RiCE: Research in Chemical Engineering

Volume 2. No. 1. 2023

Journal homepage: https://ejournal.ump.ac.id/index.php/rice

A Brief Review and Its Incorporation with Bibliometric Analysis of Phase Change Materials for Thermal Energy Storage

Farikha Maharani[1], Indah Hartati[1*]

[1]Department of Chemical Engineering, Wahid Hasyim University,
Semarang, Central Java, Indonesia, 50232
Email: hartatiprasetyo@gmail.com

Article Info

Submit:
16 June 2023

Revision:
10 August 2023

Accepted:
11 August 2023

First Online:
13 August 2023

ABSTRACT

Reduction of Food Losses and Wastes (FLW) through the use of cold chain is one strategy applied in accelerating the SDGs goals of zero hunger. The application of Thermal Energy Storage (TES) based on PCM (Phase Change Material) is considered as one of best efforts for the simultaneous reduction of food losses and wastes, reduction of energy consumption as well as preserve the right temperature for food product. This paper presents the review of phase change material for thermal energy purposes and its bibliometric analysis. Bibliometric analysis on term of cold chain logistics show that there is correlation between cold chain and terms of optimization, vehicle routing, carbon emission, refrigeration, and phase change materials. The definition of TES and PCM, as well as the advantages of TES based on latent material are described in this paper. PCMs is classified into solid-solid, solid-liquid, solid-gas and liquid-gas based on its phase. The potential generation of gas and larger volume on solid-gas and liquid-gas PCMs limits the application of those two types of PCMs. PCMs is also classified according to the phase change temperature in which low, medium and high temperature PCMs. Organic, inorganic and composite based PCMs are the classification of PCMs based on the chemical composition. Among the types of PCMs, this paper present a deep review of paraffin based organic PCMs. The appearance of term of thermal conductivity in bibliometric analysis on term of organic phase change materials is due to organic PCMs commonly have low thermal conductivity.

Keywords: cold chain, PCMs, bibliometric, thermal energy storage

1. Introduction

In 2015, the United Nations drew up Sustainable Development Goals (SDGs) in which one of its goals is Zero Hunger. Policies and strategies have been set in order to accelerate zero hunger. One of strategies for zero hunger acceleration is reduction of food losses and wastages (FLW) [1]. Food Losses (FL) is defined as the process of food loss in production and distribution stage prior of consumption stage. Food loss during production chain can occur in the pre-harvest, postharvest, storage, packaging and distribution stages (FAO, 2011). In the meantime, Food Waste (FW) is defined as qualified and consumable food but for some reasons cannot be-used or be-consumed [2].

FAO stated that the total of FLW is up to 1.3 billion tons per year which is one-third of world food production. The food loss is up to 630 million tons while the food waste is up to 670 billion tons per year [1], [2]. The recent update mentioned that 13.8% of food loss occurs on postharvest stage (FAO, 2019; UNEP, 2021). Furthermore, as much as 44% of food waste is generated on 2018 in Indonesia as reported in the data of the Ministry of Environment and Forestry (MoEF) of the Republic of Indonesia. Saudi Arabia and Indonesia are the two largest FLW producing countries in the world. The production of FLW in Indonesia is reaching 300 kg per capita per year [3].

The FLW causes negatives impact on the environment as well as on our social and economics. The global contribution of FLW on the release of greenhouse gas emissions is approximately 4.4 giga tons. The FLW generation is also impacting the economics loss. It is estimated that the loss is up to IDR 213-551 trillion/year during 2000-2019. The economics loss number is equal to 4-5% of Indonesia's

GDP [3]. On the other side, it is predicted that population in developed countries is increasing and results in the increasing of the world food supply and demand. It is estimated that the food demand has increased more than 60%. One of the main challenges in fulfilling food supply is the high rate of food losses especially in stage of production and distribution. One effort that can be applied in reducing food losses in production and distribution stages is by applied cold chain (CC) in which developed from the harvesting stage of perishable product towards the final consumers.

