International Journal of Innovation and Industrial Revolution
EISSN: 2637-0972
IJIREV
Volume 7 Issue 22 (September 2025) PP. 01-15
DOI 10.35631/IJIREV.722001

INTERNATIONAL JOURNAL OF INNOVATION AND INDUSTRIAL REVOLUTION (IJIREV)
www.ijirev.com

RESEARCH TREND ON THERMAL COMFORT IN E-HAILING VEHICLES IN MALAYSIA

Ahmad Nur Aizat Ahmad[1*], Mohamad Ali Selimin[2], Md Fauzi Ahmad[3], Ahmad Zaki Mohmad Amin[4]

[1] Department of Production and Operations Management, Faculty of Technology Management and Business, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia
Email: aizat@uthm.edu.my
[2] Department of Production and Operations Management, Faculty of Technology Management and Business, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia
Email: aliselimin@uthm.edu.my
[3] Department of Production and Operations Management, Faculty of Technology Management and Business, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia
Email: mohdfauzi@uthm.edu.my
[4] Mathematics Division, Centre for Foundation Studies in Science, Universiti Malaya, Malaysia.
Email: azaki@um.edu.my
[*] Corresponding Author

Article Info:

Article history:
Received date: 30.06.2025
Revised date: 21.07.2025
Accepted date: 14.08.2025
Published date: 01.09.2025

To cite this document:

Ahmad, A. N. A., Selimin, M. A., Ahmad, M. F., & Mohmad Amin, A. Z. (2025). Research Trend on Thermal Comfort In E-Hailing Vehicles in Malaysia. *International Journal of Innovation and Industrial Revolution, 7* (22), 01-15.

DOI: 10.35631/IJIREV.722001

Abstract:

This bibliometric analysis explores the evolving research landscape on thermal comfort in vehicles, a topic gaining prominence due to its critical role in passenger satisfaction, energy efficiency, and environmental sustainability in the transportation sector. Despite technological advancements in automotive climate control systems, thermal discomfort remains a significant concern, especially in the context of electric and shared mobility solutions. The problem is compounded by varying climatic conditions, user preferences, and the growing demand for sustainable transportation. Thus, to address this research gap, a comprehensive bibliometric study was conducted using data extracted from the Scopus database. A total of 2,526 publications were analyzed employing Scopus Analyzer for quantitative assessment, OpenRefine for data cleaning and normalization, and VOSviewer for visualizing co-authorship networks, keyword co-occurrence, and thematic trends. The analysis spanned multiple dimensions, including publication trends by year, most cited works, leading contributing countries, and collaborative networks. Numerical results indicate a significant publication surge from 2023 to 2024, with China, Germany, and South Korea emerging as top contributors. Meanwhile, highly cited articles focus on Phase Change Materials (PCMs), personal comfort systems, and advanced thermal modeling techniques, underscoring the field's technical diversity and interdisciplinary nature. Keyword analysis revealed a strong emphasis on terms such as "thermal comfort," "vehicle climate,"

International Journal of Innovation and Industrial Revolution
IJIREV
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"energy efficiency," and "smart mobility," reflecting the convergence of engineering, environmental science, and user-centered design. In conclusion, this study provides a systematic overview of the scholarly contributions to vehicle thermal comfort research, identifying key areas of focus, influential authors, and emerging trends. The findings can guide future research and innovation in vehicle design, policy development, and the deployment of intelligent thermal management systems, ultimately contributing to more comfortable and energy-efficient transportation experiences.

Keywords:

Thermal Comfort, Cabin Vehicle, User Preferences, Bibliometric Analysis

Introduction

Thermal comfort in e-hailing vehicles is a critical aspect that significantly influences user preference, satisfaction, and overall travel experience. It is defined as the condition of mind in which an individual expresses contentment with the thermal environment, and several interrelated factors, including air temperature, relative humidity, air velocity, and thermal radiation, influence this perception (Busse et al., 2015). Notably, these parameters interact dynamically within the confined space of a vehicle cabin, making it essential to maintain an appropriate thermal balance. In the context of Electric Vehicles (EVs), ensuring thermal comfort becomes even more complex due to the inherent limitations of battery energy storage. At the same time, Heating, Ventilation, and Air Conditioning (HVAC) systems in EVs substantially impact energy consumption, potentially reducing driving range by up to 50% under certain environmental conditions (Jaoude et al., 2017). As such, there is a pressing need to develop strategies that optimize thermal comfort without compromising energy efficiency. This is especially true for e-hailing applications where ride quality and operational sustainability are closely interlinked.

Numerous research efforts have been directed towards understanding the parameters influencing thermal comfort within vehicle interiors. One widely adopted approach is the use of Computational Fluid Dynamics (CFD) simulations, which enable detailed analysis of airflow characteristics, temperature distribution, and heat transfer mechanisms within the cabin. Studies utilizing CFD have demonstrated that a smaller field synergy angle, representing the angle between velocity and temperature gradient vectors, can enhance convective heat transfer, thus improving thermal comfort levels (Huo et al., 2023). Furthermore, the presence of occupants introduces significant variability in the thermal environment. Passengers obstruct airflow paths and act as heat sources, thereby modifying the distribution of air velocity and temperature throughout the cabin space (Danca et al., 2018).

