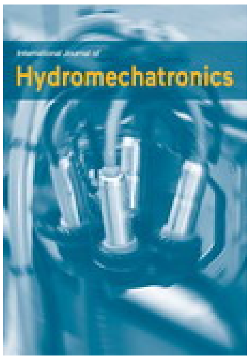

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Bibliometric insights into spray cooling research: trends, applications, and future directions

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Bibliometric insights into spray cooling research: trends, applications, and future directions

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Abstract: Spray cooling has attracted significant attention as an effective thermal management technique for electronic devices and high heat flux density chips. In this paper, CiteSpace and VOSviewer were adopted to quantitatively analyse the literature on spray cooling, pinpointing research hotspots and recent advancements. Based on the Web of Science database, 956 articles published between 2008 and 2024 were examined. A visual bibliometric analysis was conducted by CiteSpace and VOSviewer, encompassing the spatio-temporal distribution of publications, collaborations, keywords, and citation metrics. The results indicate that China, the USA, and India are the leading contributors in this field. Current research trends are shifting from traditional spray cooling towards applications in aerospace, high-performance computing, and medical aesthetics, advancing the technology toward multifunctional, eco-friendly, and sustainable directions. Furthermore, keyword clustering analysis was performed to explore prospective research trajectories. This study provides scholars a comprehensive understanding of current research hotspots and emerging trends in spray cooling.

Keywords: spray cooling; bibliometrics; cluster analysis; thermal management; keyword evolution.

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1 Introduction

In recent years, the rapid development of technologies, such as power batteries, aerospace systems, supercomputers, and large scale artificial intelligence models, has accelerated the miniaturisation and integration of electronic devices (Bellomo et al., 2025; Sundén et al., 2017). Consequently, effective heat dissipation has become increasingly critical across multiple fields (Parizad Benam et al., 2021; Cao et al., 2026). Researchers have developed multiple highly efficient cooling techniques, including microchannel cooling (Kwon et al., 2019), jet cooling (Ndao et al., 2014), and spray cooling (Ni and Ling, 2023). These methods have demonstrated exceptional results in heat transfer enhancement and increasing critical heat flux (CHF). However, microchannel cooling suffers from substantial pressure drops and susceptibility to clogging (Wang et al., 2025b), while jet impingement cooling requires high jet velocities, leading to increased pump power demand and overall system energy consumption (Eng Ewe et al., 2022). Conversely, spray cooling overcomes these limitations and stands out due to its advantages, including high heat flux removal capability, superior temperature uniformity, low working fluid flow requirements, and a simple structural design, offering considerable application potential and developmental prospects.

Spray cooling is a sophisticated thermal management technology adept at effectively dissipating extremely high heat fluxes. Its fundamental mechanism involves atomising the working fluid into fine droplets via a nozzle and uniformly applying them to high-temperature surfaces (Chen et al., 2022). This approach ensures high heat transfer efficiency, uniform temperature distribution, and minimal environmental constraints, enabling its widespread use across diverse engineering applications (Fey et al., 2003; Gong et al., 2023). The outstanding thermal performance of spray cooling is attributed to its complex and unique heat transfer processes, including droplet evaporation, droplet impact on heated surfaces, wall-film evaporation, nucleate boiling, and secondary nucleation. Based on local surface heat flux conditions, spray cooling can be categorised into single-phase and two-phase heat transfer regimes (Gong et al., 2023). In the single-phase regime, droplets impact the surface and form a stable liquid film, where heat transfer is primarily governed by forced convection with negligible film evaporation (Chen et al., 2022). In the two-phase regime, heat transfer occurs through nucleate boiling, transition boiling, and film boiling. During nucleate boiling, numerous nucleation sites form, bubbles rapidly grow and detach, and heat is effectively removed through the latent heat of vaporisation (Jin and Shirvan, 2021). Furthermore, secondary nucleation induced by droplet impact can enhance heat transfer efficiency.

The performance of spray cooling is strongly influenced by operational and geometric parameters, such as spray cone angle (Wang et al., 2025a), nozzle height (Zhou et al., 2017), working fluid mass flow rate (Yu et al., 2025), droplet velocity (Yao and Choit, 1987), droplet size distribution (Estes and Mudawar, 1995), injection pressure (Hou et al., 2013), and nozzle geometry (Wang et al., 2024b). Optimising these factors improves droplet distribution, facilitates liquid film formation, and enhances surface nucleation conditions, thereby increasing overall heat transfer performance.

Surface characteristics also play a critical role in spray cooling. Studies have shown that increasing the roughness of heated surfaces can accelerate the transition from liquid film to nucleate boiling, significantly improving heat transfer performance (Martínez-Galván et al., 2013). Moreover, micro/nano-structured surfaces substantially enhance gas-liquid phase-change heat transfer (Hu et al., 2025a; Martínez-Galván et al., 2013) by increasing nucleation site density, improving capillary liquid supply, and suppressing stable vapour film formation. However, most research has focused on the effects of individual parameters, neglecting systematic optimisation under multi-parameter coupling conditions, especially at high heat flux densities or in complex spray environments. Therefore, synergistic optimisation studies integrating experimental and numerical approaches are essential to develop design guidelines for high-performance heat management systems.

Despite significant advances in understanding droplet dynamics, heat transfer mechanisms, and surface modifications, the current spray cooling literature remains fragmented and compartmentalised. Many studies focus on isolated experimental or simulation variables, resulting in limited cross-scale and cross-parameter comparisons. This fragmented knowledge structure not only constrains the identification of new research topics and strategies but also slows the transfer and application of innovations across different domains. Consequently, bibliometric methods are needed to systematically map the global knowledge landscape of spray cooling research, examining its evolution, hotspots, and emerging trends.

Bibliometrics, developed in the 1950s, is a quantitative approach for analysing academic literature using statistical and visualisation tools (Wallin, 2005). It can identify leading authors, institutions, and countries within large, multidimensional datasets, reveal the evolution of research themes, and forecast potential breakthrough directions (Cabeza et al., 2020; Hicks et al., 2015). Although bibliometric studies have been conducted in niche areas such as cold spraying and regional temperature regulation (Abu Bakar et al., 2023; Meng et al., 2022), no comprehensive bibliometric analysis exists for spray cooling, particularly in relation to heat transfer science and thermal management. Table 1 summarises current bibliometric studies related to spray cooling.

Previous review studies have predominantly centred on the authors’ theoretical and experimental insights into spray cooling, delivering comprehensive elaborations from multiple dimensions, including heat transfer mechanisms, surface microstructures, working fluids and functional additives. In contrast, the distinctive contribution of this paper is its pioneering exploration of the spray cooling field from a bibliometric perspective. Clustering analysis performed with the Linlog/modularity algorithm in VOSviewer yielded valuable empirical conclusions. This comprehensive quantitative insight represents a core merit that cannot be achieved through traditional qualitative review approaches. Notably, this study pioneers the first customised bibliometric analysis specifically targeting the heat transfer mechanisms and thermal management applications of spray cooling. In contrast to adjacent research domains such as cold spraying, the application of bibliometric methodologies in spray cooling research remains relatively underdeveloped. Bridging this critical research gap constitutes the core breakthrough direction of the present work.

Table 1 A summary of bibliometric analyses on spray cooling

Author	*Applications*	*Key findings*
Mehmood et al. (2022)	Material engineering	Cold spray coating has potential applications in aircraft components, medical implants and protective coatings yet it has received limited research attention, especially in the context of brittle materials, underscoring the necessity of further studies in this field.
Nugroho et al. (2025)	Surface engineering	While plasma spraying and high-velocity oxygen fuel (HVOF) dominate, emerging eco-friendly spray techniques and AI-assisted designs constitute fewer than 10% of studies, indicating future research opportunities.
Meng et al. (2022)	Environmental control	Spray height was identified as a key factor governing heat transfer efficiency, while the operating water pressure of the apparatus was regulated within the interval of 2–6 MPa. It was found that the synergistic effect of high pressure and small-diameter nozzles could enhance the spray performance markedly.

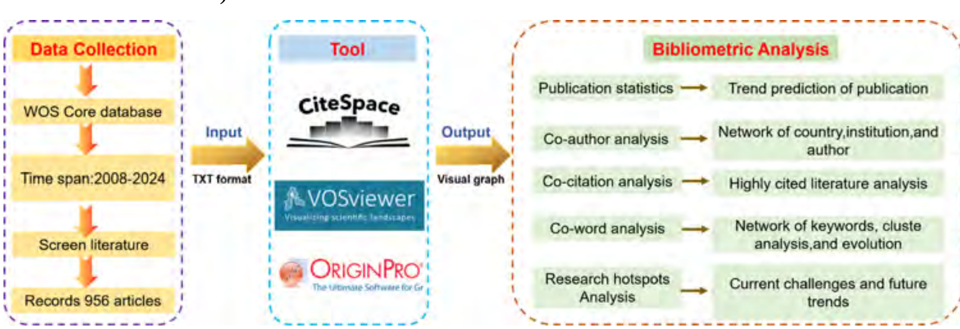
The sections of this paper are organised as follows: Section 2 details the data sources and research methodology, including the research framework, retrieval strategy, and selection criteria. Section 3 presents a comprehensive analysis of the evolution of spray cooling literature from 2008 to 2024, focusing on the relationships, contributions, and influence of countries, institutions, authors, and journals. Section 4 discusses development trends in spray cooling and provides targeted recommendations.

2 Methodology

2.1 Data source and search criteria

The bibliographic dataset was obtained from the Web of Science Core Collection (Clarivate Analytics, accessed in July 2025), a widely used and standardised database for bibliometric research (Zhou et al., 2019). The search was limited to peer-reviewed journal articles and review papers, excluded conference proceedings, book chapters, editorial materials, and other non-research document types to ensure consistency and quality.

Figure 1 Flowchart of paper selection process and visual analysis workflow (see online version for colours)



A systematic and reproducible search strategy was employed to retrieve publications directly relevant to spray cooling. The primary query string was: TS = (‘spray cooling’ OR ‘cryogen spray cooling’ OR ‘spray evaporation’ OR ‘spray boiling’ OR ‘droplet impingement cooling’ OR ‘impinging spray’ OR ‘mist cooling’ OR ‘atomised cooling’) AND TS = (‘heat transfer’ OR ‘high heat flux’ OR ‘thermal management’) with the publication period defined from 1 January 2008 to 31 December 2024. The initial search retrieved 962 records, of which 956 articles remained after excluding non-English articles. For bibliometric analysis, bibliographic information (including titles, authors, abstracts, keywords, and citation information) was exported in *full record and cited references* format.

As shown in Figure 1, deduplication was conducted by CiteSpace, confirming that no duplicate entries were present. The cleaned dataset was subsequently prepared for bibliometric mapping and knowledge-domain visualisation.

2.2 Bibliometric analysis and visualisation

Bibliometric analysis was performed by CiteSpace (version 6.4.R1) (Chen, 2006) and VOSviewer (version 1.6.20) (Van Eck and Waltman, 2010). The extracted metadata included authors, keywords, institutional affiliations, countries/regions, journal sources, and cited references. Standard bibliometric indicators (such as, annual publication totals, citation frequencies, *H*-index, and betweenness centrality) were calculated to characterised temporal trends, disciplinary distribution, and leading contributors in spray cooling research. To investigate the intellectual structure and thematic evolution of the field, VOSviewer was employed to construct co-authorship, institutional and national collaboration networks, as well as keyword co-occurrence maps. CiteSpace was applied for keyword clustering analysis. Clustering is another technique used to enhance bibliometric analysis, aiming to form thematic clusters based on the type of analysis conducted (Donthu et al., 2021). Analysing the network clusters and tracking their evolution can provide insights into the emergence and development of a research field.

