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A REVIEW OF MINIATURE CHANNELS AND NANOFLUIDS TECHNOLOGIES USED AS HEAT TRANSFER ENHANCEMENT TECHNIQUES FOR MICROCOOLING SYSTEMS

Mohamed Salah Elsherbiny[1,2*], Moustafa Ali [2], Moatsem Shahin[3], Mahmoud El-Kady[2]

[1] Renewable Energy Department, Faculty of Energy and Environmental Engineering, British University in Egypt, Cairo, Egypt,

[2] Mechanical Engineering Department, Faculty of Engineering, Al-Azhar University, Nasr City, Cairo, Egypt,

[3] Mechanical Engineering Department, Faculty of Engineering, Badr University in Cairo, Cairo, Egypt.

***Correspondence:** mohamed.salahelden@bue.edu.eg

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ABSTRACT

The synergy between nanofluids and microchannels has become a cornerstone in addressing the escalating thermal challenges across diverse industries, as this symbiotic relationship can meet stringent thermal demands. The objective of the current review is to provide a general and recent overview of all aspects, enhancement techniques, and variables related to miniature channels aligned with utilizing nanofluids from a liquid convection perspective, categorizing variables, and focusing on unique and recent methods used from experimental and numerical perspectives. Consequently, the main elements are simplified into the coolant, heat sink, and operating conditions; besides, their interactions are pivotal because there is no absolute answer for which specific combination of techniques leads to the highest enhancement; however, more complex geometries, sharp edges, and dynamic flow were preferred. Experimental and numerical findings are not identical; besides, the availability of experimental contributions is much lower, which increases the barrier to knowing the enhancement mechanisms and the phenomena behind them. Hybrid nanofluids do not always have a beneficial effect; besides, increasing Re number or particle concentration in HYNF as well; however, higher heat loads are preferred when utilizing nanofluids in MCHS. Increasing the level of hybridization showed a higher enhancement value; however, it was not tested through miniature channels. The manipulation of micro concentrations, hybridization ratios, higher levels of hybridization, porous heat sinks, bionic configurations, organic nanofluids, nanophase change materials, new modeling techniques like ANN, GA, and LBM, and carbon-based heat sinks despite the fabrication barrier are all recommended.

KEYWORDS: Numerical and Experimental Review, Microchannel Heat Sinks, Nanofluids, Hybrid nanofluids, Forced Convection Liquid Cooling

مراجعة القنوات المصغرة وتقنيات الموائع النانوية المستخدمة كتقنيات تعزيز نقل الحرارة لأنظمة التبريد الدقيق

محمد صلاح الشربينى*[1,2], مصطفى على[2], معتصم شاهين[3], محمود القاضى[2]

[1]قسم الطاقة المتجددة, كلية الطاقة و الهندسة البيئية, الجامعة البريطانية فى مصر, القاهرة, مصر،

[2]قسم الهندسة الميكانيكية, كلية الهندسة, جامعة الازهر الشريف, مدينة نصر, القاهرة, مصر،

[3]قسم الهندسة الميكانيكية, كلية الهندسة, جامعة بدر بالقاهرة, القاهرة, مصر.

***البريد الاليكتروني للباحث الرئيسي :** mohamed.salahelden@bue.edu.eg

الملخص

أصبح التآزر بين السوائل النانوية والقنوات الدقيقة حجر الزاوية في مواجهة التحديات الحرارية المتصاعدة عبر الصناعات المتنوعة ، حيث يمكن لهذه العلاقة التكافلية تلبية المتطلبات الحرارية الصارمة. الهدف من المراجعة الحالية هو تقديم نظرة عامة وحديثة على جميع الجوانب وتقنيات التحسين والمتغيرات المتعلقة بالقنوات المصغرة المتوافقة مع استخدام الموائع النانوية من منظور الحمل الحراري السائل ، علاوة على ذلك ، تصنيف المتغيرات والتركيز على الأساليب الفريدة والحديثة المستخدمة من وجهات نظر تجريبية وعددية. وبالتالي ، يتم تبسيط العناصر الرئيسية الى المبرد ، والمشتت الحراري ، وظروف التشغيل ، إلى جانب ذلك ، فإن تفاعلاتها محورية لأنه لا توجد إجابة مطلقة تؤدي إليها مجموعة محددة من التقنيات إلى أعلى تحسين ؛ ومع ذلك ، تم تفضيل الأشكال الهندسية الأكثر تعقيدا والحواف الحادة والتدفق الديناميكي. النتائج التجريبية والعددية ليست متطابقة. إلى جانب ذلك ، فإن توافر المساهمات التجريبية أقل بكثير ، مما يزيد من حاجز معرفة

آليات التعزيز والأسباب الظاهره الكامنة وراءها. السوائل النانوية الهجينة ليس لها دائما تأثير مفيد أو زيادة تركيز الجسيمات لا يأتي دائما مع ردود فعل ايجابيه ؛ إلى جانب ذلك ، فإن زيادة عدد رينولد لا يأتي دائما مع ردود فعل ايجابيه، يفضل الأحمال الحرارية الأعلى عند استخدام السوائل النانوية في القنوات الدقيقه. أظهرت زيادة مستوى التهجين قيمة تعزيز أعلى. ومع ذلك ، لم يتم اختباره من خلال قنوات مصغرة. التلاعب بالتركيزات الدقيقة ، ونسب التهجين ، ومستويات أعلى من التهجين ، والمشتتات الحرارية المسامية ، والتكوينات الإلكترونية ، والسوائل النانوية العضوية ، ومواد تغيير الطور النانوي ، وتقنيات النمذجة الجديدة مثل الشبكات العصبيه و الخورزميات الجينيه يوصى باستخدام جميعها و المشتتات الحرارية القائمة على الكربون على الرغم من حاجز التصنيع.
الكلمات المفتاحية: مراجعة عددية وتجريبية، المشتتات الحرارية للقنوات الميكرو، السوائل النانوية، السوائل النانوية الهجينة، التبريد السائل بالحمل الحرارى القسري.

1. Introduction

As broad and varied applications are found in the domain of small-sized cooling systems, miniaturized technologies have gained popularity in industries other than traditional electronics, including medical devices, aerospace, and automotive. Compact cooling systems are widely used, indicating their role in fostering innovation in various industries and guaranteeing the dependability and effectiveness of contemporary technology. The semiconductor industry has used Gordon Moore's 1965 formulation of Moore's Law as a compass, with integrated circuit transistor counts doubling every two years [1]. This observation has motivated the unrelenting search for more compact and potent electronic devices. The quantity of transistors on a chip keeps growing, consequently, the heat produced increases exponentially. Thus, there is a constant need for effective cooling solutions to keep operating temperatures at their ideal levels and stop failure or deterioration in performance. In addition to influencing the course of technological development, the ideas behind Moore's Law have also highlighted how important small and effective cooling systems are to maintaining the rate of innovation in the electronics sector. Compact equipment, area restriction, and superior liquid cooling systems are considered keywords approached by scientists and researchers, especially in electronic cooling applications, since the failure of its components by temperature rise reached 55% of all kinds of failure reasons [2].

The evolution of cooling starts with natural convection, which includes free convention and radiation effects, then forced air cooling with a metal heat sink, liquid cooling for much higher powers (forced convection), and finally, liquid cooling evaporation. The forced convection method using liquid coolant has good potential as it balances the yield and complexity of the method and could potentially become the optimum method, providing better thermal management and higher heat dissipation rates for miniature cooling systems, especially cooling electronics, with better effectiveness than forced air convection and being relatively simpler than evaporative systems. The heat transfer coefficient is the main factor used to assess the performance of coolants used for liquid-forced convection. For evaporative cooling, two terms need to be introduced, which are heat pipe HP and loop heat pipe LHP. Both use the concepts of phase-change processes and vapor diffusion in the following steps: first evaporation, then transportation, and finally condensation. Moreover, miniature channels have been introduced as a better alternative for heat transfer applications by Tuckerman and Pease [3], showing a higher possibility of dissipating higher-generated heat fluxes. Meanwhile, the nanofluid term is proposed as an innovative and promising coolant type generated by a stable colloidal composition of suspended nano-sized solid particles, usually lower than 100 nm, in conventional base fluids [4]. Suppose nanofluids are prepared by one type of nanoparticles into base fluids to enhance and modify their properties compared to conventional fluids. In that case, hybrid nanofluids are prepared by dispersing two or more particle identities, which is considered a new trend in researchers' approaches to achieving more enhancement in the heat transfer properties of cooling fluids in various applications. Introducing hybrid nanofluids created a new wave of investigations and a new generation of nanofluids for enhancing the heat transfer properties of cooling fluids; however, it increases the level of challenges that are not yet settled after reading the usage of nanofluids in a real-life application.

Regarding the exponentially increasing trend of energy consumption by data centers and supercomputers, which accounted for 1% of total world consumption by 2005, energy used by conventional cooling methods has now reached around half of that percentage. Alternatively, single-phase liquid cooling has been proposed as a vital replacement for the air-forced convective method, as it can significantly reduce overall energy consumption [5]. Microcooling has the potential for numerous vital applications in the present and future. As heat exchangers are commonly found in different technologies and applications, and due to their efficient heat dissipation from components that generate higher heat flux, tiny heat exchangers such as mini and microchannel heat sinks have emerged as superior options for the heat transfer field. As the heat surface area decreases, it becomes more challenging to cool the devices or systems. Besides the fact that electronic equipment is considered to be the perfect example of cooling challenges, the cooling of electronic equipment passes through different phases, starting with forced convective air being co-loaded and followed by convective water being cooled. Analyzing fluid flow in a mixture is considered a complication and challenge for scientists. The flow rate, temperature of the coolant, heat sink design, nature of the coolant fluid (liquid-gas), and nature of the flow (single phase-two phase) are considered to be vital factors affecting such systems. As the aim was to maximize heat transfer and minimize friction loss, attempts were made to manipulate cooling systems to meet the rising demand for increasing cooling efficiency. Besides investigating heat sinks and their enhancement capabilities, a strong wave of enhancing the coolant introduced by nanofluids followed an exponential rise in interest as nanofluids were proposed and defined as the heat transfer fluids of the future generation due to their potential capabilities, providing intriguing new opportunities. Therefore, its potential benefits had a great impact on market investment in almost all sectors of industries. Last decade, the number of publications increased by 96%, introducing a narrow area only of using nanofluids with metal oxides, which highlighted the exponential interest in that topic [6]. Specifically, the objective of this review article is to provide a general, recent overview of all aspects related to mini- and micro-channel heat sinks aligned with the use of nanofluids and hybrid nanofluids from a liquid convection cooling perspective, as well as their importance as a vital topic in numerous applications. Furthermore, this review is distributed into two sections: experimental and numerical contributions, for highlighting the gaps, opportunities, and challenges in each side of investigations; analyzing the findings through a discussion; and highlighting the contradictions and similarities of the outcomes from each study type. Framing and categorizing the huge number of topics, parameters, variables, and promising areas of investigation related to those topics might be misleading for those approaching to start their investigation into those topics. One of the novelty aspects of our contribution is categorizing the recent literature into experimental and numerical sections, which promotes a better understanding of the reasons behind the enhancement of such systems and could be a cornerstone for readers who will attempt to start investigating those topics, besides focusing on the different and unique methods that were recently used in those topics without repeating as much as possible.

The article is organized into distinct sections that are logically arranged to make it as easy as possible for readers to comprehend and grasp the ideas to achieve the highest level of clarity in the information delivery. The introductory section of our research article addresses the pervasive issue of high heat loads affecting various applications, particularly the cooling of electronic equipment. We delve into the potential solutions by introducing nanofluids as innovative trends in cooling fluids and microchannel heat sinks as promising advancements in heat sink design. The synergy of employing both in compact equipment is emphasized for their positive impact on cooling systems. This section aims to establish the critical context for our research, setting the stage for an in-depth exploration of these novel technologies, followed by stating objectives, purpose, novelty, scope, and limitations in our current review for fulfilling a current gap, highlighting the research significance, and providing a roadmap and outline for its organization.

The subsequent part will start by reviewing and discussing review articles on the previous topics and their findings to highlight our current contribution, followed by a section that systematically categorizes and lists all variables relevant to the cooling systems under study after highlighting investigators' approaches and methodologies in studying those systems, whether experimentally or numerically, and why. This comprehensive classification leads to the identification of two primary elements: coolant parameters and heat sink parameters, along with an exploration of operating conditions. A detailed discussion ensues, introducing the extraction methods of nanoparticles, their thermophysical properties, applications, preparation, and stability of nanofluids, as well as the general challenges within this context. This meticulous breakdown of variables lays the foundation for the third section, which conducts a thorough review of convective heat transfer experimental contributions, delving into the nuances of these parameters. Subsequently, the article transitions to exploring numerical contributions, scrutinizing how these variables manifest in various computational models. The ensuing discussion section critically analyzes and interprets the findings, emphasizing the synergy between experimental and numerical insights. At last, the research article concludes by summarizing key discoveries and offering recommendations for future investigations, thereby inviting further exploration and advancement in the field of compact equipment cooling systems. Finally, by synthesizing findings from diverse sources, we are aiming to highlight the collaborations among researchers globally to push the boundaries of thermal engineering in our comprehensive review, which serves as a cornerstone for further advancements in this rapidly evolving field.

2. Miniature cooling systems and techniques proposed for enhancment.

Before starting our current investigation, a comprehensive review of review articles concerning microchannel heat sinks and nanofluid technologies was done to significantly advance our understanding of the recent development of thermal management systems from different perspectives, as shown in Table 1., besides highlighting the need for our current study. Through meticulous analysis, we aimed to provide valuable insight into current research trends, emerging technologies, and potential applications in the field. Our critical evaluation of the existing literature has identified knowledge gaps, highlighted inconsistencies in reviewing the current topic, and delineated the future research directions to review the current topic from different approaches shown that thermophysical properties, preparation, characterization and nanofluid stability were hot topics, followed by attempts of reviewing different promising applications regarding using nanofluids or micro channels, beside a few contributions in some different topics like reviewing single and hybrid passive methods of enhancement, fabrication techniques of micro channels, organic nanofluids, porous heat sinks and modeling techniques, however, the contributions in reviewing mono and hybrid nanofluids aligned with geometrical parameters of micro and mini channel heat sinks and differentiating between experimental findings and numerical findings or even the convective heat transfer approach rather than the conductive one is still not much especially for recent hybrid nanofluids contributions.

No doubt, a key augmentation to the efficacy of microcooling systems is the integration of nanofluids, which could be defined as an engineered fluid with nanometer-sized particles dispersed in a colloidal state that exhibit superior thermophysical properties. Those properties enhance the overall heat transfer capabilities, enabling those systems to tackle the escalating thermal challenges associated with modern and compact designs. Utilizing those approaches could provide a more efficient and robust cooling process, addressing the growing challenges associated with heat generation and advancing thermal management. Moreover, as a research approach, it poses a significant challenge not only due to the large number of variables to consider but also because these variables may interact with each other in different ways. Thus, many researchers and investigators attempt to study the problem from various perspectives, so before going into the details, we may first categorize them based on the research type or the methodology, which could be either conceptual or empirical. Conceptual research might be categorized into mathematical, analytical, or numerical methods and approaches; however, it mostly goes into the numerical track because of the large number of variables involved and the complexity of the models that need to be solved. Thus, that classification could be simplified to either experimental or numerical. Furthermore, researchers attempt to study heat transfer from two different angles; some investigators concentrated on surface temperature, thermal resistance, and thermal performance, while others focused on thermal conductivity and how it influences heat transfer from a conductive perspective; moreover, heat transfer coefficients from a convective perspective, friction factors, performance evaluation criteria, and/or figures of merit were approached by other researchers.

Table 1. A brief review of articles related to microchannel heat sinks and nanofluids.

