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Fatty acid from recycled waste cooking oil as a phase-change material for thermal storage systems

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Fatty acids derived from waste cooking oil (WCO) are successfully processed as sustainable phase-change materials (PCMs) for thermal energy storage. This study investigated the conversion of WCO into fatty acid-based PCMs through hydrolysis and hydrogenation, optimizing reaction parameters to enhance thermal properties. A logarithmic model was developed to describe the relationship between hydrogenation time and the adjustment of melting point. The study also examined the correlation between WCO-derived fatty acids (WCOFAs) and their chemical structure, providing insights into optimizing hydrogenation conditions to achieve desired melting points (between 15 °C and 60 °C). The effects of different oil mixtures on thermal characteristics, such as melting point and latent heat, were analyzed to tailor WCOFA-based PCMs for industrial applications. Experimental results indicated that increasing hydrogenation time reduces carbon–carbon double bonds, increasing the melting point and latent heat, with fully hydrogenated WCOFAs exhibiting properties comparable to those of commercial PCMs (~150 J g^{-1}). This study highlights WCOFAs as cost-effective, environmentally friendly alternatives for thermal energy storage, contributing to sustainable waste management and resource utilization.

Introduction

Waste cooking oil

Fried foods are very popular all over the world because of their appealing color, aroma, and crispy texture. These features come from one of the oldest food preparation processes, deep frying.[1] Deep frying processes have been scientifically developed for people's health. During this process, cooking oil is hydrolyzed, polymerized, and thermally degraded (autoxidized), leading to the production of free fatty acids and cyclic/acyclic polymers. These products are considered as polar compounds.[2] When the amount of total polar compounds in the cooking oil is >25%, the oil reaches its reusability limit in food preparation and is classified as waste cooking oil (WCO).[2] WCO can be harmful to the environment and people if not properly disposed, similar to other chemicals released in daily life from kitchen waste, household materials, furniture, and cars.[3,4] For example, disposing of WCO into local water systems can cause eutrophication, which results in the disordered growth of microorganisms, phytoplankton, and algae. This disordered growth can affect the balance of the ecological environment.[5] If WCO is disposed of into the sewer system, it would cause pollution in the wastewater recycling systems. If WCO is buried in solid waste landfills, it would cause soil pollution.[5] Moreover, illegally reprocessing WCO into gutter oil for reuse would be unhealthy.[6] WCO is generated every day, posing serious environmental problems. The European Union estimates that about 1 million tons of WCO are generated every year.[7] The WCO production is about 5.6 million tons in China, 1.1 million tons in India, 1.2 million tons in the United States, and 0.57 million tons in Japan.[8] In the European Union, the capacity of the WCO refinery industry is over 21 tons per year, with only 11.6 tons being recycled. Approximately 8.1 million tons of WCO is generated in Brazil every year, but only 2.5% of them is recycled.[8]

The most common method for WCO recycling is processing it into biodiesel. The chemical reaction for biodiesel synthesis is a transesterification process. This process offers the advantages of being low cost and operating under mild conditions.[9] However, the resulting biodiesel is costly because of its high viscosity, thereby necessitating further modification. Otherwise, it cannot be directly used in normal diesel engines. Mixing with regular diesel (about 5–20%) may be required for use.[10] The

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results of previous research indicated that the cost of producing biodiesel from WCO was about 65.3% higher than that of producing regular diesel because of the pretreatment cost (15.6% of the total cost).[11] Therefore, recycling the WCO into biodiesel may not be economically feasible. In addition, due to the concern of fossil fuel pollution and the increasing market of hybrid and electric vehicles (EVs), most of the fossil fuel vehicles will be phased out and replaced by EVs.[12] Therefore, there is an urgent demand for an alternative method for WCO recycling.

Fatty acid phase-change material

Triglycerides are the main component (>95%) of WCO.[8] They are esters containing one glycerol and three fatty acids (Fig. 1), making them a good source of fatty acids. Fatty acids are known as a common type of organic phase-change materials (PCMs). They can be separated from the triglycerides with certain chemical reactions, which subsequently leads to the generation of three fatty acids and one glycerol. The byproduct of this reaction, glycerol, is the source for many products in medical and food industries.

Hydrolysis is a chemical reaction in which water is used to break down a compound. In the context of fats and oils, this involves the reaction of triglycerides (the main constituents of vegetable oils) with water to produce glycerol and fatty acids; the reaction can be expressed as follows:

$$\text{Triglyceride} + 3H_2O \rightarrow \text{glycerol} + 3\text{fatty acids}$$

The hydrolysis of triglycerides is typically catalyzed by either an acid or a base. Acid-catalyzed hydrolysis is known as acidolysis, whereas base-catalyzed hydrolysis is called saponification. Both methods are used to produce fatty acids from triglycerides. WCO contains considerable amounts of triglycerides, which can be converted into free fatty acids and glycerol through hydrolysis. This process not only recycles waste oils but also produces valuable fatty acids.

Most of the cooking oils are vegetable oils that contain a large amount of unsaturated fatty acid. The degree of saturation may affect the melting point of fatty acid. The hydrogenation process can increase the degree of saturation of waste cooking oil fatty acid (WCOFA). Hydrogenation is a chemical reaction that involves the addition of hydrogen (H_2) to an unsaturated compound, typically in the presence of a catalyst, such as platinum, palladium, or nickel;[13] the general reaction can be expressed as follows:

$$C_nH_{2n} + H_2 \rightarrow C_nH_{2n+2}$$

It shows in this reaction that the unsaturated fatty acids (with double bonds) are converted into saturated ones (without double bonds). Hydrogenation increases the melting point of fatty acids. The saturation process of double bonds makes the fatty acid chains more linear and thus enables them to pack more closely together, which increases the melting temperature.