To quantitatively assess thermal comfort, the Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) indices are commonly employed. These indices are designed to estimate the average thermal sensation and the proportion of people likely to be dissatisfied with the environment, respectively. However, due to the transient and spatially non-uniform characteristics of vehicle cabins, such as fluctuating sunlight exposure and variable ventilation, these indices often demonstrate significant variation. Consequently, this makes accurate thermal comfort prediction a challenging task (Wadhwa & Kalsia, 2023). Note that passenger preferences regarding thermal comfort can also differ based on journey duration and prevailing environmental conditions. For example, individuals undertaking short-haul trips often adjust

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EISSN: 2637-0972
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air outlet direction or intensity to achieve immediate relief. In contrast, long-haul passengers may prefer passive strategies like closing window blinds or drawing drapes to shield themselves from direct sunlight and reduce radiant heat gain (Lin et al., 2010). This behavioral divergence underscores the significance of adaptable thermal management strategies. It is also noteworthy that the optimal thermal comfort temperature ranges for short-haul and long-haul e-hailing trips have been identified as 22.4°C to 28.9°C and 22.4°C to 30.1°C, respectively. This offers a baseline for climate control system calibration (Lin et al., 2010).

In recent years, advanced predictive models incorporating variables such as local thermal sensation, mean skin temperature, and overall comfort feedback have demonstrated promise in accurately forecasting passenger comfort levels. In particular, these models enhance the ability of intelligent HVAC systems to tailor microclimate conditions within the vehicle cabin in real-time, thereby improving energy efficiency and user satisfaction (Xu et al., 2025). Such innovations represent a step forward in achieving sustainable and user-centric thermal management in the growing e-hailing industry.

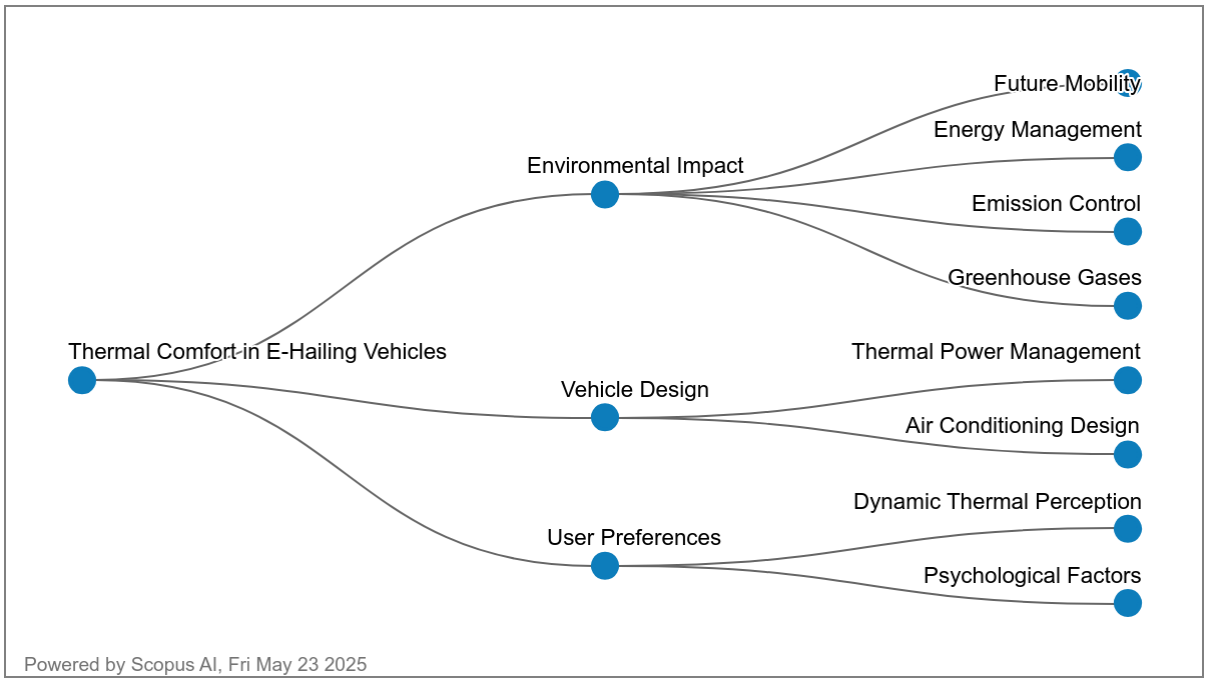

Figure 1: Overview of the Thermal Comfort and User Preference in E-Hailing Vehicles

Research Question

i. RQ1: What are the research trends in thermal comfort studies according to the year of publication?
ii. RQ2: What are the most cited articles?
iii. RQ3: What are the top 10 countries based on the number of publications?
iv. RQ4: What are the popular keywords related to the study?
v. RQ5: What are the keyword-based countries with the most citations?

Methodology

Bibliometrics involves gathering, organizing, and analyzing bibliographic data from scientific publications (Alves et al., 2021; Assyakur & Rosa, 2022; Verbeek et al., 2002). Beyond basic

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statistics, such as identifying publishing journals, publication years, and leading authors (Wu & Wu, 2017), bibliometrics includes more sophisticated techniques like document co-citation analysis. Thus, conducting a successful literature review requires a careful, iterative process to select suitable keywords, search the literature, and perform an in-depth analysis. This approach helps compile a comprehensive bibliography and achieve reliable results (Fahimnia et al., 2015). With this in mind, the study focused on high-impact publications, as they provide meaningful insights into the theoretical frameworks that shape the research field. To ensure data accuracy, Scopus served as the primary source for data collection (Al-Khoury et al., 2022; di Stefano et al., 2010; Khiste & Paithankar, 2017). Additionally, to maintain quality, the study only considered articles published in peer-reviewed academic journals, deliberately excluding books and lecture notes (Gu et al., 2019). Using Elsevier's Scopus, known for its broad coverage, publications were collected from 2000 through May 2025 for further analysis.