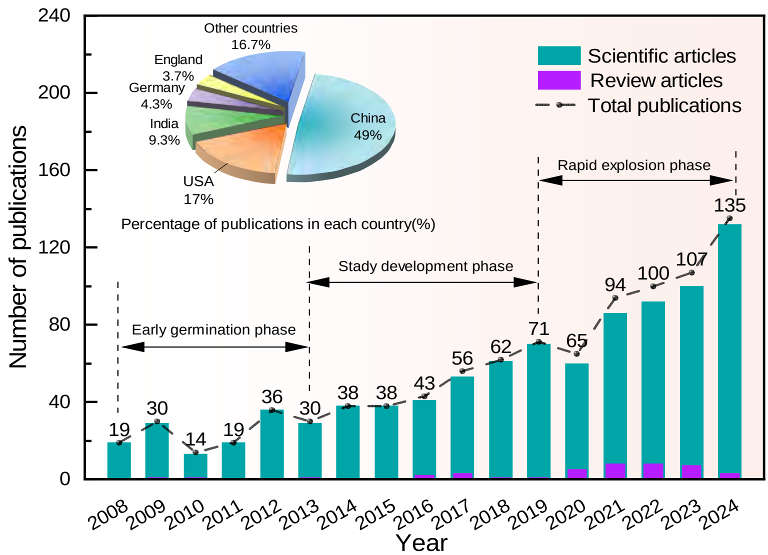
In the visualisations, node size represents either publication output or citation frequency (depending on the network type), link thickness indicates the strength of co-occurrence or collaboration, and node colour denotes cluster membership in VOSviewer or temporal segments in CiteSpace (Gao et al., 2019; Padilla et al., 2018). Cluster analysis groups related keywords or references into major research themes, while keyword evolution reveals emerging topics and shifts in research focus.

3 Results and discussion

3.1 An overview of publication trend analysis

Annual publication output is a widely used indicator of a research field’s activity, knowledge accumulation, and degree of maturity. Figure 2 illustrates the annual number of research and review articles on spray cooling from 2008 to 2024, revealing three distinct developmental phases. The field has exhibited steady growth, with a cumulative total of 956 papers indexed during this timeframe. Research papers have increased consistently, while review articles display a more irregular pattern, showing only moderate net growth over time.

Figure 2 Annual output and global distribution of spray cooling research (2008–2024) (see online version for colours)



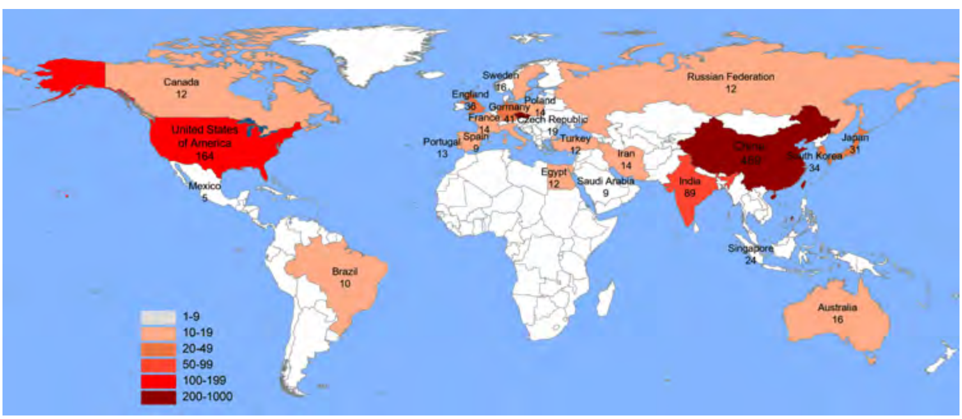
- *Early germination phase (2008–2013):* in this initial phase, publication volume was relatively modest, averaging about 25 articles per year. Annual output fluctuated considerably, indicating unstable growth. Most publications were research-focused, with relatively few review papers. This trend can be attributed to the fact that spray cooling was still in the theoretical exploratory phase of thermal management research, with the primary focus on developing experimental procedures. During this time, Silk et al. (2008) published an influential review that highlighted the application of spray cooling in spaceflight, laying the groundwork for subsequent investigations into its heat transfer mechanisms.
- *Steady development phase (2013–2019):* following the publication of two major review articles, spray cooling attracted increasing attention from the research community. Both research methodologies and theoretical foundations became more mature. For example, Liang and Mudawar (2017a) identified the critical spray fluid dynamics parameters influencing heat transfer performance and discussed enhancement strategies such as micro-and macro-scale surface modifications, liquid additives, and nanofluids. Cheng et al. (2016b) summarised research progress on spray cooling heat transfer mechanisms across three regimes (single-phase, two-phase, and CHF) and analysed influencing factors related to spray characteristics, heating surfaces, fluids, and external conditions. These studies demonstrated that application scenarios were expanding to fields such as electronic chips and energy equipment, while research themes shifted from basic mechanics to structural optimisation and application validation. This shift was driven primarily by the need to refine existing technologies rather than explore entirely new domains.
- *Rapid explosion phase (2019–2024):* the number of publications decreased in 2020, which was likely a consequence of the COVID-19 pandemic. Overall, the quantitative growth rate remains consistent with the previous period, yet this phase is

defined by a qualitative shift in research focus. Spray cooling has gained prominence in thermal management due to the growing demands of big data, artificial intelligence, cloud computing, and high-power electronic devices (Liu et al., 2023). Advances in micro/nano manufacturing have accelerated the translation of research into practical applications (Liu et al., 2025). This has led to a growing emphasis on interdisciplinary integration, combining spray cooling with bio-inspired materials, intelligent control algorithms, and multi-physics simulations. This shift reflects a move from optimising existing systems to enabling new technological paradigms, signalling a distinct evolution despite similar growth trends.

3.2 Countries/regions

Between 2008 and 2024, researchers from 58 countries contributed to publications on spray cooling. As shown in Figure 3, research output is unevenly distributed, with evident regional clustering. In the visualisation, darker red shades represent higher publication counts. The top five countries, namely China, USA, India, Germany, and England account for nearly 70% of the 672 research and review articles published during this period, underscoring China's leading role in advancing global spray cooling research.

Figure 3 Geographical distribution of publications on spray cooling (2008–2024) (see online version for colours)



To further examine international cooperation patterns, a scient metric collaboration network was constructed in Figure 4. In the network visualisation, node size indicates publication volume, node colour reflects average publication year (with darker shades denoting earlier activity), circle distance represents collaboration strength, and link thickness denotes cooperation frequency between countries or regions (Chen et al., 2023; Liu et al., 2020). The results show that China is the most active country, followed by the USA, England, Germany, and India.

Table 2 lists the top ten countries and regions ranked by publication count. China (469 papers), USA (87 papers), and India (80 papers) occupy the top three positions. This suggests that China, USA, and India dominate the global spray cooling landscape. Chinese scholars alone account for over 50% of publications in this field and rank among the highest in terms of international collaboration intensity. China is also the most central node in the collaboration network, followed by the USA, England, India, and Australia.

These countries are at the forefront of spray cooling research, with China, USA, and India playing key roles in fostering international collaboration. Looking ahead, experts from China, USA, and India are likely to remain crucial collaborators. Although Australia produces fewer articles than England, its citation impact is comparable, indicating that Australian research exerts substantial influence and is closely aligned with emerging trends in the field. England, despite a lower publication and citation count, ranks third in total link strength, suggesting significant potential for further growth. To summarise, research activity and collaboration in spray cooling are expanding globally, encompassing countries at varying levels of economic development.

Figure 4 International cooperation network overlay map (see online version for colours)

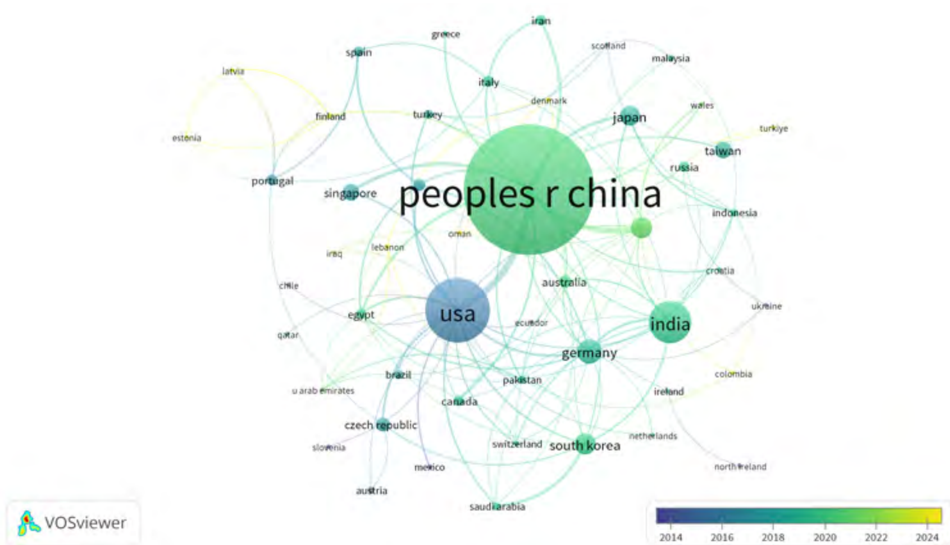


Table 2 Top-ten prolific countries in spray cooling

Rank	*Countries*	*Documents*	*Total link strength*	*Citation*	*Centrality*
1	China	469	93	10,290	0.63
2	USA	87	65	4,924	0.36
3	India	80	23	1,649	0.11
4	Germany	41	26	1,021	0.04
5	England	35	30	834	0.14
6	South Korea	34	20	578	0.01
7	Japan	31	12	433	0.02
8	Singapore	24	10	849	0.00
9	Czech Republic	19	8	266	0.03
10	Australia	16	11	813	0.06

3.3 Institutions

A comprehensive examination of research institutions highlights major contributions, the distribution of influence in spray cooling, and collaboration linkages. Seventy-five universities were selected for analysis based on a threshold of at least five publications. Figure 5 depicts the institutional collaboration network, where node connections indicate co-authorship between institutions. The visualisation shows that many leading Chinese universities (including Xi'an Jiaotong University, Dalian University of Technology, Chinese Academy of Sciences, and University of Science and Technology of China) form a tightly connected domestic cluster. In contrast, University of Illinois, Korea University, and Nanyang Technological University constitute a significant international collaboration group. Chinese Academy of Sciences exhibits the broadest collaboration, co-authoring with 14 other institutions. Xi'an Jiaotong University maintains particularly close ties with Chinese Academy of Sciences, Jiangsu University, and University of Akron.

Figure 5 Cooperation networks of institutions (see online version for colours)

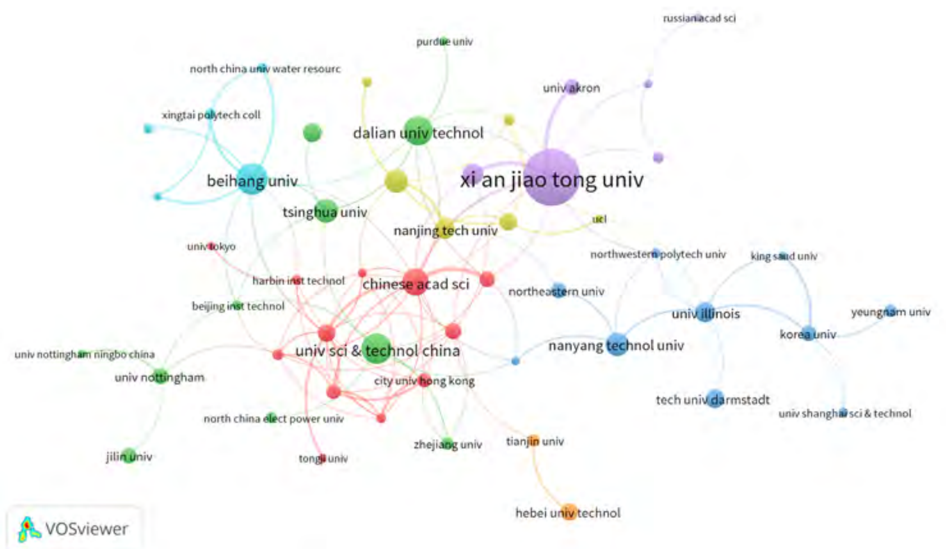


Table 3 ranks the top institutions by publication output. Xi'an Jiaotong University leads with 70 publications and 1,521 citations, followed by Chinese Academy of Sciences (57 publications, 1,834 citations) and Indian Institute of Technology System (48 publications, 1,082 citations). Notably, Dalian University of Technology produced only 27 publications but achieved 1,236 citations, largely due to two highly cited review papers by Liang and Mudawar (2017a, 2017b). In terms of betweenness centrality, only Xi'an Jiaotong University exceeds 0.2, indicating that international institutional cooperation remains limited, as also reflected in Figure 5. Greater cross-border collaboration is therefore anticipated, which would enhance the global sharing of research expertise and broaden research directions in spray cooling.

