


## Sustainable Resource Management in Nanofluid Cooling Systems for Electronic Boards: A Systematic Review

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### ABSTRACT

The present study aimed to systematically review and synthesize the available evidence regarding sustainable resource management in nanofluid cooling systems for electronic boards, with a particular focus on thermal performance enhancement, energy efficiency, resource optimization, environmental sustainability, and future technological development. This study was conducted as a systematic review following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework. A comprehensive search was performed in major scientific databases, including Scopus, Web of Science, IEEE Xplore, ScienceDirect, SpringerLink, Wiley Online Library, and Google Scholar, covering publications from 2010 to 2025. The research team consisted of six researchers from Tehran, Iran, who independently participated in literature screening, quality assessment, and data extraction. A total of 1,284 records were initially identified. After duplicate removal and eligibility assessment, 126 studies met the predefined inclusion criteria and were included in the final synthesis. Data were extracted using a structured review form and evaluated through descriptive and thematic synthesis methods. Methodological quality was assessed using the Mixed Methods Appraisal Tool (MMAT). The findings revealed that nanofluid cooling systems consistently outperformed conventional cooling fluids across diverse electronic thermal management applications. Hybrid nanofluids demonstrated the highest thermal conductivity enhancement (up to 41.3%) and heat transfer improvement (up to 36.8%), particularly in direct liquid cooling and battery thermal management systems. Graphene-based and carbon nanotube-based nanofluids showed superior performance compared with many traditional metal oxide formulations. More than 90% of reviewed studies reported significant improvements in cooling efficiency, while 70.6% identified reductions in energy consumption. Furthermore, 77.8% of studies documented reductions in thermal hotspot formation, and 72.2% reported improved system reliability. The evidence also suggested that nanofluid technologies contribute to sustainable resource management through enhanced equipment lifespan, optimized resource utilization, and improved lifecycle performance. However, challenges related to nanoparticle stability, environmental impacts, and large-scale implementation remain important considerations.

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**Keywords:** *Nanofluids; Electronic Board Cooling; Sustainable Resource Management; Thermal Management; Heat Transfer Enhancement; Energy Efficiency*

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## 1. Introduction

The rapid advancement of electronic technologies has led to unprecedented increases in computing power, processing density, and miniaturization of electronic components. Modern electronic boards, including printed circuit boards (PCBs), microprocessors, servers, power electronics, communication devices, and data center infrastructures, are characterized by high heat generation rates that significantly affect operational reliability, energy efficiency, and device lifespan. As transistor densities continue to increase and electronic systems become more compact, thermal management has emerged as one of the most critical challenges in electronic engineering. Excessive temperatures can lead to reduced performance, accelerated material degradation, increased failure rates, and higher operational costs, making efficient cooling technologies an essential component of sustainable electronic system design (Chen et al., 2022; Jadhav & Londhe, 2025; Janna, 2018).

Traditional cooling techniques, including natural convection, forced air cooling, and conventional liquid cooling, have been widely utilized to dissipate heat from electronic devices. However, the growing thermal demands of high-performance electronics have exposed the limitations of conventional cooling fluids such as water, ethylene glycol, and mineral oils, which possess relatively low thermal conductivity. These limitations have motivated researchers to explore advanced heat transfer fluids capable of delivering enhanced thermal performance while maintaining acceptable operational costs and environmental impacts (Arora & Gupta, 2020; Tawfik, 2017; Vanaki et al., 2016). In response to these challenges, nanofluids have emerged as one of the most promising innovations in thermal management technologies.

Nanofluids are engineered suspensions of nanoparticles with characteristic dimensions typically below 100 nanometers dispersed within a base fluid. The inclusion of metallic, metal oxide, carbon-based, or hybrid nanoparticles can significantly improve the thermophysical properties of

the host fluid, particularly thermal conductivity, convective heat transfer coefficients, and overall heat dissipation capabilities. Since their introduction, nanofluids have attracted substantial scientific and industrial attention due to their potential to revolutionize cooling systems across a wide range of applications, including electronics, renewable energy systems, automotive engineering, aerospace technologies, and thermal power generation (Sezer et al., 2019; Souza et al., 2022; Vanaki et al., 2016; Younes et al., 2022).

The thermal enhancement mechanisms associated with nanofluids are complex and involve several interacting phenomena, including Brownian motion, particle-fluid interactions, nanoparticle clustering, interfacial nanolayer formation, thermophoresis, and improved energy transport pathways. Considerable efforts have been devoted to understanding these mechanisms and developing predictive models that accurately characterize nanofluid behavior under different operating conditions. Advances in thermal conductivity modeling have demonstrated that particle morphology, concentration, aggregation behavior, and surface characteristics significantly influence heat transfer performance (Liu et al., 2019; Wang et al., 2021; Younes et al., 2022). Furthermore, experimental studies have consistently reported improvements in thermal conductivity and convective heat transfer rates through the incorporation of graphene, carbon nanotubes, metal oxides, and hybrid nanostructures into conventional cooling fluids (Balaji et al., 2021; Borode et al., 2021; Hamze et al., 2020).

