

From Petroleum to Bio-Oil: A Mini Review of Renewable Heat Transfer Fluids for Solar Thermal Applications

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Abstract- *The increasing global demand for clean energy has accelerated the search for sustainable alternatives to petroleum-based heat transfer fluids (HTFs) utilized in solar technologies. While conventional synthetic thermal oils exhibit strong thermal stability and effective heat transfer performance, they present several drawbacks, including high costs, reliance on fossil fuels, potential toxicity, and environmental risks associated with leakage or disposal. In this context, bio-oils derived from vegetable sources and biomass have emerged as promising renewable substitutes. These bio-oils are biodegradable, exhibit low toxicity, possess high flash points, and are abundantly available, particularly in developing countries rich in agricultural resources. Recent advancements in nanotechnology have further enhanced the thermal performance of bio-oils through the development of nanofluids that incorporate nanoparticles. This mini review examines the sources and production of bio-oil based heat transfer fluids, thermophysical properties enhancement, advantages, limitations, and contemporary applications of bio-oils in solar thermal systems. Additionally, it addresses current challenges and outlines areas for future research to facilitate the commercialization of bio-oil-based heat transfer fluids.*

Keywords: *Bio-oil, Heat Transfer Fluid, Solar Thermal Technology, Nanofluids, Renewable Energy.*

I. INTRODUCTION

In recent times, solar thermal technology has proved to be among the most promising solutions to meet the rising energy demand across the globe while minimizing greenhouse gas emissions and reducing reliance on fossil fuels (International Energy Agency, 2024). While photovoltaics uses the sun's radiation energy to generate electricity directly, solar thermal technology utilizes the sun's energy in the form of heat to heat water and air in households and industries and produce electricity by using CSP technologies among others (IRENA, 2023). Heat transfer fluid (HTF) absorbs thermal energy from the receiver tube to

transport thermal energy to thermal storage units and power generation cycle. Conventional oils and their corresponding oil-based nanofluids possess favourable thermophysical properties that make them effective HTFs, particularly for low- to medium-temperature heat transfer applications. Despite their promising thermal performance, conventional and synthetic oil-based HTFs face several limitations that constrain their long-term viability, environmental sustainability, and broader industrial application. Synthetic oils derived from petroleum resources, for example, are associated with high flammability, poor biodegradability, and progressive thermal degradation (Said et al., 2021; IEA, 2024). Prolonged exposure to elevated temperatures can deteriorate their heat transfer properties and promote the formation of varnish, sludge, and other degradation products, which may reduce system efficiency and cause fouling or blockage within heat transfer components. Other conventional HTFs, including thermal oils and ethylene glycol-based fluids, have also been investigated because of their favourable heat transfer characteristics. However, their relatively high cost, limited biodegradability, and susceptibility to thermal cracking and oxidation at elevated temperatures remain significant concerns (Kumar et al., 2021; Magaji et al, 2025). These limitations highlight the need for the development of alternative HTFs that combine high thermal stability and heat transfer performance with cost-effectiveness, environmental compatibility, biodegradability, and long-term operational stability. Then, further research is required to bridge the existing technological gap by developing sustainable and environmentally friendly oil-based HTFs capable of achieving or surpassing the performance of conventional petroleum-derived HTFs. In this context, bio-oils have emerged as promising candidates because of their renewable origin, biodegradability, relatively low environmental

impact, and potential to provide suitable thermophysical properties for heat transfer applications (Adewumi et al., 2022; Sharma et al., 2021).

This mini-review highlights the limitations associated with petroleum-based heat transfer fluids (HTFs) and emphasises the need for a transition towards sustainable bio-oil-based alternatives. Particular attention is given to the potential of bio-oils as renewable, biodegradable, and environmentally friendly HTFs for solar thermal applications. The review examines the enhancement in thermophysical properties of bio-oil-based HTFs. The review further summarises recent research on the application of bio-oil-based HTFs and nanofluids in solar thermal technologies, with emphasis on their potential to improve heat transfer and overall system efficiency. Finally, the review identifies challenges together with key research gaps and proposes future research directions.