2. Cold Chain

Cold Chain is a series of activities ensuring that freshness of food can be maintained on the appropriate and suitable condition along the supply chain. Cold chain is initiated from the harvesting, pre-conditioning, transportation, retail and serving stage in order to minimize the loss due to FLW [4], [5]. From a financial point of view, FLW has caused tremendous impact as it is estimated that global financial loss due to FLW is up to 940 billion US dollar per year. Green gas emission due to FLW is up to 4,4 giga tons per year where the imperfection of cold chain of food supply contribute 2.5% of the global carbon emission [6]. Basically, cold chain adopts refrigeration system based on high global warning potential (GWP) refrigerant. Refrigeration system on cold chain is also exploits fossil fuel-based electricity and diesels. Furthermore, the overall refrigeration system is contribute up to 30% of global energy consumption [7]–[9]. Therefore, in latest few decades, we are move together to reduce at least 40% of Green House Gas (GHS) emission on 2030.

The investigation of cold chain and its correlation with the refrigeration and carbon emission is depicted on bibliometric analysis of published paper with keywords of cold chain logistic (Figure 1). It was shown that several big nodules appear in yellow color, in which represent the state of the art of recent keywords found in latest publication, i.e optimization, vehicle routing, carbon emission, refrigeration, and phase change materials. Optimization, vehicle routing and carbon emission have a high correlation since cold chain system for perishable and seasonal product have high requirement on the choice of refrigerant and storage conditions, vehicle selection, and vehicle routing. There are several model and algorithm applied in optimize the cold chain logistics system such as ribonucleic acid-ant colony optimization algorithm [10], and location-routing-inventory problem model [11].

Refrigeration and phase change materials are two other nodules that appear in overlay visualization of bibliometric analysis of published paper with keywords of cold chain logistic as seen on Figure 1. It might be due to that one type of technology that is considered as the best option for supporting the GHS emission reduction goals is the utilization of energy storage technology. Thermal Energy Storage (TES) based on PCM (Phase Change Material) is considered as one of solution for the reduction of energy consumption as well as simultaneously preserving the right temperature for food product.

3. Phase Change Materials Based Thermal Energy Storage

PCMs are special materials which absorb, store and release high amount of energy during phase change at an almost constant temperature [1], [6], [12]. The energy is called latent heat of fusion therefore PCMs are known as Latent Heat Storage (LHS) materials while PCM based TES is also commonly known as Latent Thermal Energy Storage (LTES). In comparison with TES based on sensible materials, TES based on latent material is considered having several advantages. In order to store a certain amount of heat, TES system based on sensible materials will gain final temperature higher than the one of latent material based TES. Therefore, equipment or system with LTES can operate on a lower temperature in which impact on the lower risk of food product deterioration, lower cost of production, increase the safety and reliability of the cold chain process with LTES technology [1], [4], [13]–[15].

PCM based TES has been investigated and applied in cold chain of food supply as in domestic refrigerator, cabinet display, cold storage, and refrigerated vehicles. Incorporation of PCM near the evaporator and refrigerator show that PCM increase the condensation and evaporation temperature up to 2-4^0 C. Optimization of on/off duration of the compressor reduce the energy up to 9%. The application of PCM on the refrigeration system reduce the compressor work duty as much as 27.6% and the energy saving is as much as 13% [1], [6].