Fatty acid has been used in many insulation and thermal storage applications.[14–17] McCord *et al.* investigated decanoic acid (DA) and palmitic acid (PA) as PCMs, with melting points of 32 °C and 63 °C and latent heating of 100.98 and 154.52 J g^{-1}, respectively.[14] Nazari *et al.* developed fatty acid mixtures with coconut oil fatty acid, oleic acid (OA), and lauric acid (LA), showing specific heat of 1–5 J g^{-1} K^{-1} and latent heat up to 100 J g^{-1}, with <1% thermal degradation after 700 cycles.[15] Yuan *et al.* reviewed fatty acid PCMs, reporting that melting points (16.1–70.9 °C) and latent heat (139.8–260.0 J g^{-1}) decrease with shorter carbon chain length.[16] Liu *et al.* examined a ternary eutectic PCM (lauric acid, myristic acid, tetradecyl alcohol) and observed melting/freezing points of 28.84 °C/27.36 °C and latent heat of 194.8 and 193.8 J g^{-1}, respectively.[17]

Fatty acid is organic, natural, and non-toxic. This study investigated a method for converting the recycled WCO into a value-added fatty acid (WCOFA) to be used as an organic PCM for thermal storage application.[18,19] With the hydrogenation process, the melting point of WCOFA can be adjusted to meet the requirements for different applications. WCOFA can be a cost-effective alternative for commercial fatty acid. This study focused on the optimization of WCOFA production using sulfuric acid hydrolysis and palladium-catalyzed hydrogenation, enabling higher efficiency with lower reagent use and shorter reaction times under normal conditions. By converting WCOs into useful thermal storage materials, the overall carbon footprint of insulation and thermal storage systems can be reduced, thereby contributing to more sustainable practices.

This is the first study to explore the chemical structure–thermal property relationships of WCOFA and build the

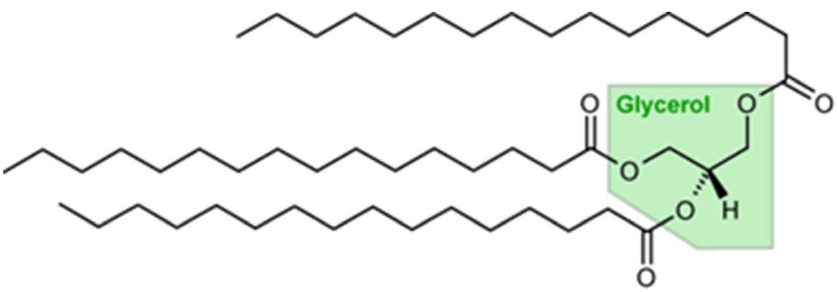


Fig. 1 Chemical structure of triglyceride.

scientific understanding on how structures/compositions affect the properties of fatty acids.

Materials and methods

Materials and equipment

Canola oil and olive oil were purchased from a local grocery store. Phosphoric acid, sulfuric acid, and sodium dodecylbenzene sulfonate (SDBS) were purchased from Sigma-Aldrich. A heating pot was used to provide the required reaction temperature for the hydrolysis process. Hydrogen gas was purchased from Airgas as the hydrogen source for the hydrogenation process. Palladium on activated charcoal (Pd/C) was purchased from Sigma-Aldrich and used as a catalyst of the hydrogenation process. An IKA C-MAG HS hot plate was used to provide the hydrogenation temperature.

Methods

Food frying involves a hydrolysis process, which facilitates the desired synthesis of fatty acids. However, other particles may also be generated from this process, such as bread flour, and some volatile compounds and invisible impurities, including protein, organic pigment and colloid.[20–22] Typically, WCO has an intense smell, which is mainly related to the volatile fraction. The volatile fraction and other invisible impurities impact the melting point (T_m) of the PCMs. Therefore, pretreatment of WCO is necessary to increase the purity of WCO and attain reproducible PCMs of high quality.

Pretreatment. A two-step pretreatment procedure has been developed. Oil (100 g) was used to synthesize fatty acids. Step 1: filtration to remove small particles using a filter. This step can be easily repeated until no visible particles are present in the WCO. Step 2: phosphoric acid treatment. This treatment has been reported to reduce acid soluble lignin (ASL), prooxidants and phospholipids in oils.[23,24]

WCO was filtered using a sieve and poured into a boiling flask. Thirty percent water was added to the boiling flask also. Then, the boiling flask was heated to 85–90 °C (temperature for treatment) in a heating pot, and the solution was stirred using a mechanical stirrer. Phosphoric acid was added under continuous stirring until the pH value reached 2–3, which allows protein decomposition, organic colorings, and deposit generation. The mixture was continuously stirred for 30 minutes and then poured into a separating funnel to remove the water solution.

Hydrolysis. The pretreated WCO is subjected to hydrolysis to prepare the desired fatty acids. The hydrolysis process is presented in Fig. 2(a). Glycerol is removed from the triglyceride, and three fatty acid molecules are produced (Fig. 3). Ester hydrolysis is a well-established reaction in organic chemistry, and many hydrolysis procedures are available in the literature.[25]

The pretreated WCO was poured into another clean and dry boiling flask equipped with a condensing device. Water as solvent, concentrated sulfuric acid as hydrolysis catalyzer, and SDBS as emulsifying agent, which accounted for 200, 10 and 8 wt% of the pretreated WCO, were added to the boiling flask, respectively.[25]

The temperature of the mixture was maintained at 200 °C under continuous stirring and condensation. The hydrolysis reaction was processed for 12 hours.[25] After hydrolysis, the mixture was poured into the separating funnel, and the lower layer of the liquid was removed (glycerol was in the lower layer). The upper layer of the liquid was obtained as WCOFA.

Hydrogenation. A hydrogenation reaction is performed for the hydrolyzed WCOs to convert unsaturated (with carbon–carbon double bonds) into saturated (alkane) fatty acids. This hydrogenation process aims to make the synthesized PCM more stable and adjust its T_m into the desired range (20–35 °C). It converts the unsaturated oleic, linoleic, and linolenic acids to saturated stearic acid, transforming them from a liquid state into a PCM suitable solid at room temperature.

The hydrogenation reaction was performed in the presence of a metal catalyst. Palladium on carbon catalyst was used as it is the most common catalyst used in the commercial hydrogenation of edible oils owing to its effectiveness in promoting the hydrogenation process.[26–28] The hydrogenation reaction can be carried out under normal environmental condition when using palladium-based catalyst. Hence, the hydrolyzed WCO was just heated to a slightly elevated temperature (70 °C) in a water bath to maintain it in the liquid state during the hydrogenation reaction process. The hydrogenation process is illustrated in Fig. 2(b). The amount of palladium carbon catalyst used in the hydrogenation reaction was only 1 wt% of the oil.