Data Search Strategy

The study employed a screening sequence to determine the search terms for article retrieval. The study was initiated by querying the Scopus database with online TITLE (thermal AND comfort) AND PUBYEAR > 2000 AND PUBYEAR < 2026, thereby assembling 10,342 articles. Afterwards, the query string was revised so that the search terms "vehicles" OR "cabin" should be focused on finalizing the search terms. This process yielded 3,826 results, which were additionally scrutinized to include only research articles published from 2000 to 2025. The final search string refinement that added subject focus to Engineering, Environmental Science, and Social Sciences included 2,526 articles used for bibliometric analysis. As of May 2025, all articles from the Scopus database relating thermal comfort and focusing on vehicles and e-hailing were incorporated in the study.

Table 1: The Search String

Scopus	TITLE (thermal AND comfort AND vehicle OR cabin OR van OR lorry OR bus) AND PUBYEAR > 1999 AND PUBYEAR < 2026

Table 2: The Selection Criterion of Searching

Criterion	Inclusion	Exclusion
Timeline	2000 – 2025	< 2020
Subject	Engineering, Environmental Science, Social Sciences	Besides Engineering, Environmental Science, Social Sciences

Data Analysis

VOSviewer is a widely recognized and user-friendly software tool for bibliometric analysis, developed by Nees Jan van Eck and Ludo Waltman at the Centre for Science and Technology Studies (CWTS) at Leiden University in the Netherlands (van Eck & Waltman, 2010, 2017). It has gained significant traction among researchers for its capabilities in visualizing and analyzing patterns within scientific literature. The software excels in producing intuitive and informative network visualizations, clustering thematically related elements, and generating density maps that offer clear representations of bibliometric relationships. Moreover, VOSviewer is particularly adept at analyzing co-authorship networks, co-citation structures, and keyword co-occurrence patterns, collectively supporting a more profound and comprehensive understanding of scholarly landscapes.

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What differentiates VOSviewer is its robust ability to translate large and complex bibliometric datasets into accessible visual formats such as maps and cluster diagrams. This visualization-centered approach allows users to easily identify research trends, thematic clusters, and relational patterns among academic entities. The software's interactive and highly navigable interface ensures that both novice users and seasoned researchers can efficiently explore vast datasets. In addition, continuous updates and enhancements to the platform reinforce its status as a cutting-edge tool in the realm of bibliometric and scientometric studies. The capacity of VOSviewer to compute a range of bibliometric indicators, adjust and customize visual displays, and integrate data from various scholarly databases makes it an essential and versatile tool for researchers. It strives to uncover insights and emerging patterns within complex research ecosystems.

In this study, bibliometric data, including publication year, article titles, authorship details, journal sources, citation counts, and keywords, were retrieved in PlainText format from the Scopus database, covering the period from 2004 through December 2024. The collected data were analyzed using VOSviewer version 1.6.19. By employing its advanced clustering and mapping algorithms, the software facilitated the identification and visualization of relationships among the data points. VOSviewer offers an effective alternative to traditional Multidimensional Scaling (MDS) techniques by positioning items within a low-dimensional space. This ensures that the spatial distance between two items accurately reflects the strength of their relatedness (van Eck & Waltman, 2010). While this aspect shares conceptual similarities with MDS (Appio et al., 2014), VOSviewer departs from MDS in its methodological approach.

Diverging from MDS, which primarily engages in the computation of similarity metrics like cosine and Jaccard indices, VOS utilizes a more fitting method for normalizing co-occurrence frequencies. This normalization approach enhances the precision of visual mappings and cluster delineations, thereby offering more meaningful and interpretable results in bibliometric analysis. This includes the Association Strength (AS_{ij}), and it is calculated as (Van Eck & Waltman, 2007):

$$AS_{ij} = \frac{C_{ij}}{w_i w_j},$$

which is "proportional to the ratio between, on the one hand, the observed number of co-occurrences of i and j, on the other hand, the expected number of co-occurrences of i and j under the assumption that co-occurrences of i and j are statistically independent" (Van Eck & Waltman, 2007).

Results and Discussion

RQ1: What are the Research Trends in Thermal Comfort Studies According to the Year of Publication?

The bibliometric data from Scopus on the topic of thermal comfort and user preference in e-hailing vehicles reveals a significant upward trend in scholarly interest over the past ten years. The data extracted from the Scopus analyzer illustrates a clear upward trend in research publications over the years, particularly accelerating from 2018 onwards. The highest number of publications occurred in 2023, with 29 entries, accounting for 10.51% of the total. This peak

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is closely followed by 2024 and 2022, each with 25 publications (9.06%), and 2021 and 2020, both with 23 publications (8.33%). These figures reflect a growing interest and heightened research activity in recent years, possibly driven by advancements in digital tools, increased funding opportunities, or emerging global challenges that spurred scholarly investigations.