It is important to note that many articles are co-authored by researchers from multiple universities and countries, which may result in double-counting in publication statistics

(Wang et al., 2024a). However, this has little impact on identifying the most influential institutions within the field.

Table 3 Top ten institutions with the highest number of publications

Rank	*Institution*	*Country*	*Documents*	*Citation*	*Centrality*
1	Xi'an Jiaotong University	China	70	1,521	0.26
2	Chinese Academy of Sciences	China	57	1,834	0.15
3	Indian Institute of Technology System (IIT System)	India	48	1,082	0.08
4	Beihang University	China	35	993	0.02
5	National Institute of Technology (NIT System)	India	32	434	0.01
6	University of Science and Technology of China	China	31	1,353	0.02
7	Dalian University of Technology	China	27	1,236	0.05
8	National Institute of Technology Rourkela	India	23	303	0.01
9	Indian Institute of Technology (IIT Kharagpur)	India	22	620	0.00
10	Tsinghua University	China	21	810	0.01

3.4 Authors

Price's Law, formulated by Derek J. de Solla Price (the pioneer of scient metrics), is expressed as follows (Shao et al., 2003):

$$M = 0.794 \times \sqrt{N_{\max}} \tag{1}$$

where M denotes the minimum number of publications required by core authors in a given field, and $N_{\max}$ represents the maximum number of core authors in the field.

The statistical analysis in Table 4 indicates that $N_{\max} = 37$. Substituting this value into equation (1) yields $M = 4.82$. In spray cooling research, the threshold for identifying core authors is set at five publications. Figure 6 presents the collaboration network among researchers, where nodes represent authors, node size indicates publication count, and links indicate cooperative relationships between scholars, typically signifying the formation of research teams. The network reveals four major collaborative clusters: the red cluster led by Chen Bin and Zhou Zhifu, the green cluster led by Liu Xiufang and Hou Yu, the blue cluster led by S.S. Mohapatra, and the yellow cluster led by A.R. Pati. These clusters generally emerge through complementary expertise, shared resources, accumulated academic networks, and long-term collaboration (Larivière et al., 2015). Their development highlights the presence of strong partnerships and shared research interests in the field of spray cooling.

Table 3 presents the ten most prolific authors and their institutional affiliations, evaluated on the basis of publication count, total citations, and *H*-index. Chen Bin is the most productive author, with 37 papers, 853 citations, and an *H*-index of 18, demonstrating his substantial academic influence in spray cooling. Six of the top ten most frequently cited authors are from China, three from India, and one from Singapore, indicating China's significant contributions to the field. Notably, Chakraborty Sudipto, despite publishing only 20 papers, has received over 600 citations. His work demonstrated that the use of nanofluids as coolants accelerates the transition from transitional boiling to nucleate boiling. The enhancement in heat transfer is attributed to nanoparticle deposition on heated surfaces during cooling, coupled with the improved thermal conductivity of the base fluid.

Table 4 Statistical table of core author information

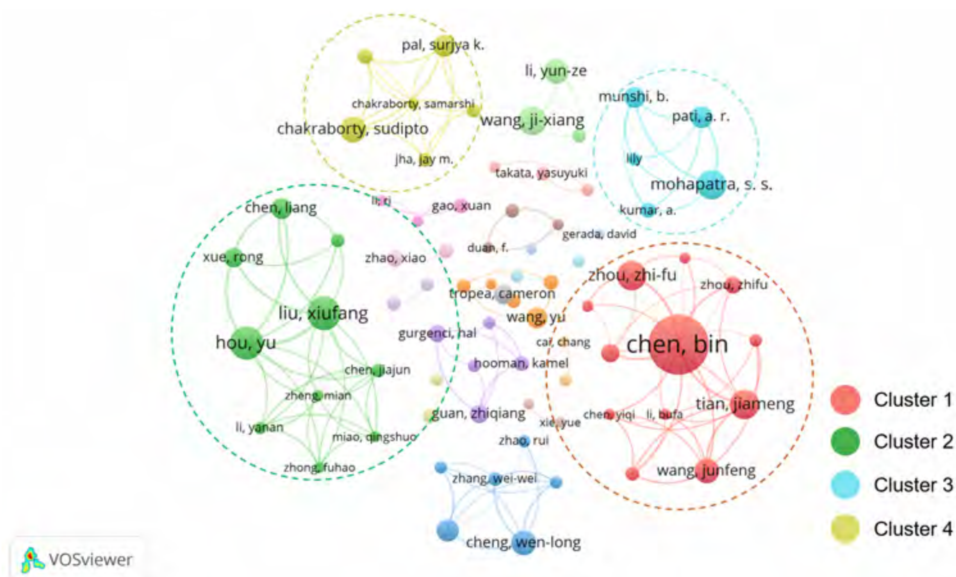
Rank	*Discipline*	*Institution*	*Countries*	*Documents*	*Citation*	*H-index*
1	Chen Bin	Xi'an Jiaotong University	China	37	853	18
2	Mohapatra Soumya	National Institute of Technology (NIT System)	India	27	424	12
3	Zhou Zhifu	Xi'an Jiaotong University	China	26	814	17
4	Wang Ting	Chinese Academy of Sciences	China	21	513	14
5	Chakraborty Sudipto	Indian Institute of Technology Kharagpur	India	20	600	14
6	Tian Jiameng	Jiangsu University	China	20	333	11
7	Surjya Kanta Pal	Indian Institute of Technology Kharagpur	India	18	591	14
8	Li YunZe	Beihang University	China	18	697	13
9	Wong Teck Neng	Nanyang Technological University	Singapore	16	694	16
10	Cheng Wenlong	University of Science and Technology of China	China	16	744	11

3.5 Analysis of journals and journal co-citation

Journals serve as primary media for disseminating academic knowledge and publishing research findings, acting as intermediaries that link research topics across different stages of the academic process (Shao et al., 2022). Dzikowski (2018) demonstrated that the frequency with which a book is cited in journal articles correlates positively with its scholarly influence. Consequently, we examined the 30 journals with the highest publication counts, as seen in Figure 7(a). *International Journal of Heat and Mass Transfer* ranks first, with 145 papers on spray cooling, followed by *Applied Thermal Engineering* with 137 papers, and *International Journal of Thermal Sciences* with 41 papers. These journals primarily publish advanced research on heat conduction, convection, radiation, phase change, mass transfer, multiphase flow, and their engineering applications.

To evaluate the relative influence of these journals, we applied the co-citation measure in VOSviewer [Figure 7(b)]. Connecting lines between journals indicate that their papers were co-cited in subsequent studies, with line thickness representing co-citation strength. The top three journals by co-citation frequency are *International Journal of Heat and Mass Transfer* (5,091 citations), *Applied Thermal Engineering* (4,355 citations), and *Experimental Thermal and Fluid Science* (953 citations). Beyond citation counts, the co-citation network was segmented into three clusters, each identified by a distinct colour. The red cluster consists of journals focusing on multiphase flow, heat and mass transfer, often cited for synthesising existing knowledge and providing direction for new research (Breitenbach et al., 2018; Cheng et al., 2016a). The blue cluster includes journals (such as *Energy Conversion* and *Management and Energy*) which emphasise renewable energy topics, including photovoltaic systems (Bevilacqua et al., 2020) and solar thermal power (Ge et al., 2018). The green cluster comprises journal (such as, *Physics of Fluids* and *Langmuir*), which concentrate on spray dynamics, fragmentation processes, multiphase flow modelling (Ray et al., 2023), and nanofluid interface behaviour (Aksoy et al., 2022). Collectively, these journals are globally recognised and constitute the most frequently cited sources in spray cooling research.

Figure 6 Co-citation knowledge spectrum of core authors (see online version for colours)



3.6 *Keywords clustering analysis*

Keywords are selected by authors through an analysis of the entire study, providing a concise summary of the research focus and its relevance to specific areas of interest. Co-occurrence analysis of keywords is a crucial method for identifying research hotspots in scientific fields (Cui et al., 2025). Using VOSviewer software, a minimum occurrence threshold of 10 yielded 144 valid keywords. Figure 8 depicts the co-occurrence network and the overlay visualisation of keywords extracted from publications on spray cooling.

The research on spray cooling can be categorised into five thematic clusters based on keywords analysis, as shown in Figure 8(a). The colour of each node represents its corresponding cluster. These studies focus on enhancing the density of nucleation sites, promoting capillary-driven rewetting, and establishing discrete pathways for liquid and vapour phases. Together, these mechanisms improve boiling heat transfer by increasing the CHF and heat transfer coefficient (HTC), while reducing the onset superheat for nucleate boiling (Wen et al., 2017). Previous studies also indicate that multi-scale micro/nano structured surfaces can increase the Leidenfrost temperature, delay vapour film formation, and mitigate the dynamic Leidenfrost (DLF) effect (Guo et al., 2024; Talari et al., 2018).

Figure 7 Most productive journals and co-citation mapping, (a) top 30 journals by publication count (b) co-citation network visualised with VOSviewer (see online version for colours)

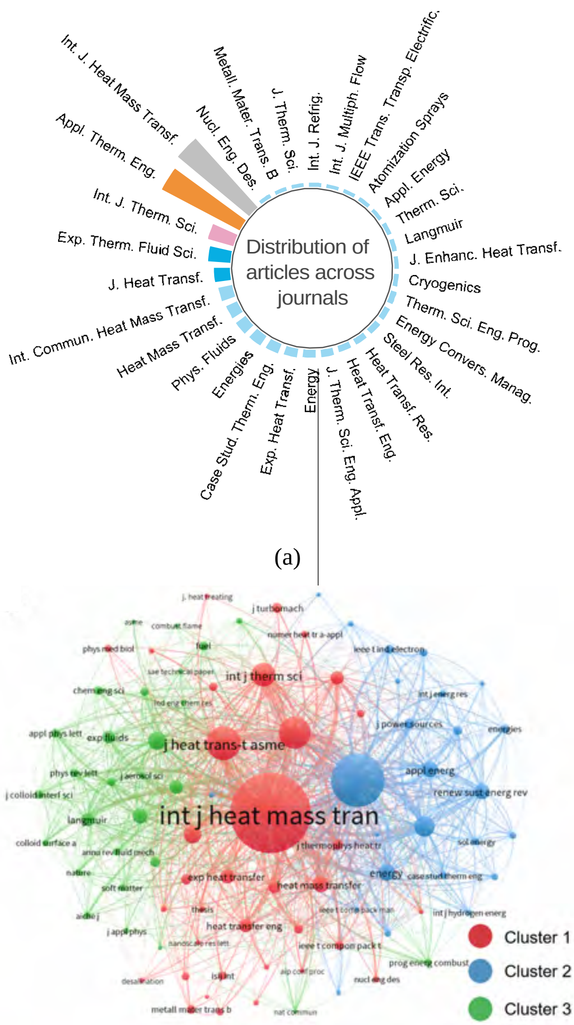
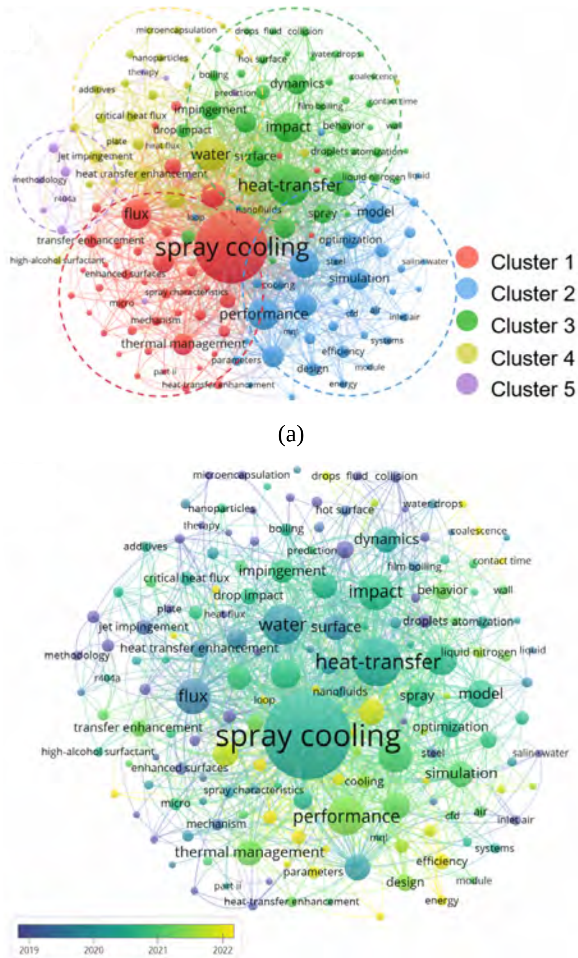