Author/Review Type	Title	Objective and Approach	Findings and Conclusions	Recommendations
Solangi et al. [7] Comprehensive Review	Thermo-physical properties and convective heat transfer	• This review aims to discuss nanofluid stability in terms of the parameters that could affect it and how to evaluate it; besides, it reviews nanofluid's thermophysical properties and their contribution to heat transfer enhancement.	• Flow velocity and volume fraction increase the enhancement level of heat transfer coefficient employing nanofluids, as proved experimentally and numerically. • Despite the importance of using surfactants for enhancing nanofluid stability, their functionality under high temperatures is a major concern. • Stability problems arise more for nanofluids prepared by the two-step method. • Long-term stability methods without affecting the thermophysical properties of nanofluids are a challenge.	• Understanding the stability and mechanisms responsible for heat transfer enhancement before involving it in practical applications remains challenging from the preparation and characterization perspectives. • Synthesizing the production costs of nanofluids significantly hinders their commercialization. • An advanced technique, including the one-step method rather than the two-step method.
Amin et al. [8] Critical review	Thermal conductivity and dynamic viscosity of mono- and hybrid organic- and synthetic-based nanofluids	• This review focused on thermal conductivity and dynamic viscosity, as they are two critical properties of any type of nanofluid, whether organic, synthetic, mono, or hybrid, that indicate their heat transfer performance, besides qualitative and quantitative stability measurement.	• The thermal conductivity ratio of nanofluids increases with increasing volume fraction, fluid bulk temperatures, and nanoparticle size. • Decreasing particle size and nanoparticle concentration decreases the dynamic viscosity of nanofluids. • While the majority of synthetic metal oxide nanofluids enhanced the thermal conductivity ratio by 20%, adding carbon-based nanoparticles increased it by less than 10%.	• Pumping power problems that are accompanied by increasing nanofluid viscosity should be investigated more. • An extensive study of organic-based nanoparticles may increase the thermal conductivity ratio with minimal impact on the dynamic viscosity of nanofluids.
Japar et al. [1] Review electronic devices	Passive methods in microchannel heat sink application through advanced geometric structure and nanofluids: Current advancements and challenges	• Critically summarize the challenges, limitations, and performance of single and hybrid passive methods of MCHS, especially with nanofluids and their parameters like nanoparticle types, concentrations, and base fluid types, and their stability. • Comprehensively summarize current designs of MCHSs that could result in higher efficiency with an acceptable pressure drop to provide a better understanding of design development.	• The hydraulic performance of a hybrid passive method was better than that of a single passive method; however, sometimes pressure drop can be high because of the friction factor influenced by the geometry structure; thus, the optimum conditions should be obtained. • Heat transfer enhancement could be improved by fluid mixing. • The surface roughness method is the best method to reduce the friction factor. However, it is ineffective if applied as a single method, but by combining it with the flow disruption method, it could be more effective thermally. • Despite nanofluid's thermal enhancements, the high-pressure drop was the main limitation; thus, each type has a limited range of concentrations to achieve optimization.	• Al_2O_3/water nanofluid is the most commonly used nanofluid, with a nanoparticle volume fraction of less than 2% suggested as higher concentrations negatively affect hydrothermal performance. • Fluid mixing can be achieved by changing the flow profile, and out-of-flow mixing is the best method to provide that; however, it results in a high-pressure drop, so the secondary flow generated by secondary channel geometry can be useful to avoid that.
Ali and Salam [9] Review	Preparation, stability, thermophysical properties, heat transfer characteristics and application	• This review aims to summarize recent progress in the improvement of heat transfer using nanofluids and on the preparation and enhancement of their stability, their thermophysical heat transfer characteristics, and different factors that might manipulate them, such as particle size, shape, surfactant, temperature, etc.	• Literature reveals that nanofluids have the potential to be utilized in numerous applications such as transportation cooling, electronic equipment cooling, nuclear and renewable applications defense, desalination, etc. • Nanofluid preparation as heat transfer fluid is costly and non-economic yet for practical implementation. • Hybrid nanofluids were not yet well investigated. • Thermophysical and heat transfer properties of carbon-based nanofluids like carbon nanotubes and graphene are very few, despite their promising hydrothermal performance. • Contributions made in the area of estimating, calculating, and correlating the thermophysical properties and heat transfer characteristics of nanofluids have not yet been formulated.	• Cost-effective methods for nanofluid preparation are still a challenge for upgrading nanofluids to the commercial level. • However, there are a lot of proposed methods for enhancing nanofluid stability, which remains a challenge for practical implementation. • The progression in stability methods like sonication timing, magnetic stirring timing, and surfactant concentration for getting their optimum values has not been settled yet. • Thermophysical properties Correlations for estimating hybrid nanofluids and carbon-based nanofluids are still in their early stages.
Deb Majumder and Das [10] Short Review	Organic Nanofluids: Preparation, Surfactants, and Applications	• This review aims to highlight preparation methods, surfactants used for stability, and areas of usage of organic and inorganic nanofluids, especially for achieving zero-energy buildings with HVAC systems.	• Recently, there has been a significant advancement in the development of organic nanofluids. There are a lot of advantages over inorganic nanofluids: cost-effectiveness, environment-friendliness, efficiency, and a higher enhancement level in their thermophysical properties like thermal conductivity, specific heat, and coefficient of thermal convection. • Organic nanofluids might be the solution to the nanofluid stability problem as the long-chain nanoparticles and their covalent behavior provide them with better stability for a longer period; however, at high temperatures, the bond strength of surfactants is reduced, and with the increase in volume fraction, the viscosity increases as well, which often leads to higher pumping power.	• More effort needs to be made to develop a better mathematical model to predict the thermophysical properties of nanofluids accurately. • The shape and geometry of the nanoparticles and their relation to nanofluid stability should be investigated more than surfactants and surfactant-free methods. • More studies should now focus on employing nanofluids in HVAC and minimizing the use of conventional refrigerants.
Saidina et al. [6] Review	Metal oxide nanofluids in electronic cooling	• This review aims to differentiate and compare conventional heat pipes (HP) and loop heat pipes (LHP) with and without nanofluids for electronic cooling. • The nanofluid fabrication, stability, surfactants, and recent works of metal oxide-based materials and parameters that influence their thermophysical properties.	• Not affecting the orientation is one of the numerous advantages of LHP, which allows it to be in different designs to suit different kinds of equipment. • Metal oxide nanoparticles are resistant to oxidation and chemically stable, so they have gained popularity to be used intensively. • The thermophysical properties of metal oxide nanofluids were influenced by the thermal conductivity, viscosity, and surface tension of their base fluids. • Surfactants are one of the methods used for enhancing stability.	• Al_2O_3 is suggested as a promising nanoparticle for cooling HP and LHP. • The stability and thermophysical properties of metal oxide nanofluids, especially for cooling electronics, need more investigation.
Chandravadhana et al. [11] Review	Mono and hybrid nanofluid-based heat sink technologies	• This review aims to discuss mono- and hybrid nanofluid preparation and characterization techniques, the analysis of MCHS, and geometries for designing parameters to examine factors like pressure drop and heat transfer coefficient and provide challenges and opportunities.	• Employing nanofluids and microchannel heat sink technologies becomes a favorable approach for researchers worldwide, besides its advantages to be used, especially in the electronic device cooling field. • Controlling the heat transfer mechanism of nanofluids is an obvious challenge due to the huge number of factors that might manipulate heat transfer characteristics. • Stability and production cost are the main obstacles to the practical implementation of nanofluids and microchannel heat sinks in various applications. • Hybrid nanofluid observations within the literature shown a greater augmentation of heat transfer.	• Electronic device cooling systems and their thermal designs are a promising field for applying nanofluid technology and need to be reviewed. • Microchannel heat sinks and nanofluids and employing both together in cooling systems still have a lot of gaps and are underdeveloped.
Aglawe et al. [12] Systematic review	Preparation, applications and challenges of nanofluids in electronic cooling	• This review aims to highlight the contributions of examining the viability of nanofluid utilization and the determination of a suitable one significant for thermal management improvement theoretically and experimentally for electronic device cooling.	• Nanofluid-based metallic nanoparticles have shown a larger improvement in cooling capacity as well as thermal performance. • Investigating and analyzing nanofluid stability deeply in both static and dynamic flow conditions is essential for further practical industrial implementation. • Researchers' contributions to investigating a wide range of inlet temperatures utilizing metal oxide and carbon-based nanofluids should be greater, whether experimentally or numerically. • Most practical literature shows that nanofluids are preferred in electronic cooling systems.	• A database for values of thermophysical properties, taking into consideration the currently proposed variables that manipulate them, like concentration, size, and method of preparation. • Applications based on nanofluids and microchannel heat sinks need a huge research effort. • Lower particle concentrations need comprehensive research and contributions using aspects like particle size interpretation, metallic nanoparticles, and stabilizing methods.

Khan et al. [13] Critical Review	Micro and mini channels, porous heat sinks with hydrophobic surfaces for single phase fluid flow	• This review focused on the experimental, numerical, and analytical applications and contributions of nanofluids in mini/microchannel heat sinks for enhanced heat transfer in cooling systems. • Advancement of the thermophysical properties of nanofluids and the uses of hybrid nanofluids in different systems, besides porous medium devices, as well as the use of superhydrophobic surfaces.	• Nanofluids are promising heat transfer coolants, and they have many advantages, especially in electronic cooling systems, despite the problems associated with their practical implementation. • Controlling thermal performance within cooling systems using nanofluids is difficult, as the factors that affect it are not only nanofluid factors but also heat sink geometrical parameters. • Hybrid nanofluids offer better thermophysical properties than nanofluids; however, the current literature shows that increasing concentrations of hybrid nanofluids enhance their properties up to a certain limit, after which there is no effect. • Two-step methods take more effort than one-step methods, but they can create more sophisticated and stable nanofluids.	• Universal correlations for heat transfer using hybrid nanofluids and their different concentrations still need to be developed, despite the contributions that have been reviewed. • Micro and mini heat sinks are practically employed to enhance heat transfer; however, porous heat sinks are not applied much yet. • Porous heat sinks with nanofluids are not much applied; besides, superhydrophobic surfaces are promising to be utilized due to their no-slip condition and no pressure loss; however, they are still challenging to create.
Joy et al. [14] Review	Fabrication and experimental study of microchannel heat sinks for cooling of electronic components	• This review focused on MCHS fabrication methods that can be done using techniques like micro-milling, electric discharge machining (EDM), laser beam machining (LBM), lithography, injection molding, and dry and wet etching. • Experimental comparisons of fluid flow and heat transfer at various output parameters are examined for numerous structures. • Variations and optimization in process parameters concerning output parameters.	• MCHS might be fabricated using various types of materials; however, the techniques used are pivotal to avoid major surface irregularities that have a significant negative impact on hydrothermal performance. Thus, EDM, wire EDM, and laser beam micromachining are preferred as they provide accurate dimensions and high surface quality; moreover, complex structures exhibit higher hydrothermal performance. • Fabrication factors, numerically or experimentally, have a remarkable influence on hydrothermal performance; besides, temperature measurement through conducted experiments reveals flow disturbances that affect performance negatively. • Variations in process parameters have a vital role in the surface quality, for example, pulse on time for EDM and pulse intensity for LBM.	• High thermal conductivity materials were recommended for its fabrication. • Because of free external disturbance, numerical analysis provides more precise results for heat dissipation than experimental studies. • The hydrothermal performance of MCHS is enhanced by utilizing hybrid or nanofluids, among many other factors like mixing of fluids, multi-jet flow channels, and implementing complex geometries of channels.
Alshuhail et al. [15] Critical Review	Thermal efficiency enhancement of mono and hybrid nanofluids in solar thermal applications	• Focusing on and discussing the methods for creating, characterization methods, characteristics, and difficulties of using hybrid nanofluids with flat plate collector FPC and their applications. • The synthesis of hybrid nanoparticles and hybrid nanofluids, characterization, thermophysical characteristics, stability, analysis, and application of mono and hybrid nanofluids in solar thermal systems, specifically flat plate collectors, are critically reviewed.	• The coolant of FPC is the only factor that manipulates and enhances its efficiency, and the majority found that this might be accomplished by utilizing nanofluids. • There are two major methodologies for creating hybrid nanoparticles: physical and chemical methods, and among them, chemical is the simplest and most affordable. • Hybrid nanofluids provide higher thermal conductivity and surface morphology, thus having a significant impact on heat conductivity. Besides, the smaller nanoparticles function better, leading to higher particle motion and consequently faster heat transfer rates. However, higher particle loadings increase viscosity despite their reduction with higher fluid temperatures. • Promoting hybrid nanofluids with turbulent flow, twisted tape, perforated plates, and porous discs may further increase thermal efficiency despite challenges.	• Mass flow rates and concentration both rose along with FPC thermal efficiency. • Hybrid nanofluids are very promising in solar thermal applications as they can increase thermal efficiency up to 62%. • Further research is required in terms of cost, stability, and pumping power of hybrid nanofluids, which should be well investigated as they are the main obstacles preventing their commercialization.
Gao et al. [16] Review	Fluid flow and heat transfer in microchannel heat sinks: Modelling review and recent progress	• This review aims to summarize comprehensively numerical methods in MCHS and nanofluids; however, incompatibility in the research content methods such as computational fluid dynamics CFD, which includes finite difference method FDM, finite element method FEM, and finite volume method FVM, molecular dynamics simulation MDS, Lattice Boltzmann methods LBM, Direct Simulation Monte Carlo DSMC, and techniques like machine learning ML, artificial neural network ANN, genetic algorithm GA, Taguchi method TM, as well as optimization methods were discussed.	• CFD can simulate a variety of boundary conditions beside complex structures; however, the requirements for mesh quality are different, while LBM can study micro- and nanoscales and is not limited by the mesh as it can determine the effects of particles • The DSMC is used to predict the flow state of thin gas using statistics based on the dynamics theory of molecular processes. MDS can simulate a smaller scale as the motion law of molecules, and both take argon atoms as the research content; therefore, they have the same computational domain. • TM is an effective statistical method that could improve the quality of experiments by achieving optimal strategies, while GA has four steps: population, selection, crossover, and mutation, and can filter and process data at the same time, which is preferable with large amounts of data. Moreover, ANN and GA have the same capability to solve nonlinear problems and strong robustness; however, they perform differently by having an input layer, a hidden layer, and an output layer, as well as the ability to perform autonomous diagnosis.	• For phase change problems, LBM is not recommended as it is difficult to track the change. • The DSMC needs an effective method to solve the problem and overcome the computational cost, as its higher accuracy attracts researchers. • MDS utilizing microchannels is still in its early phases and needs more investigation. • TM operation is simple, and the convergence speed is fast, which provides a deeper understanding of the control parameters. • Further improvement is needed for the current ANN, as it is not accurate enough and relatively slow.
Faizan et al. [17] Critical Review	Thermophysical and electrochemical properties of Ionanofluids and their applications	• Summarizes the synthesis of ionic nanofluid INFs and the influence of variables like temperature and particle concentration on their thermophysical and electrochemical properties and their usage in wide applications that might benefit from those properties. • Reviewing and comparing different INFs based on their combination and composition and enlisting the reasons behind proposing them to various applications.	• Good conductivity (thermal and ionic), high thermal stability, solubility, less vapor pressure, and strong electrochemical properties are desirable features of INFs. • No significant changes in thermal conductivity were observed using nanoparticles with ionic fluid by manipulating bulk fluid temperature; however, by increasing nanoparticle concentration, thermal conductivity was affected positively. • Thermal conductivity and particle concentration for INFs have not been extensively studied compared to heat capacity, viscosity, and density, while electrical conductivity offers impressive results. • INFs in lubrication applications have encouraging outcomes and outstanding tribological features. Moreover, INFs are promising for catalysis and separation and also provide a way of immobilizing homogenous catalysts.	• Justifications related to phenomena of changes in thermo-physical properties with operating variables are few and not established. • Few studies discussed INF factors like size and shape of nanoparticles, liquid-solid interface, adsorption layers, unusual heat or mass diffusion, and stability. • Real-life applications were less considered compared to simulators and modelers. • Reusability, regeneration, and critical comparison of different INFs from a commercial point of view need to be investigated more.
S. Kumar et al. [18] Comprehensive Review	Flow and heat transfer behavior of nanofluids in micro channel heat sinks	• The main purpose of this review is to summarize convective heat transfer, pressure drop, flow characteristics, and thermal performance of microchannel heat sinks and their geometrical parameters using nanofluids for maximizing thermal performance in terms of heat transfer and friction loss.	• Heat transfer enhancement mainly depends on the type, size, and volume fraction of nanoparticles, volume flow rate, and channel geometric parameters; moreover, using nanofluids produces a decline in conductive thermal resistance and leads to a decrease in the size of cooling devices. • The use of metal-based nanofluids increases thermal performance and increases with an increase in concentration. • The triangular grooved configuration is better than the rectangular one; the zigzag configuration is superior to the wavy one; and the convergent-divergent configuration is better than the straight one. • Single-phase model estimates for hydrothermal variables are higher than the two-phase model. • Cooling by glycerin-base nanofluids has the lowest temperature value and the lowest thermal resistance, while water-based cooling has the highest value, followed by ethylene glycol-based cooling.	• The enhancement of heat transfer within micro- and mini-channel heat sinks using nanofluids comes with a pressure drop and friction factor price, which need further investigations to avoid. • Thus, investigations must consider the effect of the pressure drop as it consequently affects the system pumping power.

From a literature point of view, cooling systems pass through different stages depending on the application, and heat load needs to be removed, so it is categorized and reviewed as follows [18]: As heat load increases, the type might change to fulfill the cooling requirement, starting with the passive type using natural convection systems, followed with the passive type using natural convection systems, followed by the semi-active type using forced convection, for example, a fan with a heat sink, that can withstand a higher heat load, then the active type introduced by combining a fan and heat sink into one unit, which had a higher cooling potential with the previous types, a liquid cooling system proposed as a higher capacity heat dissipation method over other systems, and finally phase change cooling for higher power intensity usage despite its limitations as its area restrictions, complex design, and economically more costly than others. Generally, forced convective liquid cooling systems are of great interest because of their relatively low power consumption and the possibility of applying numerous enhancement techniques.

Enhancement methods could be classified into active enhancement techniques like vibration, electrostatic fields, flow pulsation, and variable roughness or passive enhancement techniques like surface roughness, flow distribution, channel curvature, re-entrant obstructions, secondary flow, out-of-plane mixing, and fluid additives [1]. However, if we take a broader, more comprehensive perspective, it might be categorized and simplified into three main elements, which are the heat sink, cooling fluid, and operating conditions. Furthermore, in the following section, we will discuss, categorize, and mind map each element and researchers' contributions within the literature.

Beginning with the heat sink approach, Chandravadhana et al., [11] reviewed six factors to be considered for better design of heat sinks: thermal resistance (material, size, shape, and location of fin), fin efficiency, thermal interface material, and heat sink attachment method, while Khan et al., [13] concluded in a review that rectangular heat sinks were mostly used in open literature for nanofluids in MCHS and others reviewed numerous geometric microchannel shapes used in open literature studies from different researcher perspectives [18]. However, categorizing geometric parameters of heat sinks to provide a more general perspective showed that researchers mainly focused on the heat sink material and surface roughness or geometric parameters and variables such as the size of channel mini and micro versus macro or conventional, yet others examined the number of channels (single versus multiple), the pattern of channels (straight versus non-straight), the impact of continuous verses on how the channel line is interpreted, the impact of input-output conditions on how flow enters the channel and exit it, the channel's cross-sectional area and separated fins rather than continuous channels and all those variables and factors categorized and mapped and shown in Fig. 1.