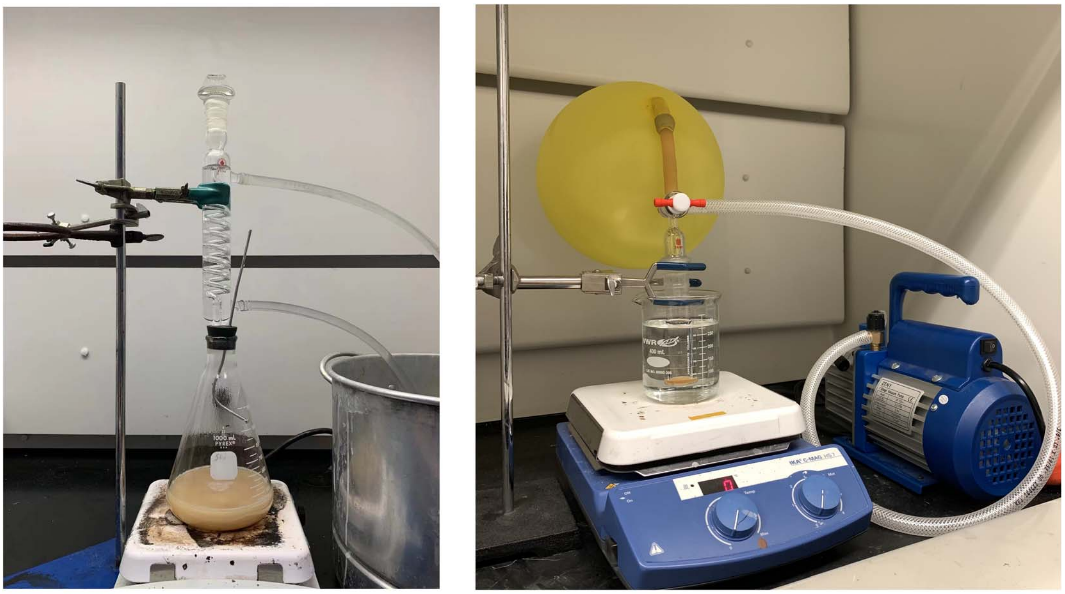
As palladium on carbon materials is relatively expensive, alternative metals, such as nickel, can also be used as the catalyst. Spongy nickel has also been used as a catalyst in some studies and industries for the hydrogenation process owing to its availability, low cost and inert nature to oil.[29–31] A nickel catalyst may require higher temperature and pressure as well as longer reaction time for the hydrogenation process;[29–31] however, nickel is relatively cheaper than palladium.

Sample preparation

Five different samples were prepared for this study; pure canola oil (sample A), canola oil 75%–olive oil 25% mixture (sample B), canola oil 50%–olive oil 50% mixture (sample C), canola oil 25%–olive oil 75% mixture (sample D), and pure olive oil (sample E).

Sample characterization

The WCOFA samples were examined *via* nuclear magnetic resonance (^{1}H NMR) spectroscopy with Varian MR 400 and infrared spectroscopy (IR) using BRUKER INVENIO R FTIR/PMA 50 to determine the chemical structure. Differential scanning calorimetry (DSC) tests were conducted on all samples to examine the thermal properties (such as melting temperature and latent heat of fusion) of WCOFA. The DSC test (PerkinElmer DSC 4000) for each sample was repeated for at least three times to obtain the average values. The temperature range in the DSC test was set at −10 °C to 80 °C and the temperature ramping rate



(a)

(b)

Fig. 2 Use of the (a) hydrolysis and (b) hydrogenation (the balloon is filled with hydrogen gas) procedures to synthesize fatty acids from WCOs.

at 2 °C min^{-1}. Nitrogen gas was used in the DSC instrument as the inert gas, with a flow rate of 20 mL min^{-1}.

Results and discussion

Nuclear magnetic resonance tests

The NMR spectroscopic data obtained for the WCOFA produced from pure olive oil (sample E) are presented in Fig. 4. Two distinct peaks observed in the range between 4.0 and 4.5 ppm are indicative of the presence of glycerol within the sample. The characteristic peaks of glycerol, a key component of triglycerides, are exhibited within this range.

After the hydrolysis process, a significant change was observed in the same range (between 4.0 and 4.5 ppm), where the two peaks associated with glycerol completely disappeared. The disappearance of these peaks suggests the successful hydrolysis of triglycerides in the WCO. During hydrolysis, the triglyceride molecules, consisting of glycerol bonded to fatty acid chains, underwent a chemical reaction that cleaved the glycerol from the fatty acids. As a result, glycerol was separated from the carbon chains, leaving behind free fatty acids as the primary component of WCOFA. This observation indicates that the hydrolysis process successfully converted the WCO into WCOFA by breaking down the triglycerides.

The glycerol produced from the hydrolysis process is a value-added byproduct and is considered to be a key ingredient due to its moisturizing, stabilizing, and emulsifying properties in pharmaceutical and cosmetic industries.

Comparison between Fig. 4(a) and (b) showed that the peak in the range between 5.0 and 5.5 ppm remained present. This peak indicated the existence of carbon–carbon double bonds within the fatty acid chains, indicating that the WCOFA were unsaturated. The presence of these double bonds is a key characteristic of unsaturated fatty acids, which would impact their chemical properties and physical behavior, such as their melting point.