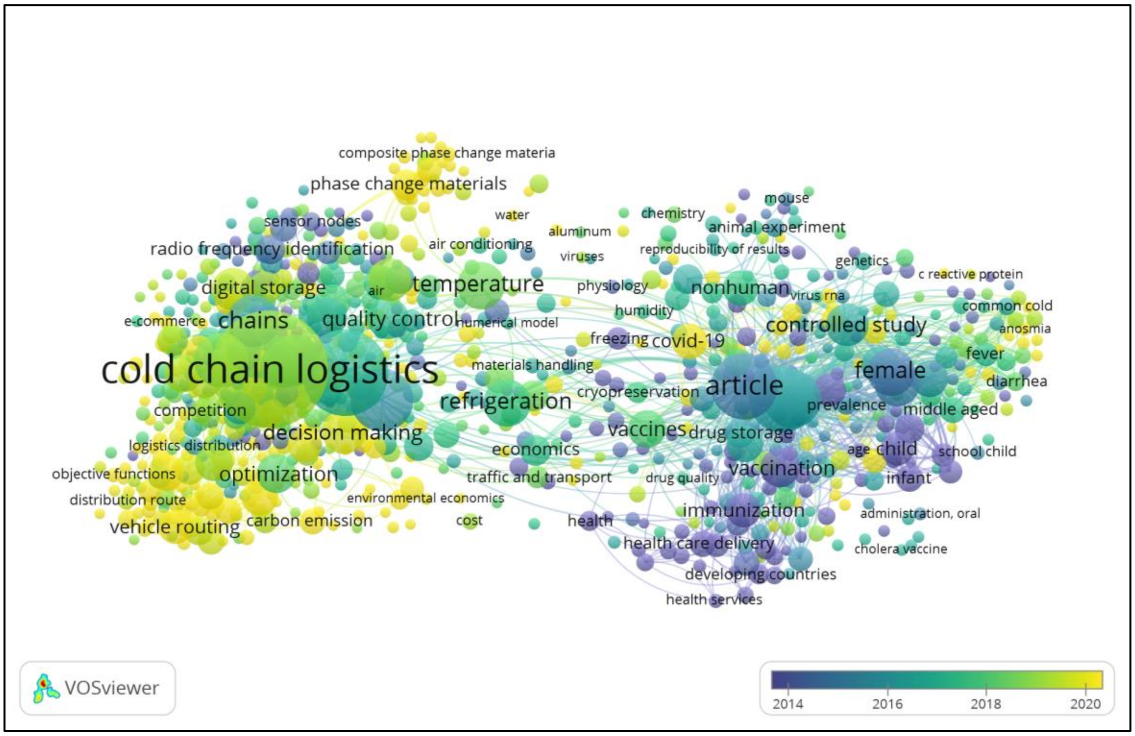

Figure 1. Overlay visualization of bibliometric analysis of published paper with keywords of cold chain logistic