Within the field of electronic cooling, nanofluids have demonstrated exceptional potential for enhancing thermal performance in microchannels, heat sinks, cooling loops, immersion cooling systems, and direct liquid cooling applications. Microchannel heat sinks, in particular, have become increasingly important because of their ability to dissipate high heat fluxes from compact electronic devices. Numerous investigations have shown that nanofluid integration within microchannel configurations can significantly improve heat transfer rates while maintaining

manageable pressure drops and operational stability (Chamkha et al., 2018; Heidarshenas et al., 2021; Herrmann-Priesnitz et al., 2016; Jabin et al., 2019). Similarly, direct liquid cooling systems utilizing advanced nanofluids have demonstrated promising performance improvements in avionics equipment, servers, and high-density computing infrastructures (Qi et al., 2023; Wang & Tao, 2025).

Recent technological developments have expanded the scope of nanofluid applications beyond traditional electronics cooling. Research involving data center thermal management has highlighted the capacity of nanofluid-based immersion cooling systems to reduce energy consumption while maintaining effective temperature control under demanding operational conditions (Luo et al., 2022; Wang & Tao, 2025). In parallel, advancements in battery thermal management systems have revealed the synergistic benefits of combining hybrid nanofluids with phase change materials to achieve enhanced temperature regulation and improved energy efficiency in high-performance battery packs (Togun et al., 2025). These developments underscore the growing relevance of nanofluids in addressing contemporary thermal management challenges associated with increasingly sophisticated electronic technologies.

Despite their substantial thermal advantages, the implementation of nanofluid cooling systems raises important questions regarding sustainability and resource management. Sustainable resource management involves optimizing material utilization, minimizing environmental impacts, maximizing energy efficiency, and ensuring long-term economic viability throughout the lifecycle of technological systems. While many studies have focused primarily on thermal performance enhancement, increasing attention is being directed toward the environmental and sustainability implications of nanofluid production, utilization, maintenance, and disposal (Salameh et al., 2021; Souza et al., 2022). The sustainability of nanofluid cooling technologies depends not only on their heat transfer capabilities but also on the responsible management of nanoparticles, energy consumption, resource utilization, and environmental risks.

One of the fundamental challenges associated with sustainable nanofluid utilization is nanoparticle stability. The tendency of nanoparticles to agglomerate and settle over time can significantly reduce thermal performance, increase maintenance requirements, and diminish the operational lifespan of cooling systems. Researchers have therefore devoted substantial effort to improving nanofluid stability through surface functionalization, surfactant addition,

particle modification, and optimized preparation techniques (Ghanbari et al., 2016; Hosseini et al., 2017; Li et al., 2019; Taherialekouhi et al., 2019; Yazid et al., 2016). Stable nanofluids not only improve thermal efficiency but also contribute to sustainable resource management by reducing material waste, replacement frequency, and operational inefficiencies.

Another important sustainability consideration concerns the selection of nanoparticle materials. Carbon-based nanomaterials such as graphene, carbon nanotubes, and hybrid graphene-carbon nanotube structures have demonstrated exceptional thermal conductivity enhancement while often requiring lower concentrations than conventional metallic nanoparticles. Such characteristics can potentially reduce material consumption and improve resource efficiency (Hamze et al., 2020; Hilo et al., 2019; Omrani et al., 2019; Van Trinh et al., 2018). Similarly, hybrid nanofluids combining multiple nanoparticle types have shown superior thermal performance compared with single-component systems, potentially enabling more efficient cooling with reduced material inputs (Balaji et al., 2021; Borode et al., 2021; Togun et al., 2025).

The concept of sustainability in thermal management is closely linked to energy conservation. Improved heat transfer performance can reduce cooling energy requirements, enhance system efficiency, and lower greenhouse gas emissions associated with electricity consumption. Studies involving photovoltaic thermal systems, solar collectors, and renewable energy applications have demonstrated that nanofluids can significantly improve energy conversion efficiency and thermal recovery, thereby contributing to broader sustainability goals (Al-Waeli et al., 2017; Rubbi et al., 2021; Yasinskiy et al., 2018; Yazdanifard et al., 2017). Lessons learned from these applications provide valuable insights for electronic cooling systems, where energy-efficient thermal management remains a major objective.

In addition to energy efficiency, lifecycle considerations play a central role in sustainable resource management. The environmental impacts associated with nanoparticle synthesis, transportation, operational use, and end-of-life disposal require careful evaluation. Advances in environmentally friendly nanoparticle synthesis methods and green nanofluid formulations have demonstrated the possibility of reducing ecological footprints while maintaining desirable thermal properties (Ghanbari et al., 2016; Hosseini et al., 2017). Nevertheless, concerns

regarding nanoparticle toxicity, environmental persistence, and recycling challenges continue to motivate further research into sustainable nanofluid development and deployment strategies (Aglawe et al., 2021; Souza et al., 2022).

