from broader network optimisation and intelligent infrastructure streams.

From the perspective of sustainable port logistics, Cluster 4 connects UAV technical feasibility with application-oriented sensing. Energy-efficient onboard processing, embedded vision, visual-inertial navigation, and sensing technologies are relevant for UAV missions that require autonomy, endurance, and reliable data acquisition [25,26]. UAV-based environmental sensing and remote monitoring also indicate potential relevance for air quality assessment, water-related infrastructure monitoring, emissions observation, and environmental risk detection [19,31]. These capabilities may support inspection, environmental compliance, safety management, operational visibility, and decision-support processes. Nevertheless, the evidence remains uneven: while hardware and sensing technologies are technically developed in several domains, their integration into port-specific workflows, data platforms, and managerial routines remains limited.

3.6.5. Overall Structure of the Bibliographic Coupling Network

The bibliographic coupling analysis shows that the field is structured around a progressive movement from hardware-level efficiency and application-oriented sensing towards networked, intelligent, and optimisation-driven UAV-enabled systems. Cluster 1 establishes the architectural relevance of UAV-assisted MEC and communication optimisation, while Cluster 3 deepens this orientation through energy-efficient resource allocation and secure computation. Cluster 2 represents a recent frontier associated with advanced optimisation and learning-based systems, and Cluster 4 provides the application and hardware foundations of the field.

Overall, the thematic structure confirms that energy efficiency is the central connecting principle across the identified clusters. It links onboard computation, communication, resource allocation, trajectory design, autonomous operation, and sustainability-oriented applications. These results reinforce the relevance of energy-efficient UAV-enabled systems as an emerging research area at the intersection of electronics, autonomous systems, intelligent infrastructures, and sustainable port logistics.

From a port-logistics perspective, the bibliographic coupling structure suggests an emerging architecture composed of four complementary layers: network connectivity and edge computing, intelligent UAV planning, energy-aware resource management, and application-oriented sensing. These layers may be relevant to port functions such as inspection, environmental monitoring, safety-related observation, asset monitoring, and operational decision support. However, the network also shows that technical studies on UAV-MEC, resource allocation, intelligent planning, and energy-efficient hardware are more developed than empirical studies in port and terminal settings. This indicates a gap between technological capability and operational integration, especially regarding port workflows, decision-support systems, environmental governance, cybersecurity procedures, and terminal management practices.

3.7. Keyword Co-Occurrence Analysis

The keyword co-occurrence analysis provides a complementary perspective on the conceptual structure of the dataset. While bibliographic coupling identifies relationships among publications based on shared references, keyword co-occurrence reveals how the main concepts, technologies, and application domains are semantically connected within the field.

Figure 6 presents the keyword co-occurrence network generated from the final dataset. In this network, nodes represent keywords, node size indicates frequency of occurrence, and links represent co-occurrence relationships between terms. The network reveals a structured set of thematic areas related to energy efficiency, UAV systems, edge computing, artificial intelligence, communication infrastructures, and sustainability-oriented applications.

The keyword co-occurrence network indicates conceptual convergence across technical and application-oriented domains. The central position of energy efficiency and UAV-related terms reflects the importance of endurance, power consumption, sensing, communication, computation, and operational reliability. At the same time, terms related to mobile edge computing, computation offloading, artificial intelligence, resource allocation, Internet of Things, environmental impact, and digital twins suggest that UAVs are increasingly studied as components of broader digital and cyber-physical infrastructures. For port logistics, this convergence is relevant because aerial data only becomes operationally useful when it can be connected to monitoring, visibility, environmental control, and management processes.

The largest and most central group of keywords is associated with energy efficiency and UAV system design. Terms such as energy efficiency, unmanned aerial vehicles, aerial

vehicle, and energy utilisation occupy central positions in the network. This confirms that energy efficiency is not a peripheral topic, but a core organising concept in the dataset. The strong association between UAV-related terms and energy-related indicators reflects the importance of battery limitations, power consumption, trajectory design, sensing operations, communication tasks, and onboard computation in UAV-enabled systems.

