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Comprehensive Review of Bio-Oil-Based Nanofluids as Cutting-Edge Heat Transfer Fluids with a Focus on Solar Thermal Systems

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ABSTRACT

The increasing demand for efficient renewable heat transfer fluids in solar system applications has intensified interest in exploring bio-oil as a renewable and sustainable alternative to conventional thermal fluids. Bio-oils, derived from biomass, offer a promising alternative for industrial applications. However, their relatively low efficiency has prompted the incorporation of nanoparticles to create bio-oil-based nanofluids. Despite the notable improvement in heat transfer effectiveness, the full-scale implementation of bio-oi-based nanofluids is constrained by several critical challenges. These include the tendency of the nanoparticles to aggregate over time, compromising long-term stability, and inherently high viscosity of the bio-oil fluid, which hinders the fluid flow and energy efficiency. Additionally, thermal stability under varying operating conditions and bio-oil scalability for industrial applications remains a significant concern. The present review comprehensively examines the potential of bio-oil-based nanofluids as an improved heat transfer fluid, focusing on their environmental and sustainable benefits over conventional fluids. It also presents recent advanced studies on bio-oil-based nanofluids, addressing critical issues related to long-term stability, thermal stability, and high viscosity through different preparation and characterization techniques to improve the thermophysical properties to optimize their performance in solar thermal systems. The review identifies key challenges and prospects for full-scale implementation of bio-oil-based nanofluids in solar thermal technologies. It aims to provide researchers in this field with valuable insight into advancing an improved heat transfer fluid that is environmentally friendly and suitable for solar thermal applications that contribute to the global transition toward a greener future.

Keywords: Bio-oil; nanofluid; stability; heat transfer fluid; sustainability; enhancement

INTRODUCTION

The conversion of solar radiation into thermal energy relies heavenly on heat transfer fluid for heat transfer and energy storage. The effectiveness of heat transfer fluids (HTFs) is directly related to the thermal performance of engineering systems such as solar collectors, heat exchangers, lubrication, and microelectronics (Harris et al. 2022; Hasbi et al. 2023; Ishak et al. 2023). Heat transfer enhancement refers to the performance or augmentation of heat transfer in any heat transport process, medium, component, device, or equipment (Ajeel et al. 2024, Ishaka et al. 2024). They include enhancing the heat transfer rate of a specific surface, minimizing the flow resistance, increasing the critical heat flow, or improving the thermal conductivity and specific heat capacity (Etminan & Harun, 2021). Researchers have explored various techniques to maximize systems efficiency to enhance the convective heat transfer, typically classified into passive, active, and compound techniques (Ho et al. 2023). Each technique mentioned above offers unique advantages in improving thermal performance. The passive technique enhances the heat transfer without needing external power, utilizing methods such as treated or rough surfaces, surface tension devices, extended surfaces like fins, inserts, coiled wires, swirl-flow devices, and additives for liquid and gas. Active techniques, on the other hand, require an external power input for the enhancement of heat transfer and include approaches like mechanical aids, surface or fluid vibration, electric or magnetic field, suction, and jet impingement, while the compound enhancement techniques combine elements of both passive and active techniques to achieve a greater enhancement that is superior to individual technique (Ajeel et al. 2024; Ho et al. 2023).

The passive technique leveraging nanotechnology recently attracted significant attention for enhancing heat transfer. Incorporating nanoparticles into HTF has revolutionized heat transfer processes, substantially improving thermal conductivity, specific heat capacity, and viscosity (Kareem & Khdir 2021). Nanomaterials such as metal oxides, carbon-based compounds, and hybrid composites into base fluids have significantly improved the system heat transfer efficiency. However, using base fluid in nanofluid applications is another concern for optimizing the system's performance efficiency. Conventional fluids such as water, synthetic oils, mineral oils, and ethylene glycol are widely used as HTFs in solar thermal systems (Ali 2022; Almalki et al. 2024; Jebali et al. 2023; Thiemann et al. 2013; Yusaidi et al. 2023). In these mixes, conventional oils attracted wider attention across various engineering applications, including cooling, heating, insulation, lubrication, cutting, and insulation (Kui et al. 2022; Kumar et al. 2022). One of the prime applications of these oils in solar thermal systems is where they serve as HTFs. Conventional oils have been used in solar thermal systems for several decades due to their favorable thermal capacity, cost-effectiveness, and good low-temperature pouring points (Pereira et al. 2022; Sofiah, Samykano, Pandey et al. 2021). However, integrating nanoparticles into these conventional oils has created oil-based nanofluids with enhanced thermal and physical properties, offering significant potential for improving oil recovery applications (Brzóska et al. 2021; Rafiq et al. 2021). Several research studies have explored the formulation of oil-based nanofluids utilizing different conventional oils combined with a range of nanoparticles and nanocomposites for solar thermal applications. These studies, employing both experimental and numerical approaches, aim to develop advanced HTFs optimized for low- and medium-temperature applications (Ledari et al. 2021; Torres et al. 2021; Diao et al. 2023; Diao et al. 2024; Yang et al. 2020; Kia et al. 2023; Shajan et al. 2021; Khan, Abid, et al. 2021; Rahman, Issa, et al. 2024; Mostafizur et al. 2023; Farhana et al. 2024; Esfe et al. 2024). These studies address key challenges related to thermal stability, long-term durability, and enhancement of thermophysical properties. Advanced preparation and characterization techniques aim to enhance conventional oil-based nanofluids' stability, thermophysical properties, and overall heat transfer coefficient.

Despite their widespread promise, conventional oils and their oil-based nanofluids counterparts possess several limitations that undermine their sustainability for future generations. For example, synthetic oils, which are derived from petroleum sources, pose a high fire risk, low biodegradability, and can degrade over time, leading to the breakdown of their heat transfer characteristics and the accumulation of varnish and sludge that can clog the systems (Rawat & Harsha 2021; Yadav et al. 2021). Other fluids, such as thermal oils and ethylene glycol, have also been proposed but have high cost, poor biodegradability, absolute lifecycle, thermal cracking, and oxidation at high temperatures (Mehrizi et al. 2023; Okogeri & Stathopoulos 2021). While progress has been made in this respect, challenges related to thermal stability, long-term stability, renewability, and sustainability of the HTF remain unsolved.

As research continues, there is a pressing need for more research studies to develop more thermally stable, cost-effective, environmentally friendly, and sustainable oil-based-nanofluids alternatives that can promote their wider implementation across diverse industries. In this context, bio-oil-based nanofluids offer an innovative alternative. They combine renewable and environmentally friendly characteristics with advanced thermal stability, long-term stability, and improved thermophysical properties. This review's primary objective is to highlight the limitations and challenges associated with conventional oils-based HTF while critically examining the potential of bio-oil-based nanofluids as an alternative heat transfer medium. The review explores the techniques and methodologies in synthesizing and upgrading bio-oil to function as HTF in solar thermal systems. It also scrutinized the recent progress in the preparation, stability, characterization, and thermophysical properties, highlighting advancement in the field demonstrated by various research studies involving mono and binary bio-oil-based nanofluids. These are fundamental to enhancing heat transfer effectiveness in solar thermal systems. Finally, the review will offer challenges, prospects, and conclusions towards advancing HTFs suitable for solar thermal applications that contribute to the global transition toward a greener future.

METHODOLOGY

This review's research methodology systematically identifies relevant information from academic literature. In this context, academic literature refers to publications in formal conferences, books, and journals. This approach is essential for the thorough completion of the review study. The selection and sourcing of information from academic publications were conducted based on the keywords of the academic journal. The primary research sources were major academic indexing databases. Only peer-reviewed publications were included to ensure rigor, ranging from 2020-2024. A total of 1400 papers were collected throughout the academic search, of which 800 articles were excluded after revising their abstract, and another 200 articles were screened due to duplication, leaving 400 articles for further screening. These 400 articles were then pre-processed further to identify the most relevant for this review, with those deemed unsuitable being removed. An additional 128 articles that were published before the year 2020 were excluded. The remaining articles were manually vetted to establish their eligibility for review, with just 135 articles chosen as most relevant to the scientific literature, of which 137 articles were vetted based on the subject area and language.

BIO-OIL BASED HTFS

SUSTAINABILITY

Conventional fluids often cause issues such as corrosion and clogging in duct and pipe sections that possess low thermal properties while also raising safety concerns due to the inclusion of nano-additives for improvement and as well the renewable and sustainable concern (Sharif, et al. 2021; Mohite et al. 2024). Some of these challenges can be addressed by utilizing fluid extracts derived from non-edible oil plant byproducts, which offer a clean, sustainable, and environmentally friendly solution with thermal properties comparable to traditional base fluids (Arias et al. 2022; Malik et al. 2024; Novita & Fudholi 2023). Bio-oils derived from biomass have several advantages: availability, sustainability, low-corrosiveness, thermal stability, low volatility, and renewability (Adekunle & Oparanti, 2023; Oparanti et al. 2020). As a versatile and renewable alternative to conventional fluids, bio-oil is promising for sustainable energy production, resource utilization, and carbon mitigation (Yu et al. 2024; Yusaidi et al. 2023). They are particularly well-suited as HTF in various applications, including solar thermal systems, industrial processes, and heat exchangers (Kumar et al. 2022). Bio-oil is a low-carbon alternative to typical fossil fuel-based HTF since it uses renewable resources such as organic waste, agricultural residues, and energy crops (Ali & Rashid., 2023). The carbon cycle associated with bio-oil is almost neutral, as the carbon dioxide emitted during combustion balances the carbon dioxide absorbed by the plants. In spills or leakage, bio-oil's strong biodegradability lowers the possibility of long-term environmental damage (Das et al. 2022). However, its improved specific heat capacity and thermal conductivity make bio-oil the most effective heat transfer medium in various engineering applications, including industrial processing and renewable energy systems. For effective performance, various production techniques such as pyrolysis or hydrothermal liquefaction effectively transform biomass into useful energy while emitting less sulfur dioxide (SO_2) and other pollutants (Supreetha et al. 2024). Bio-oil lifecycle promotes a circular economy and reduces waste that would decompose and release methane, resulting in the greenhouse gas effect. Consequently, bio-oil lowers reliance on non-renewable fossil fuels fluids and complies with international sustainability and carbon reduction objectives.

