SINERGI Vol. 30, No. 2, June 2026: 459-468
http://publikasi.mercubuana.ac.id/index.php/sinergi
http://doi.org/10.22441/sinergi.2026.2.012

Possibility of using immersion cooling technology with virgin coconut oil for split-type AC

Achmad Wibolo*, I Wayan Temaja, Ida Bagus Gde Widiantara, Made Ery Arsana, M. Yusuf
Department of Mechanical Engineering, Politeknik Negeri Bali, Indonesia

Abstract
Conventional split-type air conditioners are limited by high electrical consumption, noise from cooling fans, and bulky condenser coils that restrict installation flexibility. However, the application of immersion cooling in household AC systems remains largely unexplored. This study investigates the feasibility of using Virgin Coconut Oil (VCO) as a dielectric fluid for immersion cooling to improve energy efficiency and thermal performance. An experimental setup was developed using 20 L of SNI-compliant VCO, with the outdoor unit modified for immersion operation. Key performance parameters, including condenser coil and evaporator coil temperatures and the Coefficient of Performance (COP), were measured. Results showed condenser coil temperatures ranging from 40 °C to 58 °C and evaporator coil temperatures between 6 °C and 11 °C. The system achieved an average COP of 4.65 and reduced electrical consumption by approximately 20 %, indicating significant energy savings without compromising cooling efficiency. VCO also demonstrated suitable dielectric properties, with a breakdown voltage of 29.17 kV, near the IEC 156 threshold. These findings highlight immersion cooling with VCO as a promising, quiet, and energy-efficient alternative for household air conditioners. Further work is recommended to assess long-term reliability under varying operational conditions.

Keywords:
Coefficient of Performance (COP);
Dielectric fluid;
Energy efficiency;
Immersion cooling;
Split-type AC;
Virgin Coconut Oil (VCO):

Article History:
Received: June 14, 2025
Revised: November 3, 2025
Accepted: November 17, 2025
Published: June 6, 2026

Corresponding Author:
Achmad Wibolo
Department of Mechanical Engineering, Politeknik Negeri Bali, Denpasar, Indonesia
Email: wibolo@pnb.ac.id

INTRODUCTION

The split-type air conditioner is dominant in the Indonesian household market. Compact and practical for everyday use. The split type indicates that the outdoor construction part is separate from the indoor one. This type almost always uses convection air cooling with electric fans. This type of conventional cooling has several obstacles, namely, the additional electrical energy to drive an electric fan. There is noise from the electric fans, and the large condenser box is an obstacle to their placement. Corrosion of the condenser coil can damage the AC split installed in buildings near the coast. The latest method to improve energy efficiency and save more energy is to use immersion-cooling fluid technology. The latest technology in immersion cooling is a liquid dielectric [1][2] that absorbs heat from components by convection and releases it to the environment through a single-phase or two-phase system [3]. Many advantages of using liquid dielectrics have been reported, including a high heat transfer coefficient, stable hydrodynamic flow, and the ability to directly cool heat-generating components, resulting in more uniform temperature distribution and improved thermal management performance [4]. Examples of dielectric materials commonly used today include mineral oil (MO) and virgin coconut oil (VCO) [5]. This cooling method is commonly used in electronic devices such as computer servers [6][7], data centers [8][9], solar PV [10], batteries [2][11], and transformer strength [12][13].

Immersion cooling can cool the entire surface, unlike indirect cooling. Improves temperature uniformity by reducing local heating. It is possible to achieve high efficiency with medium coolants that have high thermal conductivity, low viscosity, and high heat capacity [14]. Several problems are related to this system. There were an electric short circuit and electrochemical corrosion. Therefore, the consideration of choosing a dielectric material is due to its ability to prevent electrical short circuits [15][16], as well as safety and health concerns, non-toxicity, good performance, chemical stability, and non-flammability. Other potential immersion refrigerants include deionized air [17], silicone-based oils, or mineral oils [18]. Those applications are proposed for electronic CPU cooling in data centers.

Implementation of immersion cooling across various equipment, including solar photovoltaic systems. Solar radiation will be optimal when the weather is sunny, cloudless, and pollution-free, but this will also raise temperatures. The heat generated by solar cells must be managed to achieve high efficiency. The energy produced by solar PV typically decreases with increasing temperature. Birbarah et al [6] reported that refrigerated solar PV can increase its efficiency by up to 47%. The cooling system utilizes air and water immersion technology, which is more effective than other mechanisms. The use of an immersion water-cooling system is particularly beneficial. An immersion water-cooling system is highly beneficial on sunny days. Immersion cooling in the data center helps control temperature rise, which, if left unchecked, can damage electronic components. The computing speed of computer servers and data centers will decrease due to rising temperatures, which can also increase electrical power consumption at the same load.