From a medium-term historical perspective, the years between 2014 and 2018 saw moderate productivity, with annual publication numbers ranging between 11 and 20. While not as prolific as the more recent years, this period laid the groundwork for the upward trajectory that followed. The consistent output during these years, especially in 2014 (5.43%), 2015 (3.62%), 2016, and 2017 (both 3.99%), indicates a stable interest in the research domain covered, though the scale was smaller. These figures suggest a maturing research field, likely characterized by early explorations and foundational studies that enabled more intensive investigation later.

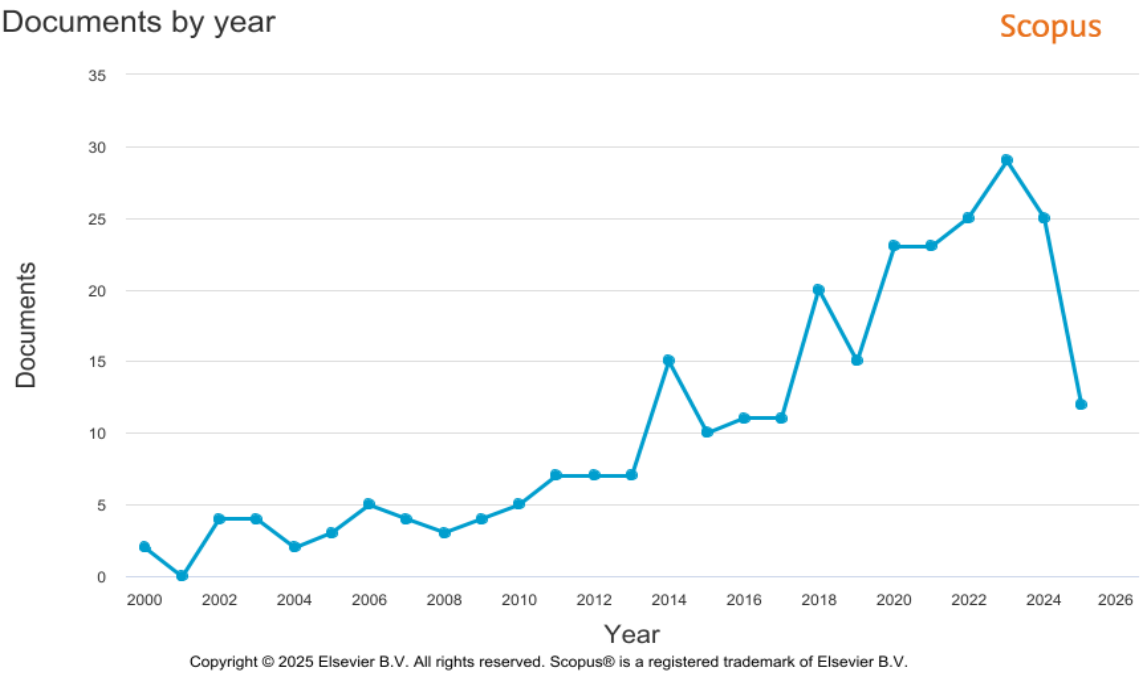

Figure 2: Trend of Research in Thermal Comfort by Years

Table 3: The Most by Year of Publication

Year	Number of Publications	Percentages (%)
2025	12	4.35
2024	25	9.06
2023	29	10.51
2022	25	9.06
2021	23	8.33
2020	23	8.33
2019	15	5.43
2018	20	7.25
2017	11	3.99
2016	11	3.99
2015	10	3.62

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2014	15	5.43
2013	7	2.54
2012	7	2.54
2011	7	2.54
2010	5	1.81

Conversely, the data from 2000 to 2013 imply relatively lower levels of publication activity, with each year contributing between 0.72% and 2.54% of total output. The sparse early years, including 2000 and 2004, with only two publications each, highlight a nascent or less prioritized research area during that time. However, a gradual increase is visible around 2010, signaling the beginning of a more active research phase. Overall, the dataset depicts a classic S-curve trend in publication growth, where initial slow progress shifts into rapid acceleration, a positive indicator of a dynamic and expanding scholarly field.

RQ2. What are the Most Cited Articles?

The bibliometric analysis of the top ten most cited articles related to thermal comfort and user preference in e-hailing or related vehicle environments highlights several key research trends. The most cited article by Lin et al. (2018) focused on thermal conductivity and Phase Change Materials (PCMs) in energy storage, amassing 737 citations. This underscores the foundational role of thermal management materials in improving comfort and energy efficiency, which are critical in confined spaces like e-hailing vehicles. Similarly, Jankowski and McCluskey (2014) specifically addressed PCMs for vehicle thermal buffering, reinforcing the practical relevance of this technology in the automotive sector.