Figure 8 VOSviewer keywords co-occurrence network, (a) thematic clusters (b) hotspot overlay (see online version for colours)



(a)

(b)

The blue cluster, defined by keywords (such as *simulation* and *performance*), reflects the growing use of numerical modelling in spray cooling research. Techniques such as computational fluid dynamics, lattice Boltzmann methods, and multi-physics coupling are applied to elucidate the dynamics of droplet-surface interactions, liquid film formation, and phase-change processes. The discrete phase model in ANSYS Fluent allows precise control of spray parameters (such as cone angle, droplet size distribution, and impact velocity). The integration of predictive models with experimental optimisation enables improved HTC, more uniform temperature and film distribution, and superior CHF performance under extreme thermal conditions. Figure 8(b) highlights this cluster in yellow, marking it as a leading research trend in spray cooling.

In the green cluster, researchers employ high-speed visualisation techniques, such as particle image velocimetry, to capture droplet impact dynamics and liquid layer evolution during spray cooling. These investigations demonstrate the influence of droplet spreading, splashing, and rewetting on local heat transfer efficiency (Bao et al., 2019). Complementary simulations using VOF and level set methods to track the liquid-vapour interface reveal correlations between splash crown shape, liquid film thickness fluctuations, and the Weber number of droplets (Jin et al., 2021). Collectively, these experimental and numerical approaches provide a strong foundation for investigating film thickness and interface dynamics in spray cooling systems.

The yellow cluster emphasises the selection and optimisation of working fluids, including water (Chen et al., 2024), additives (Wang et al., 2016), nanofluids (Marseglia et al., 2022), and microencapsulated phase change materials (Zhang et al., 2024). Enhancing heat transfer efficiency depends on optimising key thermophysical parameters, such as specific heat capacity, thermal conductivity, surface tension, and latent heat. Nanofluids, owing to their superior thermal conductivity and capillary-driven rewetting, have been shown to improve CHF and HTC in spray cooling applications (Ma et al., 2024; Ramesh and Prabhu, 2011).

The final cluster highlights medical applications of spray cooling, with keywords including port wine stain, R134a, R404a, skin, and therapy. This research explores short-duration cryogen spray cooling for protecting skin tissue, thereby enhancing therapeutic outcomes and reducing thermal damage during procedures such as laser treatment and hair removal (Aguilar et al., 2001; Zhou et al., 2016). Spray cooling has thus become a widely adopted technique in dermatology and aesthetic medicine.

3.7 Analysis of highly cited publications

Table 5 lists the ten most frequently cited publications that have significantly influenced spray cooling research. By analysing these studies and their principal findings, we highlight the pioneering contributions that have shaped the field. Their high citation counts underscore their broad impact and academic importance.

The top ten papers can be grouped into three research categories according to their subject matter:

3.7.1 Topic 1: review and mechanistic studies

Liang and Mudawar (2017a) conducted a comprehensive review of single-phase and nucleate boiling mechanisms in spray cooling, with emphasis on heat transfer enhancement strategies such as surface modification, liquid additives, and nanofluids. They also summarised CHF prediction models proposed by various research groups. A follow-up review by Liang and Mudawar (2017b) focused on transition boiling and film boiling at elevated temperatures, including discussions of the Leidenfrost point. Together, these two reviews have been cited more than 760 citations. Breitenbach et al. (2018) examined heat transfer characteristics of spray impact based on single-drop impact studies, linking microscale mechanisms with macroscale models, thereby advancing theoretical development in spray cooling.

3.7.2 Topic 2: application expansion and system integration

Habibi Khalaj and Halgamuge (2017) conducted a cross-scale assessment of air and liquid based cooling technologies for data centres, emphasising system-level energy efficiency optimisation. Saw et al. (2018) applied mist cooling to lithium-ion battery packs, demonstrating that it provides lower and more uniform temperature distributions than dry air cooling, suggesting its potential for energy storage systems. Li et al. (2024) concentrated on chip-level thermal management, identifying key challenges and proposing methods to enhance performance in chip-level thermal management.

Table 5 Top ten references with the highest co-citations

No.	*Authors*	*Title*	*Citation*	*Citation per year*
1	Liang and Mudawar (2017a)	Review of spray cooling – part 1: single-phase and nucleate boiling regimes, and CHF.	444	49.33
2	Habibi Khalaj and Halgamuge (2017)	A review on efficient thermal management of air-and liquid-cooled data centres: from chip to the cooling system.	428	47.56
3	Cheng et al. (2016a)	Spray cooling and flash evaporation cooling: the current development and application.	286	28.6
4	Breitenbach et al. (2018)	From drop impact physics to spray cooling models: a critical review	266	33.25
5	Liang and Mudawar (2017b)	Review of spray cooling – part 2: high temperature boiling regimes and quenching applications.	237	26.33
6	Saw et al. (2018)	Novel thermal management system using mist cooling for lithium-ion battery packs	227	27.38
7	Huang et al. (2022)	Thermal management of polymer electrolyte membrane fuel cells: a critical review of heat transfer mechanisms, cooling approaches, and advanced cooling techniques analysis.	132	33
8	Xu et al. (2022)	Spray cooling on enhanced surfaces: a review of the progress and mechanisms	105	26.65
9	Sarkar et al. (2023)	Review of jet impingement cooling of electronic devices: emerging role of surface engineering.	101	33.67
10	Li et al. (2024)	Comprehensive review and future prospects on chip-scale thermal management: core of data centre's thermal management.	62	31

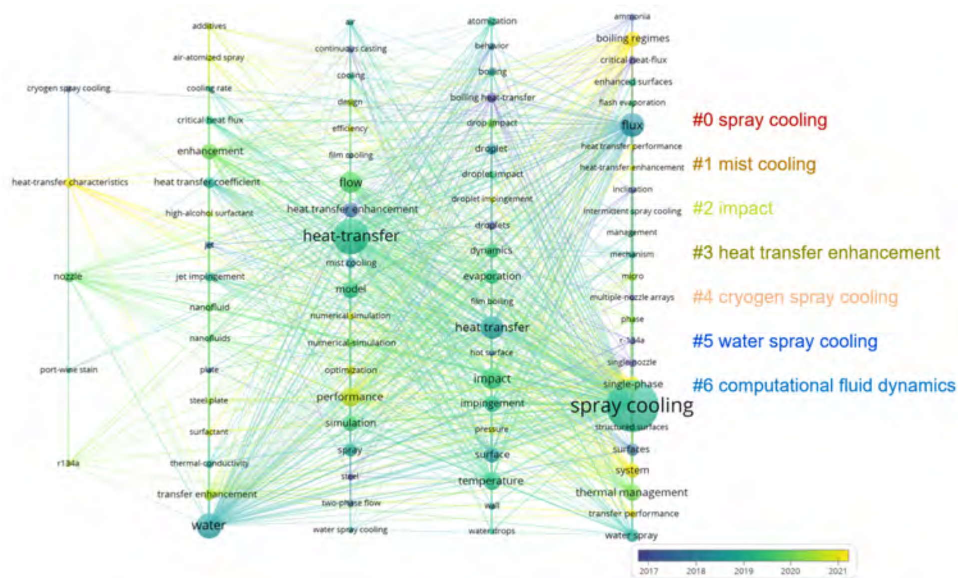
3.7.3 Topic 3: advanced working fluids and special applications

Cheng et al. (2016a) reviewed spray and flash cooling techniques, which emphasis on phase-change enhanced working fluids such nanofluids. They noted that the lack of consensus on nanofluid heat transfer properties in spray cooling and highlighted the need for future research on stable nanofluids and suitable nanoparticles. Huang et al. (2022) investigated spray/atomisation cooling for polymer electrolyte membrane fuel cells, demonstrating its benefits for thermal management. Xu et al. (2022) analysed spray cooling performance on surfaces with different structural sizes, including hybrid micro/nano structures. Sarkar et al. (2023) provided a review of surface engineering advances for jet impact cooling and discussed its potential industrial applications.

3.8 *Analysis of keywords evolution*

A keyword co-occurrence analysis was performed using the log-likelihood ratio clustering method, which identifies term groupings based on uniqueness and coverage. The analysis produced eight major clusters, with a modularity Q value of 0.4191 (> 0.3) and a mean silhouette score of 0.7568 (> 0.5), indicating a well-structured and robust clustering configuration. Figure 9 presents the keyword timeline from 2008 to 2024, showing the chronological emergence, persistence, and decline of research themes.

Figure 9 Keyword timeline view of spray cooling research (2008–2024) (see online version for colours)



The evolution of keywords in Clusters #0 and #1 is very similar, both emphasising nozzles, surface structures, heat flow, and heat transfer performance. In 2022, the rise of new energy vehicles brought ‘electric vehicles’ into prominence as a research hotspot in spray cooling. This reflects how technological development responds to market and policy drivers. The Chinese Government has introduced multiple regulations and incentives to promote the growth of the new energy vehicle industry, including subsidies, tax exemptions, and preferential policies for electric vehicle ownership (Wang et al., 2017a). These measures have led to substantial progress, positioning China as a key player in shaping the future of global transportation (Dong and Liu, 2020; Wang et al., 2022a; Zhang et al., 2013a). In the future, integrating spray cooling into electric drive system thermal management, particularly in extreme charge/discharge cycles and high-power impact thermal load scenarios, will remain a critical research and engineering challenge.

Keywords in Cluster #2, such as hot surface and liquid film, reflect growing interest in droplet – surface interactions under high heat flux conditions, especially in relation to film formation and its effect on cooling efficiency (Bhatt et al., 2017; Labergue et al., 2016).

Cluster #3 explores strategies for enhancing heat transfer, broadly classified into two categories: surface enhancement and working fluid modification. Surface modification techniques include the addition of needle ribs, fabrication of micro/nano structures, and application of surface coatings, all of which improve droplet spreading, nucleation site density, and liquid film rewetting, thereby enhancing both HTC and CHF (Zhang et al., 2015). Working fluid optimisation involves incorporating functional additives (e.g., surfactants or ionic liquids) or developing nanofluids to regulate surface tension, liquid film stability, and interfacial heat resistance (Ge et al., 2024). With advances in materials science and fluid mechanics, such methods increasing rely on multi-mechanism coupling. In the future, the research will focus on improving heat transfer performance while ensuring fluid stability and reducing maintenance costs.