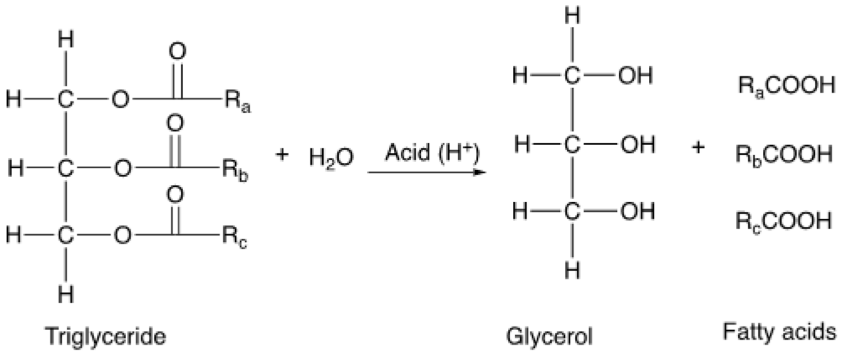
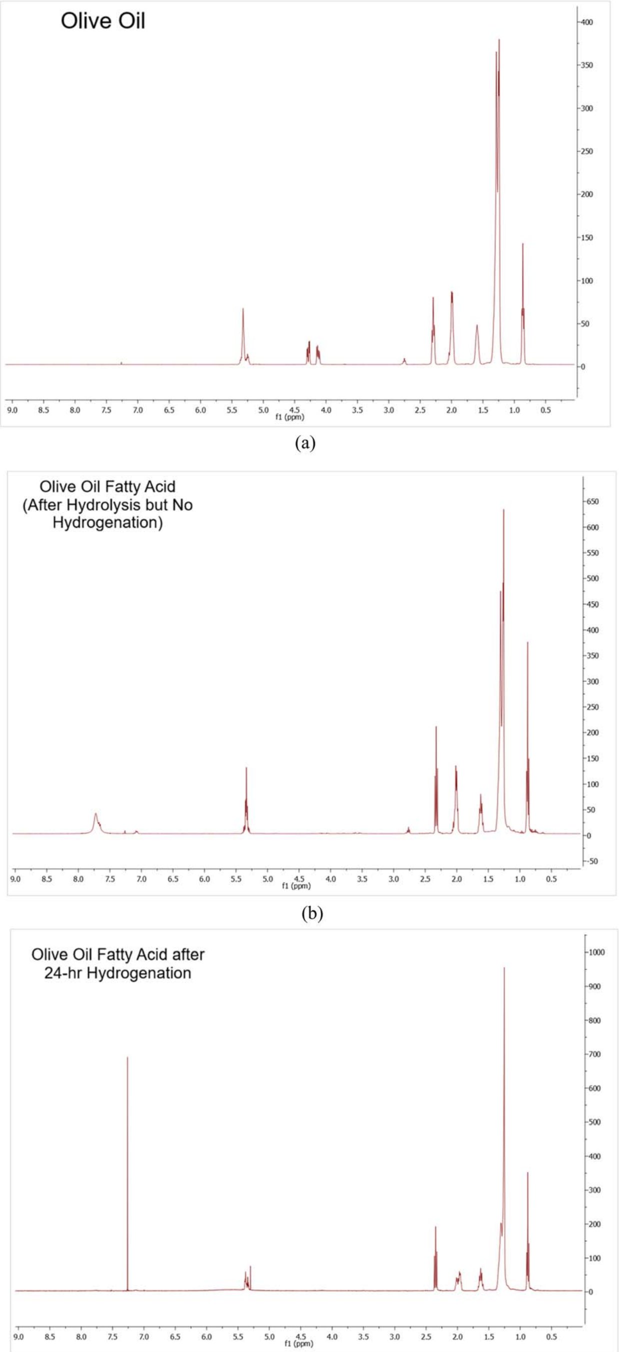


Fig. 3 Synthesis of fatty acids from WCO (triglyceride) *via* acid-catalyzed hydrolysis. Here, R_a, R_b and R_c are aliphatic chains.



(a)

(b)

(c)

Fig. 4 The NMR test results of (a) pure olive oil; (b) olive oil fatty acid (pure olive oil after the hydrolysis process); and (c) olive oil fatty acid after the hydrogenation process.

The purpose of the hydrogenation process is to break down the carbon–carbon double bonds. The process saturates the fatty acids by converting these double bonds into single bonds. The reduction in the number of double bonds increases the melting points of the WCOFAs, so that they are more solid at room temperature and their stability is enhanced for various applications.

As shown in Fig. 4(c), the peak within the 5.0–5.5 ppm range was significantly reduced after the hydrogenation process. A higher degree of saturation in the fatty acids was obtained as the double bonds have been successfully hydrogenated. This increased saturation makes them more suitable for various industrial uses where higher melting points are desired.

Infrared spectroscopy tests

All five types of fatty acids and two types of cooking oils were tested using an IR spectrometer (Fig. 5). As shown in Fig. 5, the peak observed at 1743 $\mathrm{cm^{-1}}$ corresponded to the carbonyl group (C═O) stretch in the ester functional group, represented by the chemical structure R–COOR′. This peak is characteristic of esters, which are commonly found in fats and oils, indicating the presence of ester linkages in the tested samples. Another significant peak was noted at 1705 $\mathrm{cm^{-1}}$, which is indicative of the carbonyl group (C═O) stretch in the carboxy functional group, denoted as R–COOH.

The two peaks at 2850 and 2920 $\mathrm{cm^{-1}}$ correspond to the C–H groups in the carboxylic chains. Also, the O–H bend peaks at 935 and 1413 $\mathrm{cm^{-1}}$ indicated that the O–H group from RCOOH and the C–O stretch peak at 1160 $\mathrm{cm^{-1}}$ represented the C–O group from R–COOR′. However, the O–H broad stretch peak, which is typically found between 2500 and 3300 $\mathrm{cm^{-1}}$ for all fatty acids,[32] was not clearly evidenced in Fig. 5, which could be due to the addition of SDBS during the processes. There could be a possible saponification occurring while adding SDBS, which led to the absence of O–H broad stretch peak.

Fig. 6 presents a comparison of the results of oil samples and their fatty acid samples. By overlapping the IR spectra of the oil samples and their corresponding fatty acid samples, it was observed that there were inclined curves in canola oil fatty acid and olive oil acid surrounding the C–H peaks at 2850 and 2920 $\mathrm{cm^{-1}}$. However, this phenomenon was not observed in canola oil and olive oil samples. Fatty acids are known to have an O–H stretch peak centered at 3000 $\mathrm{cm^{-1}}$. It is likely that broad O–H stretch peak was mixed with the C–H stretch peaks at 2920 and 2850 $\mathrm{cm^{-1}}$, which confirmed that the hydrolysis process was successful. Compared with the cooking oil, the spectrum of WCOFA showed shifts in several absorption bands as well as the appearance and disappearance of specific bands, consistent with the conversion of triglyceride esters into carboxylic acids.

Differential scanning calorimetry (DSC) tests

A logarithmic model was developed to describe the correlation between melting point (latent heat) and hydrogenation time:

$$y = M \times \ln x + N$$

In this model, x denotes the hydrogenation time of the reaction; y, the melting point (latent heat) of the sample after a certain time of the hydrogenation reaction; M, the reaction rate of the hydrogenation process; and N, the interception between the curve and y axis, which is also the melting point (latent heat) of samples without the hydrogenation process.