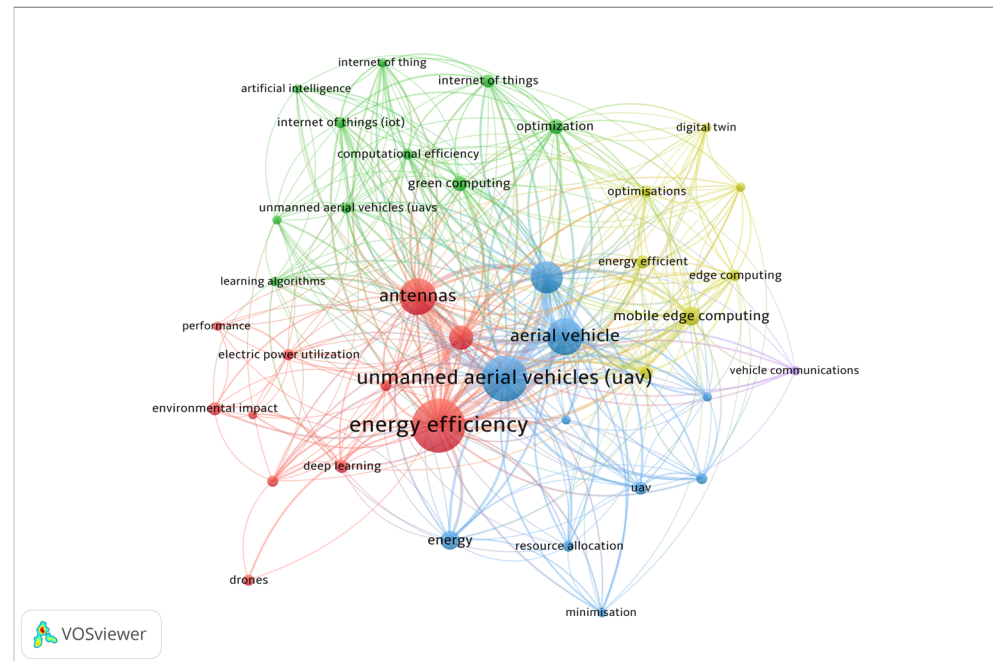


Figure 6. Keyword co-occurrence network of UAV-enabled systems relevant to sustainable port logistics. Node colours represent the thematic clusters identified by VOSviewer, node size indicates the frequency of keyword occurrence, and link thickness represents the strength of co-occurrence between keywords. The distance between nodes indicates their degree of relatedness. Visualisation generated using VOSviewer version 1.6.20.

A second thematic area is associated with edge computing and communication systems. Keywords such as mobile edge computing, edge computing, computation offloading, aircraft communication, and digital twin indicate the relevance of distributed computational architectures in UAV-enabled systems. These terms show that UAVs are increasingly studied not only as autonomous aerial platforms, but also as mobile nodes within networked infrastructures capable of supporting real-time data processing, communication, and system integration [18,22].

A third thematic area is related to artificial intelligence and optimisation techniques. Keywords such as deep learning, reinforcement learning, learning algorithms, resource allocation, and optimisation indicate the growing role of AI-enabled methods in improving UAV system performance. These techniques are particularly relevant for trajectory planning, task allocation, computation offloading, power control, resource management, and adaptive decision-making in complex operational environments [23,24].

A fourth thematic area is connected to sustainability, IoT, and environmental applications. Keywords such as Internet of Things, green computing, environmental impact, computational efficiency, and performance indicate the application-oriented dimension of the field. This group connects technological development with sustainability-related objectives, including environmental monitoring, energy-aware system operation, and data-driven decision support in logistics and port-related contexts [6,32].

Figure 7 presents the overlay visualisation of the keyword co-occurrence network. The colour gradient represents the average publication year associated with each keyword, allowing the identification of earlier and more recent research topics.