One of the major problems in AC performance is the buildup of heat in the condenser and compressor components, which reduces cooling efficiency and shortens equipment lifespan. While efforts to improve energy efficiency have been made, such as variable refrigerant flow systems and inverter technology, these still rely on forced-air mechanisms and do not address core thermal management limitations.

A growing body of research in thermal engineering has highlighted the potential of immersion cooling with dielectric liquids, such as mineral oil or synthetic fluids, to directly absorb and dissipate heat in electronics, data centers, batteries, and photovoltaic systems.

However, despite proven applications in high-performance computing and renewable energy systems, there is a noticeable gap in the literature on the use of immersion cooling in residential air conditioning systems, especially with natural, biodegradable coolants such as Virgin Coconut Oil (VCO).

Table 1 presents a comparative analysis of the thermophysical and dielectric properties of VCO, mineral oil, and synthetic oil. The VCO exhibits higher thermal conductivity and specific heat capacity, which enhance its ability to absorb and dissipate heat efficiently. In addition, its lower viscosity improves convective heat transfer performance.

Table 1. Comparison of key physical and thermal properties of VCO, mineral oil, and synthetic oil (Data compiled from [5,15,19, 20, 21]).

Property	Unit	Virgin Coconut Oil (VCO)	Mineral Oil	Synthetic Oil	Remarks
Density	kg/m³	900–920	850–890	820–860	VCO is slightly denser, enhancing convection stability
Viscosity (25 °C)	cP	25–30	40–50	35–45	Lower viscosity of VCO improves convective heat transfer
Specific Heat Capacity	kJ/kg·K	2.1	1.7–1.9	1.8–2.0	Higher heat capacity allows better thermal storage and stability
Thermal Conductivity	W/m·K	0.21	0.12–0.15	0.16–0.18	Higher conductivity enhances heat dissipation efficiency.
Breakdown Voltage (IEC 156)	kV	29.17	30–35	32–40	Comparable insulation strength for low-voltage systems
Biodegradability	–	Yes	No	Partial	VCO is renewable and environmentally friendly
Cost and Availability	–	Locally available, low-cost	Imported	Imported	VCO supports sustainable and local supply chains

From an environmental perspective, VCO is biodegradable and locally available, making it a more sustainable alternative compared to conventional dielectric fluids. The implementation of split AC with VCO oil-dielectric for submerged cooling needs to be studied to assess its effectiveness and the benefits obtained. How to use electrical energy, a quiet cooling mechanism, a more stable temperature, and a more compact outdoor design are some of the advantages that will be discussed, and the results can be used in the research phase to improve the performance of the split air conditioner.

This research aims to determine whether it is possible to use immersion cooling technology using VCO oil to be applied to split-type air conditioners, determine the performance of the condenser and evaporator temperatures, and determine their effect on the performance (COP) of the split AC.

The novelty of this study lies in its experimental application of single-phase immersion cooling technology, using VCO as the dielectric medium, in a split-type AC outdoor unit. To the best of the authors' knowledge, this is among the first studies to evaluate the thermal performance, energy efficiency, and feasibility of using VCO in this specific context. This research aims to determine whether immersion cooling can effectively lower component temperatures, reduce electricity usage, and provide a quieter, more compact cooling solution suitable for household AC systems in tropical climates. The implications of this research are twofold: (a) it introduces an environmentally friendly and energy-saving alternative to conventional forced-air cooling in residential AC systems, and (b) it opens opportunities for further development of sustainable cooling technologies using locally sourced natural materials, which could reduce dependence on synthetic coolants and enhance thermal management in various domestic applications. If proven effective on a larger scale, this approach supports green building initiatives and contributes to national energy efficiency goals.

Additionally, its breakdown voltage of 29.17 kV meets the IEC 156 safety threshold for household AC systems. Beyond technical performance, VCO is biodegradable, non-toxic, and locally available in tropical regions such as Indonesia, offering both environmental and economic advantages. These quantitative attributes reinforce the novelty of this study and justify the selection of VCO as a sustainable dielectric medium for residential split-type air conditioners [5, 15, 19, 20, 21].

The main objective of this research is to fill an existing research gap by experimentally evaluating immersion cooling with Virgin Coconut Oil (VCO) in residential split-type air conditioners. Specifically, the study aims to evaluate the feasibility, thermal performance, and energy efficiency of VCO as a dielectric medium by analyzing condenser and evaporator temperatures and determining the system's Coefficient of Performance (COP).