BIO-OIL LIFE CYCLE

The lifecycle of a natural ester extracted from bio-oil upgrading processes is preferred in systems applications due to their renewable nature and biodegradable and non-toxic characteristics (Das et al. 2022). Fatty acids are long chains of hydrocarbons generated by fats that determine their properties. These fatty acids have functional features, including thermal stability and lubrication, making them appropriate for various applications, including HTFs. Triglycerol fats are made up of glycerol bonded to three fatty acids. They can be derived from plant seeds (like vegetable oils). Triglycerides can be converted into free fatty acids and glycerol through transesterification techniques (Praveena et al. 2024). The free fatty acids can be employed in industrial applications, such as creating bio-oil-based HTFs. At the same time, glycerol can be processed into biofuels or other compounds that operate as HTFs, efficiently absorbing and transferring solar energy (Mamtani et al. 2021). At the end of their lifecycle, natural esters break down into carbon dioxide (CO_2) and water (Das et al. 2022). Natural esters are carbon-neutral because the amount of CO_2 they release during decomposition or incineration is equal to the amount of CO_2 absorbed by the plants during photosynthesis. These usually create a closed carbon cycle. Plants absorb CO_2 from the environment and store it in their biomass, including oil production seeds. Decomposition or combustion releases the same quantity of CO_2 into the environment. This balance ensures that the use of natural esters as HTFs or biofuels does not add additional CO_2 to the atmosphere, unlike fossil fuels that release CO_2 that was stored millions of years ago (Praveena et al. 2024; Das et al. 2022). The extraction and use of natural esters from biomass, combined with their environmentally friendly lifecycle and carbon neutrality, make them highly sustainable fluids for industrial applications, including solar thermal systems. They offer a closed-loop system where the CO_2 emissions are balanced by the CO_2 absorption during the plant's lifecycle. Figure 2 shows the Bio-oil life cycle extracted from coconut oil-based biomass.

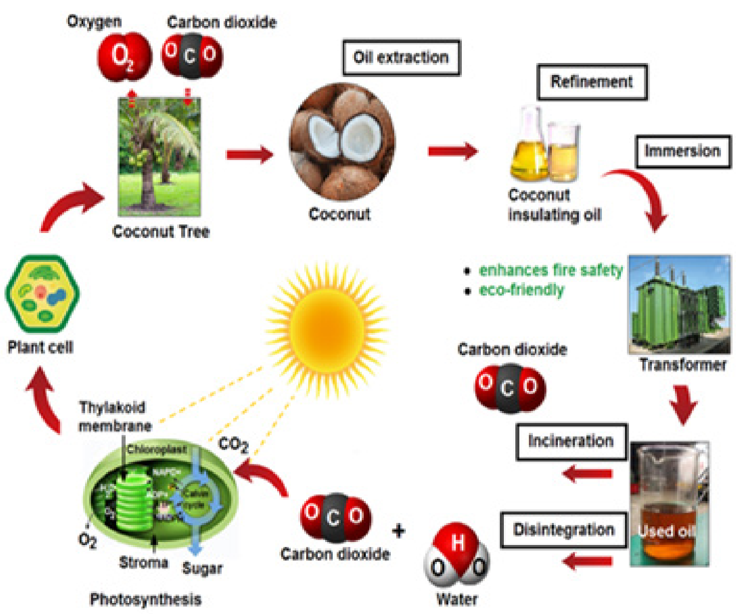


FIGURE 1. Bio-oil life cycle extracted from coconut oil (Das et al. 2022)

SYNTHESIS AND UPGRADING OF BIO-OIL

Bio-oil is a complex mixture primarily composed of carbon, hydrogen, and oxygen formed through the depolymerization and breakage of lignin, hemicellulose, and cellulose (Ahamed et al. 2021). It has a thick, dark appearance and emits a smoky odour (Hlaba 2020, Siddique et al. 2021). The oil is usually extracted from pyrolysis and hydrothermal liquefaction. It cannot be directly used as a fuel for transportation due to its higher viscosity, moisture, oxygen, lower carbon, and heating value (Nallasivam et al. 2022). The bio-oil obtained from the hydrothermal liquefaction process is typically of lower quality than heat transfer oils and hence requires upgrading to meet the standards necessary for use as a heat transfer-based fluid. Numerous techniques are employed to upgrade bio-oil as HTF. These include transesterification, esterification, supercritical, catalytic cracking, hydrogenation, molecular distillation, hydrodeoxygenation, emulsification, and catalytic pyrolysis (Volli et al. 2021). The selection of the appropriate upgrading method depends on factors such as the composition of the bio-oil, desired product specifications, type of application, and economic considerations. The most cost-effective upgrading techniques applied to HTF for medium-temperature thermal applications are explained below.

1. Transesterification is a chemical process that converts triglyceride and alcohol into esters, with glycerol as a byproduct in the presence of a catalyst (Ahamed et al. 2021). This process consists of three sequential and reversible reactions: The conversion of triglyceride, the transformation of diglycerides to monoglyceride, and finally, the glycerol as the backbone (Orege et al. 2022). Catalysts are typically employed to accelerate the reaction rate, enabling it to be completed within a short period (Nayab et al. 2022). These catalysts utilized might be classified as alkalis, acids, or enzymes. The transesterification procedure results in the production of esters and crude glycerol.
2. Esterification is the process of bio-oil upgrading, which entails transforming its organic acids and alcohols into esters, creating esterified bio-oil (Khan, Javed, et al. 2021). The method of esterification involves the reaction of organic acids found in bio-oil with alcohols, using a catalyst like sulfuric acid or an acidic ion exchange resin (Otache et al. 2021). This reaction produces ester compounds and water as a byproduct. It is crucial to remove the water to promote the completion of the reaction and prevent the hydrolysis of the ester products.

3. Emulsification is another bio-oil upgrading process involving dispersing it into water or solvents to create stable emulsions, which can serve as HTF in various applications (Epelle et al. 2022). This process enhances thermal properties, reduces viscosity, and improves stability. Water or solvents in the emulsion stabilize the interface between bio-oil and water, preventing phase separation (Liu et al. 2021). This reduces viscosity, making it easier to handle and pump in heat transfer systems. Emulsified bio-oil also shows improved compatibility with system materials and reduced corrosion potential compared to pure bio-oil (Ahamed et al. 2021). Catalytic hydrotreating is the most efficient upgrading technique that can produce bio-oil-derived HTFs for solar thermal applications. This technique is preferred for higher temperatures and longer lifetimes but is not cost-efficient. Figure 2 illustrates the flow chart for crude bio-oil upgrading processes. The bio-oil upgrading can improve thermal stability and decrease viscosity by producing lower-molecular-weight esters, which are less prone to degradation and exhibit improved flow properties and heat transfer efficiency across low, medium, and high-temperature fluid applications. Compared to its untreated counterpart, these upgrades can significantly enhance bio-oil's thermal stability and heat transfer characteristics. Creating ester compounds during upgrading may also improve thermal conductivity and specific heat capacity, ultimately boosting their effectiveness as HTF in thermal applications. However, by incorporating polar solvents like ethanol, methanol, and furfural, the bio-oil density can effectively be reduced, resulting in a more uniform mixture. Decreased density and improved stability lead to high-grade fuel production (Nanda et al. 2021). Studies have demonstrated that directly mixing ethanol or methanol with bio-oil can lower viscosity and increase the heating value (Ahamed et al. 2021; Orege et al. 2022). To further enhance the heat transfer characteristics, nanoparticles are also integrated to create bio-oil-based nanofluids. These nanofluids offer several potential enhancements, including increased thermal stability, improved heat transfer coefficients, and enhanced thermal conductivity. As a result, bio-oil-based nanofluids are more effective for heat transfer in various applications than conventional bio-oil and other HTFs.

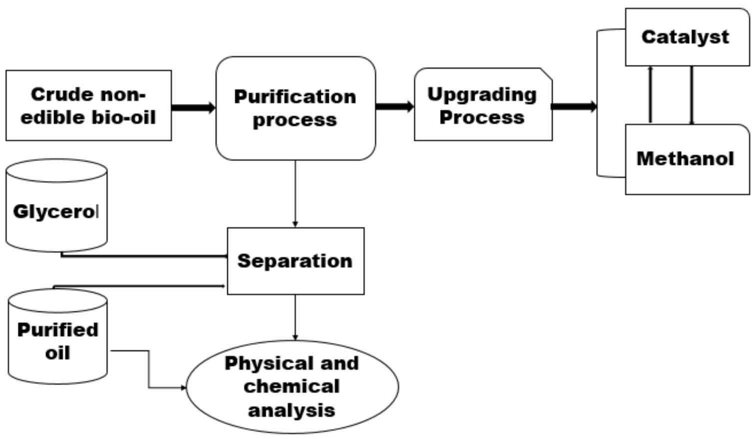


FIGURE 2. The flow chart of crude bio-oil upgrading

BIO-OIL BASED NANOFLUIDS

INTEGRATION OF NANOPARTICLES INTO BIO-OIL-BASED FLUID

Integrating nanoparticles, such as carbon-based (Graphene, Carbides, or Polymers), metallic (Gold, Silver, Iron, and Copper), and non-metallic (Aluminium Oxides, Copper oxides, and Iron oxides), in both mono and binary combinations into bio-oil can significantly enhance the heat transfer coefficient of the bio-oil to function as HTF in solar thermal systems (Brzóska et al. 2021; Chan et al. 2020). Figure 3 illustrates the classification of metallic, non-metallic, and carbon-based nanomaterials used in creating nanofluids.