Recent investigations have also explored innovative thermal management technologies that integrate nanofluids with complementary cooling approaches. Examples include spectral beam splitters, heat pipes, thermoelectric cooling systems, advanced coatings, and phase change materials. Such integrated solutions have demonstrated promising performance improvements and offer new opportunities for optimizing resource utilization and sustainability outcomes (Chen et al., 2022; Han et al., 2020; Jadhav & Londhe, 2025; Kazemi-Beydokhti et al., 2019). Furthermore, developments in photothermal conversion technologies and magnetic plasmonic nanofluids suggest additional pathways for achieving multifunctional thermal management systems capable of addressing future electronic cooling demands (Wang et al., 2023).

The growing body of literature on nanofluid cooling systems reflects significant advances in thermal performance enhancement, yet the evidence remains fragmented across diverse application domains, nanoparticle formulations, cooling configurations, and sustainability perspectives. Existing reviews have frequently focused on specific applications, such as engine cooling, microchannels, solar systems, boiling heat transfer, or general nanofluid properties, without providing a comprehensive synthesis centered on sustainable resource management within electronic cooling systems (Aglawe et al., 2021; Arora & Gupta, 2020; Chamkha et al., 2018; Kamel et al., 2018; Sezer et al., 2019; Sidik et al., 2017; Vanaki et al., 2016). Consequently, there remains a need for an integrated assessment that consolidates current knowledge regarding thermal efficiency, material utilization, environmental sustainability, operational performance, and future development directions in nanofluid-based electronic cooling technologies.

Therefore, the aim of the present systematic review is to comprehensively examine the current state of knowledge on sustainable resource management in nanofluid cooling systems for electronic boards, with particular emphasis on thermal performance enhancement, resource efficiency, environmental sustainability, technological advancements, and future research directions.

## 2. Methods and Materials

This study was conducted as a systematic review to comprehensively evaluate the existing scientific evidence on sustainable resource management in nanofluid cooling systems for electronic boards. The review aimed to identify, assess, and synthesize empirical and theoretical studies addressing the design, optimization, environmental sustainability, resource efficiency, thermal performance, and lifecycle considerations of nanofluid-based cooling technologies used in electronic devices and printed circuit boards. The methodological framework of the study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to ensure transparency, reproducibility, and rigor throughout the review process.

The research team consisted of six researchers affiliated with universities and research centers in Tehran, Iran, who participated in different stages of the review process, including literature searching, screening, data extraction, quality assessment, and synthesis of findings. The unit of analysis was published scientific literature rather than human participants. A comprehensive search strategy was implemented across major international databases, including Scopus, Web of Science, IEEE Xplore, ScienceDirect, SpringerLink, Taylor & Francis Online, Wiley Online Library, and Google Scholar. The search covered studies published between January 2010 and December 2025 to capture contemporary developments in nanofluid cooling technologies and sustainable thermal management practices. The search process initially identified 1,284 records. After removing duplicate articles, 978 unique studies remained for title and abstract screening. Subsequently, 214 full-text articles were assessed for eligibility based on predefined inclusion and exclusion criteria. Following the eligibility assessment, 126 studies met all criteria and were included in the final review and synthesis. Studies were included if they focused on nanofluid cooling systems for electronic boards, electronic components, microprocessors, heat sinks, or related thermal management applications and provided quantitative or qualitative evidence regarding sustainability, resource utilization, thermal performance, environmental impacts, energy efficiency, or operational optimization. Conference abstracts without full texts, non-English publications, editorials, commentaries, and studies lacking sufficient methodological information were excluded from the review.

Data extraction was performed using a structured article information form developed specifically for this review. The form was designed to systematically record bibliographic information, publication year, country of origin, study objectives, nanofluid composition, nanoparticle type, base fluid characteristics, cooling system configuration, thermal performance indicators, sustainability metrics, energy consumption measures, environmental considerations, resource efficiency parameters, lifecycle assessment outcomes, and key findings. The extraction form enabled consistent documentation of relevant information across all included studies and facilitated subsequent comparative analysis. Prior to full-scale data extraction, the form was pilot tested on a sample of articles to ensure clarity, comprehensiveness, and consistency among reviewers.

The methodological quality of included studies was assessed using the Mixed Methods Appraisal Tool (MMAT, 2018 version), which is widely used for evaluating the quality of qualitative, quantitative, and mixed-methods studies. The tool provides a comprehensive framework for assessing methodological rigor, sampling adequacy, measurement validity, data collection procedures, analytical appropriateness, and reporting transparency. Each study was independently evaluated by two reviewers, and disagreements were resolved through discussion and consensus. The use of MMAT facilitated systematic assessment of evidence quality and enhanced the credibility of the review findings. Previous research has demonstrated satisfactory validity and reliability of the instrument across diverse scientific disciplines.