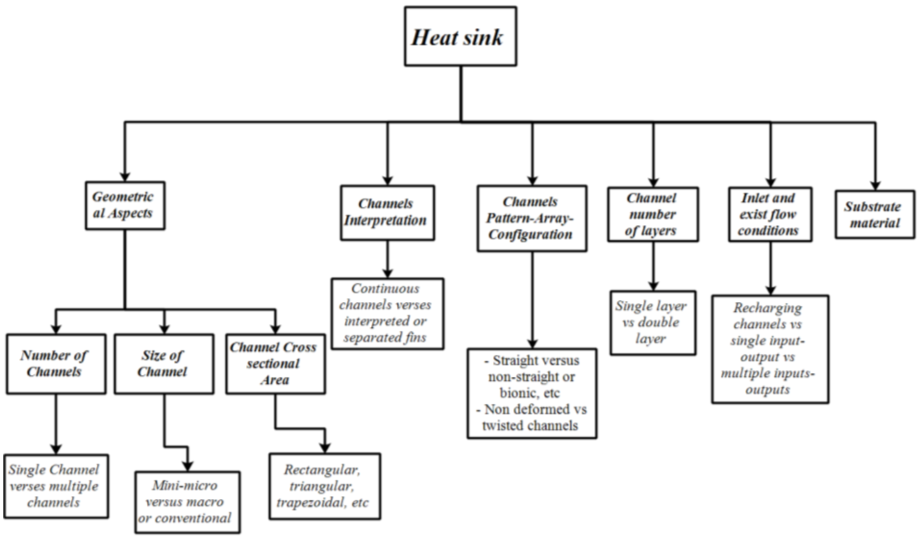

Fig. 1. Variables and parameters considered for enhancing the heat transfer capabilities of heat sinks.

Alternatively, from a coolant perspective, nanofluids pose a great interest in the literature, as they are defined as colloidal homogenous fluids synthesized by suspending nanosized solid particles in a liquid. Most of the literature agrees that it has modified properties compared to conventional fluids. Nanofluids provide numerous advantages, such as higher stability of colloidal suspension and lower pumping power and particle clogging when compared with conventional solid-liquid colloidal at the micro or macro scale. Furthermore, varying and manipulating parameters within nanofluids showed a huge impact on enhancing and improving thermophysical properties and heat transfer performance. Usually, the process of improving convective heat transfer is conducted passively, utilizing boundary conditions or the geometric configuration of heat sinks, but it always comes to its obvious constraint, which is the poor thermophysical properties of conventional coolants. That's the reason behind the intensive research wave, as nanofluids are proposed as a new generation of working fluids with huge potential in various aspects.

Let's examine, from the standpoint of a working fluid, specifically from that of particles added, as shown in Fig. 2., a categorization and mind map of the investigator's contributions to that topic. Researchers studied the particle's identity, size, and concentration in the base fluid, as well as particles with special effects (such as the magnetic effect). Others are looking into the use of multiple particle types, which are known as hybrid nanofluids. Furthermore, mixture ratios or hybridization ratios have emerged, leading us to refer to these as mono nanofluids (by adding only one type of nanoparticle), di nanofluid for two particles added, three to a tri nanofluid, etc.; however, other researchers looked into base fluid mixtures for different purposes.

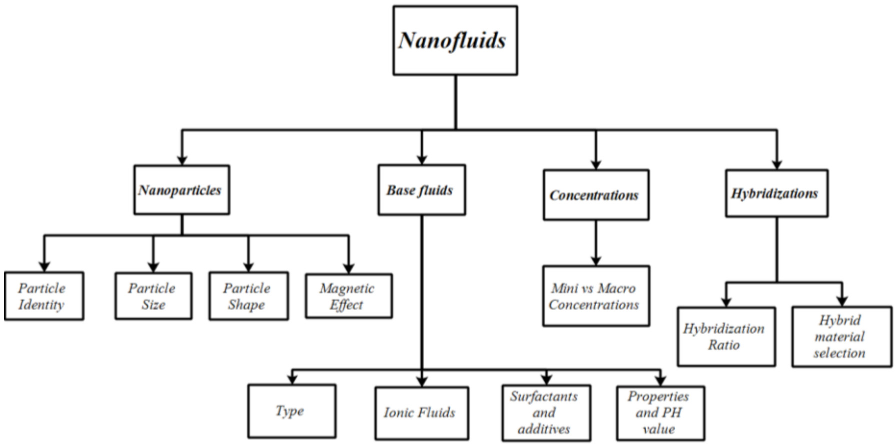

Fig. 2. Variables and parameters considered for enhancing the heat transfer capabilities of coolant by using nanofluid technology.

Furthermore, aside from variables and parameters manipulated by investigators to enhance heat transfer, there is a significant importance of nanofluid operating factors that change dynamically with those variables and shape the performance of the cooling system and how those factors could affect each other and the overall efficiency and effectiveness of the cooling system. First of all, the thermophysical properties of nanofluids and how they could be manipulated not only because of factors like concentration but also because of fluid bulk operating temperatures; besides, the phenomena that occur within testing nanofluids like particle migration, clustering, stability, and degradation, which have been proposed by some investigators as one of the reasons behind enhancement or diminished values of heat transfer capabilities, Furthermore, the heat transfer mood itself means experimenting with one-phase conditions like forced flow convection and natural convection or two-phase flow like pool boiling and evaporating, leading to the flow regime of nanofluids and how they could behave, laminar or turbulent for one-phase flow or dispersed, bubbly, mist, slug, churn, and annular for two-phase flow, or even more different flow regimes that will be discovered later. All the previously stated operating factors within studying nanofluids have to be considered and specified during the study as they have an impact on the hydrothermal overall performance and the aimed outcomes for using such kinds of engineered fluids.

Further, for the aim of preparing nanofluids, two types of methods could be used, which are the one-step method and the two-step method. The one-step method disperses and makes nanofluids in one step, and it has an advantage since it keeps nanoparticles from oxidizing. This strategy, which includes the laser ablation method, can be used to lessen the agglomeration of nanoparticles and enhance fluid stability, which lowers production costs by preventing the dispersion of drying, storing, and transporting nanoparticles. However, it could be more intricate and sophisticated than the two-step method, and so it has its limitations. The two-step method is described as making use of extracted nanoparticles and mixing them directly with base fluid; moreover, extracted nanoparticles could be done using different methods and techniques, as shown in Fig. 3., and those extraction techniques for nanoparticles are categorized as chemical, biological, physiochemical, and physical methods in the open literature [17]. The steps of mixing conducted through the two-step method are either with a mechanical mixer or magnetic stirrer, then using an ultrasonicator for a specific sonication time. This method could also use surfactants to increase the stability of the colloidal [9]. Given its capacity for large-scale production, the two-step method is widely recognized as the most effective method of processing nanofluids. and less intricate than the single-step procedure [12], it is also preferable due to its ability to make more sophisticated nanofluids like hybrid nanofluids and more stable nanofluids than the one-step method [13].

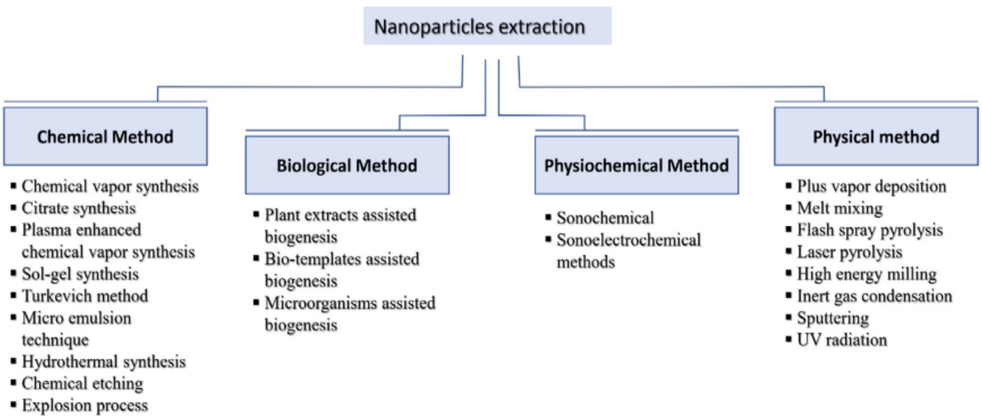

Fig. 3. Hierarchy for nanoparticle extraction methods used in open literature [17].

One of the main problems facing nanofluids is the instability of the fluid [17], and to address that problem, it could be briefly described as follows: The cause of instability is due to several factors like types of nanoparticles, base fluid, particle size, entity interactions, thermophoresis, and sonication time of preparation; then, stability enhancement methods by addition of surfactants, surface modification techniques, pH control, and ultrasonic agitation; followed by stability enhancement mechanisms like less Van der Waals force, high electrical double repulsive force, accumulation of electrons at the surface, and isomorphic substitution of ions. Enhancing nanofluid stability using surfactants is the most commonly used method after ultrasonication. Different types of surfactants are mostly used, like SDS, oleic acid, and CTAB, for preparing nanofluids or hybrid nanofluids, as reported by investigators using a two-step method for preparation and a different type of surfactant in their investigation [19-21]. Finally, characterization and stability evaluation methods used by investigators were the sedimentation photograph method, centrifugal method, zeta potential method, electron microscopy method by transmission electron microscopy (TEM) device, spectral absorbency analysis, and 3ω method [9]. However, the most commonly used one was sedimentation, as it is the easiest one. The combination of nanoparticles and hybrid nanofluids has not yet been touched on, and the correlations of thermophysical properties and heat transfer characteristics for them have not yet been formulated.

Nanofluids, a combination of base fluids and nanoscale particles, exhibit distinct thermophysical properties crucial for their performance. Firstly, their density is influenced by nanoparticle concentration, affecting the overall fluid mass and flow behavior; secondly, thermal conductivity is significantly enhanced due to the high thermal conductivity of nanoparticles, promoting efficient heat transfer; thirdly, heat capacity is impacted by the type and concentration of nanoparticles, influencing the fluid's ability to store and release thermal energy; and lastly, viscosity remains a key parameter; the specific nanoparticles and concentrations used can influence this property. Balancing these four thermophysical aspects is essential in optimizing nanofluid formulations for various applications, from improved heat exchangers to advanced cooling systems. Thermal conductivity and viscosity are the main obstacles in conventional cooling fluids as they have limited values, and it is believed that they are a critical constraint in developing engineering systems that employ fluid flow. Those properties affect heat transfer capabilities and pumping power, which in turn are related to overall cooling efficiency. In addition, a single-phase or two-phase numerical solution for predicting the heat transfer performance of nanofluids depends on how accurately and precisely the developed correlations estimate the thermo-physical properties of those modified fluids.

Generally, there are two main approaches to estimating thermophysical properties in the literature, and we can conclude that some researchers used a measuring methodology while other researchers used a modeling approach by calculating it through different proposed models. Despite the availability of many types of models to estimate thermophysical properties in the literature, they can be classified as temperature-dependent approaches or temperature-independent approaches. Starting with the Maxwell model, which can also be called by other names like the static model, the two-phase model, or even Hamilton's equation, that model concerns only the concentration of solid particles as a function of the thermophysical property model, and there are some enhancements to that model that consider particle shape as well as other factors. That's why it's also called a constant property approach. The temperature-dependent approach had a lot of developed models that not only included temperature but also other operating factors and dynamic factors, which is why they called it the variable property approach or real-time property approach, like the most famous one, the KKL model, the Corcione model, or the multi-sphere Brownian model MSBM. However, in recent studies, the analysis indicates that using a relatively old model, like the Maxwell model, gives an excellent estimation of the Nusselt number, and the difference between the Nusselt numbers predicted by the different models is only roughly 2% at specific conditions, which is not very significant because it can be executed more easily at higher hybrid nanofluid levels [22].

Nanofluids can be classified in terms of usage into various areas of study, like area heat transfer fluids, tribological fluids, coating and surfactant nanofluids, chemical nanofluids, process nanofluids, environmental nanofluids (pollution cleaning), and pharmaceutical and medical nanofluids. These areas of study can fulfill the continuous needs for improvement in various applications listed below, as shown in Fig. 4. [12]. Nanofluids provide many advantages over conventional fluids, such as a higher specific surface area between coolant entities, adjustable thermophysical properties by varying experimental parameters, higher dispersion stability, and lower particle clogging compared to microfluids, which promote system miniaturization and relatively lower pumping power for achieving an equivalent heat transfer level as conventional fluids. Nanofluids are used in numerous applications, as follows:

1. Automotive and transportation industries, like engine cooling, fueling, or transmission oils.
2. Electronic Component Cooling like micro-channel heat sinks for computers and electronics chips.
3. Refrigeration (domestic and chillers), air conditioning systems, and domestic refrigerators.
4. Renewable applications like thermal energy production and cooling of photovoltaic systems.
5. Robotics and Micro/Nano-Electro-Mechanical Systems (MEMS, NEMS).
6. Military, defense, and aerospace applications.
7. Bio-medical applications.
8. Deep drilling applications and lubrication systems.
9. Machining industry, and high-power lasers.
10. Telecommunications and telephones.
11. Conventional power plants and nuclear systems.

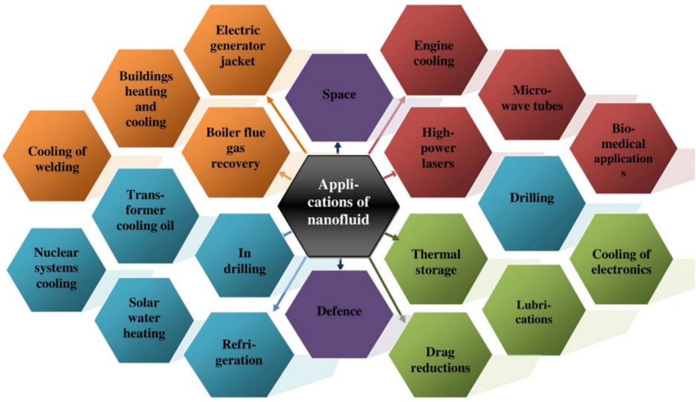

Fig. 4. Generalized applications and area of research on nanofluids [12].

Different types of nanoparticles used in literature might be classified [12] into carbon-based nanoparticles, oxide nanoparticles, magnetic nanoparticles, hybrid nanoparticles, and metal nanoparticles; however, the Al_2O_3 nanoparticle is most commonly used by around 50% of publications [1]. It is important to list and clarify the most frequently used types of nanoparticles, base fluids, and surfactants used in the literature, so they are tabulated in Table 2. [6, 23].

Table 2. Nanoparticles, base fluids, and surfactants most frequently utilized in the literature.

Type	Nanoparticles	Base fluid	Surfactant	
Metals	Au Ag Cu Fe	• Water • Propylene glycol • Ethylene glycol • Antifreeze	Ionic	• Sodium dodecylbenzene sulphonate SDS • Sodium dodecylsulphate SDS • Sodium Cholate SC
Non-Metals	TiO_2 ZrO_2 SnO_2 Fe_3O_4 Bi_2O_3 Al_2O_3 WO_3 CuO ZnO MgO Al_2Cu Diamond Graphite CNTs CNF Bi_2Te_3	• Mono-ethylene glycol • R407C • R134a • R123 • R113 • Glycerol • Ethanol • Toluene • Decene • Alcohol(C_2H_2OH) • FC72 • Polyolester oil • Synthetic oil • Automatic transmission oil • Transformer oil	Non-ionic	• Gum Arabic • Poly vinyl pyrrolidone PVP • Triton X-100 • Oleic Acid
			Cationic	• Cetyl trimethyl ammonium bromide CTAB • Benzalkonium chloride
			Amphoteric	• Lecithin • Hydroxysultaine

One of the vital and pivotal questions is why there is no definitive and solid theory for nanofluids and to answer that there are three possible reasons proposed; The first one is the strange thermal behavior of nanofluids that are different from other physical composites, suspensions, or mixtures, secondly thermal transport in nanofluids could manipulated by a set of unique parameters like particle shape and size and concentration in base fluid and finally the most crucial one multiscale issues as at least four scales could considered while investigating nanofluids: molecular scale, mesoscale, microscale and macroscale [24] and that creates a huge hurdle and challenge in conceptional investigations. However, investigators proposed various possible mechanisms that could describe why such enhancements exist, listed below as the most frequently utilized ones, and despite that, it is obvious that, despite attempts to explain such enhancements, there are still many noticeable discrepancies.

- Brownion motion of particles through base fluid molecules and solid-solid particle collisions affect thermophysical properties.
- Liquid layering describes the relationship between a liquid layer and solid particles, which results in oscillatory behavior in a normal direction to the interface because the liquid layer is more ordered than the bulk liquids. The degree of layering is determined by the strength of the bond; as the bond becomes stronger, a crystal-like structure forms in the liquid surrounding the particle, which has been demonstrated to have important effects on several properties.
- The term "nanoparticle agglomeration" refers to the experimentally observed tendency of nanoparticles to form clusters when suspended in a liquid. As a result, percolating patterns produce pathways with reduced thermal resistance; at lower particle volume fractions, the liquid would contain particle-free areas.

- Thermal or heat diffusion: different components in a multicomponent system move at a different rate in response to temperature gradients, creating concentration gradient “soret phenomena" and leading to energy transfer associated with such systems due to that concentration gradient “dufour effect”.
- Particulate flow has special characteristics such as different types of interactions between entities, fluid-to-particle, particle-to-particle, and particle-to-wall collisions.