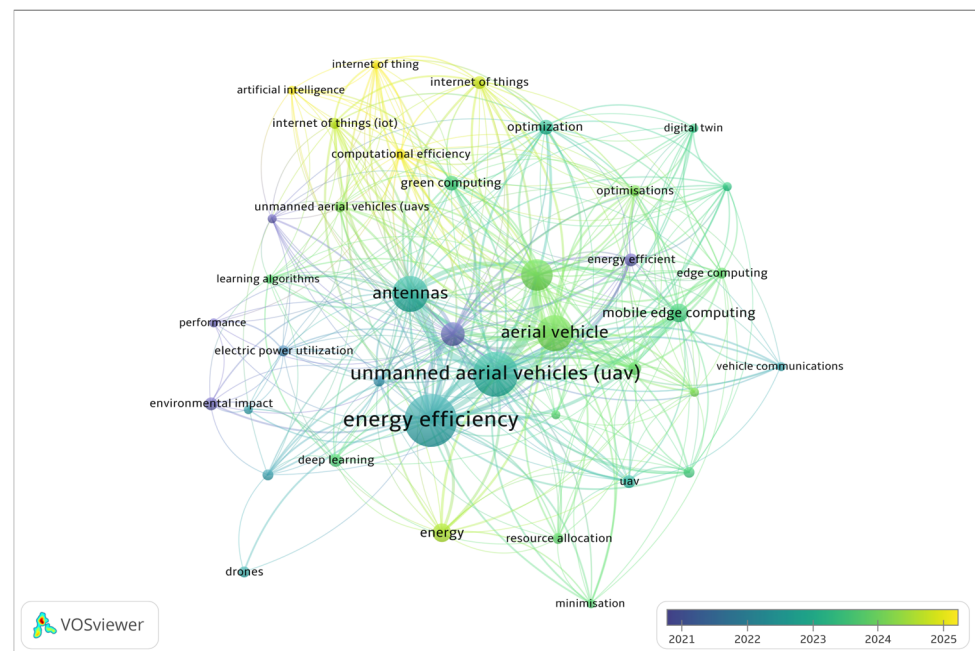


Figure 7. Overlay visualisation of keyword co-occurrence. Node colour represents the average publication year according to the scale, node size indicates the frequency of keyword occurrence, link thickness represents the strength of co-occurrence, and the distance between nodes indicates their degree of relatedness. Visualisation generated using VOSviewer version 1.6.20. Figure 8 presents the density visualisation of keyword co-occurrence. This visualisation highlights areas with stronger concentration of terms and greater conceptual proximity.

The overlay visualisation shows that earlier research topics are more strongly associated with communication infrastructure, computation offloading, and mobile edge computing. These terms reflect the initial development of the technological foundations required to integrate UAVs into distributed computing and communication environments. Subsequently, the research focus expands towards energy utilisation, resource allocation, trajectory optimisation, and performance management, indicating a transition from infrastructure-oriented research to system-level optimisation.

More recent keywords are associated with energy efficiency, deep learning, drones, environmental impact, and intelligent optimisation. This temporal pattern suggests that the field is moving towards more adaptive and sustainability-oriented UAV-enabled architectures. The emergence of environmental impact as a more recent term is particularly relevant for sustainable port logistics, as it indicates increasing attention to the relationship between UAV-enabled technologies, operational monitoring, and environmental performance.

In contrast, terms such as digital twin, environmental impact, deep learning, and green computing appear in less dense regions of the network. This suggests that these topics are still emerging within the dataset, although they are increasingly relevant for future research. Their presence indicates a gradual expansion from technical optimisation towards integrated, intelligent, and sustainability-oriented UAV-enabled systems.

Overall, the keyword co-occurrence analysis confirms that the conceptual structure of the field is organised around four main dimensions: energy-efficient UAV system design, edge computing and communication infrastructures, AI-driven optimisation methods, and sustainability-oriented applications. These dimensions are consistent with the bibliographic

coupling results presented in Section 3.6 and reinforce the central role of energy efficiency as the connecting principle across autonomous UAV systems, intelligent infrastructures, and sustainable port logistics.