II. CONVENTIONAL PETROLEUM-BASED THERMAL OILS

Conventional petroleum-based thermal oils represent one of the most popular HTFs employed in CSP and industrial heating systems due to their remarkable thermophysical characteristics. Synthesized oils, which include commercially produced Therminol VP-1 and Dowtherm A, are characterized by high thermal stability, low viscosity, and good heat transfer capability across a broad temperature range, usually reaching up to 400°C (Fernández-García et al 2020; Kalogirou, 2020). Being able to provide stable performance at high temperatures, the oils can be applied to parabolic troughs, industrial heating, and thermal energy storage systems. At the same time, conventional petroleum-based thermal oils face a number of disadvantages (Torres et al., 2021). They are produced based on non-renewable fossil sources, thus being subjected to price changes and shortage concerns related to the increasing demand for crude oil. Apart from that, the use of petroleum-based HTFs is problematic in terms of environmental concerns since they entail carbon-intensive production, toxicity, and difficulties with disposal after degradation (Saidur et al 2011; Said et al., 2021). Table 1 indicate the summary of the weakness of the oil based HTFs.

Table 1 Weaknesses of oil-based heat transfer fluid (HTFs)

Source	Weakness	What the source supports
Gomna et al. (2019)	Poor biodegradability of mineral/petroleum oils	Mineral oils have low biodegradability, reported as less than 30%, creating environmental concerns.
Gomna et al. (2019)	Limited sustainability / fossil origin	Mineral oils are derived from petroleum, and concerns exist regarding the possible limitation of oil reserves.
Gomna et al. (2019)	Flammability/fire risk	Mineral oils have a generally reported flash point of approximately 100–170 °C, creating safety concerns in high-temperature applications.
Henderson et al. (1981)	Thermal degradation	Heat-degradation experiments demonstrated the formation of degradation products from petroleum-based solar heat-transfer fluids under severe thermal conditions.
Batuecas Fernández et al. (2017)	Maximum operating-temperature limitation	Synthetic oils used in parabolic-trough CSP have a maximum operating temperature of about 393 °C, which limits the achievable operating temperature of the system.
Batuecas Fernández et al. (2017)	Environmental impact	LCA showed greater environmental impacts for synthetic oil than for the investigated molten-salt alternatives.

Source	Weakness	What the source supports
Vignarooban et al. (2015)	Thermal degradation / limited high-temperature operation	Thermal oils have defined thermal-stability limits; the review reports thermal oils operating within approximately -20 to 400 °C, while high-temperature degradation limits their use at higher temperatures.
Benoit et al. (2016)	Degradation at high temperatures	Organic oils tend to break down at temperatures around 400 °C, demonstrating their high-temperature stability limitation in concentrating solar thermal systems.
Pérez et al. (2019)	Oxidation and thermal ageing	The review identifies oxidation and hydrolysis as important ageing mechanisms affecting vegetable and thermal oils and discusses their thermal stability at elevated temperatures.

The weaknesses above provide a strong justification for investigating bio-oil-based HTFs and bio-oil-based nanofluids. Bio-oils derived from renewable resources can potentially address several of these limitations through biodegradability, renewable feedstock availability, lower environmental impact, and the possibility of enhanced thermal properties when combined with nanoparticles.

III. BIO-OIL: SOURCES AND PRODUCTION

Bio-oil refers to renewable liquid fuels and thermal fluids derived from biological resources, including vegetable oils, agricultural residues, animal fats, and lignocellulosic biomass (Das, A. K. 2022; Oparanti et al, 2021). They can be obtained through mechanical extraction, transesterification, pyrolysis, or other thermochemical conversion processes. Their renewable origin and biodegradability make them attractive alternatives to petroleum-derived heat transfer fluids. Moreover, bio-oil is considered as a low-carbon alternative to a typical fossil fuel-based HTF since it uses renewable resources such as organic waste, agricultural residues, and energy crops (Das et al, 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, A. K. 2023). Figure shows pictorial view of different types of bio-oil based HTFs.



Figure 1 Types of bio-oil based HTFs

A. Vegetable Oil-Based Bio-Oils

Vegetable oil-based bio-oils have gained considerable attention as sustainable alternatives to conventional petroleum-based heat transfer fluids (HTFs) due to their renewable origin, biodegradability, and relatively low environmental impact (Oparant et al, 2020). Derived from plant-based feedstocks, these bio-oils contribute to reducing dependence on fossil fuels while supporting the transition toward cleaner energy systems (Kalogirou, 2020). Common feedstocks include palm oil, palm kernel oil, sunflower oil, soybean oil, jatropha oil, castor oil, and cottonseed oil, many of which are readily available in agricultural economies (FAO, 2023). These oils are primarily composed of triglycerides, which provide desirable thermophysical characteristics such as high boiling points, excellent lubricity, and relatively high specific heat capacity, making them suitable for moderate-temperature solar thermal applications (Oparanti et al