METHOD

Experimental Setups

This study employed an experimental approach to evaluate the feasibility of using Virgin Coconut Oil (VCO) as a dielectric cooling medium for the outdoor unit of a residential split-type air conditioner. The original outdoor unit—comprising the compressor, condenser coil, expansion valve, and fan—was modified by replacing the air-cooled section with a sealed immersion chamber filled with VCO. The design aimed to achieve direct heat transfer between the condenser coil and the dielectric fluid, thereby eliminating fan energy consumption and improving overall heat dissipation.

The experimental configuration was developed to ensure complete fluid contact around the condenser coil and to maintain a stable convective flow within the chamber. This setup allowed accurate monitoring of thermal behavior while maintaining realistic operating conditions representative of household environments.

Dielectric Fluid and Its Properties

Virgin Coconut Oil (VCO) sourced from a certified Balinese producer was used as the immersion medium. The oil complies with the Indonesian National Standard (SNI) for purity and quality. Its key properties are: density 900–920 kg/m³, moisture content 0.1–0.5%, and breakdown voltage 29.17 kV (IEC 156). Although slightly below transformer oil specifications, this dielectric strength is sufficient for low-voltage (220–240 V) residential AC systems. The selection of VCO was based on its thermophysical advantages—low viscosity, high specific heat capacity, and biodegradability—making it suitable for safe, quiet, and energy-efficient cooling applications.

Testing Conditions and Procedure

The experiment was performed under controlled ambient conditions at 27 °C. The indoor unit cooled a 9 m² test room subjected to a constant 500 W heat load to simulate typical residential operation. The system used R410A refrigerant, and pressure-temperature readings were monitored at both the high- and low-pressure sides during operation.

Key performance parameters, including condenser and evaporator temperatures and total electrical power consumption, were continuously measured for 3000 minutes. All instruments were calibrated in accordance with ASHRAE standards to ensure accuracy. The data were used to evaluate the system's Coefficient of Performance (COP) and overall energy efficiency.

Experimental Rationale

The experimental configuration was designed to simulate realistic tropical operating conditions while enabling direct assessment of immersion-cooling performance. As illustrated in Figure 1, the system employed approximately 20 liters of VCO to ensure complete submersion of the condenser coil, thereby promoting efficient heat transfer and maintaining dielectric insulation. Removing mechanical fans eliminated parasitic power losses and enabled a more accurate evaluation of the system's thermal and energy behavior. Overall, this setup provides a robust framework for assessing the practical feasibility of VCO-based immersion cooling in residential HVAC applications.

Data Analysis

The system performance was evaluated using the Coefficient of Performance (COP), defined as:

$$COP = Q\_cooling / W\_input \quad (2)$$

Where Q_cooling is the cooling capacity (kW), and W_input is the electrical power input (kW). Data were logged and processed using Microsoft Excel to generate temperature and performance curves. The analysis focused on comparing the immersion-cooled system's efficiency, temperature stability, and potential for energy savings with conventional cooling approaches.

RESULTS AND DISCUSSION

Excessive heat generation in air conditioning systems, especially within the condenser and compressor components, poses significant challenges to performance efficiency and equipment lifespan [26][27]. This study evaluated the effect of immersion cooling using Virgin Coconut Oil (VCO) on the thermal and energy performance of a split-type air conditioner.

Condenser Temperature Performance

The condenser temperature profile throughout the 3000-minute operation period is shown in Figure 2. The temperature fluctuated between 40°C and 58°C, reflecting stable thermal performance and effective heat dissipation through the VCO medium.

Compared with a conventional fan-cooled condenser, which typically operates between 45°C and 65°C under similar ambient conditions, the immersion configuration demonstrated reduced temperature fluctuations and improved uniformity. This result confirms that direct liquid contact between the condenser coil and the VCO enhances heat transfer, minimizes localized hotspots, and maintains a more consistent surface temperature.

Similar findings were reported by M. Asim et al. [22], who observed that immersion cooling in electronic systems provides better thermal uniformity than forced-air methods due to superior convective heat transfer.