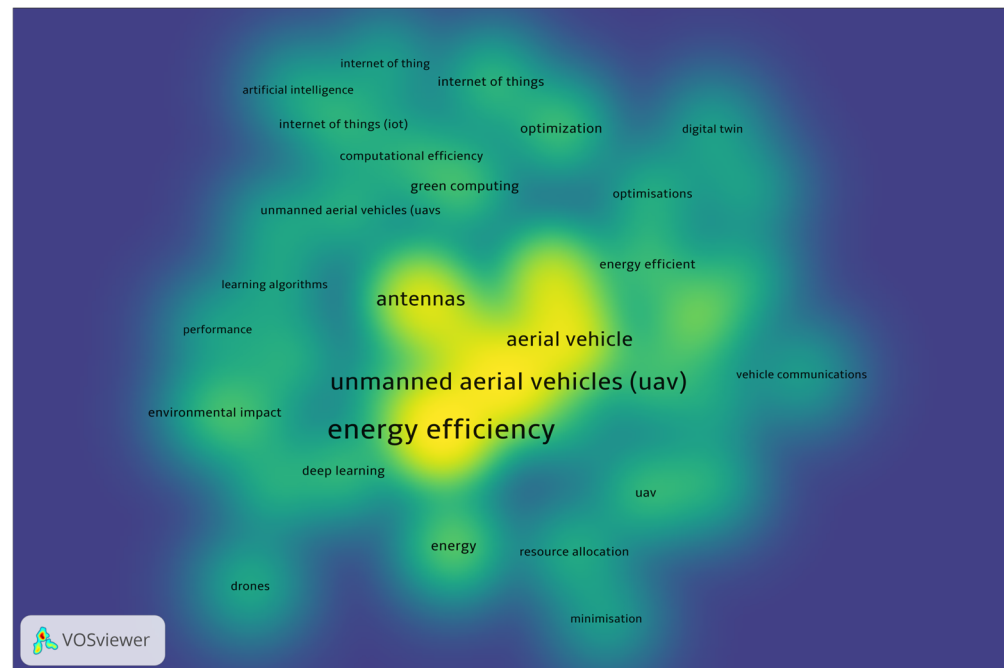


Figure 8. Density visualisation of keyword co-occurrence. Colours range from blue, indicating lower keyword density, through green to yellow, indicating higher concentration and cumulative weight of closely related keywords. Visualisation generated using VOSviewer version 1.6.20. The density map confirms that energy efficiency, unmanned aerial vehicles, and related communication and optimisation terms represent the most prominent research hotspots in the dataset. These high-density areas indicate well-established conceptual connections between UAV system design, energy-aware operation, and networked technological architectures.

From a port-logistics perspective, the keyword structure also reveals an imbalance between mature technical themes and emerging application-oriented topics. Energy efficiency, UAVs, mobile edge computing, resource allocation, and related communication terms appear more central in the network. By contrast, digital twins, environmental impact, green computing, and decision-support integration appear as less dense or more recent areas. This suggests that the link between UAV technologies and port management practices is still developing. Future studies should therefore examine how UAV-generated data can be integrated into port decision-support systems, environmental governance tools, maintenance planning, traffic coordination, and terminal management.

4. Discussion

The results show that research on energy-efficient UAV-enabled systems for sustainable port logistics is developing across several related but still weakly integrated domains. The bibliometric and systematic evidence points to a convergence between onboard energy efficiency, mobile edge computing, artificial intelligence, IoT-enabled infrastructures, environmental monitoring, and maritime-port digitalisation. However, the findings also show that the technological basis of the field is more developed than its empirical validation in port and terminal settings. Therefore, this discussion interprets the results as evidence of an emerging knowledge base and not as evidence of widespread operational adoption in ports.

4.1. Positioning of This Review in Relation to Previous Studies

To clarify the specific contribution of this review, it is important to position it in relation to previous studies that address UAV technologies, mobile edge computing, maritime digitalisation, environmental monitoring, and sustainable shipping. Existing review-oriented contributions have provided relevant insights into specific dimensions of this broader field. For example, previous studies have examined UAV research activity and collaboration patterns [16], UAV-based air pollution monitoring [19], resource management in UAV-assisted mobile edge computing [20], digitalisation trends in shipping [11], and the sustainable transition of the seaborne shipping industry [21]. However, these studies do not specifically integrate energy efficiency, UAV-enabled architectures, intelligent optimisation, mobile edge computing, and sustainable port logistics within a single analytical framework. Table 8 summarises how the present review differs from previous related contributions.

Table 8. Positioning of the present review in relation to previous studies.

Previous Study	Main Focus	Main Limitation in Relation to the Present Study	Contribution of the Present Review
Kotsemir [16]	Bibliometric analysis of UAV research activity and country-level collaboration patterns in Scopus	Provides a broad UAV research mapping, but does not focus on port logistics, energy efficiency, or sustainable maritime applications	Narrows the analysis to energy-efficient UAV-enabled systems with relevance to sustainable port logistics
Motlagh et al. [19]	UAV-based air pollution monitoring	Focuses mainly on environmental sensing and air pollution monitoring, without integrating port logistics, MEC, AI, or operational decision support	Connects environmental monitoring with broader UAV-enabled architectures for port sustainability and operational visibility
Xiao et al. [20]	Resource management in UAV-assisted mobile edge computing	Provides a technical overview of UAV-assisted MEC, but does not address port logistics or sustainability-oriented applications	Links MEC, computation offloading, and resource allocation to potential port logistics functions
Aerts and Mathys [11]	Digitalisation trends in shipping using natural language processing	Focuses on shipping digitalisation trends rather than UAV-enabled systems or energy-efficient aerial architectures	Extends the digitalisation discussion by examining UAVs as intelligent, networked, and energy-aware components of port digital infrastructure
Oloruntobi et al. [21]	Sustainable transition towards greener and cleaner seaborne shipping	Addresses sustainability challenges in shipping, but does not specifically examine UAV-enabled technologies, energy-aware architectures, or port-level applications	Connects UAV-enabled sensing, optimisation, and intelligent systems with sustainable port logistics and operational transformation