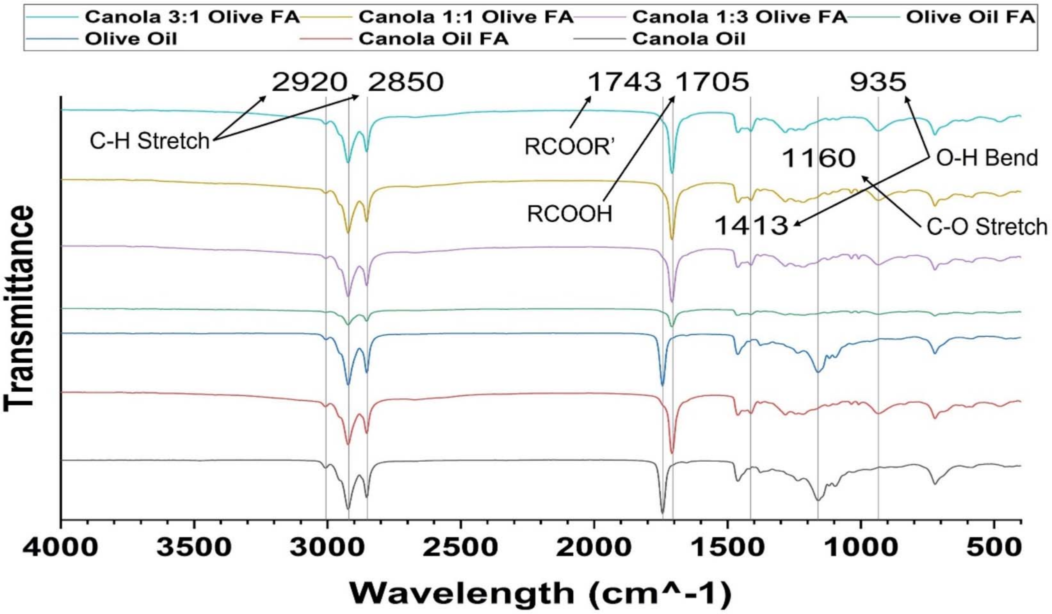


Fig. 5 IR results of all oils and fatty acids.

The logarithmic model curve-fitted data of the melting points of all samples determined from DSC are presented in Fig. 7. It is shown that the melting points of all samples increased with the hydrogenation time. At the beginning of the hydrogenation reaction, the melting points increased fast (steeper curve) as more carbon double bonds were involved in the hydrogenation reaction. As the hydrogenation reaction continued, double bonds were broken into a single bond, and the amount of carbon double bonds decreased, resulting in decreased reaction rate. After 45 minutes of hydrogenation, a much less reaction rate was observed, indicating that most of the carbon double bonds had been converted and the melting points were about to reach the highest values.

As shown in Fig. 7, there are more smoother curves of the melting point for samples A, B, C, and D than that for sample E, which was the pure olive oil fatty acid. As the hydrogenation time further increased (>10 minutes), the melting point of sample E stabilized at 68–69 °C for the heating cycle and 62–63 °C for the cooling cycle.

The logarithmic model curve fitted data of latent heat values are presented in Fig. 8. The trends of latent heat are similar to the melting point. At a short hydrogenation time, the latent heat values of all samples were extremely low. As the hydrogenation time increased, the latent heat values increased, suggesting that the higher the melting point, the higher the latent heat, indicating a lesser amount of carbon double bonds.

The highest latent heat values were provided at a hydrogenation time of 60 minutes for samples A, B, C, and D. For sample E, the fluctuation on its latent heat curve is shown, and the highest latent heat value was observed at a hydrogenation time of 20 minutes.

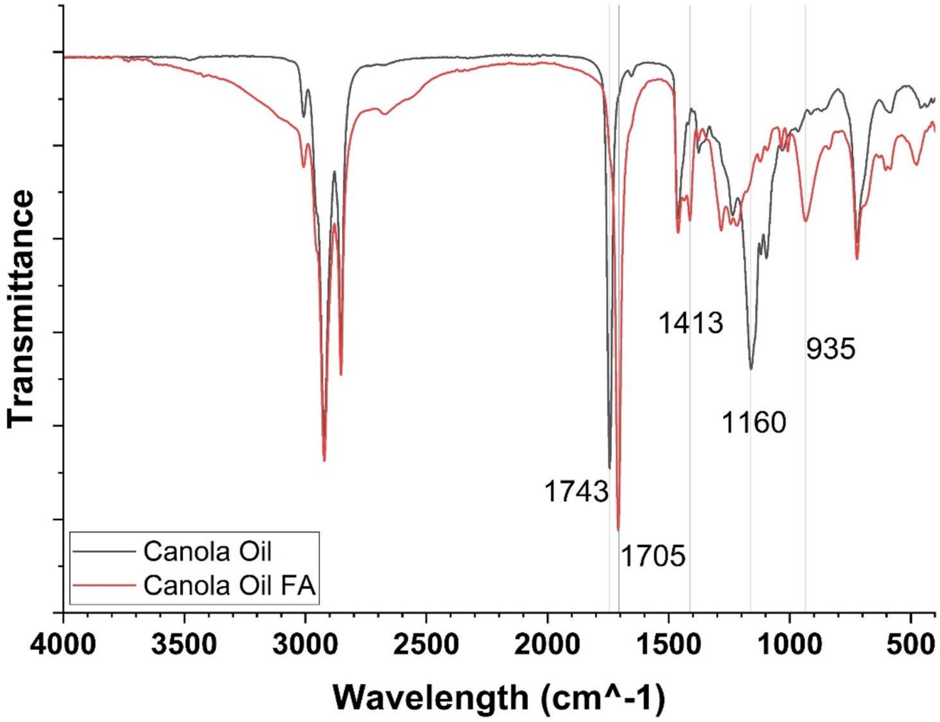
The logarithmic models of the melting point data for all samples are summarized in Table 1, whereas the logarithmic models between latent heat and hydrogenation process time are presented in Table 2.

This established logistic model accurately describes the dynamics of the hydrogenation process with $R^2 > 0.9$ for most samples.