Table 4: Top 10 Most Cited Authors

Authors	Title	Year	Source title	Cited by
Lin et al. (2018)	Review on thermal conductivity enhancement, thermal properties and applications of phase change materials in thermal energy storage	2018	Renewable and Sustainable Energy Reviews	737
Pamučar et al. (2018)	A new model for determining weight coefficients of criteria in MCDM models: Full Consistency Method (FUCOM)	2018	Symmetry	616
Vázquez-Canteli and Nagy (2019)	Reinforcement learning for demand response: A review of algorithms and modeling techniques	2019	Applied Energy	596
Lin et al. (2010)	Shading effect on long-term outdoor thermal comfort	2010	Building and Environment	563
Fontaras et al. (2017)	Fuel consumption and CO2 emissions from passenger cars in Europe – Laboratory versus real-world emissions	2017	Progress in Energy and Combustion Science	551
Jankowski and McCluskey (2014)	A review of phase change materials for vehicle component thermal buffering	2014	Applied Energy	410

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Zhang et al. (2015)	A review of the corrective power of personal comfort systems in non-neutral ambient environments	2015	Building and Environment	337
Jiang et al. (2021)	Digital twin and its implementations in the civil engineering sector	2021	Automation in Construction	314
Enescu (2017)	A review of thermal comfort models and indicators for indoor environments	2017	Renewable and Sustainable Energy Reviews	302
Yuksel and Michalek (2015)	Effects of regional temperature on electric vehicle efficiency, range, and emissions in the United States	2015	Environmental Science and Technology	295

Several top-cited studies also emphasize user-centric and environmental modeling approaches. For example, Lin et al. (2010) explored the shading effects on outdoor thermal comfort, while Zhang et al. (2015) reviewed personal comfort systems in non-neutral environments. These works suggest a growing emphasis on individualized thermal control, which is particularly relevant for enhancing user satisfaction in shared transportation modes like e-hailing. Moreover, the study by Enescu (2017) on thermal comfort models for indoor environments complemented this by offering insight into predictive models that could be adapted for vehicle interiors.

Additionally, there is a strong presence of studies integrating digital and computational methods. Vázquez-Canteli and Nagy (2019) reviewed reinforcement learning in demand response, while Jiang et al. (2021) discussed digital twins in civil engineering, both of which have implications for smart vehicle environments. The inclusion of these articles signals a shift toward intelligent systems that dynamically respond to user preferences and environmental conditions. The diversity in source journals, ranging from Applied Energy to Automation in Construction, reflects the interdisciplinary nature of this research domain, spanning energy, engineering, and environmental science.

RQ3: What are the Top 10 Countries Based on the Number of Publications?

The bibliometric data from Scopus reveals a significant geographical concentration of research output in thermal comfort and user preferences in e-hailing vehicles, with China emerging as the clear leader. Contributing to 77 publications, China accounts for nearly three times the number of articles compared to the second-ranked country, Germany. This strong lead may be attributed to China's rapid urbanization, vast domestic e-hailing market (dominated by platforms like DiDi), and significant governmental and industrial investments in smart mobility and green technologies. The high output reflects China's strategic focus on enhancing user-centric and energy-efficient transportation solutions in response to growing urban environmental challenges.

Following China, Germany (27), South Korea (23), and Romania (20) form the next tier of active contributors. Notably, Germany and South Korea are known for their strong automotive industries and technological innovation, which likely drives their academic focus on vehicle-related thermal comfort. Romania's position is notable, potentially linked to its emerging research capabilities and increased participation in European Union (EU) funded projects. Furthermore, France and the United States, despite their global academic influence, contribute

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slightly less (19 and 18, respectively). This is possibly due to a broader dispersion of research interests across various sustainability domains or a higher focus on policy and infrastructure-level studies rather than specific thermal comfort technologies.

The bottom half of the top ten list, India, Japan, Brazil, and Egypt, demonstrates moderate contributions ranging from 17 to 8 publications. India and Japan, both facing high-density urban environments and climatic variability, are naturally inclined to research thermal comfort to improve commuter satisfaction. Brazil and Egypt's presence, though smaller in scale, indicates growing regional interest in enhancing user experience in public and private transport. Overall, the distribution illustrates a global awareness of the significance of thermal comfort in e-hailing vehicles, with research being driven by both technological advancement and socio-environmental necessity.