2024). Their molecular structure also contributes to effective heat absorption and transport, which are essential for efficient thermal energy systems. However, untreated vegetable oils generally exhibit high viscosity, poor oxidation resistance, and limited thermal stability at elevated operating temperatures, which restrict their direct application in CSP systems (Sharma et al., 2021). To address these limitations, chemical modification processes such as transesterification are commonly employed to convert raw vegetable oils into bio-oil esters with improved flow behavior, enhanced thermal stability, and better oxidation resistance (Oparant et al, 2020). These modifications significantly improve their suitability for use as HTFs in solar thermal systems operating at higher temperatures. In countries with abundant oil-bearing crops, particularly palm kernel resources, vegetable oil-based bio-oils offer a promising pathway for developing locally sourced, environmentally friendly, and cost-effective heat transfer fluids for future solar energy applications.

B. Biomass-Derived Bio-Oils

Fast pyrolysis is a thermochemical conversion process that rapidly heats lignocellulosic biomass in the absence of oxygen to produce liquid bio-oil, together with gases and biochar. The resulting pyrolysis bio-oil is a complex mixture containing oxygenated compounds, organic acids, aldehydes, ketones, phenols, and other organic constituents (Magaji et al. 2025). Although these components contribute to its renewable character, they can also result in high acidity, viscosity, and poor thermal and oxidative stability, limiting the direct use of pyrolysis bio-oils as heat transfer fluids (HTFs). Consequently, upgrading and stabilization processes are generally required before their application in solar thermal systems. Nevertheless, pyrolysis bio-oils represent an abundant and potentially sustainable renewable resource for

developing alternative HTFs and reducing dependence on conventional petroleum-based thermal oils.

IV. THERMOPHYSICAL PROPERTIES OF BIO-OILS

The suitability of bio-oils as heat transfer fluids (HTFs) in solar thermal systems is strongly influenced by their stability and thermophysical properties. Parameters such as thermal conductivity, viscosity, specific heat capacity, density, and flash point determine the efficiency, pumping requirements, thermal storage capability, and operational safety of the fluid.

A. Thermal Conductivity

Thermal conductivity represents the ability of a fluid to transfer heat through conduction and is a critical parameter governing heat-transfer performance. Most vegetable oils possess moderate thermal conductivity, which is generally lower than that of conventional synthetic HTFs. However, the incorporation of nanoparticles can significantly improve their thermal conductivity and overall heat-transfer characteristics. Nanoparticles such as Al_2O_3 , TiO_2 , graphene, and carbon nanotubes have been widely investigated for this purpose (Tiwari et al, 2022). In particular, hybrid nanofluids containing Al_2O_3 – TiO_2 nanoparticles offer promising synergistic effects because the combined nanoparticles can enhance thermal transport while maintaining relatively stable dispersion (Magaji et al, 2025). Such improvements are particularly relevant to parabolic trough collector (PTC) applications, where efficient heat transfer is essential for achieving high collector efficiency. Table 2 provides the recent studies on thermal conductivity enhancement of bio-Oil-based nanofluids.

Table 2 Recent Studies on Thermal Conductivity Enhancement of Bio-Oil-Based Nanofluids

Ref.	Nanoparticles	Base fluid	Concentration	Type	Max. Thermal conductivity enhancement	Major finding / application
Okafor et al. (2024)	xGnP, TiO ₂ , MoS ₂ , and Al ₂ O ₃	soybean oil, canola oil	1 % to 7 %	Binary	109.73	The results obtained showed that the thermal conductivity of all the nanofluids decreased linearly with increasing temperature, whereas the thermal conductivity enhancement increased nonlinearly with increasing nanoparticle concentration (wt%), following a second-order polynomial relationship.
Ribeiro et al. (2023)	h-BN, CNT, h-BN@CNT	Vegetable oil	Up to 0.5 wt. %	Mono/Hybrid	39	Hybrid h-BN@CNT nanofluids produced up to 39% thermal-conductivity enhancement and showed stable suspensions without stabilizing agents, indicating potential for sustainable heat-transfer applications.
Hasbi et al. (2023)	Graphene, TiO ₂	Palm wax, beeswax, coconut oil	0.5–2.0 wt. %	Mono	46.1	Nano-enhanced bio-based phase-change materials demonstrated improved thermal conductivity and potential for thermal-energy storage applications.
Oparanti et al. (2024)	Various nanoparticles	Vegetable insulating oils	Various	Mono/Hybrid	Various	Review of green nanofluids showing the potential of vegetable-based fluids as alternatives to mineral oils; long-term nanofluid stability remains a major challenge.
Nazir et al. (2024)	ZnO–MgO	Coconut oil	0.02–1%	Binary	18	ZnO–MgO/coconut-oil hybrid nanofluid demonstrated enhanced thermal conductivity and potential for heat-