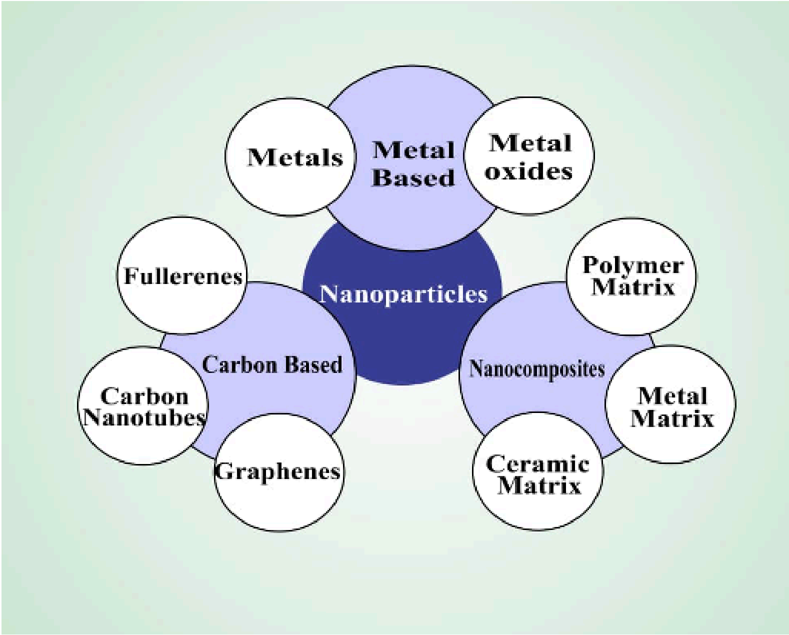


FIGURE 3. Nanoparticles classification

However, binary nanofluids, which comprise the base fluid and two or more dissimilar combinations of nanoparticles that often exhibit unique properties compared to their components, are regarded as some of the most efficient HTFs for improving solar systems due to their superior thermal characteristics (Malan & Kumar 2021). The primary goal of creating binary nanofluids is acquiring an advanced product with higher thermal conductivity, physical strength, chemical stability, and mechanical resistance than mono nanofluids (Sreekumar et al. 2022). Due to their superior thermophysical properties, binary nanofluids are increasingly used in solar thermal systems for heating and cooling applications (Kumar, Ghosh, et al. 2024). Several studies have demonstrated that mono and binary bio-oil-based nanofluids exhibit improved heat transfer capabilities (Bhattad et al. 2023; Mehta et al. 2022; Scott et al. 2022). Research studies have shown a significant enhancement in HTFs when various bio-oil-based fluids are used in solar thermal systems (Brzóska et al. 2021; Chan et al. 2020). Table 1 presents a compilation of different research studies exploring the potential of various nanoparticles and bio-oil-based fluids forming different types of nanofluids to enhance and improve the thermophysical properties of bio-oil-based HTFs. These enhancements have been applied across various solar thermal applications, including heating, cooling, and lubrication.

PREPARATION, CHARACTERIZATION AND THERMOPHYSICAL PROPERTIES MEASUREMENT

PREPARATION OF BIO-OIL-BASED NANOFLUIDS

Nanofluid production aims to increase the heat transfer fluid's effectiveness or conductivity (Tiwari et al. 2021). However, nanofluids are fluids in which nanoparticles with a diameter of less than 100 nm are suspended in the base fluid. They are dilute solutions from nanomaterials with unique and improved properties (Chakraborty & Panigrahi 2020). It has been reportedly discovered that nanofluids had been established to improve the thermal characteristics of viscosity, diffusivity, conductivity, and convective heat transfer efficiency equated with the base fluids like water, air, salt, or oil. Two famous methods are used to prepare the nanofluids, as discussed below. The one-step technique: This approach usually reduces aggregation and improves fluid stability by doing away with drying, storing, transporting, and dispersing nanoparticles. The well-known one-step preparation technique is the Physical Vapor Deposition (P.V.D.) technology, in which the stable nanofluid is created through the evaporation and condensation of nanoparticles within the base fluid (Panduro et al. 2022; Vijayan et al. 2020). The one-step technique is typically employed for mono and binary nanofluid preparation, but the second method is more appropriate for mass manufacturing. The two-step technique is a highly popular and economically sustainable approach for large-scale nanofluid production (Mehta et al. 2022; Rahman, Hasnain, et al. 2024). In this manner, nanoparticles or any other nanomaterial are prepared first to create dry powders via physical or chemical means and then dispersed in a based fluid to form an innovative liquid known as nanofluid. To ensure the suspension is effectively dispersed. The following greatest, most famous, and relevant technique is usually employed. These are mechanical or magnetic stirring, ball milling, ultrasonication, and high-pressure homogenization, which are used to distribute the nanosized powder into a base fluid (Mahamude et al. 2022; Scott et al. 2022). Prepared nanoparticles tend to agglomerate due to their large surface area and characteristics (Tiwari et al. 2021). In this respect, surfactant addition is regarded as the most famous approach to decreasing aggregation and increasing the stability of nanoparticles prepared in nanofluids. Another issue of concern in the two-step approach is the surfactants' ability to work at high temperatures. These lead to too many research investigations in this respect (Muhammad et al. 2021; Tiwari et al. 2021). The preparation of binary nanofluids gives better results through two-step techniques since the approach is best for large-scale production. Figure 4 illustrates the schematic diagram of the general procedure for bio-oil-based nanofluids preparation, characterization, and thermophysical properties measurement.

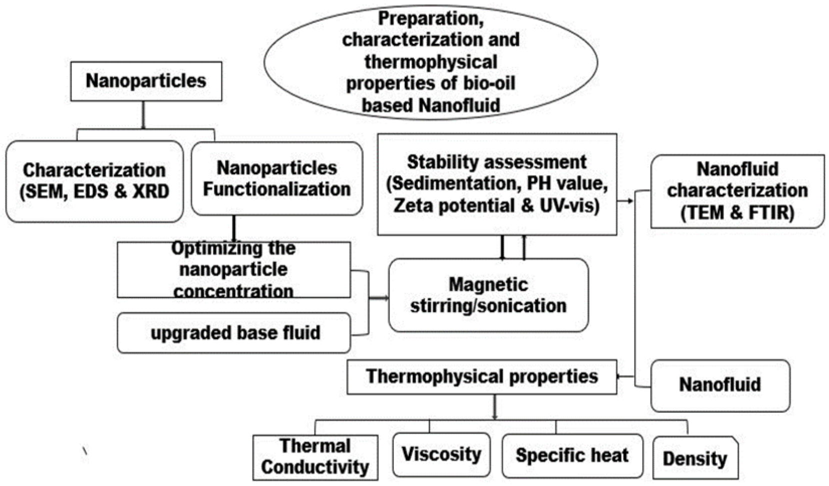


FIGURE 4. Schematic diagram of the bio-oil-based nanofluid preparation, characterization, and thermophysical properties flow measurement

BIO-OIL-BASED NANOFLUID STABILITY ENHANCEMENT AND ASSESSMENT TECHNIQUES

The stability of the nanofluid is crucial to achieving constant and effective thermophysical properties (Ajeena et al. 2022; Brzóska et al. 2021; Kumar et al. 2020). Nanoparticles usually have high short-range attraction forces, which are dominant amongst the particle pairs and have high surface energy. When particle collisions increase, aggregation will occur. If the liquid aggregates, the particle sizes will increase, and then sediment once exposed to gravitational forces (Panduro et al. 2022). Such aggregation behaviours are usually removed with repulsive forces within the nanoparticles to convey the nanofluid to a stable position. The aggregate of nanoparticles usually reduces the effectiveness of the nanofluid's heat transfer coefficient. It affects not only the stability of the nanofluid but also its thermal conductivity because nanofluid conductivity is directly propositional to stability (Panduro et al. 2022). Agglomeration is a significant challenge with bio-oil-based nanofluids, as bio-oil alone does not always provide sufficient steric hindrance or electrostatic repulsion to prevent agglomeration. Recent studies have examined the stability and rheological behaviour, including stability enhancement of bio-oil-based nanofluids. A summary of the recent stability studies is given in Table 1. Physical techniques such as ultrasonic agitation, homogenization, and ball milling are commonly used for improving fluid stability. In contrast, different researchers have employed chemical techniques such as surfactant addition, pH adjustment, and surface modification to improve the stability of the bio-oil-based nanofluid. Details of the following are given below.