This comparison indicates that the contribution of the present review lies in connecting research streams that are usually treated separately. Rather than examining UAVs only as aerial platforms, the study analyses them as energy-aware and networked components that may support sustainable port logistics when integrated with digital infrastructures and operational processes. This positioning distinguishes the review from broader UAV

bibliometric studies, technical UAV-MEC reviews, environmental monitoring surveys, and maritime digitalisation analyses.

4.2. Energy Efficiency as a Central Design Principle

Energy efficiency emerges from the dataset as a central design constraint rather than as a narrow battery-related parameter. Across the reviewed studies, it is linked to on-board computation, sensing, communication, trajectory planning, resource allocation, and autonomous operation. This indicates that UAV performance depends on the ability to balance energy use with mission requirements and system-level reliability.

The most relevant contributions support this interpretation from different technical perspectives. Studies on onboard processing and autonomous navigation highlight the importance of energy-efficient computation for endurance and reliable mission execution [25,26]. In parallel, studies on UAV-assisted mobile edge computing, resource allocation, and secure computation show that energy efficiency interacts with latency, communication reliability, cybersecurity, and computational demand [18,20,22].

For port logistics, this matters because UAV missions may involve inspection, environmental monitoring, emissions observation, safety surveillance, or emergency-related assessment. In these contexts, energy use affects not only flight duration, but also payload selection, data transmission, onboard processing, mission continuity, and the quality of information available to port managers.

Therefore, future UAV applications in port environments should not evaluate energy performance in isolation. Energy-aware planning needs to be considered together with safety requirements, regulatory feasibility, mission priority, cost, data usefulness, and integration with port decision-support workflows. This reinforces the need for evaluation frameworks that connect UAV technical performance with operational and managerial requirements in ports.

4.3. From Isolated UAV Platforms to Intelligent and Networked Systems

A second important finding is the transition of UAVs from isolated aerial platforms to components of networked and intelligent systems. The bibliographic coupling and keyword analyses show the growing relevance of mobile edge computing, computation offloading, IoT, digital twins, and communication networks in UAV-related research [18,20].

For port logistics, this transition is important because aerial data has limited operational value if it remains disconnected from port management systems. UAVs may support inspection, environmental monitoring, traffic observation, and safety-related tasks, but their contribution depends on whether the collected data can be transmitted, processed, interpreted, and incorporated into existing workflows. In this sense, UAVs should be understood as possible elements of broader cyber-physical port infrastructures, rather than as standalone devices.

The reviewed literature suggests that this integration is still at an early stage. Many studies focus on specific technical components, such as computation offloading, communication efficiency, trajectory planning, or sensing applications. Fewer studies explain how UAV data can be combined with port community systems, terminal operating systems, digital twins, environmental monitoring platforms, or governance procedures [5,11,18,20].

This gap matters for port decision support. For port authorities and terminal operators, the central question is not only whether UAVs can collect data, but how this data improves maintenance planning, safety management, environmental compliance, traffic coordination, emergency response, and resource allocation. Future research should therefore examine UAVs as part of decision-support infrastructures embedded in port operations.

4.4. Role of Artificial Intelligence and Optimisation in UAV-Enabled Architectures

The results also indicate the growing role of artificial intelligence and adaptive planning methods in UAV-related research. Recent studies apply reinforcement learning, particle swarm optimisation, stochastic games, federated learning, and AI-assisted communication techniques to improve trajectory planning, task allocation, computation offloading, resource management, and energy performance [2,23,24,45].