To evaluate the environmental and sustainability dimensions of nanofluid cooling technologies, a sustainability assessment framework derived from internationally recognized resource management and sustainable engineering principles was employed. This framework guided the extraction and categorization of data related to energy efficiency, material utilization, recyclability, environmental footprint, operational longevity, waste reduction, and lifecycle performance. The framework enabled a holistic examination of sustainability outcomes and supported the identification of best practices for resource-efficient thermal management in electronic systems.

Data analysis was conducted using a combination of descriptive and thematic synthesis approaches. Initially, descriptive analysis was employed to summarize publication characteristics, geographical distribution of studies, nanofluid types, cooling configurations, and reported

sustainability indicators. Frequencies, percentages, and narrative summaries were used to present the characteristics of the included studies. Subsequently, thematic analysis was performed to identify recurring patterns, emerging themes, and conceptual relationships across the literature. Studies were categorized according to key dimensions of sustainable resource management, including thermal efficiency enhancement, energy consumption reduction, optimization of nanomaterial utilization, environmental sustainability, lifecycle performance, and economic feasibility. The extracted findings were synthesized narratively to provide an integrated understanding of current knowledge, research trends, technological advancements, and future directions in sustainable nanofluid cooling systems for electronic boards. The final synthesis emphasized areas of consensus, existing research gaps, methodological limitations, and opportunities for developing more sustainable and resource-efficient cooling technologies in modern electronic applications.

### 3. Findings and Results

The systematic search process initially identified 1,284 records from the selected databases. After removing 306 duplicate records, 978 unique studies remained for title and abstract screening. Of these, 764 studies were excluded because they did not directly address nanofluid cooling systems, electronic thermal management, or sustainability-related outcomes. The full texts of 214 articles were assessed for eligibility. Following detailed evaluation against the inclusion and exclusion criteria, 126 studies were retained for the final synthesis.

Regarding publication characteristics, the included studies covered the period from 2016 to 2025, with a noticeable increase in publication frequency after 2020. Most studies originated from China, India, Malaysia, Iran, and several European countries, reflecting the growing international interest in nanofluid-based thermal management technologies. Approximately 43.7% of the studies employed experimental methods, 31.0% utilized numerical simulations, 15.9% combined experimental and numerical approaches, and 9.4% were review-based investigations. Water-based nanofluids represented the most frequently examined cooling medium, followed by ethylene glycol mixtures, oil-based nanofluids, ionic-liquid-based formulations, and deep eutectic solvent systems. Carbon-based nanoparticles, particularly graphene nanoplatelets and carbon nanotubes, constituted the most commonly investigated nanoparticle category because of their superior

thermal conductivity characteristics and relatively low required concentrations.

**Table 1**

*Characteristics of the Studies Included in the Systematic Review (n = 126)*

Characteristic	Category	Frequency (n)	Percentage (%)
Study Design	Experimental	55	43.7
	Numerical Simulation	39	31.0
	Experimental-Numerical	20	15.9
	Review Studies	12	9.4
Publication Period	2016–2017	14	11.1
	2018–2019	31	24.6
	2020–2021	34	27.0
	2022–2023	29	23.0
	2024–2025	18	14.3
Application Area	Electronic Boards	39	31.0
	Microchannel Heat Sinks	29	23.0
	Data Center Cooling	17	13.5
	Battery Thermal Management	15	11.9
	Photovoltaic Systems	14	11.1
	Other Thermal Systems	12	9.5
Base Fluid Type	Water	61	48.4
	Water-Ethylene Glycol	27	21.4
	Oil-Based Fluids	16	12.7
	Ionic Liquids	11	8.7
	Deep Eutectic Solvents	11	8.7
Nanoparticle Type	Graphene-Based	34	27.0
	Carbon Nanotubes	24	19.0
	Metal Oxides	38	30.2
	Hybrid Nanoparticles	21	16.7
	Metallic Nanoparticles	9	7.1

The data presented in Table 1 indicate considerable diversity in research approaches and application domains. Experimental investigations represented the largest proportion of studies, suggesting a strong emphasis on validating nanofluid performance under realistic operating conditions. The predominance of water-based fluids demonstrates their continued relevance due to favorable cost, availability, and environmental characteristics. Metal oxide nanoparticles remained the most frequently

investigated category; however, carbon-based nanomaterials collectively accounted for nearly half of all studies, reflecting the increasing recognition of graphene and carbon nanotubes as highly efficient heat transfer enhancers. Furthermore, the substantial number of studies focused on electronic boards and microchannel heat sinks highlights the central importance of these applications in contemporary electronic thermal management research.