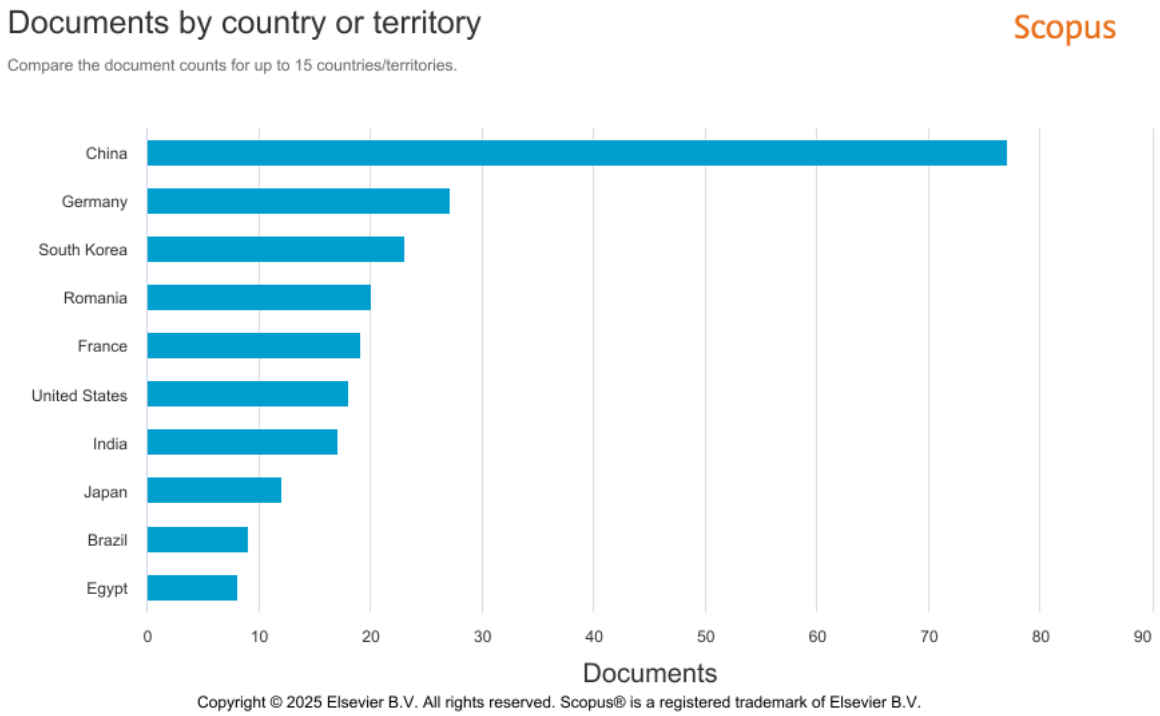

Figure 3: Document by Country

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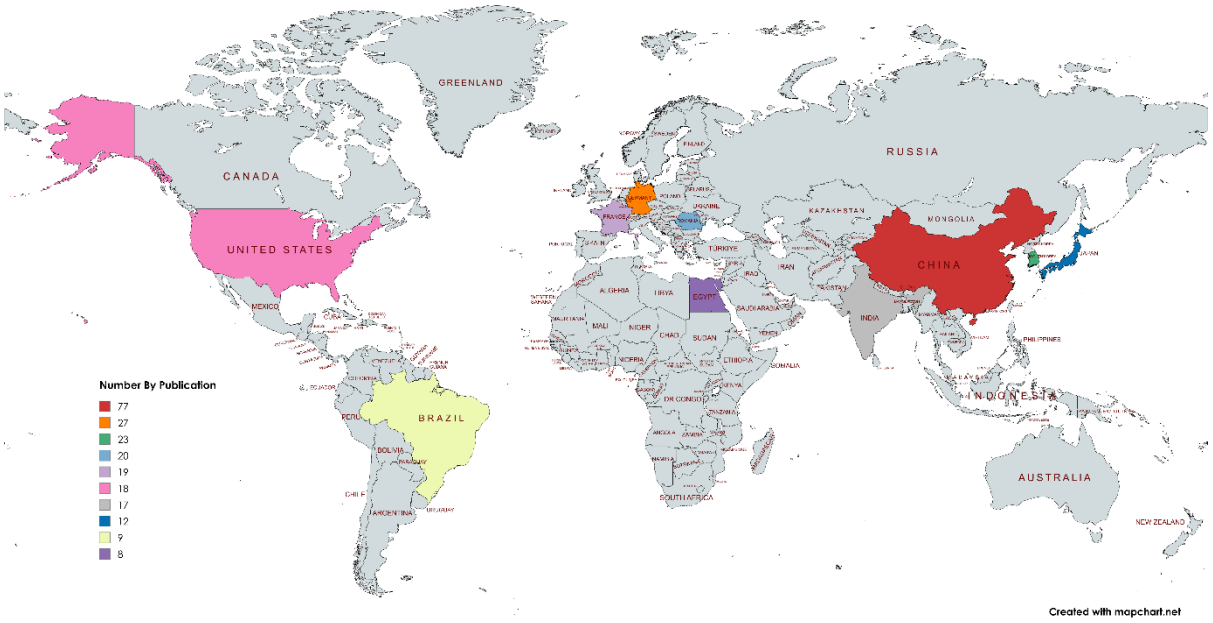

Figure 4: Number by Publication Based on Country

RQ4: What are the Popular Keywords Related to the Study?

The VOSviewer keyword analysis reveals that "thermal comfort" is by far the most dominant theme in the dataset, with 158 occurrences and the highest total link strength of 215. This indicates frequent usage and strong connections with other keywords in the research network, signifying its central role in the studied domain. Closely related terms such as "predicted mean vote (PMV)" (14 occurrences, 26 strength), "PMV" (12, 26), and PPD" (9, 21) further reinforce the focus on human thermal sensation and its prediction. This highlights a rich body of research concerned with quantifying and optimizing indoor or vehicular thermal environments for occupant comfort.

Technology-driven keywords also emerge as significant contributors. "Electric vehicle" (29, 46), "HVAC" (10, 29), "computational fluid dynamics (CFD)" (13, 24), and "CFV" (14, 28) underline the integration of engineering tools and sustainable transportation systems in thermal comfort studies. These terms suggest a strong intersection between vehicle design, energy efficiency, and environmental control technologies. Meanwhile, the presence of "aircraft cabin" (13, 22), "passenger compartment" (9, 17), and "numerical simulation" (10, 19) reflects focused applications in transportation sectors. Notably, maintaining thermal comfort under varying environmental conditions is both a challenge and a priority.

Environmental and physiological variables also hold a firm position within the research landscape. Keywords like "air conditioning" (21, 42), "air quality" (7, 12), "heating" (5, 17), and "ventilation" (6, 19) suggest ongoing investigations into indoor air systems and climate control mechanisms. Additionally, terms such as "skin temperature" (6, 10), "relative humidity" (5, 8), and "equivalent temperature" (5, 10) underscore physiological metrics used to assess thermal response. The diversity of terms, both technical and human-centered, underscores the interdisciplinary nature of thermal comfort research, bridging engineering, physiology, and environmental science to improve occupant well-being in built and mobile environments.