3. The current review for convective heat transfer contributions in litrature

In the pursuit of studying convective heat transfer, researchers have embarked on a multifaceted and intricately detailed exploration into the utilization of nanofluids and hybrid nanofluids flowing through mini- and microchannel heat sinks. The current investigation, comprising both experimental investigations and numerical simulations, constitutes a robust endeavor to unravel the complexities of enhancing heat transfer efficiency in these systems. The organization of the following part is as follows: it contains two sections of experimental investigations and numerical investigations that highlight their findings and, in each section, discuss them concerning the main elements of enhancement techniques, which are manipulating heat sink geometrical parameters and their findings, followed by manipulating cooling fluid coolant nanofluid parameters and their findings for different operating conditions to seek heat transfer enhancement. Within the realm of experimental investigations, as shown in Table 3., researchers have meticulously crafted setups to probe the behavior of nanofluids and hybrid nanofluids as they traverse heat sink configurations at miniature scales and nanofluid parameters like particle identity and concentration hybridization ratio, etc. Concurrently, numerical simulations, as shown in Table 4., employing advanced computational fluid dynamics (CFD) techniques alongside other simulation techniques, have provided a virtual laboratory for researchers to explore the intricate fluid dynamics and heat transfer phenomena occurring within these micro-scale environments. Through these simulations, researchers have been able to dissect the influence of various parameters, such as heat sink geometrical configurations and nanofluid properties, on heat transfer enhancement, offering a complementary perspective to experimental findings.

Central to both experimental investigations and numerical simulations is the manipulation of key elements fundamental to heat transfer enhancement techniques. Specifically, researchers have focused on manipulating heat sink geometrical parameters, including channel dimensions, aspect ratios, and fin arrangements, to optimize convective heat transfer performance, while others are more coolant-oriented by focusing more on the properties of cooling fluids, such as nanoparticle concentration, size, and hybridization parameters, to investigate the full potential of nanofluids and hybrid nanofluids in enhancing heat dissipation. By reviewing the findings from each study type (“experimental and numerical fronts") in that manner, it will be easier to acquire the findings for the analysis and discussion, as researchers have elucidated the intricate interplay between these parameters. The advancements represented a step forward towards the development of more efficient thermal management systems, despite the challenges with industrial implementation. They were also a fair effort, implying a better thermal system spanning diverse industries, from electronics cooling to renewable energy systems. Thus, this article endeavors to comprehensively document and analyze the contributions driving progress in convective heat transfer research, shedding light on the path toward more efficient and sustainable thermal management solutions.

3.1. Experimental investigations

Radwan et al., [23] examined the impact of Al_2O_3/water nanofluid particle size on three distinct sizes (30, 100, and 150 nm) in a conventional heat sink. They found that as particle size decreases, the heat transfer coefficient's enhancement level rises, reaching 88.74%. Furthermore, Nguyen et al., [25] examined particle sizes of 36 and 47 nm for Al_2O_3/water using a microchannel heat sink. The findings indicated that 36 nm offers greater heat transfer coefficients than 47 nm, with a maximum enhancement of 40% when compared to the base fluid. Numerous researchers have examined the impact of particle volume fractions on nanofluids. Zhang et al., [26] investigated MCHS and Al_2O_3/water at concentrations of 0.25%, 0.51%, and 0.77% percent per volume. They found that as concentration increased, the enhancement level increased up to 10.6%. In addition, Azizi et al. 2015 [27] studied MCHS and Cu-water at concentrations of 0.05-0.3% per weight and concluded that as the percentage increases, the Nu number increases. Furthermore, Wiriyasart et al., [28] investigated two volumetric concentrations, 0.005% and 0.015% for TiO_2/water and Fe_3O_4/water, and found that higher concentrations showed higher heat transfer rates. Likewise, Duangthongsuk and Wongwises, [29] investigated MCHS, SiO_2, and water. For 0.3%–0.8% volume fraction and recorded increases in Nu number with an increase in volumetric concertation. Meanwhile, Ramadan et al., [30] examined the impact of concentrations ranging from 0.05 to 0.3% per volume of hybrid nanofluids Al_2O_3-TiO_2-SiO_2/water-ethylene glycol (60:40) at a hybridization ratio of (1/3: 1/3: 1/3) through a conventional heat sink of a car radiator, and the maximum enhancement of the heat transfer coefficient recorded was 39.7% at the highest concentration tested.

Conversely, from a nanofluid perspective investigators discussed particle identity and level of hybridization effect, Zhang et al., [31] investigated Al_2O_3 and SiC /water in MCHS and Al_2O_3 decreases thermal resistance by max of 11% at the highest concentration while SiC showed no enhancement due to an agglomeration and clogging, additionally, other investigators as Ataei et al., [32] studied mini channel hybrid nanofluid compared to mono nanofluids as Al_2O_3-TiO_2/water showed enhancement of 8.82% and 6.03% in heat transfer coefficient compared to TiO_2/water and Al_2O_3/water nanofluids, respectively and mono results showed TiO_2/water and Al_2O_3/water depict 7.49% and 10.31% higher Nusselt numbers in comparison with water. Furthermore, Vinoth and Sachuthananthan, [20] studied MCHS with CuO, Al_2O_3, and Al_2O_3-CuO and found 0.3% higher values of enhancement for hybrid nanofluids compared to mono fluids; besides, Suresh et al., [21] showed a maximum enhancement of 13.56% in Nu number of Al_2O_3-Cu/water hybrid compared to water at MCHS; however, in contrast, Kumar and Singh, et al., [33] in terms of Nusselt number enhancement showed that graphene/water mono nanofluid is the best while in terms of performance evaluation criteria PEC, hybrid Al_2O_3-G/water is better than other mono nanofluids.

This study was performed for a 0.01% volume fraction and a mini-channel heat sink. Furthermore, Sriharan et al., [34] studied mini channel heat sinks for Al_2O_3-SiO_2/water, Al_2O_3-CuO/water, and CuO-SiO_2/water at relatively low 0.01% vol. for a fixed 80:20 hybridization ratio, and generally, higher values of enhancement for hybrid nanofluids were recorded, and in terms of tri hybrid nonfluids, they are very rare to find in the literature, especially for micro channel heatsinks for Al_2O_3-SiO_2/water, Al_2O_3-CuO/water, and CuO-SiO_2/water at relatively low 0.01% vol. for a fixed 80:20 hybridization ratio, and generally, higher values of enhancement for hybrid nanofluids were recorded, and in terms of tri hybrid nonfluids, they are very rare to find in the literature, especially for micro channel heatsinks for Al_2O_3-SiO_2/water, Al_2O_3-CuO/water, and CuO-SiO_2/water at relatively low 0.01% vol. for a fixed 80:20 hybridization ratio, and generally, higher values of enhancement for hybrid nanofluids were recorded, and in terms of tri hybrid nonfluids, they are very rare to find in the literature, especially for micro channel heat sink investigations. Finally, Ramadan et al., [30] studied a conventional heat sink of a car radiator as an application, Al_2O_3-TiO_2-SiO_2/water-ethylene glycol 60:40, for a concentration range of 0.05 to 0.3% vol., and found all concentrations had a higher heat transfer coefficient than the base fluid. There is a huge gap in terms of mixture ratios of hybrid nanofluids (hybridization ratios), the use of more than just two nanoparticle identities (hybridization level), and the concentration effect of those working fluids, especially those used in microchannel heat sinks.

From the perspective of heat sink parameters, some researchers focused on how manipulating channel patterns could affect convective heat transfer performance. As Duangthongsuk et al., [29] studied two patterns of continuous Zigzag CZ and cross-cutting continuous Zigzag CCZ for a chosen working SiO_2/water and found thermal performances of CCZ was better CZ by 2–6% than normal MCHS, while, Khoshvaght-Aliabadi et al., [35] focused on waving the channels and its factors, alumina nanofluid and found Nusselt number enhanced and improved either by decreasing the wave-length or increasing its amplitude, however, that could provide an additional pumping power compared to straighten ones besides performances are more noticeable by increasing fluid flow rate value, even though most of researchers preferred to choose straight pattern for various reasons. Alternatively, others investigated heat sink geometrical aspects such as cross-sectional area, aspect ratio, and fin spacing (Macro, Micro, and Mini) heat sinks, as the number of parameters considered to be high not all researcher used nanofluids in MCHS problems as Jajja et al., [36] investigated fin spacings of 0.2, 0.5,1.0 and 1.5 mm for water as cooling fluid and found that base temperature and thermal resistance of the heat sinks were dropped and heat transfer coefficient enhanced by decreasing spacing and by increasing flow rate, besides that Kumar, Sarkar, et al., [37] studied different aspect ratios (2.5-5) and hydraulic diameters (1.14-1.33 mm) for reduced graphene oxide RGO-ZnO hybrid nanofluid as a working fluid and concluded that as aspect ratio reduced heat transfer coefficient enhanced and finally, Vinoth et al., [20] choice was to study pentagonal and triangular cross-sections and found that performance evaluation criteria of pentagonal 21.12% higher than the triangular microchannel heat sink using hybrid nanofluid Al_2O_3-CuO For particle volume fraction of 0.3%.

Using phase-change material within nanofluid technology is one of the most promising new trends in research. Ho et al., [38] studied Al_2O_3/water nanofluids with microemulsion phase change material MEPCM at concentrations of 8% per weight, different Reynolds number ranges, and a mini channel heat sink ceiling. A MEPCM layer was provided to be experimented with. At 8% concentration and a Re number value of 1549, maximum enhancement values were recorded, as the average heat transfer effectiveness reported was 1.4, while the highest figure of merit FOM was 1.27. The results finally concluded that the MEPCM layer for the microchannel heat sink had an insignificant effect on cooling performance as well as thermal resistance. Moreover, Ho et al., [39] investigated a mini-channel heat sink with nano-phase change material emulsions or water as a base fluid with a mass fraction range of up to 10%. They reported that the values of the convective heat transfer effectiveness are larger than unity for most values of the Reynolds number. Thus, using n-eicosane up to 2% concentration had a positive impact on thermal resistance; however, the figure of merit decreased significantly by 44% at the highest value of the mass fraction tested, 10%, while heat flux affected positively in enhancing cooling performance, and so the optimum value of FOM occurs at the highest heat flux of 4.78 W/cm^2 and 2% concentration per mass.

Table 3. Experimental investigations for mini and microchannel heat sinks employing nanofluids and their important findings.

Author	Nanofluids parameters	Heat sinks variables	Operating conditions	Results and Findings
Radwan et al., [23]	• Al_2O_3/Water • 30,100,150 nm • 1% vol.	• Conventional • Rectangular section	• 1,1.5,2 m/s • 60,70,80 °C bulk temperature	• All particle sizes used showed an enhancement for heat transfer coefficient; as particle size decreased, the level of enhancement increased, and the highest recorded enhancement was 88.74%.
Zhang et al., [26]	• Al_2O_3/water • 0.25%, 0.51% and 0.77% vol.	• Microchannels • Circular microchannel • 0.5 mm inner diameter • Single channel	• 1132-3961 kg/ m^2.s • 69.9 and 108.9 kW/m^2 • Inlet temp. 291.15 K	• Nu number increases with increasing Re number and particle concentration for the conducted values. • The nucleotide number of nanofluid was higher than that of water, and the maximum recorded percentage was 10.6% at the highest concentration of 0.77%. • The friction factor of nanofluid recorded a maximum percentage of 7.9% compared with water.
Azizi et al., [27]	• Cu-water • 0.05-0.3% weight	• MCHS • 560 micrometers • Cylindrical	• 0.5-2 LPM • 35-50 kW/m^2	• Nu number ratio was at 0.3% wt. and 2 LPM up to 1.3. • Nu number increases with an increase in volumetric concertation.
Duangthongsuk et al., [29]	• SiO_2/water. • 0.3%–0.8% vol.	• MCHS • 28*33 mm^2 • Multiple continuous zigzag CZ and cross cutting CCZ	• Re 1000 to 10000 • 100 watts	• Higher thermal performance for nanofluid over base fluid by 3–15% as concentration increases. • The thermal performances of CCZ were better than those of CZ by 2–6% as concentration increased. • Nu number increases with an increase in volumetric concertation.
Ataei et al., [32]	• TiO_2, Al_2O_3 and Al_2O_3 -TiO_2 • Water • 0.5% vol.	• Mini-Channel • D_h =2 mm • Multiple channels • Aluminum	• 36 W • Re 400 to 1000	• Hybrid nanofluid showed a maximum enhancement of heat transfer coefficient at Re number 400 of 16.97% and a reduction of 5 °C in surface temperature. • Hybrid enhancement over mono nanofluids recorded 8.82% and 6.03% for TiO_2 and Al_2O_3, respectively, at constant Re numbers. • Mono-nanofluids showed Nu number enhancement over base fluid by 7.49% and 10.31%, respectively.
Kumar, Sarkar, et al., [37]	• RGO-ZnO • 0.01% vol.	• Mini-Channel • Dh 1.14-1.33 mm • AR 2.5-5	• Re 50 to 600 • 33.33-66.67 W/cm^2	• Aspect ratio reduction increases the heat transfer coefficient percentage by 47.2% at 0.5 LPM. • Nu number values showed a decrease, increase, and then decrease trend with the flow rate.
Kumar, Singh, et al., [33]	• Al_2O_3/water, G/water and Al_2O_3-G/ water • 0.01% vol.	• Mini-Channel	• 0.1-0.5 LPM • 50-66.7 W/cm^2 • Re 80 - 450 • Fluid inlet temp. 20-40 °C	• The ideal comparison factor, or the ratio of heat transfer coefficient to pressure drop, is provided by a hybrid nanofluid. • At 30 °C, a fluid inlet temperature of 30.93% was the highest enhancement recorded for graphene mono-nanofluid. • A hybrid nanofluid of alumina and graphene showed the optimum comparison factor. • All nanofluids showed a higher than unity value for performance evaluation criteria.
Vinoth et al., [20]	• CuO, Al_2O_3, and Al_2O_3-CuO • 0.3% vol.	• MCHS • Obliquely finned • 900 micrometers • Pentagonal and Triangular cross-sections)	• 0.1–0.5 LPM • 50 Kw/m^2	• Enhancement of heat transfer rate by 12.3% for pentagonal over triangular for HYNF, while CuO and Al_2O_3 enhanced by 4.2% and 5.5% through pentagonal cross-sectional, respectively. • Performance evaluation criteria for pentagonal cross-sectional ones were higher than triagonal ones by 21.12% when conducting hybrid nanofluid as a coolant. • Generally, higher values of enhancement are needed for hybrid nanofluids.
Sriharan et al., [34]	• Al_2O_3-SiO_2/water, Al_2O_3-CuO/water and CuO-SiO_2/water • 0.01%vol. • 80:20 hybridization ratios	• Mini-Channel • Hexagonal Tube • Channel material copper	• 15–50 LPH	• Al_2O_3-CuO hybrid nanofluid showed a maximum enhancement over pure base fluid in heat transfer coefficient of 54.5%, while the enhancement of Nu number was recorded at 28.4%. • Copper-based hybridization was more efficient than silicon-based hybridization with alumina nanofluid. • Generally, tested hybrid nanofluids performed better than base fluid.
Nguyen et al., [25]	• Al_2O_3/water • 1,3.1 and 6.8% vol. • Particle Size 36 and 47 nm	• Cooling block dim. 60.60.15 mm^3 high • Copper body	• 0.02 to 0.08 kg/s • Heated block, dim. 60.60.75 mm^3 high • Aluminum body • 100 W	• The recorded enhancement level was 40% in heat transfer coefficient. • As particle size decreased, a higher heat transfer coefficient was provided. • The temperature of the specimen block decreases clearly with increasing concentrations of nanoparticles.
Khoshvaght-Aliabadi et al., [35]	• Al_2O_3/water. • 0, 0.15 and 0.3% wt.	• Mini channels • Corrugated mini channels heat sink (CMCHS) • Aluminum alloy. • (20*100*50mm) wide, long and height, respectively.	• 50 W • Re 500 1500 • WLR=0.1, 0.2 and 0.4. (Wave-length ratio) • WAR=0.25, 0.5 and 1. (wave-amplitude ratio)	• Decreasing the wavelength and increasing amplitude have a positive effect on enhancing the Nu number value and a negative effect on the pumping power required. • Nanofluid showed better cooling performance than conventional base fluid. • The best recorded and lowest base temperatures were 30.5 °C at 20mm and 2mm wavelength and amplitude, respectively. • Overall thermal-hydraulic performances of corrugated channels are more obvious at higher flow rates, as performance evaluation criteria increased at best conditions from 2 to 3.5 by increasing only the flow rate.
Ramadhan et al., [40]	• Al_2O_3-TiO_2-SiO_2/W-EG (60:40) • 13, 50 and 23 nm respectively • 1/3: 1/3: 1/3 hybridization ratio. • 0.05 to 0.3% vol.	• Car radiator	• 2 to 12 LPM • working temp. of 70 °C • Airflow 4 m/s	• The Tri-Hybrid nanofluid heat transfer coefficient showed an increasing trend with increasing particle volume concentration. • The highest recorded enhancement value at the highest concentration was 39.7%. • As the volume concentration of tri-nanofluid increased, so did the friction factor, pressure drop, and pumping power.