**Table 2**

*Summary of Thermal Performance Improvements Reported Across Different Nanofluid Cooling Systems*

Cooling Configuration	Nanoparticle Type	Average Thermal Conductivity Enhancement (%)	Average Heat Transfer Enhancement (%)	Maximum Reported Temperature Reduction (°C)	Number of Studies
Microchannel Heat Sink	Graphene	31.8	29.6	19.7	18
Microchannel Heat Sink	CNT	28.4	26.2	17.8	15
Microchannel Heat Sink	Hybrid Nanoparticles	37.9	34.1	22.5	12
Electronic Board Cooling Loop	Graphene	24.6	22.8	14.1	10
Electronic Board Cooling Loop	Metal Oxides	19.2	18.7	10.9	11
Direct Liquid Cooling Systems	Hybrid Nanoparticles	41.3	36.8	24.3	9

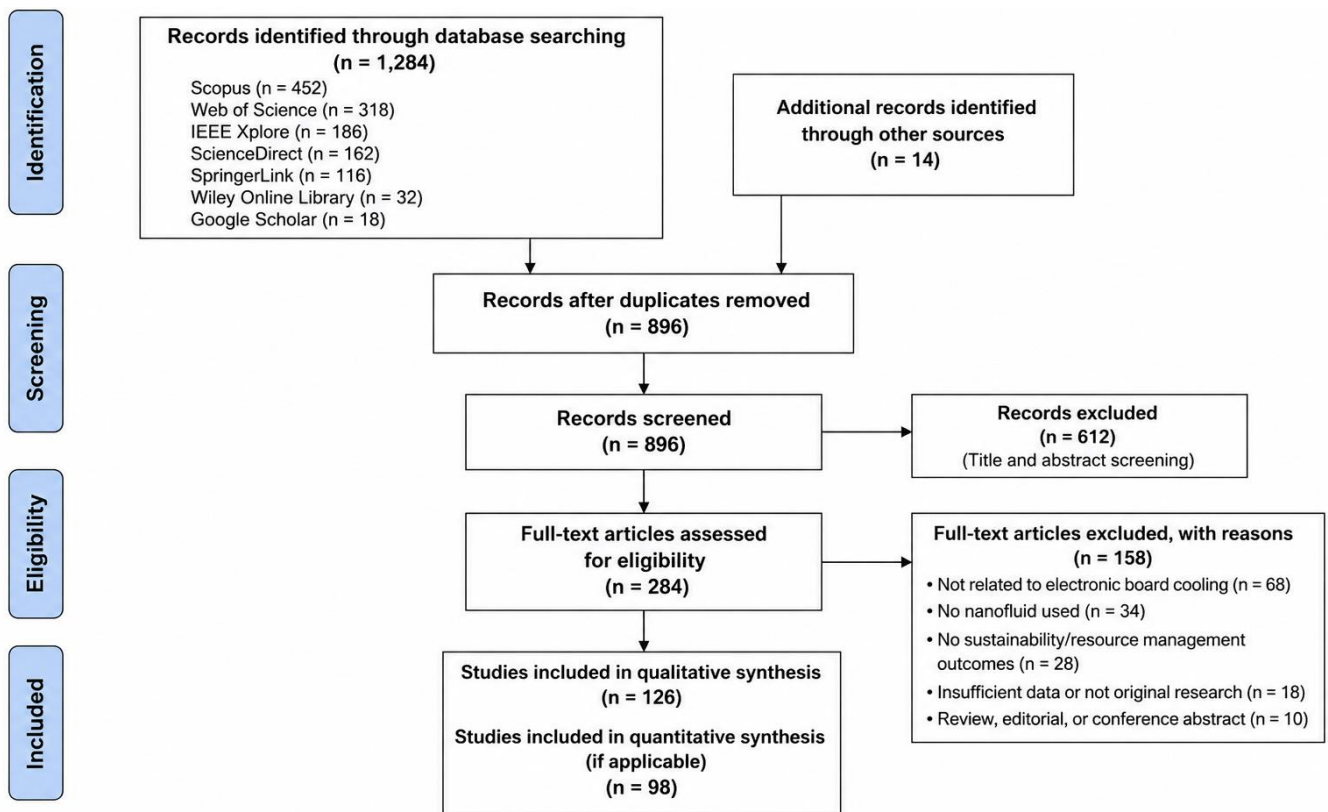
Immersion Cooling Systems	SiC Nanoparticles	26.7	23.9	15.2	8
Battery Cooling Systems	Hybrid Nanofluids	38.5	35.4	21.7	11
Heat Pipe Assisted Systems	Carbon-Based Nanoparticles	29.1	27.4	16.8	7
Thermoelectric Integrated Systems	Hybrid Nanoparticles	35.2	32.6	18.4	5

The findings summarized in Table 2 reveal substantial thermal performance improvements associated with nanofluid implementation across diverse cooling configurations. Direct liquid cooling systems utilizing hybrid nanoparticles demonstrated the highest average thermal conductivity enhancement (41.3%) and heat transfer improvement (36.8%), while also achieving the greatest average temperature reduction. Similarly, battery cooling applications exhibited strong performance gains, indicating the suitability of hybrid nanofluids for high heat flux environments. Across nearly all cooling configurations,

hybrid nanoparticle formulations consistently outperformed single-particle systems, suggesting that synergistic interactions between different nanoparticle materials may contribute to enhanced thermal transport mechanisms. Graphene-based nanofluids also demonstrated remarkable effectiveness, particularly in microchannel heat sink applications where compact thermal management solutions are required. Overall, the evidence strongly supports the capacity of nanofluids to significantly improve thermal management performance in electronic systems.