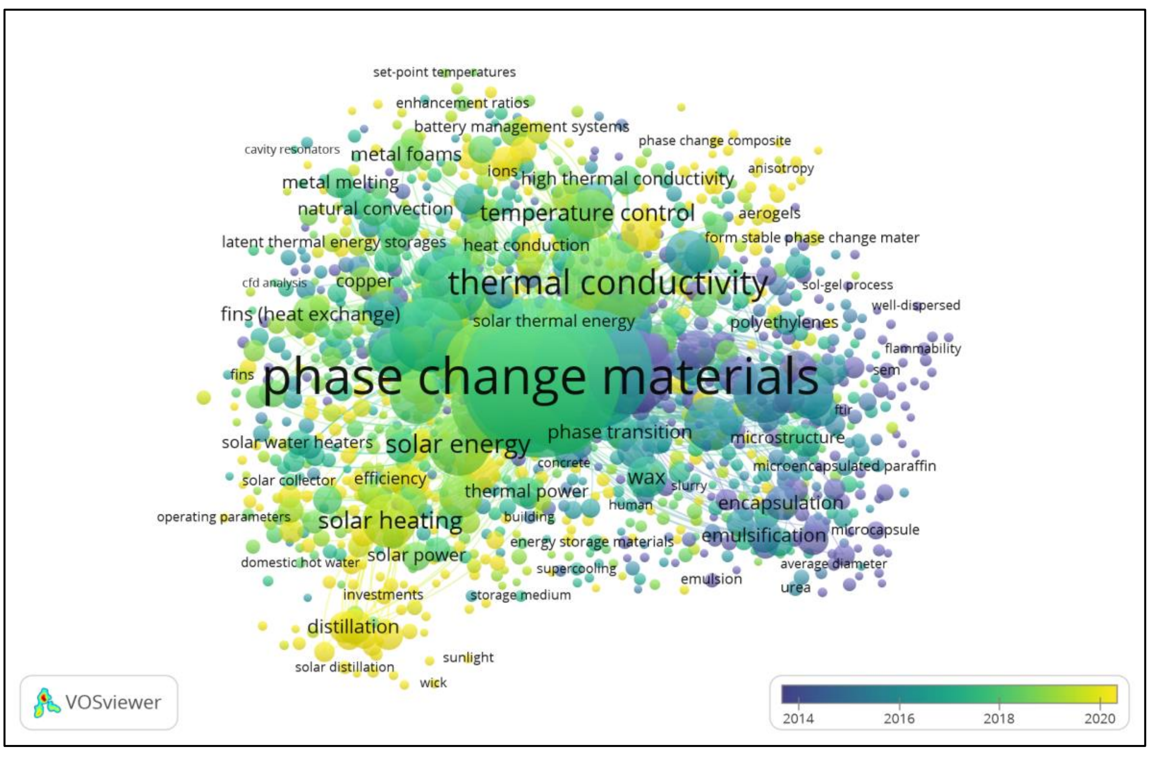

Figure 2. Overlay visualization of bibliometric analysis of published paper with keywords of organic phase change materials

Table 1. Paraffin based PCMs and its application

PCMs /Refferences	Application	Characterization	Performance
Paraffin-Lauric Acid-Expanded Graphite/ [26]	Thermal Management System for Baterry	- Thermal conductivity: 1.22 W/(mk) - melting enthalpy: 146.9 J/g - melting temperature: 36.1°C	- Maximum temperature of battery: <43°C - Temperature difference: 1.96°C
Paraffin -Expanded Graphite/[27]	Heat storage system	- thermal conductivity: 7.06 W/(m°C), - density: 1.07 g/cm3	- Average thermal efficiency: 95.3%
Paraffin-Aluminium[13]	Solar heat storage	- Density: 844 kg/m3 - Melting temperature: 53.5 - Latent heat of fusion: 266 kJ/kg - Thermal conductivity: 4.11 W/mK - Specific heat: 2.476 kJ/kg K	- Enhancement of heat transfer and heat gain - Reduction of charging time
Paraffin-Carbon Nanotubes/[28]	Thermal energy storage	- SEM and EDX characterization: no microcracks. - FTIR and TGA: good chemical compatibility and thermal stability	- The thermal storage efficiency: 71%,
LLDPE-Paraffin-Expanded graphite[29]	Heat storage	- SEM, DCS and FTIR profile of the LLDPE/W/EG composites	- The weight loss of the Shape Stabilized PCMs with addition of 15 wt% EG is 25% over 210 days - Reduction of paraffin leakage is up to 50% - Higher photostability - The melting enthalpy of SSPCMs is decreasing during aging

4. PCMs Classification

Based on its phase, PCM can be generally divided into solid-solid, solid-liquid, solid-gas and liquid-gas [5]. Polyurethane polymer synthesized from polyethylene glycol [16], as well as polyethylene glycol and cellulose [17] are example of polymer materials of PCMs. Glycol, glycerin, hexitol, 1–3 Butylene Glycol, maltitol and galactitol are some of solid-solid PCMs from polyols group [18]. Moreover $C_{10}Mn$, $C_{10}Cu$, $C_{12}Mn$, $C_{12}Cu$, $C_{14}Cu$, $C_{16}Cu$ are example of organometals PCMs [19]. Furthermore, solid liquid PCMs can be classified into organic, inorganic and eutectics. Solid gas and liquid gas PCMs are considered not practical although they are have large latent heat. The main reason for the less practical of solid-gas and liquid gas PCMs is the large volume generate by gas during phase change process. Among all of the PCMs, solid-solid PCMs have several advantages such as: (i) no leakage, (ii) no gas generation, (iii) minimum failure and corrosion of the equipment, and (iv) suitable for application in limited space. Meanwhile, low phase transition temperature, large latent heat, and no significant volume change during phase change process are advantages of solid liquid PCMs [5].

PCMs for cold energy storage purposes can also be classified according to their phase change temperature as well as their chemical composition. According to their phase change temperature, PCMs is classified into low, medium and high temperature PCMs. Low temperature PCMs is having phase change temperature less than 100°C, while medium and high temperature PCMs are having phase change temperature of 100-250°C and higher than 250°C, respectively. Moreover, according to the chemical composition, PCM can be classified into organic, inorganic, and composite-based PCM [20]. Among the various latent heat storage materials available, organic phase change materials (OPCMs) have attracted considerable attention owing to their safety, chemical stability, and compatibility with common materials [14]. Bibliometric analysis on term of organic phase change materials reveal that nodule of thermal conductivity is appear relatively bigger than the other nodules (Figure 2). The appearance of term of thermal conductivity is logic since the major challenge of the application of PCMs is that they have low thermal conductivity. Various attempts have been investigated for enhancing the thermal conductivity of organic PCMs. The thermal conductivity of organic PCMs can be enhanced by: (i) incorporation of high thermal-conductive nanoparticles within PCM; (ii) nanoinclusion of PCMs, (iii) metal, foams and wools insertion into PCMs matrix; (iv) production of composite of PCMs with powder graphite, fiber or expanded graphite [21], [22].