Ref.	Nanoparticles	Base fluid	Concentration	Type	Max. Thermal conductivity enhancement	Major finding / application
Kulandaivel et al. (2025)	SiO ₂ -CNP	Palm oil	0.1%	Binary	81.1	transfer/cooling applications. SiO ₂ -CNP/palm-oil nanofluid showed very high thermal-conductivity enhancement and good stability, making it particularly relevant as a bio-oil-based HTF.
Magaji et al. (2025)	Various nanoparticles	Bio-oils/vegetable oils	Various	Mono/Hybrid	61.1	Comprehensive experimental analysis of bio-oil-based binary nanofluids for solar thermal systems, highlighting enhanced thermophysical properties, stability of palm kernel oil based Al ₂ O ₃ -TiO ₂ binary nanofluid.

B. Viscosity

Viscosity is another important consideration because it directly influences fluid circulation, pressure losses, and pumping power. Vegetable oils generally exhibit higher viscosity than conventional petroleum-based HTFs, particularly at lower temperatures. Excessive viscosity can increase frictional losses and pumping requirements, thereby reducing the overall energy efficiency of solar thermal systems. However, the viscosity of bio-oils decreases substantially with

increasing temperature, making them more suitable for operation at elevated temperatures. Nanoparticle addition may either increase or, depending on formulation and temperature, modify the viscosity of the base fluid. Consequently, optimization of nanoparticle concentration is necessary to achieve a balance between enhanced thermal conductivity and acceptable flow resistance. Figure 2 illustrates the enhancement in the viscosity of bio-oil based HTFs.

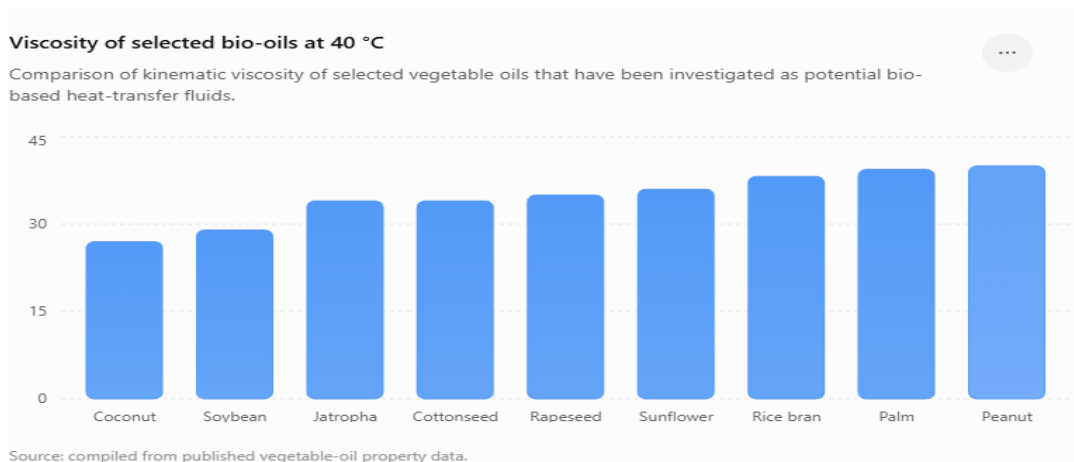


Figure 2 Kinematic viscosity of selected bio-oils at 40 °C.

It is, however, clearly reported that several factors such as 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 significantly affect the viscosity of the nanofluid (Ahmadi Nadooshan et al. 2018). Many research works have been analyzed to investigate the effect of these factors on nanofluid viscosity

C. Specific Heat Capacity

Specific heat capacity describes the amount of thermal energy required to raise the temperature of a unit mass of fluid by one degree. It is particularly important in solar thermal systems because fluids with relatively high specific heat capacity can absorb and transport greater quantities of thermal energy without excessive temperature increases. Many vegetable oils exhibit

favorable heat-capacity characteristics, making them potentially suitable for both heat-transfer and sensible thermal-storage applications. The nanofluids' specific heat usually increases with temperature and drops consequently with nanoparticle concentration increment. This behaviour is considered unique for all combinations of mono and binary nanofluids. However, specific heat decreases with increasing volume %, and the ghetto improves its ability to absorb and transfer heat. This specific heat trend is constant even for dissimilar nanoparticles, even though the aforementioned behaviour directly depends on certain parameters, including the kind of nanomaterial, temperature, and base fluid (Rubbi et al. 2021). Figure 3 prevent the schematic representation of the recent enhancement and modification of thermophysical properties of bio-oil-based nanofluids through nanoparticle incorporation.