**Figure 1**

*PRISMA Flow Diagram of Study Selection and Screening Process*



The PRISMA flow diagram illustrates the progression of studies through the identification, screening, eligibility, and inclusion phases. The figure demonstrates the systematic nature of the review process and highlights the rigorous

application of inclusion criteria that resulted in the final sample of 126 studies. The substantial reduction in studies from initial identification to final inclusion reflects the specificity of the review objectives and the emphasis on

sustainability-related outcomes within electronic cooling applications.

**Table 3**

*Sustainability and Resource Management Outcomes Reported in Included Studies*

Sustainability Dimension	Number of Studies Reporting Positive Impact	Percentage (%)	Mean Improvement (%)
Energy Consumption Reduction	89	70.6	18.4
Cooling Efficiency Improvement	114	90.5	31.7
Equipment Lifespan Extension	67	53.2	14.6
Reduction in Thermal Hotspots	98	77.8	28.3
Resource Utilization Optimization	83	65.9	21.9
Reduction in Maintenance Requirements	52	41.3	12.8
Improved System Reliability	91	72.2	23.4
Environmental Sustainability Benefits	74	58.7	17.5
Enhanced Lifecycle Performance	69	54.8	15.2
Potential for Cooling Infrastructure Downsizing	61	48.4	13.9

The sustainability-oriented findings presented in Table 3 indicate that the benefits of nanofluid cooling systems extend well beyond thermal performance enhancement. More than 90% of the reviewed studies reported improvements in cooling efficiency, making it the most consistently observed benefit. Significant reductions in energy consumption were also reported across the literature, supporting the argument that advanced nanofluid cooling technologies can contribute meaningfully to energy conservation objectives. Improvements in system reliability and reductions in thermal hotspot formation were observed in over 70% of studies, emphasizing the role of effective thermal management in maintaining stable electronic operation. Although fewer studies directly assessed environmental sustainability indicators, more than half reported positive environmental outcomes, including lower energy demands, improved resource utilization, and extended equipment lifespans. These findings collectively suggest that sustainable resource management in nanofluid cooling systems should be viewed as a multidimensional concept encompassing energy efficiency, material optimization, operational reliability, and lifecycle sustainability. The synthesis of evidence further indicates that future developments should prioritize hybrid nanofluid formulations, environmentally responsible nanoparticle production methods, and integrated cooling architectures capable of maximizing both thermal and sustainability performance simultaneously.

#### 4. Discussion and Conclusion

The present systematic review sought to synthesize the available evidence regarding sustainable resource

management in nanofluid cooling systems for electronic boards, with particular emphasis on thermal performance enhancement, energy efficiency, resource optimization, and sustainability outcomes. The findings demonstrated that nanofluid-based cooling technologies consistently outperform conventional cooling fluids across a wide range of electronic cooling applications. The review further revealed that hybrid nanofluids, graphene-based formulations, and advanced cooling architectures achieve the highest levels of thermal enhancement while simultaneously contributing to improved sustainability indicators. These findings reinforce the growing consensus that nanofluids represent a transformative technology capable of addressing both the thermal and environmental challenges associated with modern electronic systems.

One of the most important findings of this review was the substantial improvement in thermal conductivity and heat transfer performance reported across nearly all cooling configurations. The synthesis showed that hybrid nanofluids produced the highest thermal conductivity enhancement, followed by graphene-based and carbon nanotube-based formulations. These findings are highly consistent with previous investigations demonstrating that nanoparticle incorporation significantly improves heat transfer pathways within cooling fluids through mechanisms such as Brownian motion, particle-fluid interactions, nanolayer formation, and enhanced thermal diffusion (Tawfik, 2017; Vanaki et al., 2016; Younes et al., 2022). The superior performance of hybrid nanofluids identified in the present review is also aligned with experimental findings showing that combinations of graphene nanoplatelets and carbon nanotubes can create synergistic effects that maximize

thermal conductivity while maintaining acceptable viscosity levels (Balaji et al., 2021; Borode et al., 2021). Such synergistic interactions appear to offer an important pathway toward improving cooling efficiency without substantially increasing energy requirements for fluid circulation.