Jajja et al., [36]	• Water	• Flat plate heat sink • 0.2, 0.5,1.0- and 1.5-mm spacing values of channels • CPU liquid cooling system (Galaxy by Gigabyte)	• 0.5, 0.75 and 1.0 LPM • 325 W	• The highest recorded value of heat transfer coefficient increased from 1297 to 2156 W/m^2.K by using a 0.2 mm spacing heat sink instead of a flat plate, while maximum thermal resistance decreased from 0.216 to 0.03 K/W. • Increasing flow rate and decreasing channel spacing had a positive impact on heat sink base temperature and thermal resistance by dropping their values. • 40.5 °C was the lowest base temperature value for heat sinks recorded, and it was lower than the best-reported enhancement value of nanofluid and conventional heat sinks by 9%.
Wiriyasart et al., [28]	• TiO_2/water, Fe_3O_4/water • 0.005% and 0.015% vol.	• The battery cooling jacket • Aluminum frame • 79 ×650 × 65 mm (W × H × L) • Single channel	• To simulate a heat load, the dummy battery pack was filled with water and kept at a constant temperature.	• Fe_3O_4-based nanofluid heat transfer rate increased and was enhanced by 11.17% over TiO_2 nanofluid and by 12.57% over base fluid. • By reducing the Fourier effect's contribution, higher concentrations of ferrofluid and titanium nanofluid improved the Peltier effect. • Using nanofluids based on titanium and iron decreases the temperature difference and thermal resistance of the thermoelectric cooler by 4.6% and 7% for titanium and 9.6% and 14% for iron, respectively. • At higher concentrations of nanofluids TiO_2 and Fe_3O_4, pressure drop significantly increased by 0.5 and 2.7 kPa, respectively, compared to base fluid.
Suresh et al., [21]	• Al_2O_3-Cu/water • 0.1% vol.	• MCHS • circular tube • Material copper • 10 mm ID and 12 mm OD	• Heating wire 120 Ohm • Re 500-2500	• The Nusselt number maximum enhancement percentage was 13.56% using hybrid nanofluid at a specific value of Re number 1730. • The friction factor and pressure drop for hybrid nanofluid change insignificantly compared to the base fluid.
Ho et al., [38]	• Al_2O_3/water • Micro emulsion phase change material • 8% wt.	• Mini channel with a MEPCM layer in its ceiling • Rectangular Cross sectional • Aspect ratio 3	• Re 258–1549 • Thermophysical properties measured	• At 8% concentration and a Re number value of 1549, maximum enhancement values were recorded, as the average heat transfer effectiveness reported was 1.4, while the highest figure of merit was 1.27. • Embedding the MEPCM layer in the ceiling of the MCHS had no significant impact on the cooling performance or average heat transfer effectiveness.
Ho et al., [39]	• Nano-phase change material emulsions/water • Mass fraction 0%–10%.	• Mini-channel heat sink • 1-mm and 1.5-mm width and height of channel	• 60 to 600 cm^3/ min • 3.2, 3.95 and 4.78 W/cm^2 on bottom wall	• It is more appropriate to use n-eicosane with a larger mass fraction and low flow rates to reduce wall temperatures through heat fluxes. • For most Reynolds number values, the convective heat transfer effectiveness value is greater than unity. • At a Reynolds number of 1381, a heat flux of 4.78 W/cm^2, and a mass fraction of 2%, the maximum FOM of 1.098 can be reached. • For a heat flux of 3.20 W/cm^2, increasing the mass fraction from 2% to 10% resulted in a roughly 44% decrease in FOM.

3.2. Numerical investigations

Rather than experimental investigation, many investigators performed different techniques for solving heat transfer problems of nanofluids and microchannels, as some researchers used mathematical methods [41] and dimensionless analysis [42] methods, while others conducted analytical and semi-analytical methods [43, 44]. The numerical solving methods reported by Gao et al., [16] were as follows: Classical computational fluid dynamics (CFD) methods like the finite volume method FVM, the finite difference method FDM, and the finite element method FEM focused on fluid flow from a macroscopic level, while, from a mesoscale perspective, the Lattice Boltzmann method (LBM) is usually used; moreover, from a molecular level, researchers used molecular dynamic simulation (MDS) and direct simulation Monte Carlo (DSMC); additionally, the Taguchi method (TM), genetic algorithms (GA), and machine learning algorithms as artificial neural networks (ANN) are all used and trained by experimental data for predicting values and as an optimizing tool. Besides, many investigators used the weighted residual method (WRM), like the least squares method (LSM), followed by the fourth-order Runge-Kutta numerical method, to decrease the computational cost of using one of the CFD methods. Finally, the choice of solving method type depends on the problem type and fluid-heat modeling method.

Beginning with the heat sink geometric parameters, researchers focused on several factors, aiming to enhance and affect heat transfer capabilities positively and minimize friction loss as much as possible to achieve the highest hydrothermal performance. The cross-sectional area of channels, the impact of channel interpretation, various heat sink array design patterns, how flow enters and exists from channels and their geometric configurations, the number of input and output points of fluid, double layering of channels, and optimization of the channel dimensions are the most investigated parameters in the literature. The geometric configuration of mini- and micro-channel heat sinks affects both the coolant convection and substrate conduction thermal resistance; thus, several researchers have focused on geometric parameters, with some choosing to investigate mini-channels [19] and others choosing micro-channels [45]. Additionally, some researchers have chosen to model heat sinks as channels [46], while others have chosen to study heat sink fin interpretation [47, 48], but generally, most of the researchers have chosen to model them as channels. Al-Rashed et al., [48] investigated MCHS offset strip-fins, where the first parameter was the ratio of fin offset to fin length and the second was the number of fins along the channel length. CuO/ water-CMC Carboxymethyl Cellulose (CMC) in water: 0.5% wt. for the following concentrations 0.5, 1, 1.5, and 3 percent per volume was the coolant chosen, and they found the best optimum performance in the case of 1% vol., Re = 700, fin offset to the length of 1, and number of fins along the channel length of 4 from the studied parameters. Based on the literature, most of the researchers who studied microchannel heat sinks preferred to use rectangular cross-sections [49]. However, still others preferred different cross-sections like circular, triangular, and trapezoidal [50-52]. Moreover, Ma et al., [53] studied the aspect ratio range of 0.1:1 (width over height) for a rectangular cross-section of MCHS with water as a working fluid and found that the Nusselt number obtained gradually increases with the decrease of the aspect ratio under specific boundary conditions. On the other hand, Hosseini et al., [54] nanofluids CuO and Al_2O_3/water at 0 to 4% volume concentrations in MCHS and aspect ratio range from 1 to 10 (height over width) and concluded that Nusselt number increased by channel aspect ratio due to the increase in interactions between nanoparticles and the solid phase.

Alternatively, other researchers focused on the effects of the designed patterns. As a fact, most researchers used linear arrays; however, few researchers studied wavy patterns and fractal network microchannels, which received extensive focus attributed to their improvement of heat transfer efficiency without increasing pressure drop and thus pumping power like conventional linear array microchannels. Khosravi et al., [55] studied, from a second-law perspective, hybrid nanofluids of graphene-platinum/water through an MCHS with a wavy pattern for different wave amplitudes (0, 25, 50, and 75 μm) and hydraulic diameter of 580 mm and found that in terms of irreversible factors, increasing wave amplitude causes a decline in the thermal entropy generation rate, while frictional entropy rises significantly. Moreover, Singh et al., [50] studied hybrid alumina-silver/water nanofluid in a single microtube versus a wavy one, and results indicated that the microtube exhibits a better enhancement level of heat transfer coefficient than the wavy one at a constant heat flux, length, and area. Alternatively, Yan et al., [56] investigated bionic fractal patterns like Y-shaped (Y), connected Y-shaped (CY), and micro-pin fin embedded connected Y-shaped (FCY) and chose water as a working fluid for the three models and found that the heat transfer coefficients of the FCY models are higher than those of the CY model and the Y model as well. Moreover, Ghachem et al., [57] investigated a wavy pattern in a micro heat exchanger with CNT-Al_2O_3/water hybrid nanofluid for a range of wave numbers ($0 \le N \le 20$), and results showed an optimum value, as the highest heat exchanger efficiency was achieved with N = 8, 0.05% vol., and u = 50 mm/s, which is not always better for increasing the wave number, especially when nanofluids are used. Another sector of investigation was concerned with microchannel configuration, including how flow enters and exits from the channels and how that might affect heat transfer performance. Starting with Maganti et al., [58] studied the effect of parallel rectangular MCHS with one input and one output flowing through three different configurations U, I, and Z with mono nanofluid and found that FOM for the Z configuration employing nanofluid performed better than other configurations and was a more suitable solution for uniform thermal loads as it provided a good reduction in the maximum temperature. Moreover, Bahiraei et al., [59] investigated Gr-Ag/water hybrid nanofluid in an MCHS, including the following parameters: rectangular section, multiple inputs, and multiple channels (4 L configuration called A type vs. 4 U configuration called B type), and found that due to the more intense mixing, B type has better thermal performance, FOM, and uniformity and becomes more significant at higher concentrations; thus, the merit of employing the nanofluid is higher.

Furthermore, other researchers focused on a different idea, which was recharging microchannels, as Samal et al., [60] investigated recharging microchannel RMC (single flow line) with Gr-Ag/water hybrid nanofluid, which means multiple inputs and outputs for the flow in a single line with a rectangular section and U configuration, and found that RMC shows better performance than simple microchannels with a maximum performance factor value of 1.72. Furthermore, Tran et al., [61] investigated RMC in multiple flow lines with a trapezoidal section and U configuration with mono-nanofluids Al_2O_3 and TiO2/water and found a minimum thermal resistance improvement of up to 11.6%. Other researchers used a different method for increasing and improving heat transfer performance, such as using multi-layer channels. Elbadawy et al., [62] studied Al_2O_3/water mono nanofluid with single and double stacks and recorded that temperature reductions of 7.3% using a single stack and 33.5% using a double stack were achieved at the same operating conditions. Additionally, Sarvar-Ardeh et al., [63] investigated Al_2O_3-Cu/water and Al_2O_3-SiO_2/water hybrid nanofluids with double-layer MCHS because it provides better thermal performance. Furthermore, Kumar et al., [64] studied a different approach, which is the tapering factor TF, and the chosen range was 1, 0.8, 0.5, and 0.2 for a double-layer microchannel heat sink. The findings were that the Nusselt number ratio increases with the decrease in TF up to 0.32 for the Reynolds number range from 100 to 200, while for higher Re numbers up to 500, the Nusselt number ratio starts to decrease after TF = 0.31, and they concluded that it is not advantageous to use tapered channels. While many researchers focused only on the geometric parameters of heat sinks in their investigations, other researchers approached the effect of substrate material and how it could affect hydrothermal performance while using nanofluids as a working coolant. Wu et al., [46] studied MCHSs of different substrate materials like copper, silicon, or aluminum nitride with Al_2O_3/water mono nanofluid, and the findings showed that nanofluid can further decrease the thermal resistance of the MCHS when a material with higher thermal conductivity is used as a substrate of MCHSs, moreover, Tran et al., [61] investigated five different substrate materials like copper, aluminum, silicon, iron and stainless steel with Al_2O_3 and TiO_2/water mono nanofluids and found that thermal resistance using copper (the highest thermal conductivity value among other substrates) as a substrate material is improved up to 76% as compared to the values of using stainless steel 304. Finally, Hung et al., [65] studied more than five different mono-nanofluids through an MCHS with four types of substrate materials: silicon wafer, steel, aluminum, and copper. They concluded the same as the others and mentioned that a substrate material with a higher thermal conductivity yields better thermal performance.

The following section investigated researchers' contributions from the perspective of the second element in cooling systems, which is the coolant working fluid parameters. We will start reviewing the particle size factor and thermal conductivity models attached to it as researchers are concerned with particle size, mainly due to its positive effect as a factor in the thermal conductivity model chosen to estimate the thermal conductivity of nanofluids. The overall hydrothermal performance is affected by convective heat transfer coefficient values; however, there are factors like dynamic transport properties like thermal conductivity and viscosity of the working fluids that also affect the overall hydrothermal efficiency and performance of the cooling system; thus, Seyf et al., Hosseini et al., and Pourmehran et al., [54, 66, 67] all used that in their study by Koo-Kleinstreuer-Li model KKL for calculating the thermal conductivity of their nanofluids. KKL model, which contains two terms, static term and dynamic Brownian parts, and that dynamic part is functioning in temperature and particle diameter, which is the key mechanism in thermal conductivity enhancement. Thus, with decreasing particle size, the conductive thermal resistance decreased, leading to enhanced overall heat transfer performance. Seyf et al., [66] studied Al_2O_3, ZnO, and

CuO/ water-ethylene glycol (40:60) mono-nanofluids for particle sizes of 29 and 77 nm flowing through an MCHS and reported that the coolants enhance heat transfer with decreasing particle sizes, as well as, Hosseini et al., [54] studied CuO and Al_2O_3/water mono-nanofluids for particle sizes 25, 35 and 40 nm flowing through MCHS and reported as nanoparticles size declined, the difference between coolant and wall temperatures decreased, as a result of the increase in Nusselt number, additionally, Pourmehran et al., [67] investigated Cu and Al_2O_3/water mono-nanofluids for particle sizes of 35, 40, 45 and 50 nm through an MCHS and the results corroborate that by decreasing particle size fraction the Nusselt number develops and total thermal resistance decreased as well. On the other hand, Tokit et al., [47] investigated as well using KKL model Al_2O_3, CuO, and SiO_2/water mono-nanofluids for a particle sizes of 30 to 60 nm and 1 to 4% volume fraction range in interrupted MCHS and reported as particle size increases from 30 to 60 nm, the decrement in k ratio from lower to higher volume fraction were very close which lies from 0.018 to 0.017% and an apparent decrement of 0.06% is also observed for Nusselt number ratio especially at 4% volume fraction, meanwhile, Hatami et al., [68] used a different thermal conductivity model which is multi sphere Brownian model MSBM in their investigation of Cu/water mono-nanofluid for 1, 5 and 25nm particle sizes and 1,3 and 6% concentrations per volume through a MCHS and the findings reported that increasing nanoparticles diameter makes large difference between coolant and wall temperature and Nusselt number increased due to the improvement in heat transfer mechanism by large nanoparticles with high thermal conductivity, however, the most used model is the simplest model of concentration which could be called as static model, Maxwell model or Hamilton crosse's model especially in hybrid nanofluids as it is easy to expand it for more than two particle identities.

Many researchers focused on the volume concentration effect with other different parameters. First, from the literature, we could define that less than 0.1% per volume can be classified as a micro concentration, while higher than that is a macro concentration. Reviewing the literature shows that many researchers [51, 62, 64] investigated Al_2O_3/water nanofluid as a coolant at a macro-concentration level as follows: Elbadawy et al., [62] selected concentrations of 1 to 5% per volume in double stack MCHS and reported maximum heat transfer was achieved at the highest concentration of 5% and heat transfer coefficient increased by 13.12% compared to that of pure water; moreover, Kumar et al., [64] reported that the thermal performance increased with decreasing nanoparticle diameter and increasing nanoparticle volume concentration. Furthermore, Al-Rashed et al., [48] investigated another metal oxide nanofluid, which is CuO/water-carboxymethyl cellulose, as a non-Newtonian base fluid at 0.5, 1, and 3% concentration values per volume and reported a better convective HTC for nanofluid compared to the base fluid, especially at high Reynolds and volume fractions. The previous researchers that investigated nanofluid concentrations as the main parameter mostly reported a positive impact on heat transfer performance; however, other factors could affect the hydrothermal performance of nanofluids, such as heat load flux range and heat sink geometric parameters aligned with manipulating the concentrations. A different approach chosen by many investigators focuses on more than one particle identity at a zero level of hybridization and its differences in enhancement level. Researchers usually classify nanoparticle types into four categories: carbon-based, magnetic-based (Ag), oxides (Al_2O_3, CuO, TiO_2, ZnO, and silica), and hybrid or composite particles [12]. Most attempts that focused on particle type differences in their studies were concerned with thermal conductivity and thermal resistance and how that could affect thermal performance. Snoussi et al., [49] compared Al_2O_3 and Cu/Water in microchannels and showed that Cu/Water nanofluids had a higher enhancement percentage than water by 20%, while Al_2O_3 showed a 14% enhancement at the same operating conditions. Besides, there was no apparent effect on results at lower heat flux conditions for both nanofluids and pure fluid. Moreover, Seyf et al., [66] studied the performance of Al_2O_3, ZnO and CuO/ water-Ethelene glycol (40:60) at two different volume fractions 3 and 6% per volume using a temperature dependent model and the findings demonstrated that introducing a lower volume fraction of nanoparticles 3% per volume to the base fluid will significantly reduce its thermal resistance, as the reduction in thermal resistance for Al_2O_3, ZnO, and CuO nanoparticles is approximately 3.2%, 6.6%, and 8.5%, respectively, meanwhile, Mohammed et al., [51] investigated various types of nanoparticles Al_2O_3, Ag, CuO, diamond, SiO_2, and TiO_2 in MCHS for 2% volume fraction and the findings showed that diamond had highest heat transfer coefficient and Al_2O_3 had lowest, while, CuO and TiO_2 exhibit the same performance in terms of heat transfer coefficient and they concluded that when concentration increases Brownian movement increases which has a great influence on the thermal conductivity and heat transfer process.