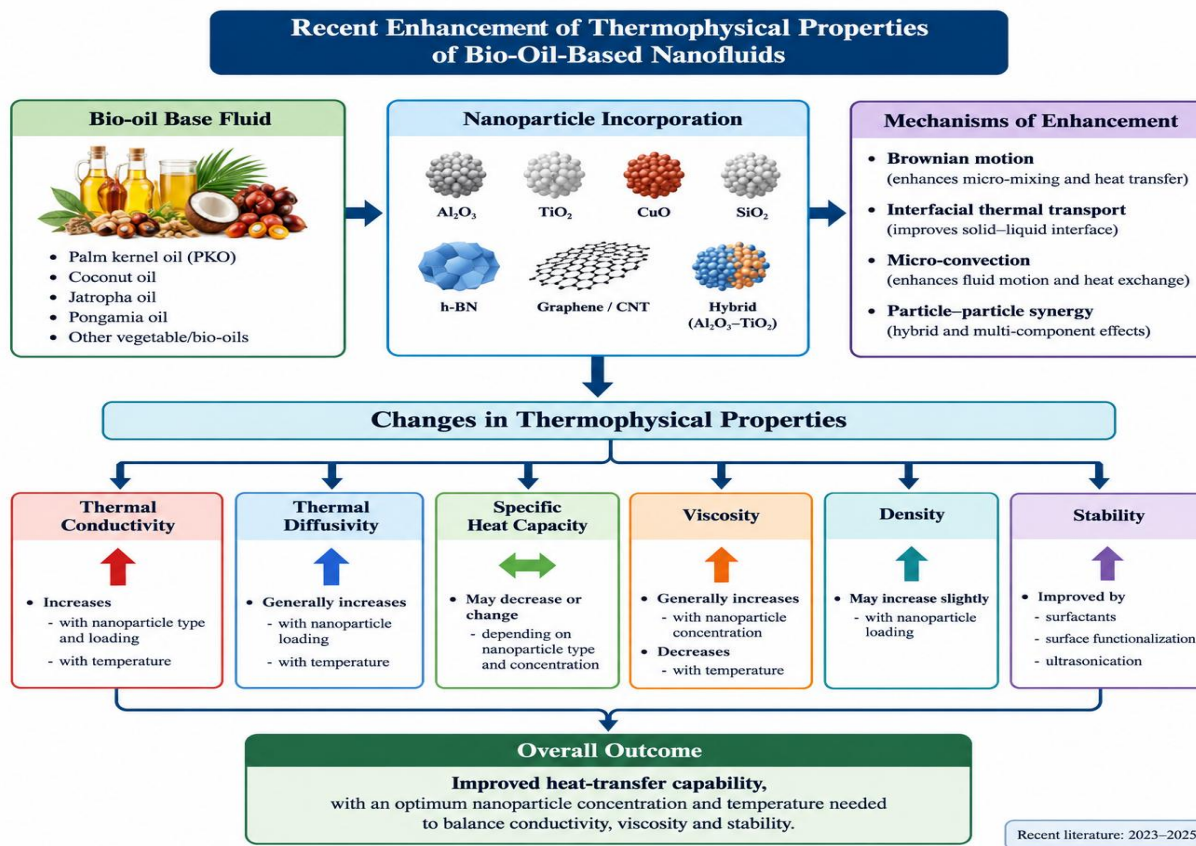


Figure 3 Schematic representation of the recent enhancement and modification of thermophysical properties of bio-oil-based nanofluids through nanoparticle incorporation.

D. Flash Point and Fire Safety

Flash point is an important safety parameter for HTFs because it indicates the temperature at which vapors can ignite. Many vegetable oils have relatively high flash points compared with petroleum-derived fluids, providing an important safety advantage by reducing fire hazards during operation. This characteristic is

particularly beneficial for decentralized and medium-temperature solar thermal installations, where operational safety, environmental compatibility, and fluid sustainability are major considerations. Recent studies of a flash point were presented in Table 3.