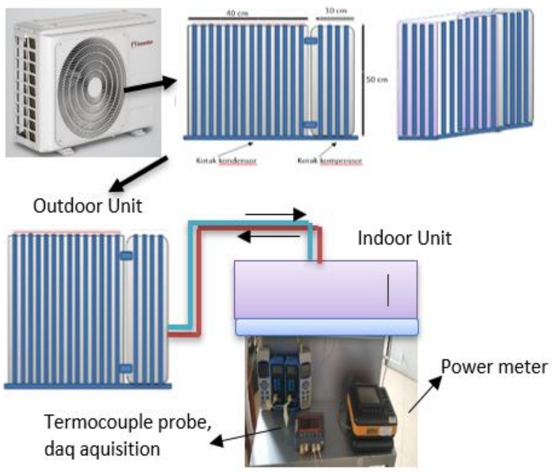

Figure 1. Experiment setup, installation of the AC split, outdoor unit, and instruments

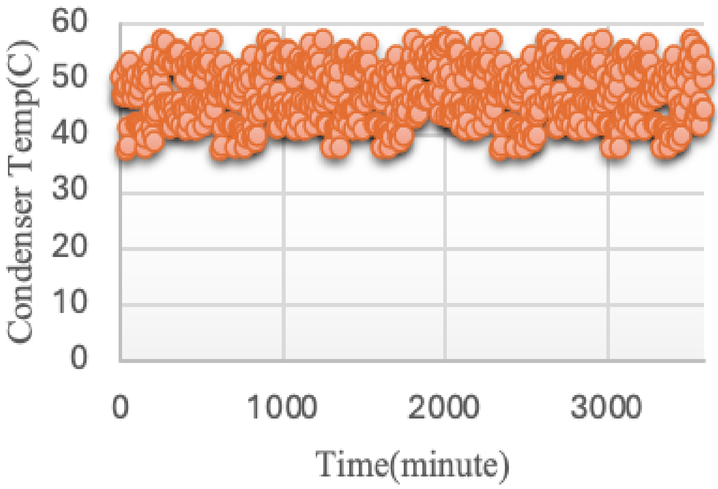

Figure 2. The variations of condenser temperature

Evaporator Temperature Performance

Figure 3 shows the evaporator temperature, which remained stable between 6°C and 11°C throughout the experiment.
This consistency indicates that the modified outdoor immersion cooling system does not compromise the evaporator's thermal performance or indoor comfort level, maintaining a room temperature of around 22°C under a constant 500 W internal load.

Compared to conventional AC systems, which may experience ±3 °C evaporator temperature oscillations under variable compressor loads, the immersion-cooled system maintained more stable thermal control. This suggests that improved condenser efficiency directly contributes to smoother evaporator operation. The result aligns with the observation of Birbarah et al. [6], who found that enhanced heat regulation in immersion-based thermal systems results in greater overall energy stability.

Energy Efficiency and COP Analysis

The system's energy consumption data were analyzed to determine its Coefficient of Performance (COP), as shown in Figure 4. The average COP recorded was 4.65, representing a significant improvement in energy efficiency compared with a baseline conventional system, which typically achieves a COP of 3.8–4.0 under similar operating conditions.

The implementation of VCO-based immersion cooling reduced total electrical energy consumption by approximately 20%, primarily by eliminating fan power and enhancing heat transfer within the dielectric fluid. This finding supports earlier studies on immersion cooling in high-performance computing and energy storage systems, which reported efficiency gains of 20–30% through direct liquid contact [19].

Overall, these results confirm that immersion cooling with VCO provides measurable thermal and energy advantages over conventional air-cooled systems, making it a promising alternative for quiet, efficient, and environmentally sustainable air conditioning applications.

Discussion on Heat Transfer Mechanism

The thermal performance of VCO as a dielectric coolant is primarily attributed to its relatively high liquid-phase heat transfer coefficient and stable insulating properties. Based on Newton's Law of Cooling, effective convective heat transfer occurs when a fluid exhibits a large temperature gradient and a sufficient surface area for contact. The finned immersion chamber in this experiment enhanced that effective surface area, promoting efficient heat dissipation from the condenser coil. The observed condenser temperature range of 40–58 °C indicates that the VCO medium successfully maintained thermal equilibrium within the system.

Furthermore, while mineral oils are widely used in immersion-cooling applications, VCO offers a renewable, biodegradable alternative with promising thermal and electrical characteristics. Its breakdown voltage of 29.17 kV, although slightly below transformer-grade standards, is sufficient for the AC's operating voltage range. Additionally, the absence of a forced fan reduces noise and simplifies the system design.