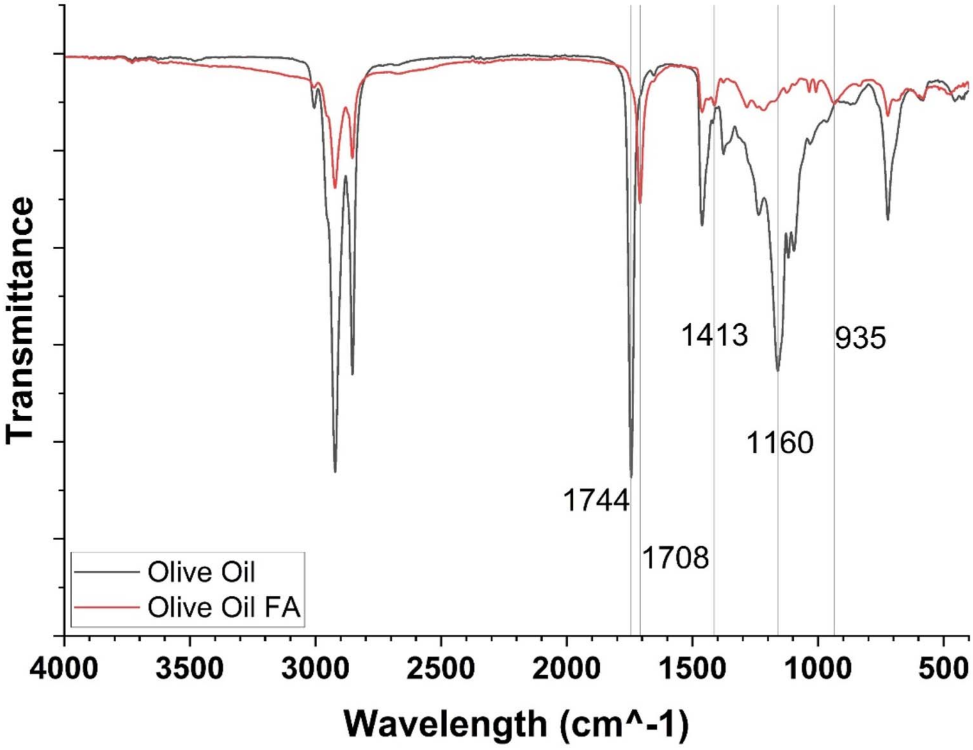
From Table 1, it can be observed that the hydrogenation reaction rate value M and the melting point values of the un-hydrogenated samples N remained at the same level for the melting point results. Notably, the effects of different oil mixture ratios were not significant, which means that whatever the mixing ratio of the oil was, the hydrogenation process could be initiated using this model.

However, the latent heat results in Table 2 show a different phenomenon compared with melting point results. The hydrogenation reaction rate value M decreased, whereas the portion of olive oil increased. The lower M value in the model indicated that the hydrogenation process in this model had a lower reaction rate than the other models, which yielded greater M value. The reason for this phenomenon is that while the portion of olive oil increased, the concentration of carbon double bonds decreased, which could significantly reduce the hydrogenation reaction rate (M value in the model).

However, in the logarithmic models of latent heat results, the N value showed an opposite trend to the M value. The N value indicated the latent heat of samples without hydrogenation. As the increased portion of olive oil would reduce the concentration of carbon double bonds in the oil mixture, it can be concluded that the concentration of carbon single bond increased with the portion of olive oil. It also meant that the oil mixture was more saturated. Therefore, as the portion of olive oil increased, the latent heat value of the samples without hydrogenation also increased, causing the N value (latent heat values of samples without hydrogenation) to increase.



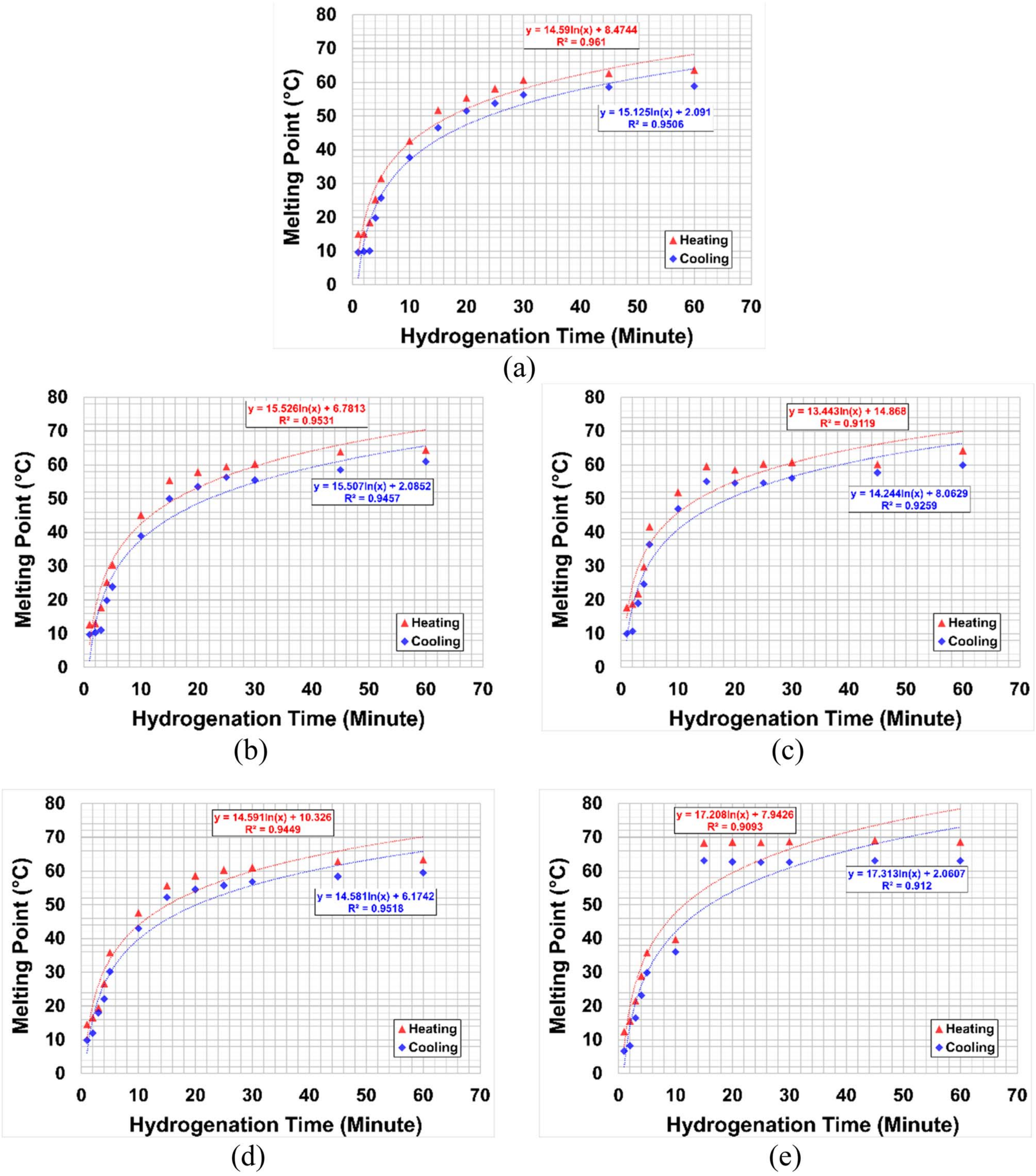
(a)



(b)

Fig. 6 IR result comparisons between (a) canola oil and canola oil fatty acid and (b) olive oil and olive oil fatty acid.