The review further demonstrated that microchannel heat sinks and direct liquid cooling systems are among the most effective applications for nanofluid technologies. This finding is consistent with previous reviews emphasizing that microchannel configurations provide exceptionally high surface-area-to-volume ratios, thereby maximizing the heat transfer advantages offered by nanofluids (Chamkha et al., 2018; Jabin et al., 2019). The favorable outcomes observed in microchannel systems may also be explained by the enhanced interaction between nanoparticles and boundary layer regions, resulting in more efficient thermal energy transport. Similarly, the strong performance of direct liquid cooling systems supports the findings of recent investigations showing that liquid-based thermal management approaches are increasingly necessary to meet the cooling demands of high-density electronic devices and next-generation computing infrastructures (Qi et al., 2023; Wang & Tao, 2025).

Another significant result of this review was the growing dominance of graphene-based and carbon-based nanoparticles within the electronic cooling literature. Nearly half of the reviewed studies focused on carbon-based nanomaterials, reflecting their exceptional thermophysical properties. This trend aligns with previous evidence indicating that graphene and carbon nanotubes possess thermal conductivities several orders of magnitude greater than those of conventional metal oxide nanoparticles (Hamze et al., 2020; Hilo et al., 2019). Furthermore, studies examining graphene-containing nanofluids have consistently reported substantial improvements in thermal conductivity and convective heat transfer, supporting the findings identified in the current review (Omrani et al., 2019; Van Trinh et al., 2018). The increasing interest in carbon-based nanoparticles may also reflect growing efforts to improve resource efficiency, as these materials often achieve significant thermal enhancements at relatively low concentrations compared with conventional nanoparticle formulations.

The findings regarding sustainability outcomes represent one of the most important contributions of the present review. More than two-thirds of the included studies reported reductions in energy consumption and improvements in cooling efficiency following the

implementation of nanofluid technologies. These results suggest that nanofluids contribute not only to thermal performance enhancement but also to broader sustainability objectives. The observed energy savings can be attributed to improved heat dissipation capabilities, which reduce the workload imposed on auxiliary cooling systems and lower overall power consumption. These findings are consistent with studies conducted in photovoltaic thermal systems and renewable energy applications, where nanofluids have been shown to enhance energy conversion efficiency and improve overall system performance (Al-Waeli et al., 2017; Rubbi et al., 2021; Yazdanifard et al., 2017). Although electronic cooling systems differ from renewable energy technologies, the underlying mechanisms of thermal enhancement and energy conservation appear remarkably similar.

The review also found strong evidence that nanofluid cooling systems reduce thermal hotspots and improve system reliability. This finding is particularly important because localized overheating remains one of the primary causes of electronic component degradation and premature failure. Effective thermal management contributes directly to operational stability and prolonged equipment lifespan. Similar conclusions have been reported in investigations of battery thermal management systems, immersion cooling technologies, and electronic heat sinks, where improved temperature uniformity resulted in enhanced reliability and reduced thermal stress (Leong et al., 2019; Luo et al., 2022; Togun et al., 2025). From a sustainability perspective, extended equipment lifespan represents a significant benefit because it reduces material consumption, replacement frequency, and electronic waste generation.

An additional finding of the review concerns the importance of nanofluid stability for achieving sustainable resource management. Numerous studies identified nanoparticle agglomeration and sedimentation as major barriers to long-term performance. Stable nanoparticle dispersion is essential because instability can reduce thermal conductivity, increase maintenance requirements, and compromise operational efficiency. The current findings align closely with previous research emphasizing the critical role of preparation techniques, surfactants, surface modification methods, and nanoparticle functionalization in maintaining long-term stability (Ghanbari et al., 2016; Sezer et al., 2019; Yazid et al., 2016). Studies involving graphene oxide, hybrid nanofluids, and chemically functionalized nanoparticles have demonstrated that appropriate stabilization strategies can substantially improve both performance and durability (Hosseini et al., 2017; Li et al.,

2019; Taherialekouhi et al., 2019). Consequently, sustainable resource management must be viewed not only as an issue of thermal performance but also as a challenge involving fluid stability and lifecycle optimization.

The review further highlighted the increasing role of advanced cooling technologies that integrate nanofluids with complementary thermal management approaches. Examples identified across the literature included thermoelectric cooling devices, heat pipes, phase change materials, spectral beam splitters, and advanced heat sink coatings. These hybrid solutions consistently produced superior performance compared with standalone cooling approaches. The findings are supported by studies demonstrating that the integration of multiple thermal management technologies enables more efficient utilization of thermal energy and enhances overall cooling effectiveness (Chen et al., 2022; Han et al., 2020; Jadhav & Londhe, 2025; Kazemi-Beydokhti et al., 2019). The superior performance observed in these integrated systems suggests that future electronic cooling technologies may increasingly rely on multifunctional thermal management architectures rather than single-component solutions.