1. Surfactant is a very important technique or method used in improving nanofluid stability, as reported by many researchers in the literature (Said et al. 2022; Tiwari et al. 2021). Surfactant addition is an effective approach to improve nanoparticle stability, but in the other way round negatively impacts the nanofluid's thermophysical properties. In this regard, surfactant molecules attaching to the surface of the nanoparticles might accelerate the thermal resistance between the base fluid and nanoparticles, thereby limiting the enhancement of operational thermal conductivity. Oleic acid, SBDS, CTAB, Thiols, and laurate salt are surfactants most often utilized in concentrated solar technology. In general, bio-oil-based nanofluids require the use of surfactants, whether the nanoparticles are metal-based or carbon-based. The need for surfactants increases with increasing nanoparticle concentration because of the intensified tendency toward agglomeration and sedimentation. Appropriate selection and optimization of surfactants are thus very crucial to achieving a stable and well-dispersed nanofluid.
2. pH control is an effective method for stabilizing the nanofluid. In this respect, adjusting the pH of the nanofluids can significantly improve their stability. The pH of the suspension must normally be kept neutral for this purpose since an acid solution or an alkaline might promote corrosion of the heat transfer surfaces and dissolution of the nanoparticles (Chaichan et al. 2023).
3. Surface modification is another method used to prepare a stable nanofluid. They are prepared via physical and chemical techniques. Hence, managing the internal stress, increasing the repulsive force between the nanoparticles, decreasing the gravitational attraction among the particles, and purposely changing the nanoparticle's surface is referred to as nanoparticle surface modification (Hawkins et al. 2023). Functionalization through the coating of nanoparticles with a molecule changes the nanoparticle's surface energy, critically resulting in greater dispersion in base fluids. (Pınar et al. 2023). Researchers employed different techniques to measure or determine the stability of the nanofluids. Techniques such as zeta potential, sedimentation, and UV-vis are recognized as effective for measuring the nanofluids' stability. The following are explain below;

a. The Zeta Potential technique is an electrical potential approach for assessing or measuring the level of the nanofluid's stability. It has been discovered that the greater the value of zeta potential, the better the nanoparticles would repel the aggregation by the greater repulsive force, causing a longer period of stability (Said et al. 2022).

b. The sedimentation approach is the easiest and most reliable for nanofluid stability tests or measurements. It is viewed naturally by observing the particle settling by relying on gravity (Ali & Salam 2020). In this process, particles normally settle down at the bottom of the container as the nanofluid clusters are superseded due to the Brownian motion to counteract the gravitation attraction. Particle size, density, and concentration greatly influence bio-oil-based nanofluid sedimentation. Metal-based nanoparticles, which are denser, are more prone to sedimentation compared to carbon-based nanoparticles. This method captures sedimentation pictures or photographs with the digital camera at intervals during the nanofluid preparation (Ali & Salam, 2020). Observed pictures will be compared to estimate or measure the nanofluid's stability. If no sedimentation occurs, then the nanofluid is said to be stable. Figure 5 indicates the stability enhancement and assessment techniques.

c. Spectral absorbance analysis using a UV-vis spectrophotometer is another effective technique for testing nanofluid stability. This technique is believed to have a firm connection between the nanoparticle's fluid concentration and absorbency intensity, as discovered by the Beer-Lambert law. The law is famous for determining the absorbance of light in a nanofluid (Chakraborty & Panigrahi 2020; Mehta et al. 2022). Several key factors influence the stability of bio-oil-based nanofluids. These include size, concentration of nanoparticles, type of base fluid, presence of surfactants, zeta potential, and pH levels (Okafor et al. 2022). Others are the preparation technique, external forces, and operating conditions, which are all crucial in enhancing nanofluids' stability.

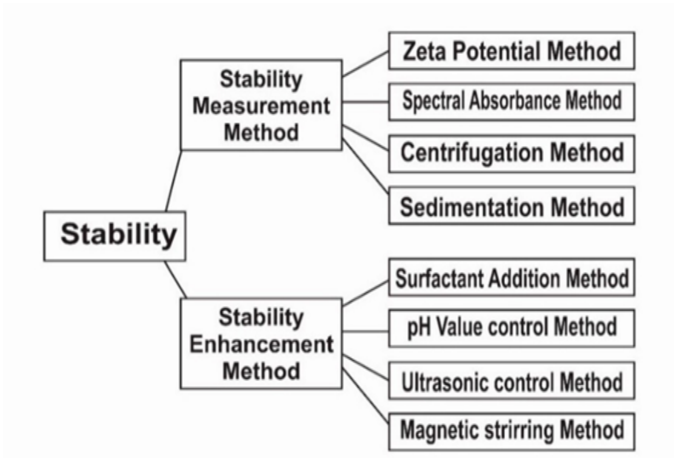


FIGURE 5. Stability enhancement and assessment techniques

The most suitable technique to evaluate nanofluid stability depends upon the study's particular objectives and the specific properties of the nanofluid under investigation. Each of the three techniques listed above has its unique strengths and weaknesses. The sedimentation technique is the most used method for determining nanofluid stability, as indicated in the literature reported in Table 1. However, zeta potential analysis is regarded as the best and standard for early stability assessments because of its capacity to measure the electrostatic forces that keep nanoparticles dispersed accurately. Nevertheless, combining two or more approaches provides a more detailed picture of nanofluid stability. Figure 6 presents the stability mechanisms for nanofluid stability.

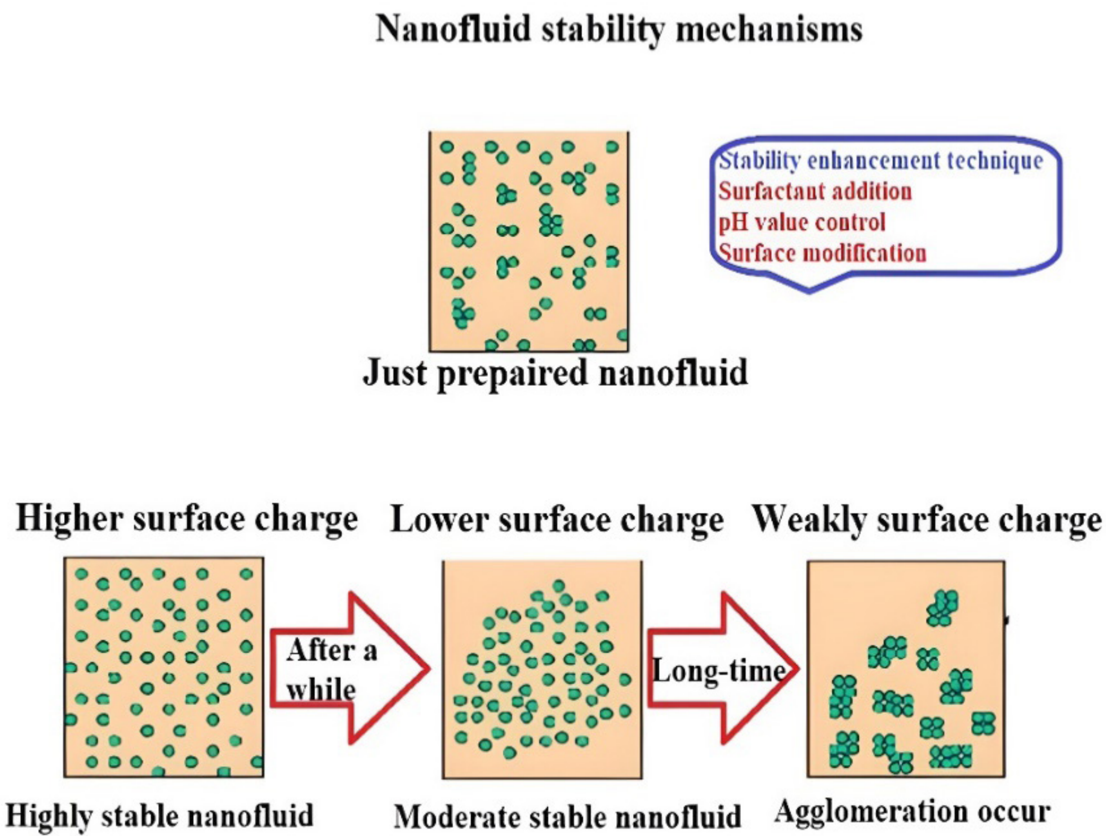


FIGURE 6. The stability mechanism of the nanofluid

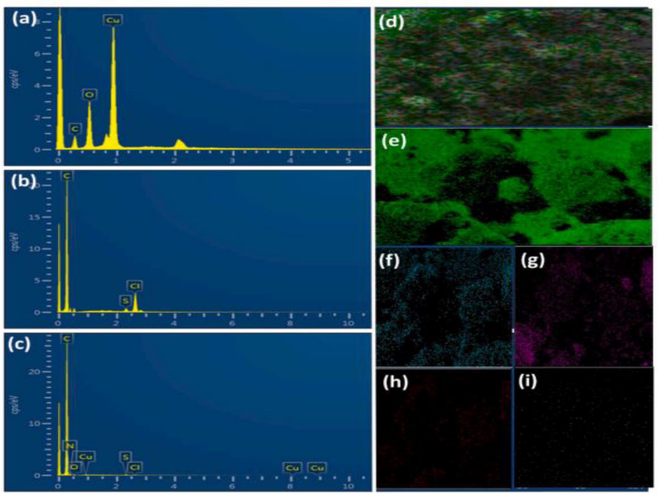
TABLE 1. Summary of the recent studies conducted on the stability of the bio-oil-based nanofluid