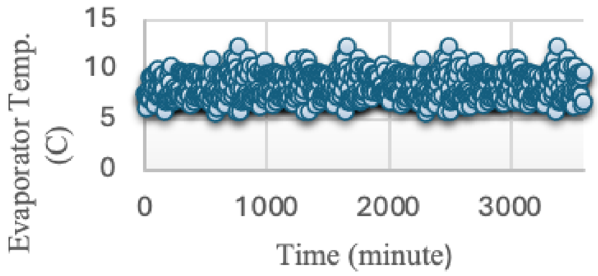

Figure 3. The variations of evaporator temperature

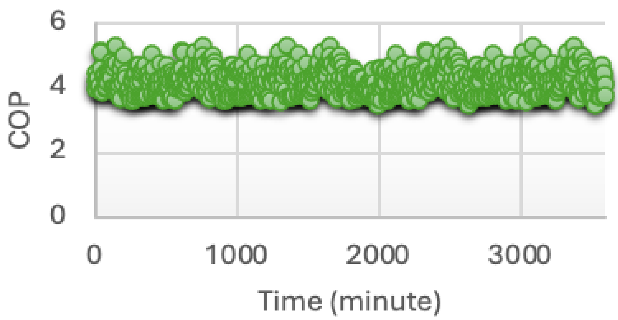

Figure 4. The variations of the coefficient of performance.

Table 2. A quantitative comparison between selected previous studies on immersion cooling and the present work

Reference	Application	Dielectric Fluid	Temp Range (°C)	COP	Energy Saving (%)	Notes
Birbarah et al. [6] (2020)	High-power electronics	Water	35–55	–	~15	Improved heat removal, but not applied to HVAC systems
Dubey et al. [16] (2021)	Li-ion battery module	Mineral oil	30–50	–	20–30	Demonstrated improved thermal management, no COP data
Zhang et al. [19] (2025)	Data center servers	Synthetic oil	35–60	–	~25	Enhanced temperature uniformity, no residential AC application
Jiang et al. [20] (2025)	Automotive battery pack	Mineral oil	30–55	–	~20	Focused on battery systems, not HVAC
Liu et al. [28] (2025)	Battery cooling with PCM + immersion	Mineral oil	32–52	–	~22	Hybrid cooling approach, not directly applicable to AC systems
This study (2025)	Split-type residential air conditioner	Virgin Coconut Oil (VCO)	40–58 (condenser) / 6–11 (evaporator)	4.65	~20	First application of VCO immersion cooling in residential AC, achieving significant efficiency gains

The improved thermal behavior is largely attributed to the higher heat transfer coefficient of liquids over gases [23], as well as the continuous surface contact in immersion cooling. Newton's law of cooling governs convection, in which a fluid with a lower temperature can extract heat more efficiently from solid surfaces [24][25]. Additionally, the use of finned chambers increased the heat exchange surface area, enhancing the cooling effect [26][27].

Furthermore, VCO as a dielectric fluid offers a sustainable and safe alternative to synthetic oils. Based on SNI 7381:2008 [34] and tested under IEC 156 [35], VCO exhibited a breakdown voltage of 29.17 kV, deemed sufficient for household AC units operating at 220–240 V.

Table 2 clearly demonstrates that previous immersion cooling studies have predominantly focused on electronic and electrochemical systems, with limited applicability to HVAC systems. In contrast, the present study provides direct experimental validation of immersion cooling performance in a residential air conditioning system using VCO, including key performance indicators such as COP and energy savings.

To further emphasize the research gap, Table 2 presents a quantitative comparison between selected previous studies on immersion cooling and the present work. As shown, most existing research focuses on electronic devices, data centers, and battery systems, with limited data on performance indicators, such as the Coefficient of Performance (COP) and energy savings, relevant to air conditioning applications. None of these studies has explored the use of Virgin Coconut Oil (VCO) or applied immersion cooling to residential split-type air conditioners. In contrast, this study demonstrates the first experimental application of VCO-based immersion cooling in a household AC system, achieving a condenser temperature range of 40–58 °C, an evaporator temperature range of 6–11 °C, a COP of 4.65, and approximately 20% energy savings. These results highlight the novelty and contribution of the current research in bridging the gap between immersion cooling technology and residential HVAC applications.

Furthermore, Kussumardianadewi et al. [37] emphasized the importance of integrating energy-efficient, sustainable technologies into building systems to improve overall performance and reduce operational costs. The approximately 20% reduction in electrical energy consumption observed in this study indicates that immersion cooling with VCO can help achieve these sustainability goals, particularly in residential HVAC applications.

In addition, Iskandar et al. [38] highlighted that system performance optimization is strongly dependent on system design and operating conditions. The stable temperature profiles observed in both the condenser and evaporator components in this study indicate that the proposed immersion-cooling configuration provides a more uniform and controlled thermal environment than conventional air-cooled systems.