Table 3. Recent studies reporting bio-oil flash point

Author(s) / Year	Bio-oil feedstock	Flash point (°C)	Method/standard	Relevance
Lawal et al. (2025)	<i>Gmelina arborea</i> seeds		ASTM methods	Demonstrated the potential of <i>Gmelina arborea</i> seed bio-oil as a renewable energy resource in Nigeria.
Mohamed et al. (2024)	Cattle dung	50 °C	ASTM-based fuel-property analysis	Reported a flash point of 50 °C and a fire point of 58 °C, indicating a reasonable safety characteristic for handling.
Koshariya et al. (2022)	Biomass-derived bio-oil	135 °C	ASTM D92	The study reported density of 980 kg/m ³ , viscosity of 7.8 cSt and flash point of 135 °C, demonstrating substantial variation in bio-oil properties depending on feedstock and processing.
Rao et al. (2022)	<i>Ficus religiosa</i> wood	130 °C	ASTM D92	The <i>Ficus religiosa</i> bio-oil had a flash point of 130 °C; the study compared it with pine, lemongrass and hardwood bio-oils, which showed 95

V. CHEMICAL MODIFICATION OF BIO-OILS

Raw vegetable oils often require chemical modification to improve their suitability as heat transfer fluids (HTFs) for solar thermal applications. Transesterification converts triglycerides into esters through reaction with alcohols, resulting in reduced viscosity, improved flow characteristics, and enhanced thermal and oxidative stability (Magaji et al. 2025). Esterification is another important treatment that reduces the concentration of free fatty acids, thereby improving storage stability and minimizing corrosion of system components (Wang et al., 2010). In addition, antioxidant additives can be incorporated to inhibit oxidation and thermal degradation during prolonged exposure to elevated temperatures. Common antioxidants include tert-butylhydroquinone (TBHQ), butylated hydroxytoluene (BHT), and naturally occurring tocopherols. These chemical modification strategies improve the physicochemical properties, operational stability, and overall performance of bio-

oil-based HTFs, making them more suitable for sustainable solar thermal energy applications.

VI. BIO-OIL-BASED NANOFLUIDS

Nanotechnology has transformed bio-oils into high-performance HTFs. The incorporation of nanoparticles into bio-oil-based heat transfer fluids (HTFs) has emerged as an effective approach for improving their thermal performance (Kumar et al., 2024; Panduru et al., 2022). Nanoparticles can significantly enhance thermal conductivity, enabling the fluid to absorb and transport heat more efficiently. They can also improve convective heat transfer by modifying fluid flow and increasing interactions between the fluid and heated surfaces. In addition, nanoparticles enhance thermal diffusion, promoting more uniform heat distribution throughout the working fluid (Wanatasanappan et al., 2022; Umar et al., 2020). These improvements can increase the thermal efficiency of solar thermal collectors by reducing temperature gradients and enhancing energy transfer from the absorber to the

HTF. Common nanoparticles investigated for solar thermal applications include aluminium oxide (Al_2O_3), titanium dioxide (TiO_2), copper oxide (CuO), and silica (SiO_2) (Tiwari et al., 2021). Therefore, bio-oil-based nanofluids offer considerable potential as high-performance and environmentally sustainable alternatives to conventional petroleum-based HTFs (Tambuwal et al., 2022). Frequently used nanoparticles include. Hybrid nanoparticles often outperform single-particle nanofluids because they combine complementary properties. However, stability of nanofluids is a critical factor governing their long-term thermal performance and practical application in solar thermal systems. Stability is influenced by several factors, including the type and concentration of surfactants, ultrasonication conditions, nanoparticle concentration, and pH control. Appropriate surfactants reduce the attractive forces between nanoparticles and the base fluid, thereby minimizing particle agglomeration and sedimentation. Ultrasonication further promotes uniform nanoparticle dispersion by breaking down particle clusters within the fluid. Controlling nanoparticle concentration and pH can also improve suspension stability and maintain consistent thermophysical properties during operation (Sofiah et al 2021). Among various surfactants, oleic acid has demonstrated considerable effectiveness in vegetable oil-based nanofluids because of its compatibility with oil-based fluids and ability to reduce nanoparticle agglomeration. Consequently, proper stabilization is essential for maintaining uniform nanoparticle dispersion, improving heat transfer performance, and ensuring reliable long-term operation of bio-oil-based nanofluids.