Cluster #4 introduces terms such as skin, port wine stain, and therapy, signalling the emergence of cryogen spray cooling in dermatological applications, particularly for vascular lesion treatment. Research in this cluster emphasised experimental observation and basic model development, laying the theoretical foundation for subsequent mechanistic and application-driven studies.

Cluster #5 emphasises water spray cooling in relation to temperature control, thermal comfort, and performance enhancement, highlighting its potential to reduce building energy consumption and mitigate extreme environmental conditions (Wang et al., 2022b).

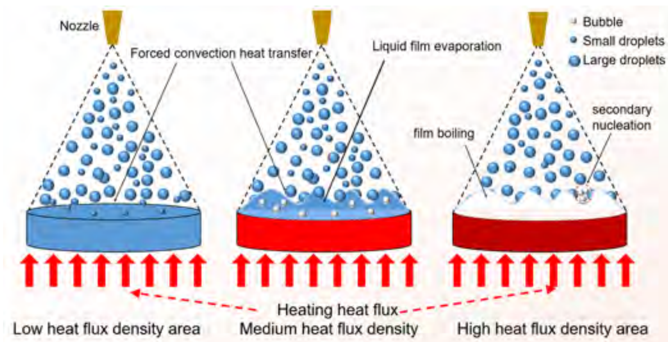
Cluster #6 demonstrates the central role of computational fluid dynamics in designing and analysing spray cooling systems. In the non-boiling area, the Euler-Lagrange wall film model is typically utilised alongside breakup, evaporation, and heat transfer models to quantitatively predict local HTC and liquid film evolution. Notably, recent simulations incorporating mechanical vibrations (Luo et al., 2023) revealed that vibrations significantly influence heat transfer performance in the non-boiling region by altering liquid film thickness fluctuations and rewetting frequency.

4 Analysis of research hotspots

4.1 Thermal concerns of spray cooling technology

Figure 10 depicts the heat transfer mechanism of spray cooling over a range of heat flux densities. At low heat flux intensity, the impacting droplet mainly undergoes a single-phase cooling process on the surface, which leads to a negligible phase transition and limited heat absorption activity. An increase in heat flux density dramatically strengthens the coupling of heat flow and phase changes upon droplet impact onto the wall surface, inducing complex phase transition behaviours and oscillatory switches between various boiling states, including liquid film evaporation, nucleates boiling, transitional boiling, and film boiling phenomena. This change is attributed to the inherent differences in heat transfer mechanisms between single-phase and two-phase zones: in the single-phase zone, heat transfer is predominantly dictated by convective heat transfer between the liquid film formed after droplet impact and the wall surface. However, in the two-phase zone, localised evaporation of the liquid and bubble formation enable latent heat exchange, leading to a dramatic elevation of cooling efficiency. As the wall temperature rises, droplets impinging on the highly heated surface will undergo instantaneous vaporisation, forming a stable gas layer that prevents droplets from coming into direct contact with the solid surface. This phenomenon is known as the DLF effect (Shirota et al., 2016). This gas layer is found to exhibit dramatic insulating properties, inducing a steep increase in thermal resistance and a rapid decline in heat transfer efficiency. Thus, the enhancement of DLF, involving the extension of gas film duration or the increase in its critical temperature, has become a central theme in the investigation of spray cooling under high heat flux density conditions.

Figure 10 Heat transfer mechanisms of spray cooling with varying heat flux densities (see online version for colours)



To overcome the problem of the degraded heat transfer efficiency induced by the DLF, several studies have systematically investigated different suppression methods (such as, fabricating micro/nanostructured surfaces with superior wettability and capillary transport (Kwon et al., 2013; Limbeek et al., 2016; Zhang et al., 2023); utilising electric fields to suppress air film formation (Shahriari et al., 2014); imposing low-frequency mechanical vibrations to break up the air film (Ng et al., 2014), and introducing surfactants to change chemical surface tension and wetting behaviour (Chen et al., 2018) to suppress the DLF effect.

The creation of micro/nanostructured surfaces with high performance has attracted extensive attention from researchers owing to its high process maturity, good controllability and repeatability, and high stability (Ali et al., 2018; Du et al., 2023). Micro/nano-structured surfaces have become a hot topic in heat transfer scale research in academia. Millimetre-scale features, such as fins, enable uniform liquid film distribution and enhance evaporation efficiency by increasing the length of the tri-phase contact line (Sodtke and Stephan, 2007). Nanoscale super-hydrophilic structures, such nanopillars, promote rapid re-wetting and thinning of the liquid layer, and thereby increase capillary-driven evaporation (Alvarado and Lin, 2011). Porous structures, such as foam copper (De Souza and Barbosa, 2012), foam graphite (Silk and Bracken, 2010), and copper micromesh (Hu et al., 2022), provide abundant nucleation sites due to their high specific surface area and various random multi-scale voids, and hence, decrease the surface superheat required for boiling onset and dramatically improve HTC.

It should be noted that while microporous structures can significantly increase the number of nucleation sites and promote nucleate boiling, the increased flow resistance they bring about may hinder bubble egress, with bubbles being trapped in the pore cavities and forming local steam blankets, thereby posing a significant challenge to the CHF. Recently, Hu et al. (2025b) recently proposed a new microporous structural design that significantly promotes nucleate boiling and allows efficient bubble egress, realising gas-liquid channel separation and significantly improving the overall performance of spray cooling. Micro-pores can be combined with multi-scale structures (such as, nano-textures and capillary channels), in the future to synergistically intensify nucleation sites, accelerate the rapid re-wetting of the liquid layer, and optimise bubble escape channels. In addition, additive manufacturing or micro/nano manufacturing technologies can be employed to carefully control pore size, depth, and distribution to adapt to different spray intensities and heat flux densities.

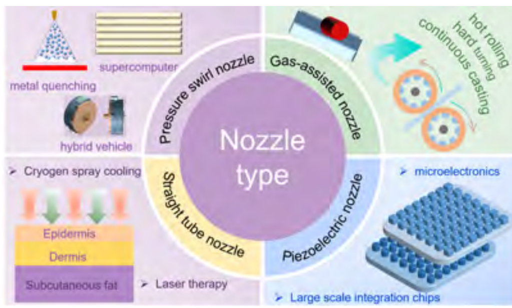
4.2 Influence and optimisation of spray cooling performance

In spray cooling, the cooling rate is a critical parameter for evaluating heat transfer efficiency, which can directly affect heat flux, HTC, and thermal surface management. Recent advances in processing technology have extended the focus beyond performance evaluation to include micro/nano scale mechanism analysis, particularly under high heat flux density conditions such as heat treatment, laser processing, and electronic device cooling. Enhancing cooling rates and maintaining uniform surface temperature have therefore become major research priorities.

Spray parameters are key factors that determine cooling performance. Spray height governs droplet distribution on the heated surface; reduced heights promote liquid film formation and enhance heat transfer (Zhang et al., 2013b). Droplet size influences evaporation and heat transfer rates, facilitating capillary-driven processes regulated by surface tension (Muthukrishnan et al., 2023). Impact velocity exerts the greatest effect on CHF (Chen et al., 2002). Spray angle determines the coverage area, while wider angles increase surface coverage, they reduce droplet velocity, necessitating a balance between cone angle and impact speed (Yu et al., 2025). The nozzle type [such as, pressure swirl nozzle (Xie et al., 2014), gas-assisted nozzle (Li et al., 2020), and straight tube nozzle (Xue et al., 2021), etc.] controls the spatial uniformity of droplet distribution. Different atomisation methods and droplet characteristics make certain nozzles more suitable for specific scenarios, as shown in Figure 11. Therefore, nozzle selection must be tailored to application-specific requirements to optimise performance.

Energy optimisation encompasses both efficiency improvement and quality enhancement. Niksiar and Rahimi (2009) investigated spray cooling performance via energy and exergy analyses, demonstrating high energy efficiency but relatively low exergy efficiency that is closely linked to tower structure. Specifically, larger tower diameter, greater height, and higher water flow rate collectively enhance exergy destruction. Similarly, Jani et al. (2016) employed exergy analysis, deriving the entropy generation rate of each component through entropy balance equations to quantify exergy destruction and efficiency. This approach enabled the identification of key exergy-loss components, providing actionable guidance for system optimisation. Looking ahead, integrating machine learning with multi-objective optimisation algorithms to construct cooling performance response surfaces from experimental data or simulations will be vital for improving system design efficiency (Deshannavar et al., 2024). Although AI-assisted optimisation studies in spray cooling remain limited, similar high heat flux cooling technologies (such as microchannel heat sinks) have successfully employed machine learning and multi-objective optimisation to achieve significant performance gains. For instance, Sikirica et al. (2022) reported a 10% reduction in maximum surface temperature and a 25% decrease in pumping power relative to baseline designs. Jani (2021) developed an artificial neural network (ANN) model for solid desiccant-steam compression hybrid air conditioning systems to predict the system's cooling capacity, power input, and coefficient of performance. Yu et al. (2024) developed a multi-objective optimisation framework using a genetic algorithm. Their results showed that compared to traditional microchannel, the optimised designs exhibited superior thermal performance. These findings suggest that comparable data-driven optimisation frameworks could be adapted for spray cooling systems, where parameter interactions are highly complex and experimental trials are resource-intensive.

Figure 11 Types of nozzles and their usage across several domains (see online version for colours)



4.3 *Clinical applications of cryogen spray cooling*

The increasing use of laser-based treatments in dermatology and cosmetic medicine has raised a critical challenge, optimising therapeutic efficacy while minimising iatrogenic thermal injury (Dewhirst et al., 2015). Cryogen spray cooling has emerged as a promising solution. The fundamental mechanism involves applying a low-temperature working fluid (e.g., R134a or R404a) onto the skin surface immediately before or during laser irradiation to achieve rapid cooling, thus reducing epidermal temperature and protecting healthy tissue from laser-induced thermal damage (Dai et al., 2025). Because of the high latent heat associated with cryogen evaporation, intense evaporative cooling can reduce epidermal temperature within milliseconds, which is faster than the characteristic thermal diffusion time to deeper tissues. This effect protects the epidermis while allowing efficient laser energy delivery to targeted structures. Consequently, cryogen spray cooling enables selective penetration of laser energy through the epidermis to pathological tissues or adipose layers, providing significant benefits in treating superficial vascular anomalies such as port wine stains (Tunnell et al., 2002).

In recent years, cryogen spray cooling has been applied to more advanced therapeutic procedures, including laser lipolysis (Xin et al., 2022, 2023); laser cartilage reshaping (Wu et al., 2013) and laser skin resurfacing (Majaron et al., 2001b). A central research challenge in these applications is controlling the cooling depth to selectively destroy target tissue without damaging surrounding structures. On the one hand, factors [such as environmental humidity (Majaron et al., 2001a), droplet characteristics (Pikkula et al., 2004), spray duration (Aguilar et al., 2003), and nozzle angle (Aguilar et al., 2004)] directly influence the cooling rate and efficiency of cryogen spray cooling. On the other hand, the skin's multilayered composition (including the epidermis, dermis, and subcutaneous fat) introduces spatial complexity to temperature distribution (Dai et al., 2025). To address this, the bio-heat transfer model (Pennes, 1998), thermal damage criterion for skin tissue (Henriques and Montz, 1947), and numerical simulations (Wang, et al., 2017b) have been employed to predict temperature variation at different depths, assess temporal and spatial tissue responses and optimise cooling strategies (Xin et al., 2023).