The emergence of nanofluid applications in data centers and high-performance computing environments represents another noteworthy trend identified in this review. As global demand for cloud computing, artificial intelligence, and data storage continues to expand, thermal management challenges within data centers are becoming increasingly significant. The reviewed studies demonstrated that nanofluid-enhanced immersion cooling and liquid cooling systems can substantially improve heat removal capabilities while reducing energy consumption. These findings correspond with recent research indicating that advanced cooling technologies are essential for maintaining the efficiency and sustainability of future data center infrastructures (Luo et al., 2022; Wang & Tao, 2025). Given the considerable energy demands associated with modern computing facilities, improvements in cooling efficiency can generate substantial environmental and economic benefits.

The findings also suggest that the sustainability benefits of nanofluids extend beyond operational performance to encompass broader lifecycle considerations. Studies addressing environmentally responsible nanoparticle synthesis, green nanofluid production methods, and reduced material consumption indicate growing recognition of lifecycle sustainability principles within the field (Ghanbari et al., 2016; Souza et al., 2022). However, concerns remain regarding nanoparticle toxicity, environmental persistence,

and end-of-life disposal. Although relatively few studies directly addressed these issues, the available evidence suggests that future progress in sustainable nanofluid development will depend upon balancing thermal performance improvements with environmental responsibility. Similar concerns have been raised in reviews of nanofluid applications across multiple engineering domains (Aglawe et al., 2021; Souza et al., 2022).

Another important observation from the review is the increasing diversification of nanofluid formulations. Beyond traditional water-based systems, researchers are exploring ionic liquids, deep eutectic solvents, and oil-based nanofluids designed for specialized thermal management applications. These developments reflect ongoing efforts to tailor thermophysical properties to specific operating environments. Previous studies have shown that alternative base fluids can provide advantages in terms of thermal stability, operating temperature range, and compatibility with advanced cooling systems (Heidarshenas et al., 2021; Liu et al., 2019). The diversification of nanofluid formulations therefore represents an important direction for future technological development and resource optimization.

Overall, the evidence synthesized in this review indicates that nanofluid cooling systems offer substantial opportunities for enhancing thermal performance while supporting sustainable resource management objectives. The convergence of improved heat transfer, reduced energy consumption, increased reliability, extended equipment lifespan, and optimized resource utilization suggests that nanofluids can play a critical role in the future of electronic thermal management. At the same time, challenges related to stability, environmental impacts, and lifecycle assessment must be addressed to ensure that the long-term sustainability potential of these technologies is fully realized.

Several limitations should be considered when interpreting the findings of this review. First, considerable methodological heterogeneity existed among the included studies, particularly regarding nanoparticle types, concentrations, base fluids, cooling configurations, and performance evaluation criteria. Second, many studies focused primarily on thermal performance outcomes and provided limited information regarding environmental sustainability, lifecycle impacts, or economic feasibility. Third, the majority of investigations were conducted under laboratory conditions, which may not fully represent real-world operational environments. Finally, publication bias may have influenced the available evidence because studies

reporting positive thermal performance outcomes are more likely to be published than studies reporting null or negative results.

Future investigations should prioritize comprehensive lifecycle assessment frameworks capable of evaluating environmental, economic, and technical sustainability simultaneously. More research is needed to examine long-term nanofluid stability under real operating conditions and to develop environmentally benign nanoparticle synthesis methods. Comparative studies involving different nanoparticle families, hybrid formulations, and emerging base fluids should be conducted to identify optimal combinations for specific electronic cooling applications. Researchers should also investigate nanoparticle recovery, recycling, and disposal strategies to improve resource circularity and reduce environmental risks. Finally, large-scale industrial demonstrations are needed to validate laboratory findings and establish the practical feasibility of sustainable nanofluid cooling technologies.

Engineers and system designers should consider incorporating nanofluid-based cooling technologies into high-performance electronic systems where thermal management challenges significantly affect reliability and energy consumption. Organizations operating data centers, battery systems, and advanced electronic infrastructures may benefit from adopting hybrid nanofluid cooling solutions capable of improving efficiency and reducing operating costs. Manufacturers should prioritize stable and environmentally responsible nanofluid formulations while implementing monitoring systems that ensure long-term performance. Policymakers and industry stakeholders should encourage the development of standards addressing nanofluid production, utilization, safety, and disposal to facilitate broader adoption of sustainable cooling technologies. Investment in interdisciplinary collaboration among materials scientists, thermal engineers, environmental specialists, and industrial practitioners will further support the successful implementation of resource-efficient nanofluid cooling systems.

#### Authors' Contributions

Authors contributed equally to this article.

#### Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

#### Transparency Statement

Data are available for research purposes upon reasonable request to the corresponding author.

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#### Declaration of Interest

The authors report no conflict of interest.

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#### Ethics Considerations

In this research, ethical standards including obtaining informed consent, ensuring privacy and confidentiality were considered.

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