VII. BIO-OIL-BASED NANOFLUIDS FOR SOLAR THERMAL AND ENERGY SYSTEMS

Several studies have investigated the application of bio-oil-based nanofluids as alternative heat transfer and cooling fluids in renewable energy systems. Millien (2020) investigated a copper (Cu) nanoparticle-based nanofluid using coconut oil and sunflower oil as base fluids at a concentration of 1.2. The study revealed that the incorporation of copper nanoparticles into bio-oil significantly improved the

heat transfer rate and overall heat transfer coefficient of the system. Mirnezami et al. (2020) investigated a binary nanofluid containing multi-walled carbon nanotubes (MWCNT) and magnesium oxide (MgO) dispersed in palm oil. The nanoparticles were employed at concentrations of 0.2, 0.25, 0.3, 0.35, and 0.4. Their findings demonstrated that the bio-oil-based binary nanofluid enhanced system efficiency while reducing the cost associated with biodiesel production. Similarly, Samyilingam et al. (2020) examined MXene nanoparticles dispersed in olein palm oil (OPO) at concentrations ranging from 0.01 to 0.2. The results showed outstanding thermal conductivity performance, with approximately 16% improvement in thermal efficiency at a flow rate of 0.07 kg/s. In addition, an approximately 9% improvement in the heat transfer coefficient was observed in the photovoltaic-thermal (PVT) system using MXene nanofluids (Samyilingam et al., 2020). Asmat-Campos (2020) investigated silver nitrate (AgNO_3)-based nanofluids using bio-oil as the base fluid. Although the specific nanoparticle concentration was not reported, the developed nanofluid demonstrated good potential for application in solar thermal systems, particularly in geographical regions characterized by low solar radiation intensity.

Rubbi et al. (2021) investigated Ti_3C_2 MXene nanoparticles at a concentration of 0.125 wt.% using soybean oil as the base fluid. The results demonstrated the effectiveness of soybean-oil-based MXene nanofluids compared with conventional cooling fluids in photovoltaic/thermal (PV/T) collectors. The system achieved overall electrical and thermal efficiencies of 15.44% and 84.25%, respectively. Tafavogh and Zahedi (2021) studied a binary MWCNT- MgO nanofluid using palm oil as the base fluid. Although the nanoparticle concentration was not specified, the results indicated that the bio-oil-based nanofluid substantially enhanced the thermal efficiency of a parabolic trough collector (PTC), achieving a thermal efficiency of 56.59%. Afolabi et al. (2022) investigated SiO_2 and Al_2O_3 nanoparticles dispersed in jatropha oil at concentrations ranging from 1 to 4. The findings showed that the addition of nanoparticles significantly improved system efficiency. In particular, the Al_2O_3 /jatropha oil nanofluid demonstrated greater efficiency enhancement,

followed by the SiO_2 /jatropa oil nanofluid, when compared with the use of pure jatropa oil. Permanasari et al. (2023) investigated graphene nanoparticles at a concentration of 0.1 using virgin coconut oil as the base fluid in a PVT system. Their results demonstrated considerable improvements in both thermal and electrical performance, with thermal and electrical efficiency enhancements of 25.169% and 8.632%, respectively. More recently, Brakna and Benzenine (2024) investigated a binary Al_2O_3 -MWCNT nanofluid using bio-oil as the base fluid. Their findings showed that the application of the binary nanofluid in a double-tube heat exchanger resulted in a remarkable 77.8% enhancement in the heat transfer rate, demonstrating the strong potential of bio-oil-based hybrid nanofluids for thermal energy applications. Kenfack et al. (2024) investigated TiO_2 nanoparticles dispersed in vegetable oil. Although the nanoparticle concentration was not specified, numerical analysis of the thermophysical properties of the bio-oil-based nanofluid demonstrated a 12.08% improvement in electrical efficiency of the

photovoltaic configuration compared with conventional PV systems.

Overall, these studies demonstrate that bio-oil-based nanofluids have considerable potential as alternatives to conventional petroleum-based heat transfer and cooling fluids. The incorporation of metallic, metal-oxide, carbon-based, and MXene nanoparticles generally improves thermal conductivity, heat transfer coefficients, and overall thermal or electrical efficiency. The reported improvements—ranging from approximately 9% enhancement in heat transfer coefficient to 77.8% enhancement in heat transfer rate—indicate the potential of bio-oil-based nanofluids for applications in PTC, PVT, PV cooling, heat exchangers, and other solar energy systems. However, further research is required to address long-term stability, optimal nanoparticle concentration, viscosity, thermal degradation, cost, and large-scale system performance.



Figure 4 Mojave Solar Project in California showing the parabolic trough solar collector field.

Experimental investigations demonstrate that vegetable oils can successfully transport thermal energy while maintaining acceptable efficiencies under moderate operating temperatures.