Overall, compared to previous studies by Sukarman et al. [36], Kussumardianadewi et al. [37], and Iskandar et al. [38], this research introduces a novel application of immersion cooling in residential air conditioning systems using a biodegradable dielectric fluid. This approach not only improves thermal performance but also enhances energy efficiency and environmental sustainability.

Compared to previous studies, the present work demonstrates a novel application of immersion cooling in residential HVAC systems using a natural dielectric fluid. Most prior research has focused on electronics, batteries, and data centers, with limited evaluation of system-level performance such as COP in air conditioning systems. The obtained COP value of 4.65 and the approximately 20% energy savings are consistent with, and in some cases exceed, those reported for electronic cooling applications. This indicates that immersion cooling using VCO is not only technically feasible but also competitive with conventional air-cooling technologies, particularly in tropical climates where thermal loads are relatively high.

CONCLUSION

This study demonstrates the feasibility of applying immersion cooling technology using Virgin Coconut Oil (VCO) as a dielectric medium in residential split-type air conditioning systems. The system achieved stable thermal performance, with condenser temperatures ranging from 40 °C to 58 °C and evaporator temperatures between 6 °C and 11 °C. An average Coefficient of Performance (COP) of 4.65 was obtained, along with approximately 20% reduction in electrical energy consumption.

The results confirm that VCO possesses suitable thermophysical and dielectric properties for effective cooling. Compared to conventional air-cooled systems, the proposed approach offers advantages in energy efficiency, noise reduction, and environmental sustainability.

The findings highlight the potential of VCO-based immersion cooling as an energy-efficient, low-noise, and eco-friendly alternative for future air-conditioning technologies, particularly in tropical regions. Future work should focus on long-term reliability testing, oil aging behavior, and system integration studies to validate commercial scalability and lifecycle performance.

This research contributes to expanding the application of immersion cooling technology from electronics to HVAC systems. Future work should focus on long-term operational stability, oil degradation characteristics, and system scalability to support real-world implementation.

ACKNOWLEDGMENT

The authors would like to thank the Electricity and Control LAB Team for providing the facilities that enabled this research to be carried out and published properly.

REFERENCES

[1] A. Wahab, A.-U.-H. Najmi, H. Senobar, N. Amjady, H. Kemper, and H. Khayyam, "Immersion cooling innovations and critical hurdles in Li-ion battery cooling for future electric vehicles," *Renewable and Sustainable Energy Reviews*, vol. 211, p. 115268, Apr. 2025, doi: 10.1016/j.rser.2024.115268.

[2] X. Li, L. Lv, X. Wang, and J. Li, "Transient thermodynamic response and boiling heat transfer limit of dielectric liquids in a two-phase closed direct immersion cooling system," *Thermal Science and Engineering Progress*, vol. 25, p. 100986, Oct. 2021, doi: 10.1016/j.tsep.2021.100986.

[3] I. W. Kuncoro, N. A. Pambudi, M. K. Biddinika, and C. W. Budiyanto, "Optimization of immersion cooling performance using the Taguchi Method," *Case Studies in Thermal Engineering*, vol. 21, p. 100729, Oct. 2020, doi: 10.1016/j.csite.2020.100729.

[4] J. W. Han, K. S. Garud, E. H. Kang, and M. Y. Lee, "Numerical Study on Heat Transfer Characteristics of Dielectric Fluid Immersion Cooling with Fin Structures for Lithium-Ion Batteries," *Symmetry (Basel).*, vol. 15, no. 1, 2023, doi: 10.3390/sym15010092.

[5] N. A. Pambudi, A. Sarifudin, R. A. Firdaus, D. K. Ulfa, I. M. Gandidi, and R. Romadhon, "The immersion cooling technology: Current and future development in energy saving," *Alexandria Eng. J.*, vol. 61, no. 12, pp. 9509–9527, Dec. 2022, doi: 10.1016/j.aej.2022.02.059.

[6] P. Birbarah *et al.*, "Water immersion cooling of high power density electronics," *International Journal of Heat and Mass Transfer*, vol. 147, p. 118918, Feb. 2020, doi: 10.1016/j.ijheatmasstransfer.2019.118918.

[7] N. Agung Pambudi, A. Muhamad Yusuf, and A. Sarifudin, "The Use of Single-Phase Immersion Cooling by Using Two Types of Dielectric Fluid for Data Center Energy Savings," *Energy Engineering*, vol. 119, no. 1, pp. 275–286, 2022, doi: 10.32604/EE.2022.017356.