Author	Nanoparticle	Base fluid	Technique	Duration	Approach	Type	Concentration	Surfactant
Umar et al. (2020)	Al_2O_3	PKO	Two-step	-	Zeta potential	Mono	0.1, 0.2, 0.4, 0.6, & 1.0	SBDS
Sofiah et al. (2021)	CuO-PANI	RBD palm olein base oil	Two –step	-	Sedimentation	Mono & Binary	1, 5& 10	Additives
Singh & Sharma (2022)	Al_2O_3 & ZiO	Jatropha	Two-step	48 hours	UV-vis & Zeta potential	Mono & Hybrid	0.5	-
Seyedzavvar et al. (2020)	CuO	Vegetable oil	One-step	36 hours	Zeta-potential	Mono	0.5 & 1	-
Jyothish et al. (2022)	Al_2O_3+ZrO_2	Jatropha	Two-step	24 h	Sedimentation	Hybrid	0.25,05 &1	ILS
Brzóska et al. (2021)	MWCNTs	1,2-propanediol &1,3-propanediol	Three-step	14-Months	MiniSpin Eppendorf centrifuge & Sedimentation	Mono	0.5, 1.0, 1.5, & 2.0	N-vinylpyrrolidone
Giraldo et al. (2022)	SiO_2-C_1 and SiO_2-C_2, SiO_2-RH	Soapnut fruit	Two-step	-	Sedimentation	Mono	-	SBDS
Khan et al. (2022)	G.O. and TiO_2	Ester Easter	Two-step	72h	Sedimentation	Mono	0.5-1	Oleic acid
Amizhtan et al. (2022)	Silica	Synthetic easter ester	Two-step	-	Zeta potential	Mono	0.02,0.04,0.06 & 0.08	CTab, Oleic acid and Span-80
Das (2023)	ZnO	Coconut oil	Two-step	-	Sedimentation	Mono	0.04–0.05	Oleic acid
Fernández et al. (2020)	TiO_2 & ZiO	Vegetable oil	Two-step	-	Sedimentation	Mono	-	-
Mostafizur et al. (2022)	Al_2O_3	Methanol	Two-step	-	Zeta potential	Mono	0.05-0.15	-
Das (2024)	SiO2, TiO_2, ZnO	Coconut oil	Two-step	30 days	Zeta potential	Mono	0.1	
Tsovilis et al. (2024)	FeO_3	Natural easter ester	Two-step	-	-	Mono	0.005, 0.05, & 0.5	-
Permanasari et al. (2023)	Graphine	Coconut-oil	Two-step	30 days	Zeta potentials	Mono	0.1	SBDS & CTAB
(Permanasari et al. 2023)	G.N.P.	Virgin coconut oil	Two-step	30 days	Sedimentation	Mono	0.1	PVP non-ionic, S.D.S. anionic, and CTAB cationic
Kulandaivel et al.(2024)	SiO_2–CNP	Palm oil	Two-step	60 days	Sedimentation	Binary	0.1	-
Rozaidi Zaharudin & Radhiyah Abd Aziz (2021)	TiO_2	Palm oil, sunflower oil, canola oil and corn oil	Two-step	30 days	Zeta potentials	Binary	-	-

CHARACTERIZATION OF BIO-OIL-BASED NANOFLUIDS

Researchers have employed different methods and techniques to characterize mono or binary nanoparticles. The characterization methods employed were mostly used to identify the morphology of the nanoparticles. These include F.E.S.E.M, S.E.M., T.E.M., UV-vis, X.R.D, E.D.A.X and Raman spectroscopy (Kawira 2020; Kumar, Tiwari et al. 2024; Millien 2020; Said et al. 2022; Tiwari et al. 2021). The functions of these digital devices are as follows: Field emission scanning electron microscopy (F.E.S.E.M) gives topographical and elemental information about nanocomposites. Scanning electron microscopy (S.E.M.) provides variations in the particles' structure and shape and the nanostructured materials' morphology (Panduro et al. 2022; Tiwari et al. 2021). Transmission electron microscopy (T.E.M.) and scanning electron microscope (S.E.M.) are considered suitable electronic devices used to study the shape and size of the nanoparticle distribution in the base fluid. The U.V-vis is a well-regarded monitoring device that monitors the dynamic of the dispersion process and characterizes the quantitative optical absorption by using several wavelengths of light passing over the target nanofluid (Zulfiqar et al. 2024). Energy dispersive X-ray (E.D.A.X) analysis usually reveals the crystal structure of nanocomposite particles. X.R.D is an analytical technique used primarily to determine materials' crystallographic structure, composition, and physical properties (Okafor et al. 2022; Yadav et al. 2021). The Fourier transform electron microscopic (F.T.I.R) identifies several characteristic absorption bands arising from the organic components of the bio-oil and that of the nanoparticles. The structural composition and homogeneity of the bio-oil nanofluids are usually discovered by Raman spectroscopy (Peng et al. 2021). For a comprehensive analysis of bio-oil-based nanofluids, combined characterization techniques such as X.R.D, S.E.M., E.D.X., T.E.M., U.V-vis, and F.I.I.R are necessary (Mohite et al. 2024; Sofiah, Samykano, Pandey, et al. 2021). These characterization techniques provide detailed information on the bio-oil-based nanofluid's shape, size, dispersion, and properties. Table 2 illustrates some characterization techniques employed by different research studies to examine the nanoparticles and the resulting nanofluids. These are X.R.D, F.T.I.R, S.E.M., E.D.X., T.D.S., T.E.M., and other relevant characterization of the bio-oil-based nanofluids.

TABLE 2. Bio-oil-based nanofluids characterization techniques employed by different research studies

Ref	Analysis	Description
Sofiah, Samykano, Shahabuddin, et al. (2021)		This study employs X.R.D, E.D.X., T.G.A, T.E.M., and F.T.I.R techniques to characterize CuOPANI/RBDL-based nanofluids.

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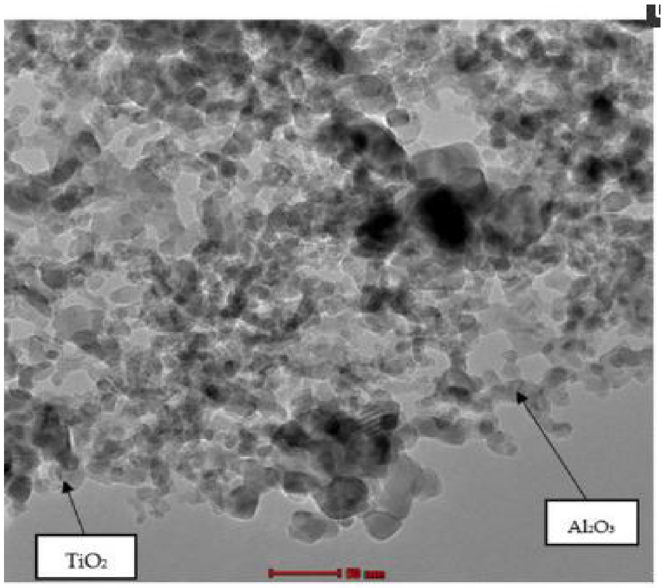
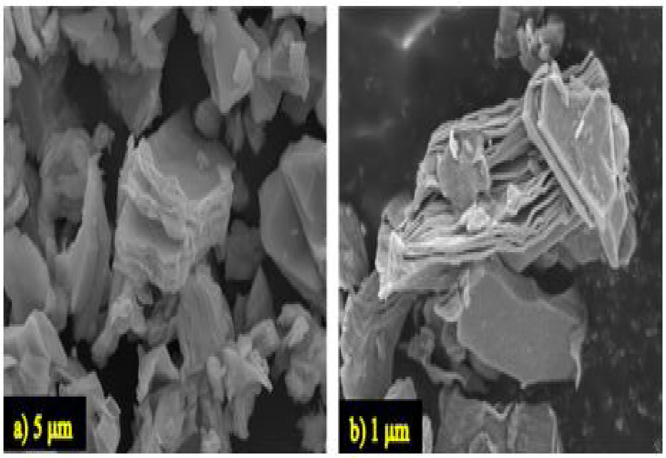
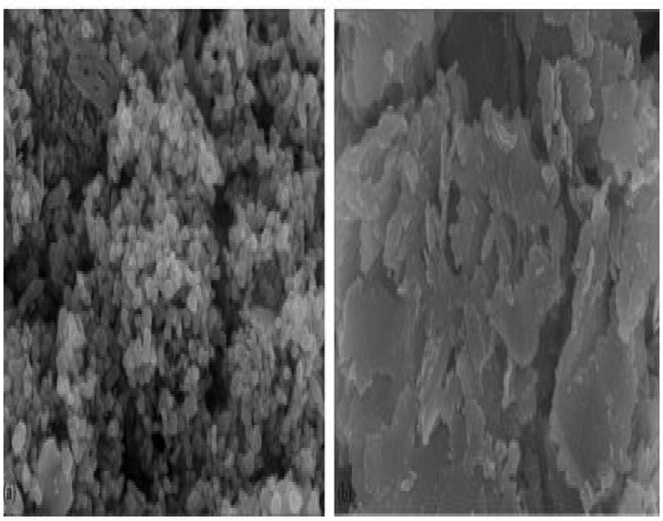
Wanatasanappan et al. (2022)		The study utilized X.R.D and T.E.M. analysis to characterize the nanoparticle and binary Al_2O_3-TiO_2/Vegetable oil nanofluids.
Rubbi et al. (2021)		This study utilized S.E.M. and F.T.I.R to characterize the nanoparticle and resulting nanofluids.
Nazir et al. (2024)		This study utilized S.E.M. and X.R.D to characterize the binary ZnO-MgO/Coconut oil nanoparticles and resulting nanofluids.

THERMOPHYSICAL PROPERTIES OF BIO-OIL AND BIO-OIL-BASED NANOFLUIDS

Bio-oils derived from biomass pyrolysis have immense potential as heat transfer fluids owing to their renewable and adaptable nature. They can serve as an environmentally friendly alternative to traditional HTFs since their composition can be tailored by blending with solvents or adding various additives to enhance specific properties. For example, dilution or chemical modification can decrease bio-oil viscosity, improving fluid flow and the efficiency of heat transfer systems. Similarly, incorporating nanoparticles increases thermal conductivity, improving this major limitation of bio-oils. The source of biomass and the pyrolysis process impact the thermophysical characteristics of bio-oils (Edamaku et al. 2022). Consequently, accurate bio-oil mixture selection and optimization are crucial for thermal applications. The proper modifications can make bio-oils a sustainable and real-life substitute for conventional heat transfer in industrial systems. Several researchers have conducted experiments on the thermophysical properties of bio-oil (Afolabi et al. 2022; Lu et al. 2008; Ramasamy et al. 2021; Wanatasanappan et al. 2022)

In the case of bio-oil-based nanofluid, thermophysical properties are crucial for characterizing the heat transfer capabilities of the bio-oil-based nanofluid. The behaviour of these thermophysical characteristics in nanofluid is influenced by various factors such as stability, surfactant concentration, volume concentration, and temperature (Shah et al. 2020). Nanofluid stability is crucial to achieving constant and effective thermophysical properties. Generally, the choice of appropriate nanoparticles, base fluid type, and methods used to prepare nanofluids, concentration, pumping power, size, shape, sonication time, and temperature are very important for obtaining better thermophysical properties of the bio-oil-based nanofluid. The parameters that describe the thermophysical properties of the nanofluid are the thermal conductivity, viscosity, specific heat capacity, and density. The descriptions of the thermophysical properties of the nanofluids are as follows.