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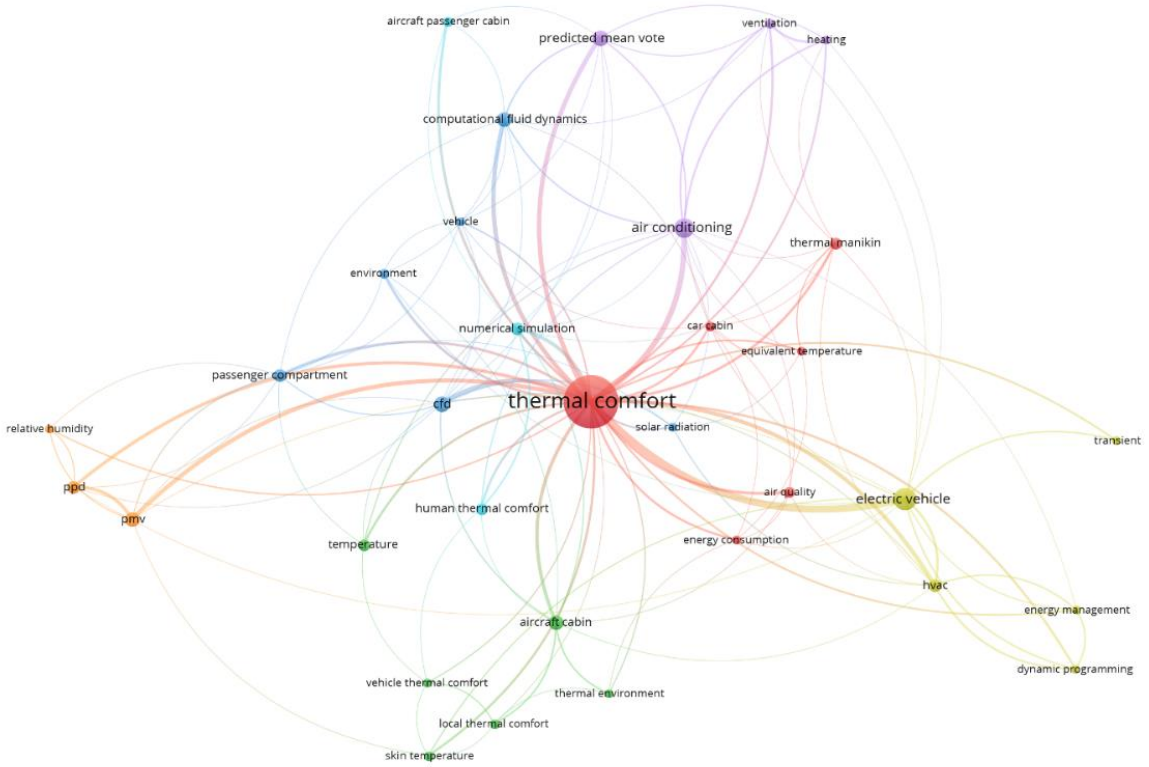

Figure 5: Network Visualization Map of Keywords' Co-Occurrence

Table 5: Network Visualization Map of Top 10 Keywords' Co-Occurrence

ID	Keyword	Occurrences	Total link strength
390	Thermal comfort	158	215
146	Electric vehicle	29	46
10	Air conditioning	21	42
83	Cfd	14	28
311	Predicted mean vote	14	26
22	Aircraft cabin	13	22
103	Computational fluid dynamics	13	24
302	Pmv	12	26
197	Hvac	10	29
265	Numerical simulation	10	19

RQ5. What are the Keyword-Based Countries with the Most Citations?

The keyword-based country with the most citations analysis from VOSviewer reveals that China leads significantly in terms of research output with 77 documents, accompanied by the highest citation count of 712 and a total link strength of 84. This suggests prolific contributions and a central position in collaborative networks, indicating China's dominance and influence in the field. Despite having only 20 documents, Romania ranks second in citations (562) and exhibits a high total link strength (73). This stresses the exceptional impact and strong connectivity of Romanian research, potentially due to highly cited or collaborative studies.