For port logistics, these methods are relevant because UAV missions may need to operate under changing and constrained conditions. Vessel movements, cargo handling activities, restricted areas, weather variability, safety rules, communication limitations, and battery capacity can affect how UAV missions are planned and executed. In this context, AI-supported methods may assist with mission scheduling, routing, task prioritisation, energy-aware flight planning, and computation offloading.

However, the reviewed literature remains mainly focused on models, simulations, and algorithmic development. This means that the main research gap is not only technical performance, but also operational translation. More evidence is needed on how AI-supported UAV methods can be embedded in port management routines, terminal operating systems, port community systems, digital twins, and environmental monitoring platforms.

Therefore, future research should examine whether these methods can support reliable decision-support mechanisms in port operations. This includes evaluating how UAV missions are prioritised, how aerial data is used by port managers, and how automated recommendations can be aligned with safety, regulation, cybersecurity, environmental control, and operational needs.

4.5. Practical Implications for Port Logistics and Management

The findings have practical implications for port authorities, terminal operators, environmental managers, safety teams, and digital infrastructure planners. The review indicates that UAVs may support port operations in four main areas: inspection and asset monitoring, environmental control, safety and emergency response, and operational decision support.

First, UAVs can improve inspection and asset monitoring by providing flexible aerial observation of infrastructure, cargo areas, access zones, and hard-to-reach assets. This may reduce manual exposure to hazardous areas and support more frequent condition assessment. Second, UAV-based sensing can contribute to environmental monitoring by supporting air quality observation, emissions assessment, water-related monitoring, and detection of environmental risks [6,19,31]. Third, UAVs may support safety and emergency response by improving situational awareness during incidents, restricted-area monitoring, traffic observation, and risk detection. Fourth, UAV-generated data can strengthen port decision support when integrated with terminal operating systems, port community systems, environmental monitoring platforms, digital twins, and maintenance planning tools [5,11].

These implications depend less on the drone as an isolated device and more on the capacity of the port organisation to integrate aerial data into existing operational and managerial routines. For this reason, UAV adoption should be treated as part of a broader digital infrastructure strategy. Key implementation requirements include data governance, cybersecurity, regulatory compliance, airspace coordination, interoperability with port systems, staff training, and clear procedures for transforming aerial data into operational decisions.

Therefore, the practical value of UAVs in port logistics should be assessed through their contribution to visibility, safety, environmental performance, response time, maintenance planning, and decision quality. The evidence reviewed in this study suggests strong technological potential but also shows that applied validation in port and terminal contexts

remains limited. Future implementations should therefore be supported by pilot projects, measurable operational indicators, and integration with port management processes.

4.6. Research Gaps and Future Directions

The review identifies four main research gaps. The first concerns the limited number of empirical studies conducted in operational port and terminal settings. Much of the literature focuses on technical models, simulations, conceptual frameworks, or applications in adjacent domains. Future research should therefore include field studies, pilot projects, and case-based evaluations involving port authorities, terminal operators, logistics providers, and technology developers.

The second gap concerns system integration. UAV applications in ports should not be evaluated only in terms of flight performance or data collection capacity. Future studies should examine how aerial data can be integrated with terminal operating systems, port community systems, digital twins, environmental monitoring platforms, maintenance systems, and emergency management procedures. This is essential for understanding whether UAVs can improve operational planning, environmental control, safety management, and managerial decision quality.

The third gap relates to performance measurement. Further research should define indicators capable of assessing the operational, environmental, safety, and economic value of UAV deployment in port logistics. These indicators may include inspection time, response time, avoided human exposure, data latency, energy consumption, emissions monitoring capability, maintenance efficiency, cost-effectiveness, and contribution to decision support.

The fourth gap concerns governance and implementation. UAV adoption in ports raises questions related to airspace coordination, cybersecurity, data ownership, liability, regulatory compliance, staff training, and organisational readiness. These aspects remain underexplored in the reviewed literature, although they are critical for moving from experimental use to reliable operational deployment.

Future research should therefore move beyond isolated technological development and address UAV-enabled systems as part of integrated port management architectures. Comparative studies across different port types, regulatory contexts, terminal configurations, and environmental conditions would help clarify where UAVs generate the highest operational and sustainability value. This would also support the development of decision-oriented frameworks for evaluating when, how, and under what conditions UAV deployment is justified in sustainable port logistics.