1. Thermal conductivity is generally propositional to nanofluid stability, viscosity, pumping power, and pressure drop during transport (Brzóska et al. 2021). It is demonstrated that the little the particle shape and size, the greater the thermal conductivity of the nanofluid (Ajeena et al. 2022). It is believed from the researcher's consensus that thermal conductivity is frequently improved per temperature increment. Bio-based nanofluids that combine CAPB and coconut oil, for example, have demonstrated increased stability and improved thermal conductivity when the concentration of nanoparticles increases (Shariff et al. 2021). In comparison to coconut oil and soybean oil-based nanofluids, palm oil-based nanofluids demonstrated superior thermophysical properties, including the highest thermal conductivity and lowest viscosity. These findings came from experimental studies on vegetable oil-based hybrid nanofluids suspended with Al_2O_3-TiO_2 nanoparticles (Wanatasanappan et al. 2022). The thermal conductivity enhancement of the bio-oil-based nanofluids deduced from various outputs is given in Figure 7.
2. Viscosity is a critical parameter that usually determines the nanofluids' overall rate of flow and flow resistance. A liquid's viscosity ordinarily changes when small particle volume fractions of nanoparticles are added, and it could be minimal or maximum, subject to the quantity of the nanoparticle added (Panduro et al. 2022). When the nanoparticle volume fraction increases, then the viscosity of the nanofluid increases to a high value. It is, however, clearly understood that several factors affect the nanofluid's viscosity. These include the surface nature of the particle, temperature, surfactants, the base fluid ionic strength, particle shape and size, pH values, electric double layer, and van der Waals forces, respectively (Sepehrnia et al. 2022).
3. Density is an essential thermophysical characteristics parameter determining how well nanofluids operate in real-life applications. The density of a binary fluid is usually the summation of the density and volume concentration of the nanoparticles and the base fluid. The density of the interfacial layer is higher than that of the working fluid and equally lower than that of nanoparticles (Ajeena et al. 2022; Zapata et al. 2022).
4. Specific heat capacity This parameter usually increases with temperature and drops with concentration increments. This behaviour is considered unique for all combinations of nanofluids. This trend is constant even with the different nanofluids, even though the behaviours directly depend on certain parameters such as nanomaterial, temperature, and base fluid (Okafor et al. 2022; Rubbi et al. 2021; Vignesh et al. 2022). Many research studies demonstrated this specific heat capacity behaviours (Vuggirala et al. 2023; Yadav et al. 2021).

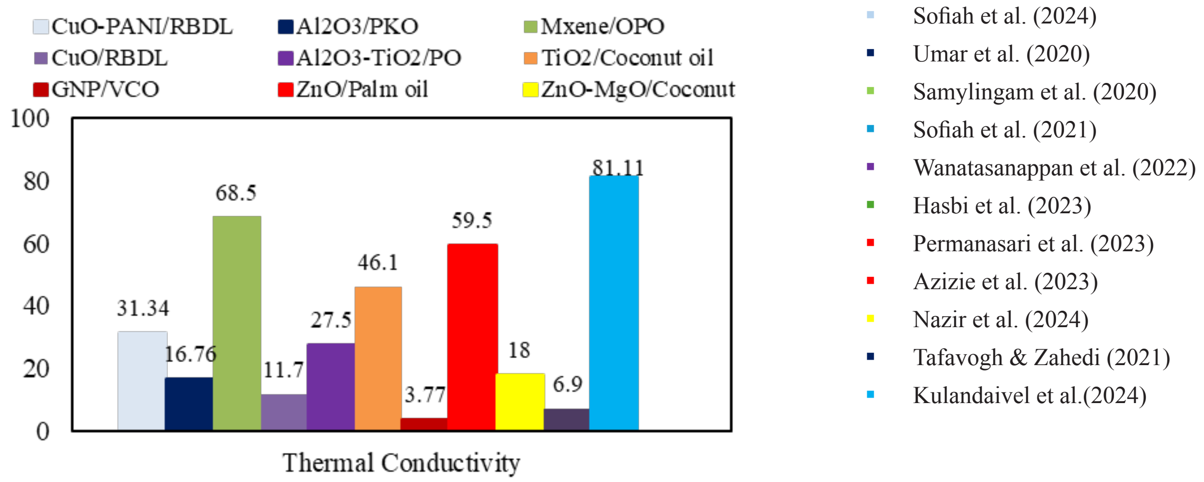


FIGURE 7. Thermal conductivity enhancement of the bio-oil-based nanofluid from various research outputs

The thermophysical characteristics of bio-oil-based nanofluids directly influence the heat transfer effectiveness. Researchers can assess how effectively the bio-oil-based nanofluid impacts heat transfer applications in solar thermal systems for cooling and heating through thermophysical properties through investigations as a developed sustainable and environmentally friendly alternative HTFs. Bio-oil must meet specific thermophysical properties criteria stated in standards such as EN14214 to be fully implemented in industrial applications Singh et al. (2023). Evaluating these qualities guarantees that the nanofluid can operate consistently under the conditions of certain applications. However, these thermophysical properties can enable researchers to demonstrate possible environmental and economic benefits, such as lower energy usage or emissions, compared to standard fluids. The summary of the recent studies conducted on the thermophysical properties of bio-oil-based nanofluids is given in Table 3.

TABLE 3. Summary of the recent studies conducted on thermophysical properties of bio-oil-based nanofluids

Ref	Nanoparticles	Base fluid	Concentration (%)	Type of nanofluid	Max. thermal conductivity (%)	Max. Viscosity (%)	Stability	Temp. Range (°C)	Enhancement
Permanasari et al. (2023)	GNP	virgin coconut oil (VCO)	0.1	Mono	0.158 W/m. K	-	30	-	The bio-oil-based nanofluid significantly enhanced the thermal and electrical efficiencies of a PVT to 25.169% and 8.632%
Sofiah et al. (2024)	CuO-PANI	RBDL	1, 5 & 10	Binary	31.34	-	30	30-80	The modified bio-oil-based fluid with improved stability and thermal conductivity makes it a good HTF in solar thermal systems.
Umar et al. (2020)	TiO_2	PKO	0.2, 0.4, 0.6, 0.8, 1	Mono	16.76	2.3 mPas	30	-	The thermophysical properties obtained from the bio-oil-based nanofluid make it a potential HTF in solar thermal systems.
Samylingam et al. (2020)	MXene	Olein Palm Oil (OPO)	0.01, 0.03, 0.05, 0.08, 0.1, & 0.2	Mono	68.5	61	-	25-70	The outstanding performance in thermal conductivity enhances the HTF in PVT to improve thermal and electrical efficiencies.

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Sofiah et al. (2021)	CuO	RBD palm olein	0.04, 0.1, 0.36, 1.91, 1.92 & 1.93	Mono	11.7	20.25	30	30-80	The mono nanofluid produced from bio-oil can be a potential HTF in solar thermal systems
Azizie et al. (2023)	ZnO	Palm oil	0.02, 0.04, 0.06, 0.08, 0.1, 0.12 & 0.14	Mono	59.1	53.01	-	30-60	An improved thermal conductivity obtained suggests improving the HTF for insulating and cooling applications.
Tafavogh & Zahedi (2021)	GO	HBS	0.1, 0.3 & 0.5	Mono	6.9	-	-	-	The good thermophysical properties obtained resulted in an 8 % improvement in heat transfer and a 77 % increase in electrical conductivity, promising as a pertinent cooling technique for PEMFC stacks.
Wanatasanappan et al. (2022)	Al_2O_3 -TiO_2	coconut oil, soybean oil, and palm oil	0.2, 0.4, & 0.6	Binary	27.5	17.772		25-65	The bio-oil binary nanofluid improved thermophysical properties and stability, which make it a good HTF in solar thermal systems.
Hasbi et al. (2023)	Graphene and Titanium oxide	palm wax, beeswax, and coconut oil	0.5, 1.0, 1.5, & 2.0	Mono	46.1	-	-	-	Results obtained for thermal conductivity improvement of nano-enhanced BPCMs demonstrated that bio-oil-based P.C.M.s have a high potential for usage as latent thermal heat storage in building applications.
Kulandaivel et al.(2024)	SiO_2–CNP	Palm oil	0.1	Binary	81.11	-	60	-	The improved stability and enhanced thermal conductivity make it a good HTF.
Nazir et al. (2024)	ZnO-MgO	Cocunut oil	0.02-1	Binary	18	-	-	30-80	Coolant-based HTFs excel in thermal conductivity, addressing heat transfer challenges.