Future research is expected to emphasise precision cooling and personalised therapy. Real-time regulation of cryogen spray cooling maybe achieved by integrating infrared thermal imaging, thin film thermocouples, and other sensing technologies to provide temperature feedback during treatment. For instance, Qenawy et al. (2024) developed an intermittent strategy to reduce film deposition, enhance heat transfer and reduce cryogen consumption by coupling with a cold air jet. Their results demonstrated that this approach achieved lower minimum surface temperatures and reduced thermal resistance of the residual film. At the same time, comprehensive evaluation of working fluids (including vaporisation characteristics, dermal compatibility, and ecological sustainability) will be essential for advancing the clinical translation and long-term viability of cryogen spray cooling.

5 Limitations

Acceptance of research findings requires careful consideration of study limitations. This study focused exclusively on scientific and review papers published in English in the Web of Science Core Database. Consequently, relevant studies published in other languages, indexed in different databases, or presented at conferences may have been overlooked. Nonetheless, this study contributes to the literature by offering a comprehensive assessment of spray cooling research (including, publishing trends, current state, and future directions). The strong scientific foundation of the selected studies, combined with the application of rigorous quantitative and qualitative methods, enhances the validity of this study and mitigates the aforementioned limitations.

6 Conclusions and prospects

This study employed the bibliometric tools (CiteSpace and VOSviewer) to systematically analyse the research topics, hotspots, and trends in spray cooling, thereby providing valuable insights for researchers in the field. A total of 956 papers published between 2008 to 2024 in the Web of Science Core Database were examined, and a knowledge domain map was constructed by information visualisation technology. Several conclusions can be drawn.

1 Publications related to spray cooling have shown a steady upward trend, particularly after 2020. As the world’s top three countries in publication volume, China, the USA, and India have delivered significant contributions to this research domain. Institutional research mapping indicates that Xi’an Jiaotong University leads the field in both the number of publications and citation counts. Influential scholars include, Chen Bin, Mohapatra Soumya, Zhou Zhifu, Wang Ting, Chakraborty Sudipto, and Tian Jiameng. Additionally, core journals in spray cooling include *International Journal of Heat and Mass Transfer, Applied Thermal Engineering* and *International Journal of Thermal Sciences.*

2 Keyword analysis revealed persistent themes (such as, spray cooling, droplet impact, enhanced heat transfer, and computational fluid dynamics). Enhanced heat transfer has been a primary focus of spray cooling, and is frequently cited in the literature. Keyword evolution further indicates that research has shifted from macro-scale investigations toward to micro/nano-scale advancements. Among cited works, Liang and Mudawar (2017a) received the most attention for its systematic review of single-phase and nucleate boiling mechanisms, enhanced heat transfer strategies, and its valuable guidance for future research.

3 Prospective trends in spray cooling include:

   a integration of machine learning and deep learning for real-time system regulation under varying heat flux densities and environmental conditions

   b the use of micro/nano-structured surfaces, functional coatings, and 3D printing to precisely control droplet dynamics and improve heat transfer efficiency

   c the expansion of applications beyond traditional electronic chip cooling into aerospace, high-performance architecture, medical aesthetics, and other domains.

Overall, substantial advancements have been achieved in spray cooling research, yet several critical challenges persist. Most current studies, for example, we analysed papers published from 2008 to 2024 and found that most spray cooling research relies heavily on experiments, with relatively few numerical simulations. This is partly because simulating spray cooling is complex and demands significant computational resources. Additionally, spray cooling involves droplet breakup, collision, evaporation, condensation, and coupled heat transfer between gas, liquid, and solid phases. Existing models (such as VOF, level set and Eulerian-Lagrange coupling models) struggle to balance computational efficiency and accuracy. Future research should focus on multiscale simulations that bridge microscopic droplet dynamics with macroscopic heat transfer characteristics, thereby addressing the scale adaptation shortcomings of existing models.

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Declarations

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abu Bakar, I.A., Omar, N.I., Yusuf, Y. and Abdul Rahim, T. (2023) 'Reflection and future perspectives in cold spray technology: a bibliometric analysis', *Journal of Thermal Spray Technology*, Vol. 32, No. 6, pp.1576–1595.

Aguilar, G., Majaron, B., Viator, J., Basinger, B., Karapetian, E., Svaasand, L., Lavernia, E. and Nelson, J. (2001) 'Influence of spraying distance and postcooling on cryogen spray cooling for dermatologic laser surgery', *Proc SPIE*, Vol. 4244, pp.82–92.

Aguilar, G., Vu, H. and Nelson, J.S. (2004) 'Influence of angle between the nozzle and skin surface on the heat flux and overall heat extraction during cryogen spray cooling', *Physics in Medicine & Biology*, Vol. 49, No. 10, pp.147–153.

Aguilar, G., Wang, G.X. and Nelson, J.S. (2003) 'Effect of spurt duration on the heat transfer dynamics during cryogen spray cooling', *Physics in Medicine & Biology*, Vol. 48, No. 14, pp.2169–2181.

Aksoy, Y.T., Liu, L., Abboud, M., Vetrano, M.R. and Koos, E. (2022) 'Role of nanoparticles in nanofluid droplet impact on solid surfaces', *Langmuir*, Vol. 39, No. 1, pp.12–19.

Ali, H.M., Qasim, A., Malik, S. and Murtaza, G. (2018) 'Techniques for the fabrication of super-hydrophobic surfaces and their heat transfer applications', in Volkov, K. (Ed.): *Heat Transfer – Models, Methods and Applications*, IntechOpen, Rijeka.

Alvarado, J.L. and Lin, Y-P. (2011) 'Multiple droplet impingements on nanostructured surfaces for enhanced spray cooling', *ASME/JSME Thermal Engineering Joint Conference,* p.T10241.

Bao, J., Wang, Y., Xu, X., Niu, X., Liu, J. and Qiu, L. (2019) 'Analysis on the influences of atomization characteristics on heat transfer characteristics of spray cooling', *Sustainable Cities and Society*, Vol. 51, p.101799.

Bellomo, L., Marini, G., Benedetto, M.D., Lidozzi, A. and Solero, L. (2025) 'Performance evaluation for advanced two-phase cooling for power electronic converters', *2025 International Conference on Clean Electrical Power (ICCEP),* pp.398–403.

Bevilacqua, P., Bruno, R. and Arcuri, N. (2020) 'Comparing the performances of different cooling strategies to increase photovoltaic electric performance in different meteorological conditions', *Energy*, Vol. 195, p.116950.

Bhatt, N.H., Lily, Raj, R., Varshney, P., Pati, A.R., Chouhan, D., Kumar, A., Munshi, B. and Mohapatra, S.S. (2017) 'Enhancement of heat transfer rate of high mass flux spray cooling by ethanol-water and ethanol-tween20-water solution at very high initial surface temperature', *International Journal of Heat and Mass Transfer*, Vol. 110, pp.330–347.

Breitenbach, J., Roisman, I.V. and Tropea, C. (2018) 'From drop impact physics to spray cooling models: a critical review', *Experiments in Fluids*, Vol. 59, No. 3, p.55.

Cabeza, L.F., Chàfer, M. and Mata, É. (2020) 'Comparative analysis of Web of Science and Scopus on the energy efficiency and climate impact of buildings', *Energies*, Vol. 13, No. 2, p.409.

Cao, H., Lin, Z., Zhang, D., Wang, Y. and Sun, Y. (2026) 'Design and optimization of thermal management system for cylindrical battery pack combining liquid cooling with phase change materials based on nondominated sorting genetic algorithm', *Energy*, Vol. 342, p.139591.

Chen, C. (2006) 'CiteSpace II: detecting and visualizing emerging trends and transient patterns in scientific literature', *Journal of the American Society for Information Science and Technology*, Vol. 57, No. 3, pp.359–377.

Chen, H., Cheng, W., Peng, Y. and Jiang, L. (2018) 'Dynamic Leidenfrost temperature increase of impacting droplets containing high-alcohol surfactant', *International Journal of Heat and Mass Transfer*, Vol. 118, pp.1160–1168.

Chen, H., Ruan, X., Peng, Y., Wang, Y. and Yu, C. (2022) 'Application status and prospect of spray cooling in electronics and energy conversion industries', *Sustainable Energy Technologies and Assessments*, Vol. 52, p.102181.

Chen, R., Chow, L.C. and Navedo, J.E. (2002) 'Effects of spray characteristics on critical heat flux in subcooled water spray cooling', *International Journal of Heat and Mass Transfer*, Vol. 45, No. 19, pp.4033–4043.

Chen, S., Xiong, J., Qiu, Y., Zhao, Y. and Chen, S. (2023) 'A bibliometric analysis of lithium-ion batteries in electric vehicles', *Journal of Energy Storage*, Vol. 63, p.107109.

Chen, T., Liu, Z., Han, Q., Shi, J. and Li, W. (2024) 'Parametric study of water spray cooling on enhanced relatively large surfaces', *International Journal of Heat and Fluid Flow*, Vol. 107, p.109355.

Cheng, W., Zhang, W., Chen, H. and Hu, L. (2016a) 'Spray cooling and flash evaporation cooling: the current development and application', *Renewable and Sustainable Energy Reviews*, Vol. 55, pp.614–628.

Cheng, W-L., Zhang, W-W., Chen, H. and Hu, L. (2016b) 'Spray cooling and flash evaporation cooling: the current development and application', *Renewable and Sustainable Energy Reviews*, Vol. 55, pp.614–628.

Cui, R., Ran, Y., Shu, D., Huang, Q., Song, Q., Wang, H., Zhu, J. and Yuan, W. (2025) 'Recent advances in green deep eutectic solvents for lithium-ion battery recycling: a perspective on bibliometric analysis', *Journal of Environmental Management*, Vol. 377, p.124670.

Dai, X.L., Zheng, W., Wang, Z., He, Z., Yang, W. and Wang, Y. (2025) 'Investigation of bio-heat transfer with variable physical parameters during cutaneous laser therapy combined with cryogen spray cooling', *International Journal of Heat and Mass Transfer*, Vol. 239, p.126609.

de Souza, A.G.U. and Barbosa Jr, J.R. (2012) 'Spray cooling of plain and copper-foam enhanced surfaces', *Experimental Thermal and Fluid Science*, Vol. 39, pp.198–206.

Deshannavar, U.B., Thakur, S.H., Gadagi, A.H., Kadapure, S.A., Paramasivam, S., Rajamohan, N., Possidente, R. and Gatto, G. (2024) 'Optimisation studies on performance enhancement of spray cooling – machine learning approach', *Case Studies in Thermal Engineering*, Vol. 64, p.105422.

Dewhirst, M.W., Abraham, J. and Viglianti, B. (2015) 'Chapter six – evolution of thermal dosimetry for application of hyperthermia to treat cancer', in Sparrow, E.M., Abraham, J.P. and Gorman, J.M. (Eds.): *Advances in Heat Transfer*, pp.397–421, Elsevier, Amsterdam.

Dong, F. and Liu, Y. (2020) 'Policy evolution and effect evaluation of new-energy vehicle industry in China', *Resources Policy*, Vol. 67, p.101655.

Donthu, N., Kumar, S., Mukherjee, D., Pandey, N. and Lim, W.M. (2021) 'How to conduct a bibliometric analysis: an overview and guidelines', *Journal of Business Research*, Vol. 133, pp.285–296.

Du, J., Li, Y., Wang, X. and Min, Q. (2023) 'Inhibiting the Leidenfrost effect by superhydrophilic nickel foams with ultrafast droplet permeation', *ACS Applied Materials & Interfaces*, Vol. 15, No. 34, pp.41121–41129.

Dzikowski, P. (2018) 'A bibliometric analysis of born global firms', *Journal of Business Research*, Vol. 85, pp.281–294.

Eng Ewe, W., Fudholi, A., Sopian, K., Solomin, E., Hossein Yazdi, M., Asim, N., Fatima, N., Pikra, G., Sudibyo, H., Fatriasari, W., Heru Kuncoro, A., Supriyadi Ali Nandar, C. and Abimanyu, H. (2022) 'Jet impingement cooling applications in solar energy technologies: systematic literature review', *Thermal Science and Engineering Progress*, Vol. 34, p.101445.