These two logarithmic models accurately describe the changes in the melting point and latent heat during the hydrogenation process. As the degree of saturation increases, the melting point of the fatty acids rises, and the latent heat, which reflects the energy required to change the state of the fatty acids, changes correspondingly. The models not only fit



(a)

(b)

(c)

(d)

(e)

Fig. 7 Logarithmic model curve fitted data of the melting points of all the samples at different hydrogenation times: (a) sample A, (b) sample B, (c) sample C, (d) sample D, and (e) sample E.

the theoretical understanding of the process but also closely align with the experimental data, demonstrating their validity.

Moreover, these models match the observed experimental phenomena, reinforcing their accuracy. For example, the increase in the melting point as hydrogenation progresses is consistent with the observed solidification of the fatty acids, whereas the logarithmic decrease in the reaction rate reflects the slowing down of the process as saturation is approached. This consistency between the models and experimental results provides a robust framework for understanding the hydrogenation process and predicting the behavior of fatty acids under varying conditions.

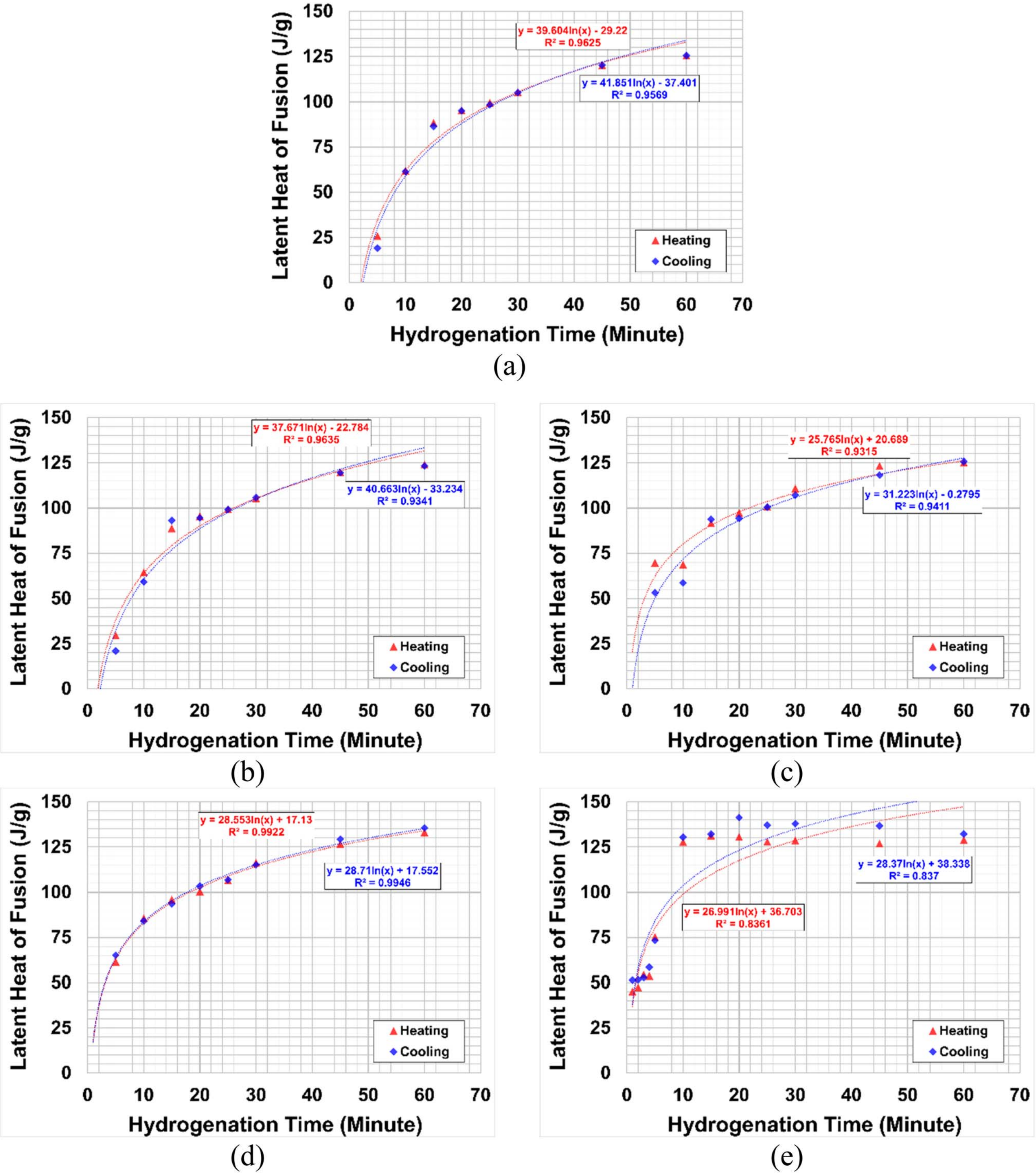


Fig. 8 Logarithmic model curve fitted data of latent heat of all the samples at different hydrogenation times: (a) sample A, (b) sample B, (c) sample C, (d) sample D, and (e) sample E.

Thermal properties of WCOFA PCM

The DSC results indicate that hydrogenated WCOFAs exhibit melting points in the range of 15–60 °C and latent heat values approaching 150 J g^{-1}. As shown in Table 3, the obtained melting point and latent heat values are comparable to those reported for fatty acid-based PCMs[14–19] and other commercial PCM products.[33] This similar thermal performance suggests that the hydrogenation process effectively converts unsaturated fatty acids into more thermally stable saturated structures, thereby increasing the enthalpy of phase transition.