As hybrid nanofluids (HYNF) were introduced as a new generation of nanofluids with enhanced properties and heat transfer capabilities, researchers recently started to investigate HYNFs and their effects on other parameters. Singh et al., 2020 [50] investigated microtubes with an Al_2O_3/water versus Al_2O_3-Ag/water (0.5:0.5) mixture ratio for an overall concentration range of 1 to 3% per volume and Reynolds number range from 50 to 1000, and their findings were that a maximum of 11.03% increase in heat transfer coefficient was obtained as HYNF reveals superior heat transfer properties, besides, with the increase in volume fraction, higher enhancement levels of heat transfer coefficient were obtained, as, concentration is more significant for influencing heat transfer capabilities at superior heat transfer properties, moreover, concentration is more significant for influencing heat transfer capabilities at a lower Reynolds number than at a higher Reynolds number. Furthermore, Samal et al., [60] and Bahiraei et al., [59] both studied Gr-Ag/water di-nanofluid. Samal et al., [60] showed in recharging micro channels at different micro concentrations from 0.02, to 0.1% per volume that total entropy generation decreases with increasing volume fraction and the average heat transfer coefficient increases with the increase in both volume concentrations and velocity with maximum enhancement of 15%, moreover, Bahiraei et al., [59] investigated two different configurations at same micro concentrations and reported surface temperature and thermal resistance reduced and cooling uniformity improved for both heat sinks by increasing either velocity or concentration and so at higher concentration the merit of employing the nanofluid is higher from 2nd law of thermodynamics perspective as nanofluid has a lower irreversibility. On the other hand, Singh et al., [69] investigated the hybridization effect of Al_2O_3 with other particle identities like MWCNT, Ag, Cu and TiO_2 to create a di-nanofluid in a conventional heat exchanger shell and tube condenser and recorded that an increase in thermal conductivity is the primary cause of the convective heat transfer coefficient's enhancement with volume concentration, besides, hybridization with Ag showed the highest enhancement of (3.2%), followed by Cu (3.1%), TiO_2 (2.99%), and MWCNT (2.93%) hybrid nanofluids, as compared to the base fluid, according to the results of the overall heat transfer coefficient enhancement with the increase in volume concentration at 1% concentration, however, when comparing saving costs with payback period for conventional heat sink it's not feasible for practical implementation. In addition, Sarvar-Ardeh et al., [63] studied Al_2O_3-Cu/water and Al_2O_3-SiO_2/water di-nanofluids for a concentration of 1, 3, and 5% per volume in double-layered MCHS at Reynolds numbers ranging from 50 to 400 and recorded that increasing volume concentration of both nanofluids reduces thermal resistance; however, the maximum temperature reduction is about 9.2 °C at the lowest Reynolds number ranging from 50 to 400 and recorded that increasing volume concentration of both nanofluids reduces thermal resistance; however, the maximum temperature reduction is about 9.2 °C at the lowest Reynolds number ranging from 50 to 400 and recorded that increasing volume concentration of both nanofluids reduces thermal resistance; however, the maximum temperature reduction is about 9.2 °C at the lowest Reynolds number ranging from 50 to 400 and recorded that increasing volume concentration of both nanofluids reduces thermal resistance; however, the maximum temperature reduction is about 9.2 °C at the lowest Reynolds number of 50 and maximum concentration of 5%, and for Al_2O_3-SiO_2/water nanofluid, Al_2O_3-SiO_2/water nanofluid has a better cooling capacity compared to Al_2O_3-Cu/water. Moreover, Souby et al., [45] investigated hybrid di nanofluid and tri nanofluid MgO-TiO_2 and CuO-MgO-TiO_2 with water as a base fluid in a micro-channel for volume fraction range of 0.1-0.5 percent and Reynolds range up to 1000 and recorded higher values of convective heat transfer coefficient obtained when using hybrid nanofluids as the reduction rate of surface temperature increases as Reynolds number decreased so the highest enhancement in the heat transfer effectiveness was 42.4% for tri nanofluid and 21% for di nanofluid, whereas the thermal effectiveness improvement was 32.1% and 18.9%, respectively, and they concluded that low volume fractions and Reynolds values for hybrid nanofluids comprise higher performance. Additionally, Shahsavar et al., [70] investigated Fe_3O_4-CNTs/water di-nanofluid in a mini-channel heat sink for Fe_3O_4 concentrations ranging from 0.1 to 0.9% per volume, while for CNTs concentrations ranging from 0.1 to 1.35 percent per volume, the hybridization ratio was different by combining different values of those concentrations, and they concluded that using a hybrid nanofluid with a low concentration was the best way to maximize the performance of the heat sink under investigation while using a high concentration of nanofluid generated the least amount of entropy.

Furthermore, for hybrid nanofluids, Krishna et al., [71] investigated di-nanofluid through an MCHS and its hybridization ratio effect for MWCNT (Multi-Walled Carbon Nano Tubes)-CuO/water 0.25:0.75 and 0.5:0.5 and compared with CuO/water mono-nanofluid at an overall concentration range in the base fluid of 0.5, 1, 2, and 3% per volume. Their findings were that hybrid nanofluids performed better than mono-nanofluids, and the enhancement of heat transfer increased with increasing volume concertation percentage. They recorded a maximum enhancement value for hybrid nanofluids that was higher in percentage than CuO and MWCNT mono nanofluids by 4.68% and 12.64%, respectively. Additionally, Kumar et al., [72] studied Al_2O_3-TiO_2 di-nanofluid in a mini-channel heat sink with its all-possible hybridization ratios from 0:10 to 10:0 at similar particle size and particle shape for an overall concentration of 0.1% per volume, both numerical and experimental results revealed that hybrid nanofluids had no enhancement value or effect for same shape and size particles used, besides, experimental enhancement was higher than numerical ones as findings showed a maximum enhancement of 12.8% and 8.5% respectively for using an alumina-based mono-nanofluid to measure the convective heat transfer coefficient, conversely, as temperature drops and the volume fraction of nanoparticles increases, pressure drop and friction factor rise, thus, among all combinations TiO_2 (0:10) was the least effective nanofluid and so no optimum value has been observed while varying the particle mixture ratio in hybrid nanofluids. However, Zahan et al., [73] investigated Cu-Ag-Zn/DW, EG, and DW:EG (50:50) and (60:40) tri-nanofluid for the following hybridization ratios (0:1/2:1/2), (1/2:0:1/2), (1/6:1/6:2/3), (1/6:2/3:1/6) and (1/3:1/3:1/3) for a conventional size convergent-divergent nozzle for an overall concentration range of 0.01 to 4% vol. for (1/3:1/3:1/3), Nu enhances by 8.33, 9.31, 9.94, and 10.30% due to ranging solid concentration from 0.01 to 4% using base fluids like DW, DW:EG (60:40), DW:EG (50:50), EG, respectively. Also, (1/6:2/3:1/6) showed a relatively higher heat transfer coefficient compared to other combinations.

Table 4. Numerical investigations for mini and microchannel heat sinks employing nanofluids and their important findings.

Author	Nanofluids parameters	Heat sinks variables	Operating conditions	Results and Findings
Farsad et al., [74]	• Al_2O_3, CuO, Cu/water • 11 nm • 0, 2, 4, 6, 8% vol.	• MCHS • Material Copper • Irregular geometric channels • One input, one output	• 1,237 W/cm^2 • 0.3 LPM	• Al_2O_3 nanofluid maximum increment in cooling performance and decrease in wall temperature recorded 4.5% and 3%, respectively, compared to the base fluid at the highest conducted concentration. • Nanofluids reduce both the thermal resistance and the temperature difference. • Increasing the concentration from 2 to 8% increases the reduction in wall temperature by 1% for Al_2O_3. • Metal nanofluids improved higher than oxide metal nanofluids.
Shahsavar et al., [70]	• Fe_3O_4-CNTs/water • Fe_3O_4 from 0.1 up to 0.9% vol. • CNTs from 0.1 up to 1.35 % vol. • Hybridization ratio is a different combination of those concentrations	• MCHS • Parallel symmetric bifurcation flow distributors • Rectangular section	• Re 500-1500 • 80000 w/m^2 is • Applied at bottom surface	• Hybrid nanofluids showed a higher convective heat transfer coefficient and frictional entropy generation rate as Re number values increased. • Increasing uniformity of surface temperature and decreasing thermal resistance and surface temperature by increasing the Re number value of hybrid nanofluid. • Recommendation: for best performance, apply a low concentration of hybrid nanofluid. • The minimum entropy generation was at a high concentration of hybrid nanofluid.
Snoussi et al., [49]	• Al_2O_3 and Cu/Water • 1 and 2% vol.	• MCHS • Rectangular section. • Material copper • Width 215 µm	• 100 to 300 W • Re 100 to 1000	• At lower heat loading ranges, there is no apparent difference in results when using nanofluids. • Wall surface temperature decreased, and there was a higher heat flux effect with increasing nanoparticle concentration. • The pressure drops of the nanofluids increased with the increase in Re. • Al_2O_3 and Cu-based nanofluids reported higher heat transfer performance by 14 and 20% over pure water at the same operating conditions.
Krishna et al., [71]	• MWCNT (Multi-Walled Carbon Nano Tubes)-CuO/water and CuO/water • 0.25:0.75 ,0.5:0.5 Hybridization ratio • 0.5, 1, 2, 3 % vol.	• MCHS • Cylindrical section • Multiple channels • Cell diameter 60 micro meter	• Re 500 to 2000	• Raising concentration values enhances heat transfer for all nanofluids. • The maximum recorded enhancement in Nusselt number was for hybrid nanofluid at the highest examined concentration. • Results reported that hybrid nanofluid enhancements were 4.68% and 12.64% higher compared to mono-nanofluids CuO and MWCNT, respectively.
Mohammed et al., [75]	• Al_2O_3/water • 1, 2.5, 5% vol.	• MCHS • Rectangular shaped • Channel width 280 µm • Dh 339.15 µm	• Re 100–1000 • 100 to 1000 w/m^2	• Under extremely high heat flux values, heat transfer coefficient, and wall shear stress increased while wall temperature and thermal resistance decreased with increasing volume concentration. On the other hand, at lower heat flux conditions, no significant changes were recorded. • The highest concentration of 5% couldn't increase or enhance heat transfer through the system. • A slight increase in pressure drops, and its value increases with increasing Re number.
Mohammed et al., [51]	• Al_2O_3/water, Ag/water, CuO/water, Diamond/water, SiO_2/water, TiO_2/water. • 2% vol.	• MCHS • Al material • Triangular shaped • Dh 230 µm • Multiple channels	• 10 to 20 ml/min • Re 100–1000 • 100 w/m2	• CuO and TiO_2 showed the same performance, while diamond nanofluid showed the highest performance and alumina showed the lowest one in terms of heat transfer coefficient enhancement. • In terms of pressure drop, all nanofluids showed a slightly higher value compared to the base fluid, and SiO_2 nanofluid showed the highest increased value, while Ag was the lowest. • Recommended diamond nanofluid as a preferable option to attain higher heat transfer enhancements. However, Ag is recommended to achieve a lower pressure drop.
Seyf et al., [66]	• Al_2O_3, ZnO and CuO/ water-Ethelene glycol mass 40:60 • 0.03, 0.06 vol. • 29 and 77 nm	• MCHS • Rectangular section • Channel height and channel width 800, 283mm.	• 100 to 1000 cm^3/min	• Heat transfer was enhanced as the particle size of suspensions decreased. • Brownian motion is a key mechanism in thermal conductivity enhancement, and so it has a tangible effect on the cooling performance of the system. • CuO showed the best performance, followed by ZnO, and finally Al_2O_3 for cooling microchannel heat sinks.
Elbadawy et al., [62]	• Al_2O_3/water • 1% to 5% vol.	• MCHS • Rectangular • Single and double stack	• 100 w/cm^2 • Re 200-1500	• The maximum recorded enhancement by reduction of surface temperature for single stack and double stack was 7.3% and 33.5%, respectively, at the highest tested concentration. • As nanoparticle volume concentration increases, the cooling process improves for both single and double stacks. • The maximum recorded increase in pressure drop for a single stack was 10% at the highest tested concentration. • Because of the cooling performance improvement, an estimation of the volume reduction was found to be 62.6% for a single stake at the highest concentration conducted volume fraction.
Sarvar-Ardeh et al., [63]	• Al_2O_3-Cu/water and Al_2O_3-SiO_2/water • 1, 3, and 5% vol.	• MCHS • Rectangular, multiple channels • Double-layered	• Re 50-400 • 100 w/cm^2.	• SiO_2 hybridization of alumina has a better cooling capacity compared to Cu hybridization. • An increase in the volume concentration of both nanofluids reduces thermal resistance. • Al_2O_3-SiO_2 hybrid nanofluid gives lower wall temperatures than Al_2O_3-Cu. • For the Al_2O_3-SiO_2 hybrid nanofluid at the highest volume concentration and Re number of 50, the maximum recorded temperature reduction is about 9.2 °C.

A. Kumar et al., [64]	• Al_2O_3/water • 10, 20, 30, 40 nm • 2,4,6,7% vol.	• Double layer microchannel heat sink (DL-MCHS) • Rectangular, one channel • Silicon material • 10*10*1.5 mm height	• 100 w/cm^2 • 83 to 177 m LPM • Re 100 to 500 • Multiple tapering factors	• The findings showed maximum heat transfer was obtained at a tapering factor of 0.32, and the thermal performance of Al_2O_3 nanofluid is better than that of water. • In the range of Re numbers from 100 to 200, Nu numbers increased with a decreasing trapping factor up to 0.32, while in the range of 300 to 500, Nu numbers started to decrease after a trapping factor of 0.31. • At a higher trapping factor, pumping power was higher. • Overall, using a tapered channel has no significant advantage.
Wu et al., [46]	• Al_2O_3/water • 1, 4.5% vol.	• MCHS • Rectangular, multiple channels • Substrate materials copper, silicon or aluminum nitride. • Width and height 60 and 400 μm • 110 channels	• 200 W/cm2 • Re < 500	• Increasing concentration and inlet flow velocity increase nanofluid pumping power in microchannel heat sinks. • The decrease in the specific heat capacity of nanofluids degrades the heat transfer benefit due to the enhancement of their thermal conductivity. • Nanofluid has a greater impact on the thermal resistance of microchannels when using a higher substrate thermal conductivity material. • It can be concluded that the criteria for choosing a suitable nanofluid depend on providing a good enhancement level in thermophysical properties compared with the base fluid.
Tran et al., [61]	• Al_2O_3 and TiO_2/water • 5nm • Optimization of thermal performance	• MCHS • Multi-nozzle trapezoidal • Five substrate materials copper, aluminum, Silicon, Iron, stainless steel. • 157.7 <Dh <248.2 mm	• 100–1450 W/cm^2 • Inlet temperature from 15°C to 75°C • Re 900	• Copper substrate material thermal resistance enhanced up to 76% compared to stainless steel. • Using TiO_2 nanofluid could dissipate heat flux up to the maximum conducted range. • Double-layer microchannel improved thermal resistance by 36.6%, while multi-nozzle improved by 11.6%. • A negligible difference in the overall thermal resistance between Al_2O_3/water and TiO_2/water nanofluids is encountered. • The thermal resistance of both nanofluids showed nearly the same values with no noticeable difference.
Hung et al., [65]	• Mono nanofluids • Al_2O_3, CuO, TiO_2, Diamond, Cu and Ag • Ethylene glycol, Engine oil and water • 0.5, 1, 2 and 5% vol.	• MCHS • Rectangular cross section • Multiple channels • Substrate materials silicon wafer, steel, aluminum copper • Channel width 85 micrometer	• Q=100 W/cm^2	• Nanofluids affect thermal performance positively and pumping power negatively. • Nanofluids with lower values of dynamic viscosity showed much improvement in thermal performance. • Water as a base fluid showed the highest enhancement values, while engine oil had the lowest. • Substrate materials with a higher thermal conductivity value showed better overall performance. • The best-recorded percentage of heat transfer performance was 21.6% for Al_2O_3 and diamond. • The optimum concentration recorded was 2%, and its thermal resistance value was 0.084 for Al_2O_3 nanofluid.
Zahan et al., [73]	• Cu-Ag-Zn • DW, EG, DW-EG 50:50 and DW-EG 60:40 • 0:1/2:1/2, 1/2:0:1/2, 1/6:1/6:2/3,1/6:2/3:1/6, and 1/3:1/3:1/3 hybridization ratios 0.01 to 4% vol.	• Conventional • Convergent-divergent nozzle	• Re 20-300	• Ethylene glycol base fluid with a 1/3:1/3:1/3 hybridization ratio showed the maximum increase in Nu number by 10.30% as concentration increased from 0.01 to 4%. • By increasing concentration, the Nu number increased differently for changing base fluid for the same hybridization ratio; distilled water showed the lowest enhancement percent of 8.33%. • The 1/6:2/3:1/6 hybridization ratio of tri-nanofluid showed a relatively higher heat transfer coefficient compared to other combinations.
Souby et al., [45]	• MgO-TiO_2/water, CuO-MgO-TiO_2/water • 0.1-0.5% vol.	• MCHS • multiple channels • Rectangular section • Straight channel	• Re 200-1000 • 100 w/cm^2	• By increasing the Re number and volume concentration percentage, convective heat transfer improved. • Increasing Re number and concentration had a positive effect on surface temperature, thermal resistance, and entropy generation by increasing their reduction rate. • Tri-hybrid nanofluid showed better heat transfer efficiency than di-hybrid nanofluid over the tested types conducted throughout the study.
Hatami et al., [68]	• Cu/water • 1,5,25nm • 0.04 vol.	• MCHS • multiple channels • Rectangular section • Straight channel • 100, 400, 800 micro meters width • 100, 300, 500 micro meters length	• 1000 w/m^2	• Increasing the fin width of the microchannels decreases the temperature of both the nanofluid and the fin, and consequently, the Nu number positively improves. • As the particle size of suspensions increased, the Nu number increased due to the improvement of the heat transfer mechanism. • Increasing the aspect ratio improves entity interactions, which leads to a numerator number increment. • The minimum friction factor point is the optimum design of MCHS, which is obtained when the aspect ratio is 2.45.
Tokit et al., [47]	• Al_2O_3, CuO, and SiO_2 • 30 to 60 nm • 1 to 4% vol.	• Interrupted microchannel heat sink (IMCHS) • Rectangular • Length and width of 10 and 0.057 mm	• 650 kW/cm^2 • Re 140 to 1034	• At a lower concentration of 1%, the highest thermal conductivity ratio enhancement recorded for Al_2O_3, CuO, and SiO_2 was 1.09%, 1.08%, and 1.03%, respectively, while at a higher concentration of 4%, it was 1.18%, 1.17%, and 1.04%, respectively. • As concentration increased, the enhancement ratio increased for SiO_2, Al_2O_3, and CuO, which were 163.9%, 11.1%, and 9.4%, respectively.