[8] A. Niazmand, P. Murthy, S. Saini, P. Shahi, P. Bansode, and D. Agonafer, "Numerical Analysis of Oil Immersion Cooling of a Server Using Mineral Oil and Al2O3 Nanofluid," in *ASME 2020 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems*, American Society of Mechanical Engineers, Oct. 2020. doi: 10.1115/IPACK2020-2662.

[9] B. B. Kanbur, C. Wu, S. Fan, and F. Duan, "System-level experimental investigations of the direct immersion cooling data center units with thermodynamic and thermoeconomic assessments," *Energy*, vol. 217, p. 119373, Feb. 2021, doi: 10.1016/j.energy.2020.119373.

[10] R. Kong, H. Zhang, M. Tang, H. Zou, C. Tian, and T. Ding, "Enhancing data center cooling efficiency and ability: A comprehensive review of direct liquid cooling technologies," *Energy*, vol. 308, p. 132846, Nov. 2024, doi: 10.1016/j.energy.2024.132846.

[11] M. Suresh Patil, J.-H. Seo, and M.-Y. Lee, "A novel dielectric fluid immersion cooling technology for Li-ion battery thermal management," *Energy Conversion and Management*, vol. 229, p. 113715, Feb. 2021, doi: 10.1016/j.enconman.2020.113715.

[12] E. Solai, M. Guadagnini, H. Beaugendre, R. Daccord, and P. Congedo, "Immersion Cooling of a Lithium-Ion Battery Pack: Experimental Dataset and Numerical Simulation Under Uncertainties," *SSRN Electronic Journal*, 2021, doi: 10.2139/ssrn.3946848.

[13] M. G. Bashirov, A. S. Khismatullin, and E. V. Sirotina, "Cooling System Oil-Immersed Transformers with the Use of a Circulating Sulfur Hexafluoride," SSRN Electronic Journal, 2020, pp. 613–621. doi: 10.1007/978-3-030-39225-3_67.

[14] E. Manikandan *et al.*, "A comprehensive review on the impact of nanofluid in solar photovoltaic/thermal system," *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering*

Science, vol. 236, no. 9, pp. 5078–5096, May 2022, doi: 10.1177/09544062211055651.

[15] T. Sudhakar, R. Muniraj, T. Jarin, and S. Sumathi, “Nanofluid-enhanced vegetable oil blends: a sustainable approach to breakthroughs in dielectric liquid insulation for electrical systems,” *Biomass Conversion and Biorefinery*, vol. 15, no. 6, pp. 9011–9034, Mar. 2025, doi: 10.1007/s13399-024-05681-4.

[16] P. Dubey, G. Pulugundla, and A. K. Srouji, “Direct Comparison of Immersion and Cold-Plate Based Cooling for Automotive Li-Ion Battery Modules,” *Energies*, vol. 14, no. 5, p. 1259, Feb. 2021, doi: 10.3390/en14051259.

[17] P. Chen, S. Harmand, and S. Ouenzerfi, “Immersion cooling effect of dielectric liquid and self-rewetting fluid on smooth and porous surface,” *Applied Thermal Engineering*, vol. 180, p. 115862, Nov. 2020, doi: 10.1016/j.applthermaleng.2020.115862.

[19] C. Zhang, H. Wang, Y. Huang, L. Zhang, and Y. Chen, “Immersion liquid cooling for electronics: Materials, systems, applications and prospects,” *Renewable and Sustainable Energy Reviews*, vol. 208, p. 114989, Feb. 2025, doi: 10.1016/j.rser.2024.114989.

[20] Z. Jiang *et al.*, “A high-efficiency immersion cooling system with integrated flow distribution plates for vehicle-scale high-energy-density battery modules,” *Energy*, vol. 330, p. 136885, Sep. 2025, doi: 10.1016/j.energy.2025.136885.

[21] D. B. Olawade, T. T. Popoola, E. Egbon, and A. C. David-Olawade, “Sustainable healthcare practices: Pathways to a carbon-neutral future for the medical industry,” *Sustainable Futures*, vol. 9, p. 100783, Jun. 2025, doi: 10.1016/j.sftr.2025.100783.

[22] M. Asim *et al.*, “Advancements in thermal management solutions for electric vehicle high-power electronics: Innovations, cooling methods, and future perspectives,” *Journal of Energy Storage*, vol. 111, p. 115344, Mar. 2025, doi: 10.1016/j.est.2025.115344.

[23] C.-H. Zou, D. Li, T. Yan, and Y.-L. Zhou, “Numerical investigation of coupled heat transfer between He-Xe gas and liquid lithium for intermediate heat exchanger of space reactor,” *Applied Thermal Engineering*, vol. 275, p. 126909, Sep. 2025, doi: 10.1016/j.applthermaleng.2025.126909.