Furthermore, the two main structures of organic PCMs are hydrogen and carbon. Organic PCMs are usually classified as paraffin and non-paraffin. Paraffin based PCMs is comprised of straight chain alkanes (paraffin waxes), while non-paraffin based PCMs are comprised of poly-ethylene glycols, fatty acids and their derivatives, as well as poly-alcohols and their derivatives [14]. Paraffin waxes in which usually consist of straight-chain n-alkanes (CH_3-$(CH_2)n$-CH_3) ranging from C-10 (n-dodecane) to 54 (n-Octacosane) are typically having medium and low-temperature phase change and considered as one of the most important groups of PCMs. Kahwaji and White [23] stated that a good PCMs should have a broad range of melting temperature. The melting point of PCMs should match the temperature range of the application. Paraffin waxes are have a broad range of melting temperature ranging from -30°C to 95°C [23]. They are also has a lot of advantages such as have high latent heat, high enthalpy of fusion, low steam pressure during melting, no phase separation during repetitive phase transitions, chemically and thermally stable, self-nucleation, inert, reliable, long lasting, inexpensive, non-corrosive, low super cooling, good solid-state formability, odorless, accessible, ecologically safe, non-toxic and compatible with several material such as aluminium alloys, stainless steel, most copper, nickel and magnesium alloys and type I PVC [14], [15], [23]–[25].

All those attractive features of paraffin PCMs have made paraffin waxes and their mixtures being investigated for various energy storage applications (Table 1). However, paraffin is also known for some disadvantages which limits their practical application such as the limited availability, possibility of reactions during the phase change, facile leakage, phase separation after long-term use, limited biodegradability, relative high price, nearly flammable, low heat conductivity, and they are not compatible with several materials such as polypropylene, cast acrylic, silicone rubber, ABS plastic and nylon [23], [25].

5. Conclusion

The application of TES based on PCM is considered as one of best efforts for the simultaneous reduction FLW as part of strategies of accelerating the SDGs goals of zero hunger. The application of TES based on PCM also impact on reduction of energy consumption as well as preserve the right temperature for food products. Bibliometric analysis on term of cold chain logistics show optimization, vehicle routing and carbon emission have high correlation since cold chain system for perishable and seasonal product have high requirement on the choice of refrigerant and storage conditions, vehicle selection, and vehicle routing. Refrigeration and phase change materials nodules also appear in overlay visualization of bibliometric analysis since that PCM is considered as the best option for supporting the GHS emission reduction goals is the utilization of energy storage technology. PCMs is classified into solid-solid, solid-liquid, solid-gas and liquid-gas based on its phase. The potential generation of gas and larger volume on solid-gas and liquid-gas PCMs limits the application of those two types of PCMs. PCMs is also classified according to the phase change temperature in which low, medium and high temperature PCMs. Organic, inorganic and composite based PCMs are the classification of PCMs based on the chemical composition. Term of thermal conductivity appears on bibliometric analysis on keywords of organic phase change materials. The appearance of thermal conductivity is due to the major challenge of the application of organic PCMs as the result of their low thermal conductivity. Various attempts such as (i) incorporation of high thermal-conductive nanoparticles within PCM; (ii) nanoinclusion of PCMs, (iii) metal, foams and wools insertion into PCMs matrix; (iv) production of composite of PCMs with powder graphite, fiber or expanded graphite have been investigated for enhancing the thermal conductivity of organic PCMs.

Refferences

[1] M. Calati, K. Hooman, and S. Mancin, "Thermal storage based on phase change materials (PCMs) for refrigerated transport and distribution applications along the cold chain: A review," *Int. J. Thermofluids*, vol. 16, no. October, p. 100224, 2022, doi: 10.1016/j.ijft.2022.100224.