APPLICATION OF BIO-OIL-BASED NANOFLUID AS A HEAT TRANSFER FLUID IN VARIOUS ENGINEERING APPLICATIONS

As a renewable and eco-friendly HTF for low, medium, and high-temperature applications, bio-oil derived from biomass products such as vegetable sources demonstrated significant promise (Danane et al. 2020; Ramasamy et al. 2021). Bio-oil-based nanofluids, consisting of nanoparticles dispersed throughout the base fluid, represent the fluids typically derived from biomass. Due to their non-volatile nature, high availability, and renewable sources, bio-oils are an excellent replacement for conventional fluids in solar system applications (Doucet & Germanaud, 2023). Previous studies have shown that bio-oil can be chemically transformed into HTF with properties that meet industry standards, such as EN14214 (Pecha et al. 2021). Thus, bio-oil offers a promising avenue for sustainable heat transfer solutions, offering a renewable and efficient alternative to conventional HTFs. The dispersion of nanoparticles into the oil can improve thermal conductivity, viscosity, density, specific heat, and heat transfer characteristics of bio-oil. The application of bio-oil-based nanofluids is diverse, including heat transfer applications in thermal management systems, heat exchangers, electronics cooling, and solar energy systems are just a few of the many uses for bio-oil-based nanofluids (Ariffina et al. 2021). Furthermore, bio-oil-based nanofluids can be used for lubrication, enhanced oil recovery, and biomedical fields. Table 4 summarizes the bio-oil-based nanofluid research studies conducted by various research studies in engineering applications as HTFs. Figure 8 illustrates the factors that influence the performance of bio-oil-based nanofluids as HTFs. The performance effectiveness of bio-oil-based nanofluids in heat transfer applications is determined by carefully balancing nanoparticle concentration, type of nanoparticles, nanoparticles combination, thermal stability, long-term stability, and base fluid thermal characteristics. Optimizing these parameters guarantees better heat transfer performance while maintaining acceptable viscosity and flow characteristics for solar thermal applications.

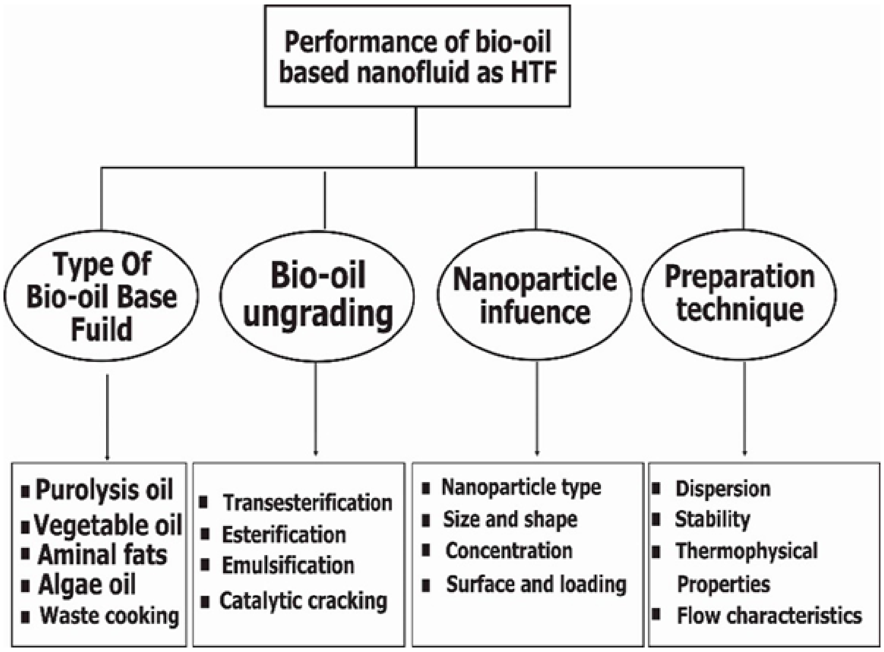

FIGURE 8. Factors influencing the performance of bio-oil-based nanofluid as HTFs

TABLE 4. Bio-oil nanofluids as HTFs in various engineering applications

Author	Nanoparticle	Base fluid	Technique	Stability	Approach	Type	Concentration	Application
Umar et al. (2020)	Al_2O_3	PKO	Two-step	-	Zeta potential	Mono	0.1, 0.2, 0.4, 0.6, & 1.0	PVT
Sofiah et al. (2021)	CuO-PANI	RBD palm olein base oil	Two-step	-	Sedimentation	Mono & Hybrid	1, 5& 10	HTF in thermal systems
Singh & Sharma (2022)	Al_2O_3 & ZiO	Jatropha	Two-step	48 hours	UV-vis & Zeta potential	Mono & Hybrid	0.5	Machine application
Seyedzavvar et al. (2020)	CuO	Vegetable oil	One-step	36 hours	Zeta-potential	Mono	0.5 & 1	Grinding operation
Jyothish et al. (2022)	Al_2O_3-ZrO_2	Jatropha	Two-step	24 h	Sedimentation	Hybrid	0.25,05 &1	M.Q.L.
Brzóska et al. (2021)	MWCNTs	1,2-propanediol &1,3-propanediol	Three-step	14-Months	MiniSpin Eppendorf centrifuge & Sedimentation	Mono	0.5, 1.0, 1.5, & 2.0	Green HTF
Giraldo et al. (2022)	SiO_2-C_1 and SiO_2-C_2 SiO_2-RH	Soapnut fruit	Two-step	-	-	Mono	-	Green HTF
Khan et al. (2022)	G.O. and TiO_2	Ester	Two-step	72h	Sedimentation	Mono	0.5-1	

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Tambuwal et al. (2022)	TiO_2	Jatropha–Neem	Two-step	-	Sedimentation	Mono	0.2 to 1.0	Insulating oil
Amizhtan et al. (2022)	Silica	Synthetic ester	Two-step	-	Zeta potential	Mono	0.02,0.04,0.06 & 0.08	HTF
Fernández et al. (2020)	TiO_2 & ZiO	Vegetable oil	Two-step	-	Sedimentation	Mono	-	Dielectric application
Mostafizur et al. (2022)	Al_2O_3	Methanol	Two-step	-	Zeta potential	Mono	0.05-0.15	HTF
Oparanti et al. (2020)	Al_2O_3 & TiO_2	PKO	Two-step	-	-	Mono	0.01-0.2	Transformer insulation
Almalki et al. (2024)	TiO_2	AlSBA-15	Two-step	-	T.E.M.	Mono	-	HTF
Oparanti et al. (2022)	$SiO_2 – WO_3$	Neem oil ester	Two-step	-	-	Binary	0.2- 1	High voltage Transformer application
Tsovilis et al. (2024)	FeO_3	Natural ester	Two-step	-	-	Mono	0.005, 0.05, & 0.5	Transformer
Permanasari et al. (2023)	Graphine	Coconut-oil	Two-step	30 days	Zeta potentials	Mono	0.1	PVT
Permanasari et al. (2023)	GNP	Virgiin coconut-oil	Two-step	30 days	Sedimentation	Mono	0.1	PVT
Sabri et al. (2024)	TiO_2-WS_2	RBD Palm Oil	Two-step	-	-	Binary	0.025	Metalworking Fluid

COMPARATIVE ANALYSIS BETWEEN THE CONVENTIONAL OIL AND BIO-OIL BASED NANOFLUID AS HTF

The choice among these two fundamental fluids depends on the specific application requirements, environmental regulations, cost constraints, and desired efficiency. However, bio-oil-based nanofluids represent a novel solution with high thermal conductivity and efficiency and offer a balance of environmental benefits and improving thermal performance. Still, they come with the highest costs and require careful management of nanoparticle-related issues. Thus, conventional oil-based fluids remain cost-effective and reliable. Here is the summary of the performance comparison between conventional oil and bio-oil-based derived HTFs.

Oil-Based HTFs:

1. High thermal stability and thermal conductivity for and cost-effective.
2. Environmental concerns, lower biodegradability, and higher long-term costs.

Bio-Oil-Based HTFs:

1. It is environmentally friendly, renewable in nature, has higher biodegradability, and lower toxicity.
2. It has superior thermal conductivity and heat transfer efficiency.
3. Higher cost, potentially lower thermal efficiency, and possibly higher maintenance needs.

HEAT TRANSFER PERFORMANCE OF BIO-OIL-BASED NANOFLUIDS IN SOLAR THERMAL SYSTEMS

In solar thermal collectors, significant effort has been dedicated to developing hybrid PVT systems to enhance the performance efficiency of both electrical and thermal efficiencies (Azeez et al. 2024; Din et al. 2024; Ishak et al. 2023). However, nanofluids-based HTFs exhibit promising heat transfer performance (Bassam et al. 2023; Said et al. 2022). These nanofluids are effective HTF media in all concentrated solar collectors (C.S.P.) and photovoltaic/thermal (PV/T) due to their increased thermal conductivity and heat transfer effectiveness. Research studies have shown that the nanofluids can effectively remove heat from the P.V. cell, improving its electrical and thermal efficiency. Compared to conventional fluids, hybrid binary nanofluids have a higher capacity to absorb radiation (Kawira 2020; Kazaz et al. 2022). Accordingly, bio-oil-based nanofluids present a viable way to raise heat transfer efficiency in solar collectors, advancing the development of sustainable energy production (Ali et al. 2020). Recently, researchers have found that utilizing bio-oil-based nanofluids or nanofluids to solar thermal systems such as parabolic trough solar collectors (P.T.C.s), flat plate collectors (F.P.C.s), and photovoltaic/thermal panels (PVTs) increases thermal conductivity, heat transfer rates, and boosts system efficiency while mitigating renewable and sustainable potentials. Table 5 summarizes some research outputs using bio-oil heat transfer in solar thermal systems. Research findings have found that bio-oil-based fluid's non-edible exploration has improved thermophysical properties and can be used as a heat transfer fluid at high temperatures. Similarly, it shows improved physicochemical characteristics and the feasibility of using bio-oil fluid as an alternative to transformer fluids for cooling and insulation (Ajani et al. 2023; Khan et al. 2022). However, integrating nanoparticles into bio-oil will undoubtedly further enhance the thermophysical properties of the bio-oil fluid, as reported from the literature, making it suitable for C.S.P. technology, particularly in medium temperature and higher applications.