[24] Y.-D. Ye *et al.*, “A multi-physics model-based approach for macro-structured surface design to enhance heat transfer in R410A flash spray cooling systems,” *International Journal of Heat and Mass Transfer*, vol. 247, p. 127179, Sep. 2025, doi: 10.1016/j.ijheatmasstransfer.2025.127179.

[25] S. Jain and K. R. Sharma, “Numerical analysis of MHD Casson fluid with non-linear mixed and bio-convection over a non-linear vertical stretching sheet, considering multiple slip and suction/injection effects,” *Thermal Advances*, vol. 3, p. 100034, Jun. 2025, doi: 10.1016/j.thradv.2025.100034.

[26] D. S. Loenko and M. A. Sheremet, “Effect of solid/porous finned system on cooling of heat-generating element in a cavity filled with non-Newtonian nanosuspension and bottom heat-conducting substrate,” *Energy*, vol. 329, p. 136663, Aug. 2025, doi: 10.1016/j.energy.2025.136663.

[27] Y. Mou *et al.*, “Experimental and simulation-guided novel design of finned air-gap cooling plate for enhancing vacuum air-gap membrane distillation efficiency,” *Journal of Membrane Science*, vol. 732, p. 124264, Aug. 2025, doi: 10.1016/j.memsci.2025.124264.

[28] J. Liu, Q. Yang, S. Huang, and H. Wang, “Optimization of battery thermal management system based on phase change materials coupled with immersion cooling,” *Journal of Energy Storage*, vol. 127, p. 117118, Aug. 2025, doi: 10.1016/j.est.2025.117118.

[29] M. Azarifar, M. Arik, and J.-Y. Chang, “Liquid cooling of data centers: A necessity facing challenges,” *Applied Thermal Engineering*, vol. 247, p. 123112, Jun. 2024, doi: 10.1016/j.applthermaleng.2024.123112.

[31] C. Wang, H. Yu, L. Xian, G. Liu, L. Chen, and W.-Q. Tao, “Study on the operation strategy of the water cooling system in the single-phase immersion cooling data center considering cooling tower performance,” *Energy and Buildings*, vol. 324, p. 114890, Dec. 2024, doi: 10.1016/j.enbuild.2024.114890.

[32] G. Liu, Y. Ding, S. Ma, C. Sui, and L. Xiang, “Impact of thermal and electric energy storage on operational costs and emissions of ship with different propulsion systems,” *Journal of Energy Storage*, vol. 128, p. 117215, Aug. 2025, doi: 10.1016/j.est.2025.117215.

[33] N. I. Labra-Cáceres, L. F. Grisales-Noreña, R. I. Bolaños, J. A. Guzmán-Henao, and O. D. Montoya, “Energy management system for PV-based distributed generators in AC microgrids using an adapted JAYA optimizer to minimize operational costs, energy losses, and CO2 emissions,” *Results in*

Engineering, vol. 25, p. 104397, Mar. 2025, doi: 10.1016/j.rineng.2025.104397.
[34] N. S. Prasanna, M. Selvakumar, N. Choudhary, and K. S. M. S. Raghavarao, “Virgin coconut oil: wet production methods and food applications – a review,” *Sustain. Food Technol.*, vol. 2, no. 5, pp. 1391–1408, 2024, doi: 10.1039/D4FB00093E.
[35] D. B. Olawade, T. T. Popoola, E. Egbon, and A. C. David-Olawade, “Sustainable healthcare practices: Pathways to a carbon-neutral future for the medical industry,” *Sustainable Food Technology*, vol. 9, p. 100783, Jun. 2025, doi: 10.1016/j.sftr.2025.100783.
[36] Sukarman et al., “Heat transfer and pressure characteristics of Tri Ethylene Glycol/water and Ethylene Glycol/water mixtures in copper pipe heated flow systems,” *SINERGI*, vol. 29, no. 3, pp. 563–572, 2025, doi: 10.22441/sinergi.2025.3.001.
[37] B. D. Kussumardianadewi, A. E. Husin, and L. Sinaga, “Renewable energy in chemical industrial buildings for cost performance,” *SINERGI,* vol. 29, no. 1, pp. 21–32, 2025, doi: 10.22441/sinergi.2025.1.003.
[38] H. R. Iskandar, E. Taryana, and Y. B. Zainal, “Modelling and analysis of rooftop PV as an energy optimization of flat roof and gable roof mounting system,” *SINERGI*, vol. 28, no. 1, pp. 1–12, 2024, doi: 10.22441/sinergi.2024.1.001.