Al-Rashed et al., [48]	• CuO/ water-CMC • Carboxymethyl Cellulose 0.5% wt. • Non- Newtonian • 0.5,1,1.5,3% vol.	• MCHS • Offset strip-fin	• 100 w/cm^2 • Re 100 to 700	• Nanofluid showed an improvement in heat transfer coefficient, especially at higher values of volume concentration and Re number. • Surface temperature reduction can be achieved either by increasing concentration above 1.5% or by increasing the Re number. • The maximum recorded heat transfer coefficient enhancement ratio was 2.29, while the minimum entropy generation was 2.7% lower when compared to the base fluid. • The optimal performance condition was at 1% volume fraction and a Re number value of 700 fins offset to a length of 1 and 4 fins along the channel length.
Hosseini et al., [54]	• CuO, Al_2O_3/water • 25, 35 and 40 nm • 4% vol.	• MCHS • Rectangular • Multiple channels • Aspect ratio 1-10 • Porosity 0-1	• Magnetic field effect	• Al_2O_3 nanofluid showed higher values of Nu number enhancement compared to CuO. • The magnetic field had a positive impact on enhancing the Num number momentum increment. • Increasing the aspect ratio enhances the Nu number due to entity interaction; besides, decreasing particle size enhances the Nu number due to decreasing the temperature difference between the coolant and wall. • Increasing the volume concentration of nanoparticles improves Brownian movement, which influences the heat transfer process positively.
Ma et al., [53]	• Water working fluid	• MCHS • Rectangular section • Single channel • Aspect ratios 0.1:1	• Re up to 400	• The decreasing aspect ratio gradually increases the Nusselt number and thermal entrance length. • Decreasing the Re number diminishes the aspect ratio effect of increasing the Nu number. • When the Re number is higher than 50, its effect on thermal entrance length could be neglected.
Bahiraei et al., [59]	• Gr-Ag/water • 0.02, 0.06 and 0.1% vol.	• MCHS • Rectangular, multiple inputs, multiple channels • 4 L configuration A vs 4 U configuration B • Heat sinks 111.6 mm^2 • Material copper	• Inlet velocities of 0.5, 1, 2 and 3 m/s • 100 W/cm^2.	• Thermal resistance is reduced by increasing either velocity or volume fraction. • Configuration B had better thermal performance and figure of merit, especially when employing higher concentrations; besides, it had lower irreversibility based on the 2nd law of thermodynamics. • The more intense the mixing, the greater the enhancement and improvement in heat transfer performance. • Nanofluid showed a higher figure of merit at higher concentrations through the microchannel types tested.
Samal et al., [60]	• Gr-Ag/water • 0, 0.02, 0.06 and 0.1% vol.	• Recharging microchannel (RMC). • Width of one channel =0.4mm, Height of one channel=0.4mm.	• v = 0.25 and 1m/s	• Using a recharging microchannel provides a better performance factor and recodes a maximum value of 1.72. • Increasing concentration or flow velocity enhances hybrid nanofluid cooling performance and increases the average heat transfer coefficient. • Decreasing concentration and increasing flow velocity both improve the average Nusselt number value.
Bahiraei et al., [76]	• Gr-Ag • $(NH3)_2OH$ solution. • 0, 0.02,0.06, 0.1% vol.	• MCHS • Ribs • Secondary channels	• Re = 100 to 500	• Using hybrid nanofluids significantly improves micro-heat sink performance. • Increasing concentrations of nanoparticles and increasing Re number have many benefits, as they decrease surface temperature, enhance uniformity of temperature distribution, and decrease the size of hot spots at high temperatures. • Heat transfer coefficient enhancement values increased by increasing both concentration and Re number at the test range; for example, at a Reynolds number value of 100, increasing concentration from 0% to 0.1% enhanced heat transfer coefficient by 17%.
Yan et al., [56]	• Water	• MCHS • Bionic fractal Pattern • Y-shaped (Y), connected Y-shaped (CY) and micro pin fin embedded connected Y shaped (FCY),3 models	• 30 to 170 W/cm^2 • 100 to 400 mLPM	• Micro-channels with bionic fractal patterns showed higher heat transfer capabilities than conventional patterns. • In terms of heat transfer coefficient enhancement, the FCY model showed the best, followed by the CY, and finally the Y model. • The FCY model had more uniformity of temperature distribution over other models in terms of the cost of higher-pressure loss; besides, the CY model is better than the Y model in terms of temperature uniformity.
Ghachem et al., [57]	• CNT-Al_2O_3/water • 20:80 hybridization ratio • 0 to 0.05% vol.	• Micro heat exchanger • Rectangular cross sectional • Wavy pattern. • Stainless steel material	• Inlet velocity ($5 \leq u \leq 100$) mm/s • Wave number ($0 \leq N \leq 20$)	• For flow velocities higher than 50 mm/s, nanofluid had a significant effect on the reduction of heat exchanger size. • The waving number of channels in the heat exchanger had an optimum value for providing higher thermal efficiency. • The highest recorded efficiency was at 50 mm/s, with an 8-wave number and the highest concentration.
El-Khouly et al., [19]	• CuO/Water • 50 nm • 0.5-5% vol.	• Mini-Channel • Channel Area of 15 cm^2	• 0.006-0.012 kg/sec • 130 watts	• For numerical validation, an experimental setup was done. • 1% enhancement in thermal conductivity by using nanofluid. • 1.47 enhancement in thermal-hydraulic performance at the highest volume concentration and 800 Re number.
Maganti et al., [58]	• Al_2O_3, CNT, G, and CuO/ DW	• MCHS parallel • 3 configurations U, I, and Z • Dh 10 micro meter	• 2000 W/m^2 • Re 50	• All nanofluids showed enhancement of graphene, CNT, Al_2O_3, and CuO in that order from higher to lower, respectively. • The Z configuration had the highest figure of merit compared with other configurations tested. • Overall, using microchannels with nanofluids showed a promising result for use in microprocessor cooling.

Tafarroj et al., [77]	• TiO_2/water • 0, 0.5, 1, and 2% vol.	• MCHS • 40 channels	• Re 400 and 1200 • 50.6, 60.7, and 69.1 W	• Nusselt number and heat transfer coefficients were 0.3% and 0.2% higher using nanofluids, respectively. • Three different thermal conductivity models are used for calculating the experimental Nusselt number of nanofluid. • Artificial Neural Network ANN is used as an optimizing tool for predicting the experimental Nusselt number numerically.

4. Findings and disscussion

The quest for efficient convective heat transfer in miniature cooling systems has driven extensive research into novel technologies, with a particular focus on nanofluids and hybrid nanofluids. Concurrently, the adoption of mini and microchannel heat sinks has emerged as a prominent trend aligned with utilizing nanotechnology in enhancing thermal management systems. This discussion delves into the diverse factors influencing convective heat transfer enhancement experimentally and numerically within these cutting-edge technologies. By exploring their synergistic effects, we are aiming to illuminate the latest contributions and techniques that might have a profound impact on various industries, particularly in cooling electronic equipment and advancing renewable applications. After providing a general and recent overview in all aspects, framing and categorizing the huge number of factors and variables related to mini and micro-channel heat sinks aligned with the use of nanofluids and hybrid nanofluids from a liquid convection cooling perspective as their importance as a vital topic in numerous applications and for further studies approaching that topic to avoid being overwhelmed by such factors. Moreover, we illustrate our contribution by categorizing the recent literature into experimental and numerical sections, which promotes a better understanding of the reasons behind the enhancement of such systems. What we might call a disturbance in experimental methods could be a significant reason behind enhancing heat transfer values, and that vanishes and is excluded in numerical simulations by assumptions and specific boundary conditions for decreasing their computational power needs. However, tools like machine learning tools using algorithms like ANN and GA could be useful for analyzing experimental data in addition to modeling techniques. Finally, we are more findings-oriented by comparing different research outcomes, starting with review article outcomes and followed by focusing on different and unique methods that were recently used in those topics without repeating as much as possible.

Review article findings show that higher stability for nanofluids or hybrid nanofluids, better stability methods, optimum values of mixing methods like sonication time and surfactant type or magnetic stirrer timing, a free surfactant method for stability or implementing ionic nanofluids, and other types of surfactant-based base fluids with a higher stability feature in different real applications are still missing. Besides, the need to propose new innovative nanofluids with higher stability could affect the thermophysical properties of nanofluids. Moreover, the reasons behind such an enhancement, its mechanism, and the phenomena behind it should be intensively investigated to provide an innovative solution to a lower production cost of nanofluids before practical implementation and commercialization, because approaching the sustainability of nanofluid technology depends on generating an innovative method for reusability and regeneration of such technology.

Despite the progress made in estimating the thermophysical properties of nanofluids, a universal model is still recommended, or at least models for carbon-based organic nanofluids and hybrid nanofluids, as their proposed models are very few. Besides, there is no universal correlation for convective heat transfer of nanofluids; moreover, experimental contributions are less than models and numerical studies, which increases the barrier to understanding the phenomena and the mechanism behind such enhancements or diminished values sometimes. As far as our knowledge, there is no review article concerned with different types of CFD modeling like FVM, FDM, and FEM, the advantages and disadvantages of each type, and the different algorithms used in each type, especially with microchannels utilizing nanofluids and hybrid nanofluids. However, new numerical methods look promising beside conventional macro simulation CFDs like LBM, DSMC, and MDS that have a lower scale perspective, especially because of the nature of nanofluids as a multi-scale issue like molecular scale, mesoscale, microscale, and macroscale. Additionally, methods like TM and ML, like ANN and GA, could provide a higher rate of analysis of experimental contributions, which leads to a better understanding of heat transfer mechanisms.

Organic “carbon-based” nanofluids are promising due to a lot of advantages, like higher stability and heat transfer values; however, they need to be investigated more. Moreover, metal nanoparticles over metal oxide and manipulating lower particle volume fractions, or “micro concentrations,” are recommended for more investigation as micro concentrations have promising thermal results and a relatively lower pressure drop and pumping power, which are related to and accompanied by the viscosity of nanofluids that also need more contributions, especially for miniature heat sink systems. Moreover, hybrid passive methods for enhancing heat transfer are always better than one passive method, as fluid mixing is a key factor in enhancing heat transfer capabilities; however, there is no correlation between which passive methods are preferred for utilizing nanofluids and why. Additionally, a high thermal conductivity material for heat sinks was recommended not only because of its higher heat transfer capabilities but also because it increases the enhancement power of using nanofluids; however, materials like carbon-based were not investigated nor reviewed, and porous heat sink types were also compared to metallic heat sinks, specifically when employing microchannel technology aligned with hybrid nanofluids. Generally, nanofluids with complex geometrical parameters of microchannels need more implementation in different applications as they are still rare in the literature. Moreover, heat pipes, loop heat pipes, and two-phase systems need to be investigated, utilizing microchannels and nanofluids more in parallel to forced convective heat transfer systems.

Experimental literature findings show that for mono nanofluids at mini and microchannel heat sinks, as the particle size gets smaller heat transfer coefficient enhancement increases for different natures of nanoparticles whether metal oxide-based or metal-based nanoparticles, besides, higher levels of macro concentrations show a better enhancement values of heat transfer despite a few studies reported at extremely high macro concentrations the enhancement level decreased, however, there is no specific maximum value recommended to avoid nor a correlation between it and heat sink channel size or even a united reason for such performance, on the other hand, at micro concentration level, mono nanofluids performed higher thermally than its hybridization for di hybrid metal oxide-based-carbon nanofluids [33] and lower thermally than its hybridization for di hybrid metal oxide-based-metal oxide nanofluids [20, 32] which means that experimentally using hybrid nanofluids not always enhances heat transfer capabilities. Moreover, for hybrid nanofluids at mini and micro channel heat sinks, it's not available in the literature studying the manipulation of concentration, whatever the macro or micro, hybridization ratio effect, or higher level of hybridization; however, tri hybrid nanofluids are found only in conventional heat sink sizes and reported an enhancement with increasing concentration at a range between micro and macro concentration values [40]. Moreover, for hybrid nanofluids through microchannel heat sinks, increasing concentration of all types of di hybridization like "metal oxide-based-carbon", "metal oxide-based-metal", "metal oxide-based-silicon oxide" or "metal oxide-based-metal oxide" enhances heat transfer coefficient values [39, 40], despite that all of them by increasing Reynolds number and flow velocity the influence of concentration is more significant as compared to the lower Reynolds number which means the enhancement increment level increases by increasing flow velocity and Reynolds number there is an exception as "metal oxide-based-metal oxide" at a higher range of Re number behave differently and it's better to decrease Reynolds number to have a higher yield of heat transfer enhancements, besides, "metal oxide-based-metal" as well shown in other studies an optimum value of Reynolds number as the enhancement not were up to certain limit of Reynolds number [33, 37]. Additionally, if we compare different types of di-hybrids nanofluid experimentality, we will find that "metal oxide-based metal" has shown a higher thermal performance than "metal oxide-based metal oxide." However, other studies have shown that "metal oxide-based metal oxide" has shown a higher enhancement over "metal oxide-based silicon oxide" [34].

Furthermore, for mono-nanofluids and mini-channel configurations, corrugated and wavey mini-channel heat sinks, zigzag configurations are better thermally than straight configurations, especially with increasing volumetric flow rate, decreasing wavelength, and increasing amplitude for the corrugated one or increasing the barrier by cross-cutting zigzag, which means more fluid mixing and a higher probability of nanoparticles hitting the heat sink walls. Impact and collision lead to higher enhancement values; however, a higher pressure drop and pumping power were recorded [29, 35]. For the cross-sectional area of heat sink channels, rectangular cross-sectional the mostly used in literature, reducing aspect ratio and decreasing the spacing between channels have a positive impact thermally for conventional and mono nanofluids as well [36-38], pentagonal cross-sectional performed better thermally than triangular cross-sectional for mono and hybrid nanofluids [20], however, other studies without a comparison between cross-sectional area types, studied hexagonal and circular with mono and/or hybrid nanofluids [21, 26, 27, 34], consequently, it's noticeable employing nanofluids in microchannel heat sinks with a more sharp edges configurations leads to more enhancement values, however, it's not settled yet in all levels of concentrations macro and micro nor at all levels of hybridizations. Phase change materials were recently tested and reported that micro-emulsion phase change material was insignificant with a mini-channel heat sink; however, nano-emulsion phase change material is better thermally up to a certain level of concentration; however, utilizing micro- or nano-phase change material is still in its early stages. Additionally, mini-channel heat sinks were mostly used rather than microchannel heat sinks in experimental investigations, and that could be because of the difficulties of the fabrication of microchannels. Besides, investigating a different heat loading range with micro or mini channels with nanofluids, hybrid nanofluids, or pours of medium heat sinks is still experimentally missing. Moreover, investigations employing hybrid nanofluids and microchannel heat sinks are very rare to find; besides, experimental contributions compared to numerical ones are very few, which both highlight the gap in the physical mechanism and the phenomenal explanations and reasons behind such enhancement values.

Numerical literature findings show that most attempts focused on particle type differences; their studies were concerned with thermal conductivity and thermal resistance and how that could affect the overall thermal performance, not convective properties. Moreover, the static model, Maxwell model, or Hamilton's model—different names for the same model—were mostly used in the literature, especially in estimating the thermophysical properties of hybrid nanofluids, as that model is simpler to expand for more than two particle identities, and that model can also be categorized as a temperature-independent model because it is not concerned with flow operating conditions. Alternatively, another more advanced temperature dependent models like Koo-Kleinstreuer-Li KKL model added a dynamic Brownion part to the static part to evaluate the thermal conductivity of nanofluids through micro channels and always shown that as the size of particles decreases the enhancement of heat transfer and Nusselt number increases, however, in some cases the level on increment was insignificant, while, different models like Multi sphere Brownian model MSBM shown the opposite as increasing nanoparticles diameter makes large difference between coolant and wall temperature and Nusselt number increased due to the improvement in heat transfer mechanism, on the other hand, when testing a different models together a relatively old model, like the Maxwell model, gives an excellent estimation of the Nusselt number and the difference between the Nusselt numbers predicted by the different models is only roughly 2% at specific conditions which highlights the need of a universal model despite the contributions done. On the other hand, many simulations preferred to use a user-defined function (UDF for experimental correlations) for a temperature-dependent method, especially for hybrid nanofluids, as it's obvious that a universal model for estimating nanofluids and hybrid nanofluids is still missing. However, there are a lot of contributions and models proposed that need to be intensively reviewed further and discussed deeply to provide at least a better understanding of their optimum usage in different conditions.