TABLE 5. Summary of the research work conducted on bio-oil-based nanofluid as a HTFs in solar thermal systems

Author	Nanoparticle	Concentration (%)	Base fluid	System enhancement
Millien (2020)	Cu	1.2	Coconut oil Sunflower oil	This research study revealed that using copper bio-oil-based nanofluid can improve the systems' heat transfer rate and overall heat coefficient.
Afolabi et al. (2022)	SiO_2 & Al_2O_3	1-4	Jatropha	Efficiency increases significantly with Al_2O_3/jatropha, then SiO_2/jatropha, compared with jatropha.
Mirnezami et al. (2020)	MWCNT-MgO	0.2,0.25,0.3,0.35 & 0.4	Palm oil	Bio-oil-based binary nanofluid increases efficiency and decreases the cost of biodiesel production.
Tafavogh & Zahedi (2021)	MWCNT-MgO	-	Palm oil	The bio-oil-based nanofluid used in this research significantly enhances thermal efficiency to 56.59% in the PTC system.
Permanasari et al. (2023)	Graphene	0.1	Virgin coconut oil	The PVT system efficiency results indicate thermal and electrical enhancement of 25.169% and 8.632%, respectively.
Brakna & Benzenine (2024)	Al_2O_3-MCWT	-	Bio-oil	The enhancement in heat transfer rate of a double tube heat exchanger utilizing Al_2O3-MWCNT/bio-oil binary nanofluid reached 77.8%
Asmat-Campos (2020)	$AgNO_3$	-	Bio-oil	The nanofluid developed was a good candidate for application in solar thermal systems, specifically in geographical areas where the intensity of solar radiation is low.
Samylingam et al. (2020)	MXene	0.01, 0.03, 0.05, 0.08, 0.1, & 0.2	OPO	The outstanding performance in thermal conductivity displays about 16% higher thermal efficiency improvement at 0.07 kg/s flow rate, and about 9% heat transfer coefficient improvement is found for the PVT with MXene nanofluids.
Kenfack et al. (2024)	TiO_2	-	Vegetable oil	The numerical analysis of bio-oil-based nanofluid thermophysical properties makes the P.V. configuration a 12.08 % improvement in electrical efficiency over conventional P.V. systems.
Rubbi et al. (2021)	Ti_3C_2	0.125	Soyabean oil	Results demonstrated the overall effectiveness of the Soybean oil based MXene nanofluids over conventional fluids used for cooling purposes in the PV/T collector, with the overall electrical and thermal efficiency of the PV/T system of 15.44% and 84.25%

DISCUSSION

As reported from numerous research studies, bio-oil-based nanofluids can be employed as HTF in concentrated and non-concentrated solar thermal systems due to their several advantages, which include improved thermophysical properties, high availability, low volatility, non-hazardous, environmentally friendly, and renewable and sustainable nature. However, exploration, synthesis, upgrading, and real-life implementation are required to obtain the potential applications of these fundamental fluids. Many recent research studies indicate the potential of bio-oil-based nanofluid as an HTF in solar thermal applications. It is evident from the literature reported in Table 5 that the utilization and application of bio-oil-based nanofluids in solar thermal systems still need the utmost attention, even though these nanofluids' potential as HTF has shown improvement in certain applications. More research studies must be conducted by selecting bio-oil nanofluids based on nanoparticle characteristics, pH value, and stability, which is crucial for optimizing solar energy capture and utilization. Integrating bio-oil-based binary nanofluids in solar thermal technology will also be promising for increasing energy efficiency and sustainability.

CHALLENGES AND FUTURE PROSPECTS OF BIO-OIL-BASED NANOFLUID AS A HEAT TRANSFER FLUID

As an HTF, bio-oil faces several challenges, including limited thermal stability, higher viscosity, contaminants, homogeneity, compatibility, cost, and thermal conductivity (See Figure 9). Its limited thermal stability can lead to degradation at high temperatures. In comparison, its higher viscosity can result in higher pumping costs and system failures. Additionally, bio-oil may not be compatible with all materials used in existing heat transfer systems, necessitating modifications or specific materials. The production and upgrading processes can be expensive, making bio-oil less economically viable than conventional fluids.

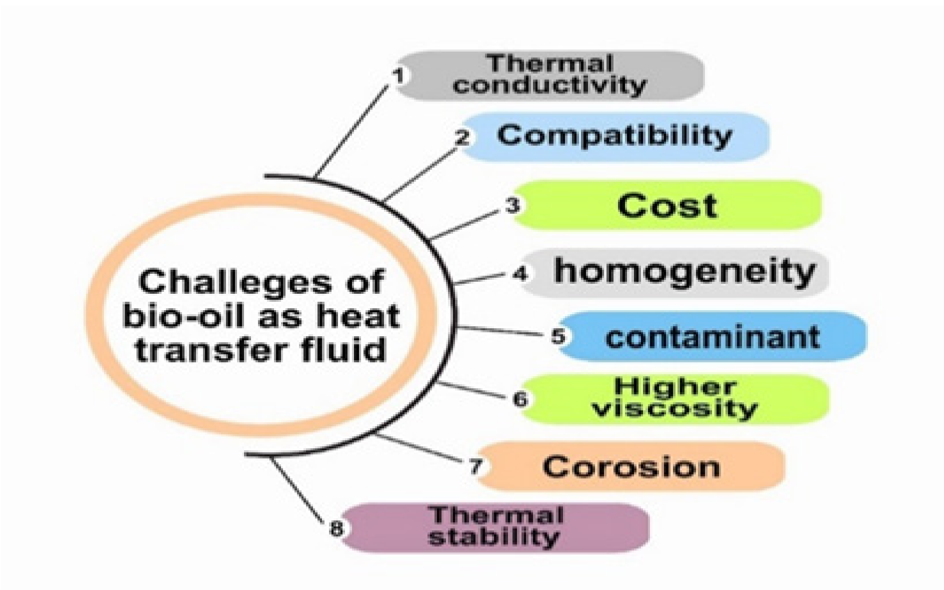

FIGURE 9. Challenges of bio-oil as HTFs

Integrating nanoparticles into bio-oil enhances heat transfer effectiveness in many applications, such as solar systems. Thus, employing bio-oil-based nanofluids as HTF faces a lot of challenges. These include base fluid selection, nanoparticle concentration, maintaining nanofluid stability, which is a very crucial factor due to the aggregation of the nanoparticles over time, which causes system fouling, maintaining ideal nanofluid viscosity and thermal degradation, which results in undesirable byproducts, and acidic properties of bio-oil which may lead to corrosion. Further research is required to optimize formulation, thermal stability, material compatibility, safety, and regulatory and standardization. Most of the research output on bio-oil-based nanofluids has concentrated on their applications in transformers, minimum quantity lubrication (M.Q.L.), cooling, lubrication, and insulation. However, there is a noticeable lack of studies on their potential applications in solar thermal systems. This specifies a significant gap in the current research landscape. To address this, more advanced investigations are needed into mono and binary bio-oil nanofluids, specifically in solar thermal technology. Such research could potentially enhance the efficiency and effectiveness of solar thermal systems, promoting their adoption and contributing to advancing solar energy technologies. Research on bio-oil-based nanofluids and nanoparticle synthesis can enhance sustainability by focusing on sustainable raw material sourcing, eco-friendly extraction processes, and the integration of renewable energy. However, applying green chemistry principles, minimizing waste, and using energy-efficient methods can make nanoparticle synthesis more sustainable. Optimizing formulations for mono and binary nanofluids would ensure desired properties with minimal environmental impact. Further research studies should focus on obtaining superior bio-oil-based nanofluids for heat transfer through synthesizing nanoparticles from renewable sources and developing binary nanofluids. These efforts could contribute to developing efficient HTFs that enhance solar thermal systems' performance derived from biomass.

CONCLUSION

1. Generally, numerous studies deducted from the literature reported in this review highly recommend nanofluid utilization as an HTF. These are due to their ability to enhance the fluids' thermal conductivity and overall heat transfer coefficient. Bio-oil-based nanofluids started receiving attention due to their improved thermophysical properties, widespread availability, non-toxicity in nature, environmentally friendly characteristics, and renewable and sustainable nature. They are also promising to be used in heat transfer mechanisms such as solar collectors, heat exchangers, and cooling systems. Their exceptional thermal characteristics can enhance heat transfer rates, resulting in more effective energy conversion and utilization across various industrial and residential environments. They also offer environmental benefits due to their biodegradable nature and could be used in other applications, such as electrical transformers to replace mineral oil for cooling and insulation and biomedical and pharmaceutical sectors. Below are the summaries of the main findings drawn from this review.
2. The overview of the effectiveness of the oil-based nanofluid and their binary combination into various systems as a heat transfer fluid for insulation, cooling, lubrication, and medium and high-temperature applications was reported from numerous research studies conducted experimentally or numerically. The effectiveness of oil-based nanofluids and their binary combinations in various systems derived from this review was promising due to their enhanced thermal and physical properties. They provide significant improvements in heat transfer for lubrication, cooling, insulation, and heating, making them suitable for a wide range of applications. The recent advancement towards green, sustainable, and environmentally friendly HTF driven researchers to bio-oil-based nanofluid, contributing to the global transition toward a greener future.
3. A general overview of the potential of bio-oil as an HTF, including its synthesis and upgrading for use as an HTF and enhancement applications in various systems. It was revealed that upgrading bio-oil through transesterification, esterification, and other upgrading techniques chemically transforms it into HTF with properties that meet industrial standards such as EN14214.
4. The challenges associated with the utilization of bio-oil-based nanofluid as an HTF. Oil, bio-oil, and bio-oil-based nanofluids can be used as heat transfer fluids and provide several benefits for operational performance and thermal efficiency. While conventional oils are readily available and cost-effective, bio-oils offer green, renewable, and sustainable substitutes, and bio-oil-derived nanofluids have improved thermal characteristics and efficiency. Depending on the application's particular needs, each option has a unique set of benefits that can be utilized to enhance system sustainability and performance.

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DECLARATION OF INTREST

None.

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