Estes, K.A. and Mudawar, I. (1995) 'Correlation of sauter mean diameter and critical heat flux for spray cooling of small surfaces', *International Journal of Heat and Mass Transfer*, Vol. 38, No. 16, pp.2985–2996.

Fey, U., Engler, R.H., Egami, Y., Iijima, Y., Asai, K., Jansen, U. and Quest, J. (2003) 'Transition detection by temperature sensitive paint at cryogenic temperatures in the European Transonic Wind tunnel (ETW)', *20th International Congress on Instrumentation in Aerospace Simulation Facilities, ICIASF '03*, pp.77–88.

Gao, Y., Ge, L., Shi, S., Sun, Y., Liu, M., Wang, B., Shang, Y., Wu, J. and Tian, J. (2019) 'Global trends and future prospects of e-waste research: a bibliometric analysis', *Environmental Science and Pollution Research*, Vol. 26, No. 17, pp.17809–17820.

Ge, L., Gao, Y. and Meng, X. (2024) 'Effect of ethanol addition on enhancing the cooling performance improvement of spray system', *Case Studies in Thermal Engineering*, Vol. 63, p.105357.

Ge, M., Wang, Z., Liu, L., Zhao, J. and Zhao, Y. (2018) 'Performance analysis of a solar thermoelectric generation (STEG) system with spray cooling', *Energy Conversion and Management*, Vol. 177, pp.661–670.

Gong, Y., Zhao, J., Li, W., Ai, Q., Gong, J., Shuai, Y. and Sun, C. (2023) 'Experimental investigation on heat transfer characteristics of liquid nitrogen spray cooling for large area', *Energies*, Vol. 16, No. 1, p.403.

Guo, Y., Liu, X., Ji, J., Wang, Z., Hu, X., Zhu, Y., Wang, J., Du, Y., Liu, K. and Jiao, Y. (2024) 'Suppressed Leidenfrost effect on the rough tool surface with negative skewness for high-efficiency evaporation cooling', *Applied Thermal Engineering*, Vol. 242, p.122445.

Habibi Khalaj, A. and Halgamuge, S.K. (2017) 'A review on efficient thermal management of air-and liquid-cooled data centers: from chip to the cooling system', *Applied Energy*, Vol. 205, pp.1165–1188.

Henriques, F. and Montz, A.R. (1947) 'Studies of thermal injury: I. The conduction of heat to and through skin and the temperatures attained therein. A theoretical and an experimental investigation', *The American Journal of Pathology*, Vol. 23, No. 4, pp.530–549.

Hicks, D., Wouters, P., Waltman, L., De Rijcke, S. and Rafols, I. (2015) 'Bibliometrics: the Leiden Manifesto for research metrics', *Nature*, Vol. 520, No. 7548, pp.429–431.

Hou, Y., Liu, X., Liu, J., Li, M. and Pu, L. (2013) 'Experimental study on phase change spray cooling', *Experimental Thermal and Fluid Science*, Vol. 46, pp.84–88.

Hu, Y., Lei, Y., Liu, X. and Yang, R. (2022) 'Heat transfer enhancement of spray cooling by copper micromesh surface', *Materials Today Physics*, Vol. 28, p.100857.

Hu, Y., Lei, Y., Liu, X. and Yang, R.J.S.B. (2025a) 'Record-high heat transfer performance of spray cooling on 3D-printed hierarchical micro/nano-structured surface', *Science Bulletin*, Vol. 70, No. 2, pp.223–231.

Hu, Y., Liu, X. and Yang, R. (2025b) 'Enhanced spray cooling on patterned perforated micromesh surface', *Science China Technological Sciences*, Vol. 68, No. 4, p.1420101.

Huang, Y., Xiao, X., Kang, H., Lv, J., Zeng, R. and Shen, J. (2022) 'Thermal management of polymer electrolyte membrane fuel cells: a critical review of heat transfer mechanisms, cooling approaches, and advanced cooling techniques analysis', *Energy Conversion and Management*, Vol. 254, p.115221.

Jani, D.B. (2021) 'Performance analysis of hybrid cooling systems using artificial neural network', *Science and Technology for the Built Environment*, Vol. 7, pp.12–20.

Jani, D.B., Mishra, M. and Sahoo, P.K. (2016) 'Exergy analysis of solid desiccant – vapour compression hybrid air conditioning system', *International Journal of Exergy*, Vol. 20, pp.517–535.

Jin, Y. and Shirvan, K. (2021) 'Study of the film boiling heat transfer and two-phase flow interface behavior using image processing', *International Journal of Heat and Mass Transfer*, Vol. 177, p.121517.

Jin, Y., Zhou, H., Zhu, L. and Li, Z. (2021) 'Dynamics of single droplet splashing on liquid film by coupling FVM with VOF', *Processes*, Vol. 9, No. 5, p.841.

Kwon, B., Maniscalco, N.I., Jacobi, A.M. and King, W.P. (2019) 'High power density two-phase cooling in microchannel heat exchangers', *Applied Thermal Engineering*, Vol. 148, pp.1271–1277.

Kwon, H.M., Bird, J.C. and Varanasi, K.K. (2013) 'Increasing Leidenfrost point using micro-nano hierarchical surface structures', *Applied Physics Letters*, Vol. 103, No. 20, pp.365–689.

Labergue, A., Gradeck, M. and Lemoine, F. (2016) 'Experimental investigation of spray impingement hydrodynamic on a hot surface at high flow rates using phase Doppler analysis and infrared thermography', *International Journal of Heat and Mass Transfer*, Vol. 100, pp.65–78.

Larivière, V., Gingras, Y., Sugimoto, C.R. and Tsou, A. (2015) 'Team size matters: collaboration and scientific impact since 1900', *Journal of the Association for Information Science and Technology,* Vol. 66, No. 7, pp.1323–1332.

Li, J-X., Li, Y-Z., Li, E-H. and Li, T. (2020) 'Numerical investigation on the thermodynamic characteristics of a liquid film upon spray cooling using an air-blast atomization nozzle', *Entropy,* Vol. 22, No. 3, p.308.

Li, Z., Luo, H., Jiang, Y., Liu, H., Xu, L., Cao, K., Wu, H., Gao, P. and Liu, H. (2024) 'Comprehensive review and future prospects on chip-scale thermal management: core of data center's thermal management', *Applied Thermal Engineering,* Vol. 251, p.123612.

Liang, G. and Mudawar, I. (2017a) 'Review of spray cooling – part 1: single-phase and nucleate boiling regimes, and critical heat flux', *International Journal of Heat and Mass Transfer*, Vol. 115, pp.1174–1205.

Liang, G. and Mudawar, I. (2017b) 'Review of spray cooling – part 2: high temperature boiling regimes and quenching applications', *International Journal of Heat and Mass Transfer*, Vol. 115, pp.1206–1222.

Limbeek, M.A.J.V., Shirota, M., Sleutel, P., Sun, C., Prosperetti, A. and Lohse, D. (2016) 'Vapour cooling of poorly conducting hot substrates increases the dynamic Leidenfrost temperature', *International Journal of Heat and Mass Transfer*, Vol. 97, pp.101–109.

Liu, H., Hong, R., Xiang, C., Lv, C. and Li, H. (2020) 'Visualization and analysis of mapping knowledge domains for spontaneous combustion studies', *Fuel*, Vol. 262, p.116598.

Liu, P., Kandasamy, R., Ho, J.Y., Wong, T.N. and Toh, K.C. (2023) 'Dynamic performance analysis and thermal modelling of a novel two-phase spray cooled rack system for data center cooling', *Energy*, Vol. 269, p.126835.

Liu, X., Yang, J., Zou, Q., Hu, Y., Li, P., Tan, L., Miljkovic, N. and Yang, R. (2025) 'Enhancing liquid-vapor phase-change heat transfer with micro/nano-structured surfaces', *ACS Nano*, Vol. 19, No. 10, pp.9513–9589.

Luo, Z., Liang, K., Chen, X., Li, Z., Wang, X., Zhou, H. and Wang, Y. (2023) 'Numerical investigation of the effect of vibration on spray cooling heat transfer in the non-boiling region', *Case Studies in Thermal Engineering,* Vol. 51, p.103518.

Ma, X., Aldhaleai, A., Liu, L. and Tsai, P.A. (2024) 'Nanofluid drop impact on heated surfaces', *Langmuir,* Vol. 40, No. 7, pp.3640–3650.

Majaron, B., Kimel, S., Verkruysse, W., Aguilar, G., Pope, K., Svaasand, L.O., Lavernia, E.J. and Nelson, J.S. (2001a) 'Cryogen spray cooling in laser dermatology: effects of ambient humidity and frost formation', *Lasers in Surgery and Medicine*, Vol. 28, No. 5, pp.469–476.

Majaron, B., Verkruysse, W., Kelly, K.M. and Nelson, J.S. (2001b) 'Er:YAG laser skin resurfacing using repetitive long-pulse exposure and cryogen spray cooling: II. Theoretical analysis', *Lasers in Surgery and Medicine*, Vol. 28, No. 2, pp.131–137.

Marseglia, G., Sanches, M., Ribeiro, A.P.C., Moreira, A.L.N. and Moita, A.S. (2022) 'Thermofluid characterization of nanofluids in spray cooling', *Applied Thermal Engineering*, Vol. 210, p.118411.

Martínez-Galván, E., Antón, R., Ramos, J.C. and Khodabandeh, R. (2013) 'Influence of surface roughness on a spray cooling system with R134a. Part I: heat transfer measurements', *Experimental Thermal and Fluid Science,* Vol. 46, pp.183–190.

Mehmood, A., Zunaid, M. and Madan, A.K. (2022) 'A bibliometric analysis of cold spray coating process using VOSviewer', *Materials Today: Proceedings*.

Meng, X., Meng, L., Gao, Y. and Li, H. (2022) 'A comprehensive review on the spray cooling system employed to improve the summer thermal environment: application efficiency, impact factors, and performance improvement', *Building and Environment*, Vol. 217, p.109065.

Muthukrishnan, S., Tan, X. and Srinivasan, V. (2023) 'High-efficiency spray cooling of rough surfaces with gas-assist atomization', *Applied Thermal Engineering*, Vol. 221, p.119764.

Ndao, S., Peles, Y. and Jensen, M.K. (2014) 'Effects of pin fin shape and configuration on the single-phase heat transfer characteristics of jet impingement on micro pin fins', *International Journal of Heat and Mass Transfer*, Vol. 70, pp.856–863.

Ng, B., Hung, Y. and Tan, M.K. (2014) 'Suppression of Leidenfrost effect via low frequency vibrations', *Soft Matter*, Vol. 11, No. 4, pp.775–784.

Ni, Q. and Ling, X. (2023) 'Experimental study on heat transfer performance using a hybrid cooling method combined of a flat-plate heat pipe and spray cooling', *Thermal Science and Engineering Progress*, Vol. 46, p.102200.

Niksiar, A. and Rahimi, A. (2009) 'Energy and exergy analysis for cocurrent gas spray cooling systems based on the results of mathematical modeling and simulation', *Energy*, Vol. 34, No. 1, pp.14–21.

Nugroho, A., Daud, S., Puranto, P., Mamat, R., Bo, Z. and Ghazali, M.F. (2025) 'Next-generation thermal spray coatings for military use: Innovations, challenges, and applications (bibliometric review 2015–2025)', *Digital Chemical Engineering*, Vol. 17, p.100259.

Padilla, F.M., Gallardo, M. and Manzano-Agugliaro, F. (2018) 'Global trends in nitrate leaching research in the 1960–2017 period', *Science of the Total Environment*, Vol. 643, pp.400–413.

Parizad Benam, B., Sadaghiani, A.K., Yağcı, V., Parlak, M., Sefiane, K. and Koşar, A. (2021) 'Review on high heat flux flow boiling of refrigerants and water for electronics cooling', *International Journal of Heat and Mass Transfer*, Vol. 180, p.121787.