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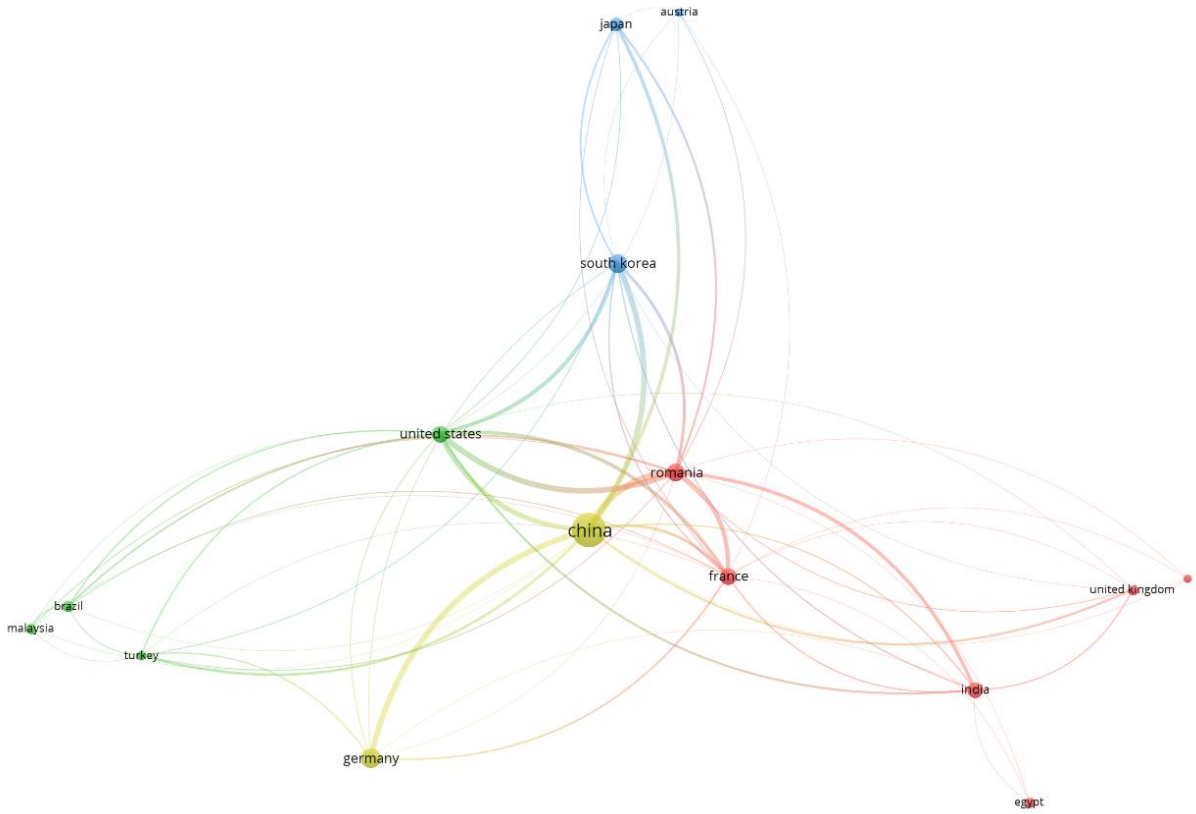

Figure 6: Keyword-Based Countries with the Most Citations Analysis

The United States, Germany, France, and South Korea follow closely, each demonstrating both considerable output and influence. The United States, with 18 documents and 474 citations, showcases a high citation-to-document ratio and strong link strength (59), reflecting impactful research and extensive international collaboration. Germany, while producing more documents (27), has a lower link strength (26), suggesting potentially more localized or independent research. Accordingly, France and South Korea share an equal total link strength of 45, although France records slightly more citations per document, implying a higher impact on individual papers.

India, Japan, Portugal, and Malaysia contribute to the field at a more modest scale, with fewer documents and citations. While India and Japan have moderate citation counts (157 and 139, respectively), they have relatively low link strengths, indicating their research may be less integrated into global networks. Portugal and Malaysia have the fewest documents (5 and 7), with citation numbers of 79 and 71, respectively, and minimal link strengths (4 and 8). These figures suggest emerging engagement or specialized research niches rather than broad influence. However, the presence of these countries reflects growing global participation and interest in the domain.

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Table 6: Keyword-Based Countries with Most Citations Analysis

Country	Documents	Citations	Total link strength
China	77	712	84
Romania	20	562	73
United States	18	474	59
Germany	27	404	26
France	19	377	45
South Korea	23	252	45
India	17	157	27
Japan	12	139	22
Portugal	5	79	4
Malaysia	7	71	8

Conclusion

This study aimed to examine the bibliometric landscape of research on thermal comfort in vehicles, primarily identifying key publication trends, influential works, and leading contributors in the field. The analysis addressed several research questions concerning publication growth over time, citation patterns, geographical distribution, keyword prominence, and the scholarly impact of contributing countries. Thus, by employing Scopus Analyzer, OpenRefine, and VOSviewer, the study successfully processed and visualized a dataset of 2,526 academic articles. It, ultimately, offers a comprehensive overview of the current state and development trajectory of the field.

The findings highlighted a notable rise in research interest, particularly between 2023 and 2024, reflecting increased academic engagement driven by technological advancements and growing environmental concerns. China emerged as the dominant contributor, both in terms of publication volume and citation impact, followed by countries such as Germany, South Korea, and Romania. Prominent themes included thermal modeling, PCMs, and user-centered comfort technologies, pointing to a multidisciplinary convergence of engineering, environmental science, and user experience. The keyword analysis further underlined the centrality of concepts such as “thermal comfort,” “PMV,” “HVAC,” and “electric vehicles” in shaping the discourse.

This bibliometric investigation contributes valuable insights into the structure and dynamics of research on vehicle thermal comfort, informing future directions for academics, engineers, and policymakers. Practical implications include the development of intelligent thermal control systems, improved cabin design, and enhanced passenger comfort strategies. However, limitations such as reliance on a single database and exclusion of grey literature suggest that further research could expand the scope by integrating additional sources and qualitative assessments. Nevertheless, bibliometric analysis proves to be an effective tool for mapping scholarly progress and identifying strategic opportunities for innovation in vehicle thermal comfort research.

Acknowledgements

This research was supported by Universiti Tun Hussein Onn Malaysia (UTHM) through MDR (vot Q690).

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International Journal of Innovation and Industrial Revolution
IJIREV
EISSN: 2637-0972
Volume 7 Issue 22 (September 2025) PP. 01-15
DOI 10.35631/IJIREV.722001

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