[2] J. M. Boiteau and P. Pingali, "Can we agree on a food loss and waste definition? An assessment of definitional elements for a globally applicable framework," *Glob. Food Sec.*, vol. 37, no. July 2022, p. 100677, 2023, doi: 10.1016/j.gfs.2023.100677.

[3] Bappenas, "Food Loss and Waste in Indonesia Supporting the Implementation of Circular Economy and Low Carbon Development," pp. 1–111, 2021.

[4] N. Lin, C. Li, D. Zhang, Y. Li, and J. Chen, "Emerging phase change cold storage materials derived from sodium sulfate decahydrate," *Energy*, vol. 245, p. 123294, 2022, doi: 10.1016/j.energy.2022.123294.

[5] Y. Sha, W. Hua, H. Cao, and X. Zhang, "Properties and encapsulation forms of phase change material and various types of cold storage box for cold chain logistics: A review," *J. Energy Storage*, vol. 55, no. PA, p. 105426, 2022, doi: 10.1016/j.est.2022.105426.

[6] S. Burgess, X. Wang, A. Rahbari, and M. Hangi, "Optimisation of a portable phase-change material (PCM) storage system for emerging cold-chain delivery applications," *J. Energy Storage*, vol. 52, no. PB, p. 104855, 2022, doi: 10.1016/j.est.2022.104855.

[7] M. Noro, R. M. Lazzarin, and F. Busato, "Solar cooling and heating plants: An energy and economic analysis of liquid sensible vs phase change material (PCM) heat storage," *Int. J. Refrig.*, vol. 39, pp. 104–116, 2014, doi: 10.1016/j.ijrefrig.2013.07.022.

[8] T. Schröder, L. P. Lauven, T. Sowlati, and J. Geldermann, "Strategic planning of a multi-product wood-biorefinery production system," *J. Clean. Prod.*, vol. 211, pp. 1502–1516, 2019, doi: 10.1016/j.jclepro.2018.12.004.

[9] E. Gao, Z. Zhang, Q. Deng, H. Jing, X. Wang, and X. Zhang, "Techno-economic and environmental analysis of low-GWP alternative refrigerants in cold storage unit under year-round working conditions," *Int. J. Refrig.*, vol. 134, no. July 2021, pp. 197–206, 2022, doi: 10.1016/j.ijrefrig.2021.11.007.

[10] L. Y. Zhang, M. L. Tseng, C. H. Wang, C. Xiao, and T. Fei, "Low-carbon cold chain logistics using ribonucleic acid-ant colony optimization algorithm," *J. Clean. Prod.*, vol. 233, pp. 169–180, 2019, doi: 10.1016/j.jclepro.2019.05.306.

[11] K. Li, D. Li, and D. Wu, "Carbon Transaction-Based Location-Routing- Inventory Optimization for Cold Chain Logistics," *Alexandria Eng. J.*, vol. 61, no. 10, pp. 7979–7986, 2022, doi: 10.1016/j.aej.2022.01.062.

[12] L. Dash and P. Anna Mahanwar, "a Review on Organic Phase Change Materials and Their Applications," *Int. J. Eng. Appl. Sci. Technol.*, vol. 5, no. 9, pp. 268–284, 2021, doi: 10.33564/ijeast.2021.v05i09.045.

[13] A. Khyad, H. Samrani, M. N. Bargach, and R. Tadili, "Energy storage with PCMs: Experimental analysis of paraffin's phase change phenomenon & improvement of its properties," *J. Mater. Environ. Sci.*, vol. 7, no. 7, pp. 2551–2560, 2016.

[14] S. Rashidi, M. Samimifar, M. H. Doranehgard, and L. K. B. Li, *Organic Phase Change Materials*. Elsevier Ltd., 2021.

[15] N. Sarier and E. Onder, "Organic phase change materials and their textile applications: An overview," *Thermochim. Acta*, vol. 540, pp. 7–60, 2012, doi: 10.1016/j.tca.2012.04.013.

[16] C. Alkan, E. Günther, S. Hiebler, Ö. F. Ensari, and D. Kahraman, "Polyurethanes as solid-solid phase change materials for thermal energy storage," *Sol. Energy*, vol. 86, no. 6, pp. 1761–1769, 2012, doi: 10.1016/j.solener.2012.03.012.