Pennes, H.H. (1998) 'Analysis of tissue and arterial blood temperatures in the resting human forearm', *Journal of Applied Physiology*, Vol. 85, No. 1, pp.5–34.

Pikkula, B.M., Tunnell, J.W., Chang, D.W. and Anvari, B. (2004) 'Effects of droplet velocity, diameter, and film height on heat removal during cryogen spray cooling', *Annals of Biomedical Engineering*, Vol. 32, No. 8, pp.1131–1140.

Qenawy, M., Chen, Y., Wang, J., Tian, J. and Chen, B. (2024) 'Intermittent cryogen spray cooling coupled with cold air jet for heat transfer enhancement and cryogen saving of laser dermatology', *Physics of Fluids*, Vol. 36, No. 2, p.023304.

Ramesh, G. and Prabhu, N.K. (2011) 'Review of thermo-physical properties, wetting and heat transfer characteristics of nanofluids and their applicability in industrial quench heat treatment', *Nanoscale Research Letters*, Vol. 6, No. 1, p.334.

Ray, S., Chi, Y., Zhang, P. and Cheng, S. (2023) 'Head-on collision of unequal-size droplets on a wetting surface', *Physics of Fluids*, Vol. 35, No. 2.

Sarkar, S., Gupta, R., Roy, T., Ganguly, R. and Megaridis, C.M. (2023) 'Review of jet impingement cooling of electronic devices: emerging role of surface engineering', *International Journal of Heat and Mass Transfer*, Vol. 206, p.123888.

Saw, L.H., Poon, H.M., Thiam, H.S., Cai, Z., Chong, W.T., Pambudi, N.A. and King, Y.J. (2018) 'Novel thermal management system using mist cooling for lithium-ion battery packs', *Applied Energy*, Vol. 223, pp.146–158.

Shahriari, A., Wurz, J. and Bahadur, V. (2014) 'Heat transfer enhancement accompanying Leidenfrost state suppression at ultrahigh temperatures', *Langmuir the ACS Journal of Surfaces & Colloids*, Vol. 30, No. 40, p.12074.

Shao, X., Zhang, X. and Wang, W. (2003) 'Comparison of density functional theory and molecular simulation methods for pore size distribution of mesoporous materials', *Acta Physico-Chimica Sinica*, Vol. 19, pp.538–542.

Shao, Z., Tan, B., Guo, Y., Li, T., Li, X., Fang, X., Wang, F., Zhang, Q. and Wang, H. (2022) 'Visualization and analysis of mapping knowledge domains for coal pores studies', *Fuel*, Vol. 320, No. 6, p.123761.

Shirota, M., Van Limbeek, M.A., Sun, C., Prosperetti, A. and Lohse, D. (2016) 'Dynamic Leidenfrost effect: relevant time and length scales', *Physical Review Letters*, Vol. 116, No. 6, p.064501.

Sikirica, A., Grbčić, L. and Kranjčević, L. (2022) 'Machine learning based surrogate models for microchannel heat sink optimization', *Applied Thermal Engineering*.

Silk, E.A. and Bracken, P. (2010) 'Spray cooling heat flux performance using POCO HTC foam', *Journal of Thermophysics and Heat Transfer*, Vol. 24, No. 1, pp.157–164.

Silk, E.A., Golliher, E.L. and Paneer Selvam, R. (2008) 'Spray cooling heat transfer: technology overview and assessment of future challenges for micro-gravity application', *Energy Conversion and Management*, Vol. 49, No. 3, pp.453–468.

Sodtke, C. and Stephan, P. (2007) 'Spray cooling on micro structured surfaces', *International Journal of Heat and Mass Transfer*, Vol. 50, Nos. 19–20, pp.4089–4097.

Sundén, B.A., Abbood, S. and Wu, Z. (2017) 'Effects of engineered micro/nanostructures on nucleate pool boiling heat transfer', *Nanoscience & Nanotechnology-Asia*, Vol. 7, No. 2, pp.155–161.

Talari, V., Behar, P., Lu, Y., Haryadi, E. and Liu, D. (2018) 'Leidenfrost drops on micro/nanostructured surfaces', *Frontiers in Energy*, Vol. 12, No. 1, pp.1–21.

Tunnell, J.W., Torres, J.H. and Anvari, B. (2002) 'Methodology for estimation of time-dependent surface heat flux due to cryogen spray cooling', *Annals of Biomedical Engineering*, Vol. 30, No. 1, pp.19–33.

Van Eck, N.J. and Waltman, L. (2010) 'Software survey: VOSviewer, a computer program for bibliometric mapping', *Scientometrics*, Vol. 84, No. 2, pp.523–538.

Wallin, J.A. (2005) 'Bibliometric methods: pitfalls and possibilities', *Basic & Clinical Pharmacology & Toxicology*, Vol. 97, No. 5, pp.261–275.

Wang, C., Deng, L., Zhang, Y., Zhao, M., Liang, M., Lee, L-C., Cristhian, C-O., Yang, L. and He, T. (2024a) 'Farmland phytoremediation in bibliometric analysis', *Journal of Environmental Management*, Vol. 351, p.119971.

Wang, J., Cui, B., Salmean, C., Chen, X., Yan, X., Mao, Y. and Yao, S. (2024b) 'Machine-assisted quantification of droplet boiling upon multiple solid materials', *Nano Energy*, Vol. 125, p.109560.

Wang, K., Zheng, L.J., Zhang, J.Z. and Yao, H. (2022a) 'The impact of promoting new energy vehicles on carbon intensity: causal evidence from China', *Energy Economics*, Vol. 114, p.106255.

Wang, Y., He, F., Lv, Z., Yang, W. and Wang, Q. (2022b) 'Experimental investigations on thermal performance of spray cooling double skin façade in hot humid climate region', *Energy and Buildings*, Vol. 277, p.112605.

Wang, N., Pan, H. and Zheng, W. (2017a) 'Assessment of the incentives on electric vehicle promotion in China', *Transportation Research Part A: Policy and Practice*, Vol. 101, pp.177–189.

Wang, R., Chen, B. and Wang, X. (2017b) 'Numerical simulation of cryogen spray cooling by a three-dimensional hybrid vortex method', *Applied Thermal Engineering*, Vol. 119, pp.319–330.

Wang, X., Chang, X., Liu, J., Gao, J., Wu, J. and He, H. (2025a) 'Experimental investigation of high-pressure methanol spray characteristics for engines', *Applied Thermal Engineering*, Vol. 271, p.126388.

Wang, Y., Ma, X., Ouyang, Z. and Liang, S. (2025b) 'Comprehensive analysis of forced convection heat transfer enhanced by metal foam with pore density gradient structure', *Solar Energy Materials and Solar Cells*, Vol. 285, p.113549.

Wang, Y., Zhou, N., Yang, Z. and Jiang, Y. (2016) 'Experimental investigation of aircraft spray cooling system with different heating surfaces and different additives', *Applied Thermal Engineering*, Vol. 103, pp.510–521.

Wen, R., Li, Q., Wang, W., Latour, B., Li, C.H., Li, C., Lee, Y-C. and Yang, R. (2017) 'Enhanced bubble nucleation and liquid rewetting for highly efficient boiling heat transfer on two-level hierarchical surfaces with patterned copper nanowire arrays', *Nano Energy*, Vol. 38, pp.59–65.

Wu, E.C., Sun, V., Manuel, C.T., Protsenko, D.E., Jia, W., Nelson, J.S. and Wong, B.J. (2013) 'Ex vivo investigations of laser auricular cartilage reshaping with carbon dioxide spray cooling in a rabbit model', *Lasers in Surgery and Medicine*, Vol. 28, No. 6, pp.1475–1482.

Xie, J.L., Gan, Z.W., Wong, T.N., Duan, F., Yu, S.C.M. and Wu, Y.H. (2014) 'Thermal effects on a pressure swirl nozzle in spray cooling', *International Journal of Heat and Mass Transfer*, Vol. 73, pp.130–140.

Xin, H., Deng, C., Zhou, H., Sang, X. and Chen, B. (2022) 'Histopathological evaluation of the R134a multipulsed spray cooling assisted 1210 nm laser lipolysis by the murine model in vivo', *Lasers in Surgery and Medicine*, Vol. 54, No. 10, pp.1298–1308.

Xin, H., Yu, F., Deng, C., Chen, M., Li, D. and Chen, B. (2023) 'Parametric investigation of multi-pulsed cryogen spray cooling for skin protection during hyperthermal laser lipolysis through in vitro experiment and numerical simulation', *International Journal of Thermal Sciences*, Vol. 190, p.108294.

Xu, R., Wang, G. and Jiang, P. (2022) 'Spray cooling on enhanced surfaces: a review of the progress and mechanisms', *Journal of Electronic Packaging*, Vol. 144, No. 1, p.21.

Xue, R., Ruan, Y., Liu, X., Zhong, X., Chen, L. and Hou, Y. (2021) 'Internal and external flow characteristics of multi-nozzle spray with liquid nitrogen', *Cryogenics*, Vol. 114, p.103255.

Yao, S.C. and Choit, K.J. (1987) 'Heat transfer experiments of mono-dispersed vertically impacting sprays', *International Journal of Multiphase Flow*, Vol. 13, No. 5, pp.639–648.

Yu, C., Yang, M., Yao, J., Melhi, S., Elashiry, M., El-Bahy, S.M., Tan, S., Li, Z., Huang, S., Bao, E. and Zhang, H. (2024) 'Optimization on microchannel structures made of typical materials based on machine learning', *Advanced Composites and Hybrid Materials*, Vol. 7, No. 6, p.189.

Yu, S., Zhou, N., Tang, G., Shen, H., Zhu, H., Li, J., Chu, Y., Li, X., Ma, J. and Wang, Q. (2025) 'Numerical simulation study on factors influencing the heat transfer performance of spray cooling', *Thermal Science and Engineering Progress*, Vol. 64, p.103834.

Zhang, G., Ma, L. and Dearn, H.K. (2023) 'Directional transport behaviour of droplets on the surfaces with asymmetric slanted cone arrays', *International Journal of Hydromechatronics*, Vol. 6, No. 4, pp.380–399.

Zhang, J., Zhu, D., Liu, Y., Chen, Y. and Ma, S. (2024) 'Experimental investigation of spray cooling heat transfer with microcapsule phase change suspension', *International Journal of Heat and Mass Transfer*, Vol. 229, p.125720.

Zhang, X., Wang, K., Hao, Y., Fan, J-L. and Wei, Y-M. (2013a) 'The impact of government policy on preference for NEVs: the evidence from China', *Energy Policy*, Vol. 61, pp.382–393.

Zhang, Z., Li, J. and Jiang, P. (2013b) 'Experimental investigation of spray cooling on flat and enhanced surfaces', *Applied Thermal Engineering*, Vol. 51, No. 1, pp.102–111.

Zhang, Z., Jiang, P., Christopher, D.M. and Liang, X. (2015) 'Experimental investigation of spray cooling on micro-, nano-and hybrid-structured surfaces', *International Journal of Heat and Mass Transfer*, Vol. 80, pp.26–37.

Zhou, N., Chen, F., Cao, Y., Chen, M. and Wang, Y. (2017) 'Experimental investigation on the performance of a water spray cooling system', *Applied Thermal Engineering*, Vol. 112, pp.1117–1128.

Zhou, Q., Pei, J., Poon, J., Lau, A.Y., Zhang, L., Wang, Y., Liu, C. and Huang, L. (2019) 'Worldwide research trends on aristolochic acids (1957-2017): suggestions for researchers', *PloS One*, Vol. 14, No. 5, p.e0216135.

Zhou, Z., Wang, R., Chen, B., Yang, T. and Wang, G. (2016) 'Heat transfer characteristics during pulsed spray cooling with R404A at different spray distances and back pressures', *Applied Thermal Engineering*, Vol. 102, p.813–821.