5. Conclusions

This study examined the evolution, intellectual structure, and thematic development of energy-efficient UAV-enabled systems for sustainable port logistics through a bibliometric and systematic review of 49 peer-reviewed publications indexed in Scopus between 2001 and 2026. The findings provide a structured overview of an emerging and interdisciplinary research field shaped by the convergence of autonomous UAV systems, energy efficiency, mobile edge computing, artificial intelligence, optimisation, IoT-enabled infrastructures, and sustainability-oriented applications.

The temporal analysis indicates a clear transition from an exploratory phase, marked by low and fragmented scientific output, to a more dynamic expansion phase from 2019 onwards. Citation impact is concentrated mainly in studies published between 2022 and 2023, while the increase in publications from 2024 onwards suggests growing academic attention to intelligent, autonomous, and energy-aware UAV-enabled systems. This pattern reflects both the novelty of the field and its increasing relevance to electronics, communication networks, autonomous systems, and sustainable logistics.

The analysis of influential publications, contributing authors, publication sources, publishers, and geographical distribution confirms that the field remains fragmented but technically rich. IEEE, MDPI, and Elsevier appear as the main publication platforms in the dataset, each contributing to different dimensions of the field. IEEE is strongly associated with communication systems, edge computing, resource allocation, and technical optimisation. MDPI contributes to application-oriented and sustainability-related research, while Elsevier supports broader system-level and interdisciplinary perspectives.

The bibliographic coupling and keyword co-occurrence analyses identified four main thematic dimensions: UAV-assisted mobile edge computing and network optimisation; advanced optimisation and intelligent UAV systems; energy efficiency and resource allocation in UAV-MEC systems; and application-oriented developments and energy-efficient hardware. Across these dimensions, energy efficiency emerges as the central organising principle, linking onboard computation, communication, sensing, trajectory planning, autonomous operation, resource allocation, and sustainability-oriented applications.

The results also show that UAVs are increasingly being conceptualised not merely as isolated aerial platforms, but as intelligent, networked, and energy-aware components of broader cyber-physical systems. This transition is particularly relevant for sustainable port logistics, where UAVs may support infrastructure inspection, environmental monitoring, operational visibility, emissions observation, risk detection, safety management, and decision support. However, the literature still provides limited evidence of integrated and validated UAV-enabled architectures deployed in real port environments.

This study contributes to the literature by consolidating fragmented research streams into a coherent analytical framework. It provides a system-oriented understanding of how UAV-enabled technologies have evolved across energy efficiency, autonomous system design, edge computing, artificial intelligence, optimisation, and sustainability-oriented applications. It also highlights the need to bridge the gap between technological development and operational implementation in port logistics.

The study has limitations. The dataset is restricted to publications indexed in Scopus and reflects the bibliographic coverage available at the time of data extraction. Although Scopus provides broad coverage of engineering, electronics, computer science, transportation, and applied technology research, relevant studies indexed in other databases may not have been included. In addition, citation-based indicators are affected by publication age, which means that recent studies may have lower citation counts despite their potential relevance. Finally, the relatively small size of the dataset reflects the emerging nature of the field but limits the generalisation of some findings.

Future research should focus on the empirical validation of UAV-enabled systems in real port environments. Particular attention should be given to integrated architectures combining UAVs, edge computing, IoT infrastructures, digital twins, artificial intelligence, environmental monitoring platforms, and port management systems. Further studies should also assess the environmental, operational, safety, and managerial performance of UAV deployment, including energy consumption, avoided emissions, response time, human exposure reduction, cost-effectiveness, interoperability, cybersecurity, regulatory feasibility, organisational readiness, and contribution to decision quality.

Overall, energy-efficient UAV-enabled systems represent a promising research and application domain for sustainable port logistics. Their future relevance will depend not only on technological advances in UAV autonomy, energy management, and intelligent system design, but also on the capacity to integrate these systems into reliable, secure, and decision-oriented port infrastructures.

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Institutional Review Board Statement: This study is based exclusively on published scientific literature and does not involve human participants, interviews, surveys, or the collection of personal data. Therefore, ethical approval and informed consent were not required.

Data Availability Statement: The data supporting the findings of this study are derived from the Scopus database. The dataset was generated based on the search query and selection criteria described in the methodology section. Due to database access restrictions, the raw data cannot be publicly shared. However, the search string and methodological procedures are provided to ensure the reproducibility of the study. The processed dataset supporting the findings of this study is available from the corresponding author upon reasonable request.

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