[17] M. Wojda and T. M. Wójcik, "Novel solid - Solid phase change material based on polyethylene glycol and cellulose used for temperature stabilisation," *MATEC Web Conf.*, vol. 18, pp. 0–3, 2014, doi: 10.1051/matecconf/20141803009.

[18] S. N. Gunasekara, R. Pan, J. N. Chiu, and V.

Martin, “Polyols as phase change materials for surplus thermal energy storage,” *Appl. Energy*, vol. 162, pp. 1439–1452, 2016, doi: 10.1016/j.apenergy.2015.03.064.

[19] A. Fallahi, G. Guldentops, M. Tao, S. Granados-Focil, and S. Van Dessel, “Review on solid-solid phase change materials for thermal energy storage: Molecular structure and thermal properties,” *Appl. Therm. Eng.*, vol. 127, pp. 1427–1441, 2017, doi: 10.1016/j.applthermaleng.2017.08.161.

[20] T. Feng, J. Ji, and X. Zhang, “Research progress of phase change cold energy storage materials used in cold chain logistics of aquatic products,” *J. Energy Storage*, vol. 60, no. October 2022, p. 106568, 2023, doi: 10.1016/j.est.2022.106568.

[21] Z. Ling, J. Chen, T. Xu, X. Fang, X. Gao, and Z. Zhang, “Thermal conductivity of an organic phase change material/expanded graphite composite across the phase change temperature range and a novel thermal conductivity model,” *Energy Convers. Manag.*, vol. 102, pp. 202–208, 2015, doi: 10.1016/j.enconman.2014.11.040.

[22] L. Fan and J. M. Khodadadi, “Thermal conductivity enhancement of phase change materials for thermal energy storage: A review,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 1, pp. 24–46, 2011, doi: 10.1016/j.rser.2010.08.007.

[23] S. Kahwaji and M. A. White, “Organic Phase Change Materials for Thermal Energy Storage: Influence of Molecular Structure on Properties,” *Molecules*, vol. 26, pp. 1–18, 2021, doi: 10.1016/j.pmatsci.2014.03.005.

[24] Z. Sunxi, Z. Xuelai, L. Sheng, L. Yuyang, and X. Xiaofeng, “Performance study on expand graphite/organic composite phase change material for cold thermal energy storage,” *Energy Procedia*, vol. 158, pp. 5305–5310, 2019, doi: 10.1016/j.egypro.2019.01.642.

[25] N. Payam, F. Yashar, and J. Fatemeh, “Phase Change Material (PCM) as the Smart Heat-Storing Concept: A Brief Review,” *Ann. Mar. Sci.*, vol. 6, no. 1, pp. 034–038, 2022, doi: 10.17352/ams.000029.

[26] G. Zhang, Y. Sun, C. Wu, X. Yan, W. Zhao, and C. Peng, “Low-cost and highly thermally conductive lauric acid–paraffin–expanded graphite multifunctional composite phase change materials for quenching thermal runaway of lithium-ion battery,” *Energy Reports*, vol. 9, pp. 2538–2547, 2023, doi: 10.1016/j.egyr.2023.01.102.

[27] Y. Li, Z. Fu, M. Xue, Z. Shao, Y. Li, and Q. Zhu, “Experimental study on preparation and thermal storage properties of expanded graphite/paraffin wax as a shape-stabilized phase change material,” *Energy Reports*, vol. 8, pp. 324–331, 2022, doi: 10.1016/j.egyr.2022.09.149.

[28] N. H. Almousa *et al.*, “Paraffin wax [as a phase changing material (Pcm)] based composites containing multi-walled carbon nanotubes for thermal energy storage (tes) development,” *Crystals*, vol. 11, no. 8, pp. 1–14, 2021, doi: 10.3390/cryst11080951.

[29] I. Krupa, P. Sobolčiak, H. Abdelrazeq, M. Ouederni, and M. A. Al-Maadeed, “Natural aging of shape stabilized phase change materials based on paraffin wax,” *Polym. Test.*, vol. 63, pp. 567–572, 2017, doi: 10.1016/j.polymertesting.2017.09.027.