VIII. CHALLENGES LIMITING COMMERCIALIZATION

While being an attractive alternative sustainable HTF for use in solar thermal systems, the development of bio-oil nanofluid-based HTF faces some technical and technological issues preventing its commercialization. Technical barriers include oxidative decomposition, thermal instability, high viscosity, moisture

sensitivity, and aggregation or sedimentation of nanoparticles, which may negatively impact the heat transfer efficiency, pumpability, lifetime of the HTF, and reliability. Vegetable oil shows high oxidative and thermal decomposition when exposed to high temperatures, oxygen, and moisture (Márquez-Ruiz et al., 2019). The second issue is the stability of nanofluids because the concentration, dispersion, viscosity, and colloidal stability of nanofluids highly depend on their performance in concentrating solar collectors (Rubbi et al., 2021). Lastly, the standardization and reliability of nanofluids are commercialization barriers. There is currently only one ASTM Standard D7665-22 that offers the guidelines for assessing biodegradability, non-hydrolysability, water-free heat transfer fluids. As far as the standards for bio-oil nanofluids for solar thermal application are concerned, there is not much literature on them, and thus long-term testing is necessary. In the future research, one has to address the issues of chemical modification and formulae of bio-oils in order to improve their oxidation resistance, thermal stability, and viscosity. The efficient surface functionalization of nanoparticles will increase the stability and heat transfer properties of bio-oil nanofluids (Rubbi et al., 2021). Despite encouraging progress, several barriers remain.

IX. CHALLENGES AND FUTURE RESEARCH DIRECTIONS

- Despite the considerable potential of bio-oil-based heat transfer fluids (HTFs) and nanofluids for solar thermal applications, several technical challenges continue to limit their practical deployment and commercialization. Oxidative degradation during prolonged heating can alter the chemical composition and thermal properties of bio-oils, while their relatively high viscosity at ambient and low temperatures may increase pumping requirements and reduce heat-transfer efficiency. In addition, some bio-oils exhibit limited thermal stability at temperatures above approximately 300°C and may be sensitive to moisture, which can adversely affect their physicochemical properties and long-term reliability. Therefore, improved formulation, purification, and quality-control

procedures are necessary to ensure consistent performance.

- Another important challenge is the chemical complexity of certain bio-oils, particularly fast-pyrolysis bio-oils. These oils generally contain substantial quantities of oxygenated compounds, including acids, aldehydes, ketones, phenolics, and other reactive species. Such compounds can contribute to high acidity, corrosiveness, poor storage stability, and undesirable changes during prolonged thermal exposure. Consequently, chemical and catalytic upgrading may be required before these bio-oils can be reliably used as HTFs. Standardized procedures for feedstock selection, oil production, nanoparticle dispersion, thermal characterization, stability assessment, and quality control are also required to facilitate meaningful comparison between studies and support eventual industrial standardization.
- Finally, future investigations should move beyond laboratory-scale thermal performance and incorporate life-cycle, environmental, and techno-economic assessments. Comparative studies should evaluate bio-oil-based nanofluids against conventional mineral and synthetic HTFs in terms of energy efficiency, greenhouse-gas emissions, biodegradability, resource availability, operating costs, and overall environmental impact.

X. CONCLUSION

Bio-oil-based heat transfer fluids (HTFs) represent a promising renewable and environmentally sustainable alternative to conventional petroleum-derived fluids for solar thermal applications. Vegetable oil-based bio-oils offer several advantages, including biodegradability, relatively favorable thermophysical properties, low toxicity, and improved safety, while biomass-derived oils provide an additional opportunity for agricultural and waste-resource valorization. Nevertheless, challenges associated with oxidation, viscosity, thermal degradation, moisture sensitivity, and long-term stability continue to restrict their large-scale application. Recent advances in chemical modification, purification, and nanofluid technology have demonstrated significant potential for overcoming these limitations. In particular, hybrid nanofluids containing Al_2O_3 - TiO_2 nanoparticles can

improve thermal conductivity and heat-transfer characteristics, thereby enhancing the thermal efficiency of solar collectors. However, further research is required to establish their long-term stability and reliability under realistic operating conditions. For resource-rich countries, bio-oil-based HTFs could contribute significantly to sustainable concentrating solar power (CSP) development by reducing dependence on petroleum-based thermal fluids, promoting local agricultural value addition, and supporting renewable-energy industrialization. Future studies should therefore emphasize long-term experimental validation, life-cycle assessment, techno-economic analysis, and field-scale demonstration. These efforts will be critical for translating laboratory-scale advances into commercially viable and sustainable solar thermal technologies.

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