The relatively broad melting temperature range of the hydrogenated WCOFAs is attributed to the coexistence of

Table 1 The melting point *versus* hydrogenation of all WCOFA samples

Sample	Relation	R^2 value
A (heating)	$y = 14.59\ln(x) + 8.4744$	0.961
B (heating)	$y = 15.526\ln(x) + 6.7813$	0.9531
C (heating)	$y = 13.443\ln(x) + 14.868$	0.9119
D (heating)	$y = 14.591\ln(x) + 10.326$	0.9449
E (heating)	$y = 17.208\ln(x) + 7.9426$	0.9093
A (cooling)	$y = 15.125\ln(x) + 2.091$	0.9506
B (cooling)	$y = 15.507\ln(x) + 2.0852$	0.9457
C (cooling)	$y = 14.244\ln(x) + 8.0629$	0.9259
D (cooling)	$y = 14.581\ln(x) + 6.1742$	0.9518
E (cooling)	$y = 17.313\ln(x) + 2.0607$	0.912

Table 2 The latent heat *versus* hydrogenation of all WCOFA samples

Sample	Relation	R^2 value
A (heating)	$y = 39.604\ln(x) - 29.22$	0.9625
B (heating)	$y = 37.671\ln(x) - 22.784$	0.9635
C (heating)	$y = 25.765\ln(x) + 20.689$	0.9315
D (heating)	$y = 28.553\ln(x) + 17.13$	0.9922
E (heating)	$y = 26.991\ln(x) + 36.703$	0.8361
A (cooling)	$y = 41.851\ln(x) - 37.401$	0.9569
B (cooling)	$y = 40.663\ln(x) - 33.234$	0.9341
C (cooling)	$y = 31.223\ln(x) - 0.2795$	0.9411
D (cooling)	$y = 28.71\ln(x) + 17.552$	0.9946
E (cooling)	$y = 28.37\ln(x) + 38.338$	0.837

multiple saturated fatty acid species with varying carbon chain lengths. This feature may be advantageous for applications requiring thermal regulation across a wider temperature interval, rather than a sharp phase transition at a narrow temperature range. Furthermore, the high latent heat values further indicate the suitability of WCOFAs for efficient thermal energy storage, particularly in low-to-medium temperature applications, such as building energy management and solar thermal systems.

Different cooking oil types and their mixtures have been used in this study. The initial composition of the WCO feedstock had a limited influence on the hydrogenation outcome and resulting thermal properties. Therefore, the hydrogenation reaction of varied original WCO compositions results in a similar saturated fatty acid distribution. Consequently, the thermal performance of the resulting WCOFAs remains predictable and reproducible across the different waste oil sources used in this study. This finding is critical for large-scale implementation, as it alleviates concerns related to feedstock variations.

Table 3 Melting points and latent heats of common fatty acid and commercial PCMs

	Melting point (°C)	Latent heat (J g^{-1})
Decanoic acid	32	100.98
Palmitic acid	63	154.52
Oleic acid and lauric acid mixture		100
Ternary eutectic PCM (lauric acid, myristic acid, and tetradecyl alcohol)	28.84	194.8
Commercial PCM from PureTemp	68	213

Relation between structure and thermal properties

As shown in Fig. 4(b) and (c), after the 60 min hydrogenation process, the peaks of carbon double bonds within the range of 5.05.5 ppm significantly decreased compared with the fatty acids without the hydrogenation, as shown in Fig. 4(b) and (c). Meanwhile, Fig. 7(e) and 8(e) present the melting points and latent heat of fusion of olive oil fatty acid with and without 60 min hydronation process. It can be concluded that the olive oil fatty acid without hydrogenation had more carbon double bonds on the carboxylic chains. This chemical character led to a lower melting point and latent heat of fusion. After hydrogenation was applied, the amount of carbon double bonds decreased (Fig. 4(b) and (c)), whereas the melting point (Fig. 7) and latent heat (Fig. 8(e)) increased. Therefore, the relationship between the amount of carbon double bonds in the fatty acid carboxylic chains and the melting point/latent heat of fusion was determined. As more carbon double bonds are in the chemical structure of olive oil fatty acid, the melting point and latent heat of the fatty acid were relatively lower than those of the olive oil fatty acid with lesser amount of carbon double bonds. In addition, as there was a limited amount of carbon double bonds, when the carbon double bonds were completely consumed by hydrogenation, the melting point and latent heat reached the highest value as the fatty acid was fully saturated. Most WCOs contained similar carboxylic chains. Their WCOFAs have similar relationship between the amount of carbon double chains and the melting point/latent heat of fusion. The mixing ratio of different WCOs only slightly affects the thermal performance.

While the carbon double bonds were completely consumed by hydrogenation, the melting point and latent heat of WCOFAs would reach their highest value and would not be increased.

Conclusions

Hydrolysis and hydrogenation were successfully employed to convert WCO into fatty acid-based PCM for thermal energy storage applications. Through hydrolysis and hydrogenation, the triglycerides in WCO were broken down into free fatty acids, and their degree of saturation was systematically modified to tailor thermal properties. A key outcome of this research is the development of a logarithmic model that quantitatively describes the association between hydrogenation time, melting point, and latent heat. The model demonstrates that as hydrogenation progresses, carbon–carbon double bonds are reduced, leading to a considerable increase in melting point and latent heat.

The experimental results indicated that fully hydrogenated WCOFAs exhibited melting points ranging from 15 °C to 60 °C, with latent heat values reaching approximately 150 J g^{-1}, which was comparable to other common fatty acid PCMs[14–19] and commercial PCMs.[33] This finding highlights the potential of WCOFAs as cost-effective and environmentally sustainable alternatives to conventional PCMs. Moreover, the study established that the composition of the initial oil mixture had a limited impact on the hydrogenation process, enabling consistent predictability of thermal properties across different WCO sources.

By repurposing waste cooking oil into valuable thermal storage materials, this study contributed to waste reduction and improved energy efficiency. The use of WCOFAs in insulation and thermal management applications can reduce reliance on synthetic PCMs, lower electricity costs, and support the development of a circular economy. The findings also highlight the feasibility of optimizing the hydrogenation process to produce tailored PCMs suitable for diverse industrial and commercial applications. Ultimately, this study presents a sustainable, scalable, and economically viable solution for converting waste oils into high-performance thermal storage materials, thereby promoting environmental conservation and resource efficiency.

Author contributions

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Conflicts of interest

There are no conflicts to declare.

Data availability

The data described in the manuscript will be available upon request.

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