For mono nanofluids at macro concentrations through microchannel heat sinks, increasing concentration up to a certain limit increases the heat transfer performance significantly, however, at a higher levels of macro concentrations decreasing volume fraction had more enhancement effect [66, 75] which means increasing macro concentrations not always comes with a positive feedback and also there is no specific maximum value of macro concentration defined as it differs from researcher to another, moreover, it is not settled yet which metal oxide identity performed better than the others as they are tested at

different operating conditions and heat sink geometrical parameters [47, 65, 66, 74] which highlights the idea of how vital the interactions between each element of methods of enhancement and the pivotal need for investigating the reasons behind such enhancements, however, metal-based and carbon-based mono nanofluids were better than metal oxide-based ones despite their disadvantages as metal oxides are more stable chemically than metal-based one and carbon-based still on its early phase of investigations[49, 58], while, investigating micro concentrations of mono nanofluids weren't as much as macro concentrations.
For hybrid nanofluids through microchannel heat sinks, increasing concentration of all types of di hybridization like "metal oxide-based-carbon", "metal oxide-based-metal", "metal oxide-based-silicon oxide", "metal oxide-based-metal oxide" or "metal-based-carbon" enhances heat transfer coefficient values [45, 59, 70, 76], however, all of them except "metal oxide-based-metal" and "metal oxide-based-silicon oxide" by increasing Reynolds number and flow velocity the influence of concentration is more significant as compared to the lower Reynolds number which means the enhancement increment level increases by increasing flow velocity and Reynolds number, besides, "metal oxide-based-carbon" shown an optimum value of Reynolds number as the enhancement were up to a certain limit of Reynolds number [57, 59, 60, 63, 70, 76]. Additionally, the hybridization of "metal oxide-based-metal oxide" di hybrid nanofluids and by investigating different hybridization ratios showed no enhancement in heat transfer coefficient at all compared to their mono nanofluid types that had enhancement values over base fluid, however, the hybridization of "metal oxide-based-carbon" di hybrid nanofluids shown an enhancement in heat transfer coefficient over their mono nanofluid types [63], moreover, many studies recommended a lower concentration for hybrid nanofluids for many reasons like higher stability, lower pressure drop and enhancement values over pure base fluids despite not mentioning or discussing the reasons behind such thermal enhancement for lower concentrations of hybrid nanofluids [70]. Additionally, studying hybridizing different natures of nanoparticles showed that "metal oxide-based-metal" di hybrid nanofluids showed a higher enhancement level over hybridizing "metal oxide-based-metal oxide" type or "metal oxide-based-carbon" type, however, other studies shown that "metal oxide-based-silicon oxide" performed better than "metal oxide-based-metal" type [63, 71]. Moreover, tri hybrid nanofluid showed an enhancement over di hybrid nanofluid for "metal oxide-based" hybridization; besides, an equal hybridization ratio for "metal-based" tri nanofluids was the best hybridization ratio; however, that test of hybridization ratio was through a conventional-size heat sink; consequently, it is obvious that investigating hybrid nanofluids at higher levels of hybridization or the effect of different hybridization ratios, especially through microchannel heat sinks, has not been investigated enough yet [45, 73].
Furthermore, for mono-nanofluids and microchannels, increasing the aspect ratio (height over width) increases the Nusselt number and enhances thermal performance. Besides, using a substrate material with a higher thermal conductivity for heat sinks enhances the capabilities of nanofluids and decreases their thermal resistance. Moreover, bionic configuration in microchannels is a promising configuration proposed recently using conventional fluids and showed significant enhancement values over conventional microchannels; however, to our knowledge, it has not yet been tested employing nanofluids or hybrid nanofluids [53, 54, 56, 65]. For both mono or hybrid nanofluids with micro channels, straight array of micro channels performed thermally better than a wavy array and increasing waving value gives a lower value heat transfer coefficient, besides, using trapped channels over conventional micro channels are not preferred as well, while, employing a double layered channels over a single layer ones leads to a better thermal performance, besides, for single input-output flow, Z configuration in channels pattern better than U configuration which is better than I configuration, additionally, for multiple input-output flow, 4 U configuration in channels pattern better than 4L configuration, moreover, for a single or multiple flow lines, recharging micro channels which means a finite number of inputs and outputs, performed better thermally than simple channels [57-60] and those findings showed that a more sharp edges not smooth ones beside a more dynamic fluid flow leads to a higher enhancement values of heat transfer rates and that could be due to increasing the probabilities of nanoparticle to wall collisions, consequently, hydrothermal performance of nanofluids with different heat sink geometric parameters or heat loading range aligned with manipulating the concentrations were not well investigated yet, however, a few studies shown that the heat transfer rate enhancement in lower heat flux loading is insignificant and so it seems by increasing heat flux it unleashes the potentials of nanofluids in enhancing thermal performance but the relation between different heat sink geometric parameters while manipulating concentration at different levels were not settled yet.
Although experimental and numerical findings are closely related, there is a contradiction in their findings, like that hybridizing mono nanofluids is worse for enhancing the heat transfer coefficient for "metal oxide-based carbon" di hybrid nanofluids and better for "metal oxide-based metal oxide" experimentally, while numerically they behave the opposite, which means hybrid nanofluids not only do not have a positive impact on enhancing heat transfer capabilities but also the type of hybrid nanofluid that gives the worst values over mono nanofluids is not settled and differs based on study type. Additionally, when comparing the findings of hybrid nanofluids against each other's numerically it shows that "metal oxide-based-metal" showed a higher performance thermally over other metal oxide combinations like "metal oxide-based-metal oxide" or "metal oxide-based-carbon", however, few studies show that "metal oxide-based-silicon oxide" shown a higher enhancement over "metal oxide-based-metal", on the other hand, experimentally, "metal oxide-based-metal shown a higher performance thermally over "metal oxide-based-metal oxide" as well, however, other studies shown that "metal oxide-based-metal oxide" shown a higher enhancement over "metal oxide-based-silicon oxide", so, like mono nanofluids it is not settled yet based on nature which combination is better. Furthermore by investigating the Reynolds number effect on heat transfer enhancement of nanofluids, mostly all mono and hybrid nanofluids show an increment value of enhancement with increasing Reynolds number; however, for hybrid nanofluids, numerically, "metal oxide-based metal" and "metal oxide-based silicon oxide" behave differently as heat transfer coefficient increases with decreasing Reynolds number, and in some cases, "metal oxide-based carbon" had an optimum value, while experimentally, at much higher levels of Reynolds number range, "metal oxide-based metal oxide" heat transfer coefficient increases as well with decreasing Reynolds number, and in some cases, "metal oxide-based metal" had an optimum value. Furthermore, using wavy channels experimentally showed an enhancement over straight channels, while

numerically they were the opposite, which is quite interesting and means that more needs to be known about the mechanism of enhancement and the phenomena behind such values. Additionally, there are a lot of factors that are tested numerically only and need to be tested experimentally, like utilizing nanofluids and hybrid nanofluids, generally with microchannels and not with mini-channels. Moreover, the literature reveals that experimental enhancement values of heat transfer rates were higher than numerical enhancement values in mini-channel heat sinks, which is surprising and unexpected as the disturbance in experimental methods should logically lead to a lower value of enhancement over numerical methods that use assumptions for simulating with lower computational power. However, from another perspective, this finding highlights how explaining the nanofluid phenomena and the mechanisms behind such enhancements is vital. Additionally, applying nanofluids or hybrid nanofluids to conventional heat sinks is not yet feasible for practical implementation as the cost is higher compared to the payback period. However, applying nanofluids or hybrid nanofluids with microchannels and miniature cooling systems needs to be tested feasibly and economically, and the yield must be different as the total working fluid is much lower. Besides, generally, there is a huge gap in the practical implementation of nanofluids and hybrid nanofluids, or even in economic or commercial studies.

5. Conclusions and future recommendations

In conclusion, this review delves into the advancements and insights gained in the field of heat transfer enhancement through the integration of microchannel heat sinks and nanofluid technologies over conventional methods. These innovative approaches have demonstrated significant improvements in thermal performance, especially when harnessing their benefits together, offering promising solutions for addressing challenges in electronic devices, energy systems, and other critical domains for sustainable and efficient thermal management solutions. We have outlined the main conclusions, difficulties, gaps, and opportunities, offering a direction for upcoming studies.

5.1. Highlighted findings and conclusions

- All enhancement methods could be classified into three main elements: coolant, heat sink, and operating conditions, in addition to the active methods that could be used.
- Brownian motion, liquid layering, nanoparticle agglomeration, Soret phenomena, Dufour effect, and different entity interactions and collisions like nanoparticles, base fluid particles, and heat sink walls are the currently proposed reasons behind such enhancement of nanofluids; however, there is still a huge gap in understating the behavior of nanofluids, especially the hybrid ones.
- Less particle size showed a better hydrothermal performance for mono nanofluids at mini channel heat sinks experimentally, while, numerically particle size beside concentration used in temperature independent approach in estimating thermophysical properties as the most used method in literature like the static model and recently temperature-dependent models like KKL were introduced and all shown that less particle size is more preferable as it increases the thermal conductivity of nanofluids, however, MSBM shown the opposite, moreover, the temperature-dependent approach used recently by many investigators in their CFD studies as well by user-defined functions UDF for an experimental correlations' created specifically for the nanofluid types used not a general or universal model, additionally, testing different model shown that the differences were insignificant as it accounts around 2%.
- Increasing macro concentrations are better for heat transfer coefficients up to a certain limit for mono and hybrid nanofluids through mini or microchannel heat sinks; moreover, there is no absolute answer as to which metal oxide-based mono nanofluid performed better because operating conditions, heat sinks, geometric factors, and nanofluid variables are all correlated to the enhancements shown by utilizing nanofluids in those systems. Besides, metal-based and carbon-based nanofluids are better than metal oxide-based mono nanofluids thermally; furthermore, micro-concentrations show a promising potential and are preferred for hybrid nanofluids; however, they are not tested much with mono nanofluids through microchannels.
- Hybridizing mono nanofluids at mini channel heat sinks is worse for enhancing heat transfer coefficient for "metal oxide-based-carbon" di hybrid nanofluids and better for "metal oxide-based metal oxide" experimentally, while numerically, "metal oxide-based-metal oxide" showed no enhancement and "metal oxide-based-carbon" showed enhancement over their mono nanofluid values, which means hybrid nanofluids do not always have a positive impact on enhancing heat transfer capabilities.
- Numerically, "metal oxide-based metal" has shown a higher performance thermally over combining metal oxide with metal oxide or with carbon; however, few studies have shown that "metal oxide-based silicon oxide" has shown a higher enhancement over "metal oxide-based metal." On the other hand, experimentally, "metal oxide-based metal" has shown a higher performance thermally over "metal oxide-based metal oxide" as well; however, other studies have shown that "metal oxide-based metal oxide" has shown a higher enhancement over "metal oxide-based silicon oxide.".
- In both numerically and experimentally, increasing levels of hybridization from di to tri hybrid nanofluids showed a better enhancement value; however, it was tested mostly in conventional heat sink sizes, not in micro or mini channels, and for the same particle nature, beside an equal or near-equal hybridization ratio for tri hybrid, there were better other mixture ratios at the same volume fraction.
- Generally, increasing the Reynolds number at any concentration level enhances the heat transfer coefficient for mono nanofluids, however, for hybrid nanofluids numerically "metal oxide-based-metal" and "metal oxide-based silicon oxide" behave differently as the heat transfer coefficient increases with decreasing flow rate and Reynolds number and in some cases "metal oxide-based-carbon" had an optimum value, while, experimentally, at much higher levels of Reynold

number range for “metal oxide-based-metal oxide” heat transfer coefficient increases as well with decreasing flow rate and Reynolds number and in some cases “metal oxide-based-metal” had an optimum value, however, for all other combinations of di hybrid found in literature, it behaves like mono nanofluids whatever experimentally or numerically, besides, it might be connected to concentration level and channel geometric parameters.

- Higher heat loading employing nanofluids experimentally and numerically leads to a higher heat transfer coefficient enhancement, which promotes the idea that increasing heat loading range activates and unleashes nanofluid potential; however, it is not studied much for microchannels with nanofluids and hybrid nanofluids.
- Nanophase change martial is better thermally, as microphase change martial was insignificant through microchannels.
- Heat sinks with high thermal conductivity substrate material increase the enhancement effect of nanofluids; besides, it is noticeable that mini channels have been experimentally investigated a lot compared to microchannels and pour heat sinks due to the fabrication barrier.
- Increasing aspect ratio (height over width), double-layered, recharging channels, channel interpretations, multiple inputs and outputs, Corrugated and zigzag configurations over straight one, decreasing channels spacing and pentagonal cross-sectional area over triangular cross-sectional all shown a higher enhancement values over conventional micro channel utilizing nanofluids, consequently, that generally illustrate with more sharp edges and more complex geometries utilizing nanofluids leads to more enhancements as the probability of particle to wall impacts and collisions increases, however, it’s not tested enough with hybrid nanofluids aligned with manipulating concentration levels, on the other hand, surprisingly wavy configurations were not recommended or have an optimum value and a certain limit as their effect were insignificant based on numerical studies, however, experimental studies shown the opposite which means there is more needed to be known about the mechanism of enhancement, beside, bionic configurations are promising to employ over conventional microchannels, however, it is not tested yet with nanofluids.
- Experimental enhancement values were higher than numerical values, which highlights that explaining the nanofluid phenomena behind such enhancements is vital, besides, using hybrid nanofluids in conventional heat sinks was not feasible economically, and more efforts had to be made for their commercialization despite their significant heat transfer capabilities.

Every technology suffers a lot before generating the optimized and valuable results or applications, despite massive progresses made, there are still some discontinuities and opportunities which seek attention of researchers as well as industrials, thus, some challenges still require more emphasis for future studies and solutions are still required for fulfilling issues and gaps as in the following part future recommendation/prospects are listed.

5.2. Recommendation for future work

- Investigating hybrid nanofluids by manipulating macro or micro concentrations not available through microchannel heat sinks as well as micro concentrations for mono nanofluids; besides, manipulating hybridization ratios and higher levels of hybridization not available as well; besides, taking into consideration various complex microchannel geometric parameters; moreover, micro concentrations are recommended for testing for hybrid nanofluids and nanofluids as well through microchannel heat sinks; besides, an equal hybridization ratio for higher levels of hybridization and different particle nature for a higher level of hybridization.
- More experimental contributions and application-based investigations are recommended for unitizing nanofluids and hybrid nanofluids through mini- and microchannel heat sinks.
- Investigating and monitoring the proposed reasons and proposing new reasons that clarify the real phenomena and behavior and provide a physical explanation behind the enhancement or diminished values of heat transfer capabilities of cooling systems employing nanofluids and hybrid nanofluids, especially though microchannel heat sinks, with more focus on hybrid nanofluids, might be the key to a deep understanding of nanofluid hydrothermal performance.
- New modeling techniques using machine learning, like ANN or GA, could help analyze the experimental data and clarify the reasons behind such performance, besides, micro modeling techniques like LBM and MDS.
- Organic carbon-based nanofluids like graphene and CNT and hybrid organics, along with nanophase change materials, are recommended for further analysis through microchannel heat sinks, as they could be the solution to the disadvantages of nanofluids like viscosity, higher pressure drop, production cost, and sustainability.
- Reviewing and comparing all models related to predicting thermophysical and electrochemical properties, regardless of temperature-dependent or independent approaches for mono- and hybrid nanofluids, is still a justified approach.
- Porous surfaces, graphene heat sinks, and bionic configurations are recommended for further investigations utilizing nanofluids and hybrid nanofluids.

The transformative impact on thermal management across various industries becomes increasingly tangible. The recent contributions can be considered an important reference for those interested in starting their investigation using nanofluids and microchannels. The knowledge gained from this review paves the way for future research and development in this vital area of engineering as we move toward more effective and sustainable heat transfer solutions. Further investigation into novel materials, design approaches, and computational modeling methods will surely deepen and open up new possibilities.

Nomenclature

Chemical formula	
Al_2O_3	Aluminum oxide
CuO	Copper oxide
ZnO	Zinc oxide
Ag	Silver
TiO_2	Titanium oxide
SiO_2	Silicon oxide
Cu	Copper
Fe_3O_4	Iron oxide
Au	Gold
Cu	Copper
Zn	Zinc
ZrO_2	Zirconium oxide
MgO	Magnesium oxide
SnO_2	Tin oxide
Bi_2O_3	Bismuth oxide
WO_3	Tungsten trioxide
Bi_2Te_3	Bismuth telluride
Greek symbols	
ρ	Density
μ	Dynamic viscosity
k	Thermal conductivity
ϕ	Nanoparticles volume fraction%
Abbreviation	*Description*
SDS	Sodium dodecyl sulfate
CTAB	Cetyl trimethyl ammonium bromide
LPM	Liter per min
CPU	Central processing unit
HVAC	Heating ventilation and Air conditioning
HP	Heat pipe
LHP	Loop heat pipe
FPC	Flat plate collector
CFD	Computational fluid dynamics
FVM	Finite volume method
FEM	Finite element method
FDM	Finite difference method
LBM	Lattice Boltzmann Method
MDS	Molecular diffusion method
TM	Taguchi method
DSMC	Direct Simulation Monte Carlo method
MEMS	Micro Electro-Mechanically Systems
NEMS	Nano Electro-Mechanically Systems
MCHS	Micro channel heat sink
CMCHS	Corrugated micro channel heat sink
RMC	Recharged micro channels
TEM	Transmission electron microscopy
SAED	Selective area electron diffraction
DAQ	Data acquisition
FOM	Figure of merit
EG	Ethelene glycol
CNT	Carbon nanotube
MWCNT	Multi wall carbon nanotube
RGO	Reduced graphene oxide
DW	Distillated water
CZ	Continues zigzag
CCZ	Cross cutting zigzag
PEC	Performance evaluation criteria
FOM	Figure of merit
HYNF	Hybrid nanofluid
HTC	Heat transfer Coefficient
INF	Ionic nanofluids
KKL	Koo-Kleinstreuer-Li model
MSBM	Multi sphere Brownian model
ML	Machine learning
GA	Genetic Algorithm
ANN	Artificial neural network
WRM	Weighted residual method
EDM	Electric Discharge Machining
LBM	Lithography Injection Molding
ID	Inner diameter
OD	Outer diameter
AR	Aspect Ratio
WLR	Wave to length ratio
WAR	Wave to amplitude ratio
TF	Trapping factor
Dimensionless	*Description*
Nu	Nusselt number
Re	Reynold number
Pr	Prandtl number

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