

## Research Article

# Development of Date Pit–Polystyrene Thermoplastic Heat Insulator Material: Physical and Thermal Properties

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This study is aimed at developing a thermoplastic composite based on date pit powder waste for use as a thermal insulator in building industries. Date pits are the by-product of date stoning, either for the production of pitted dates or for the manufacture of date paste. The date pit powder (DPP) used in this study was obtained from the UAE University farm in Al Foah, UAE. DPP waste contents ranging from 0 wt.% to 50 wt.% were used to prepare the DPP-polystyrene composite. Date pit powder was mixed with polystyrene using a melt extruder, and then the mixture was transferred to the hot press to produce the final sample. The thermal and physical characteristics of the produced composites were measured experimentally and analyzed theoretically in terms of date pit and polystyrene properties. The characterized properties of the DPP-polystyrene composites, namely, density, thermal conductivity, water retention, thermal stability, and microstructure, showed that a stable composite material with insulation and construction capacity can be formed by the addition of date pit powder to the polystyrene matrix. The theoretical modeling of the measured thermal conductivity and the scanning electron microscope (SEM) monographs supported the hypothesis of date pit agglomeration in the composite matrix. The prepared composites showed low thermal conductivity (0.0515–0.0562 W/m K at 25°C) and very low density (457–630 kg/m<sup>3</sup>), thus demonstrating their potential for use as a thermal insulator for building materials. In addition, replacing one-third of the classical construction wall content with DPP-polystyrene composite showed promise for constructive applications as a thermal insulator with 85% reduction in the overall thermal conductivity. Indeed, these properties are similar to those of other conventional insulating materials. This will lead to produce an inexpensive insulation material that exploits a common waste product in date fruit-producing countries.

## 1. Introduction

In 2016, 39.5% of the energy worldwide was used to heat and cool buildings [1]. The amounts of energy used to control the temperature of residential and commercial buildings that year were 16843 and 15,082 trillion BTU, respectively [1]. According to the U.S. Energy Information Administration [2], 52% of the total energy in U.S. homes was used for space heating in 2016. This percentage could have been higher in countries with hot climate, such as the United Arab Emirates (UAE). By 2012, electricity consumption in the UAE had reached a value of 10.17 MW h/capita [1]. By 2013, electricity demand in the UAE had reached 105 billion kilowatt hours,

placing the UAE among the highest electricity consumers per capita in the world. Moreover, the electricity power demand has been reported to increase by 10% annually [3]. Therefore, considerable research has recently been devoted to minimizing energy consumption.

The use of natural fibers and powders to reinforce polymers is a well-established practice, and bio-based composites are increasingly used in different industrial sectors such as automotive and construction [4, 5]. The low density of natural fibers makes them as suitable synthetic fiber (e.g., glass, carbon, and aramid fibers) substitutes for different applications. Although in a lot of cases, the addition of natural fibers to polymer matrices reduces its mechanical strength [5–7],

the specific mechanical properties of natural fibers come closer to those of synthetic fibers. In addition, the use of natural fibers in polymer composites has many advantages like their low cost, renewability, biodegradability, nontoxicity, insulation capacity, and low machine wear [7]. A broad variety of fibers with different physical, thermal, and mechanical properties are abundantly available in nature for the development of high-performance composites.

Date palm trees are widespread in many areas of the world. In 2011, worldwide date production was more than seven million tons. Almana and Mahmoud [8] reported that the pits account for around 10% of the total weight of dates. Aldhaheeri et al. [9] studied the chemical composition of the pits of three different date palm trees planted in UAE. The date pits were found to contain six ingredients in varying amounts, namely, neutral detergent fiber, acid detergent fiber, ash, crude protein, crude fat, and moisture. These date pits, resulting from both home consumption and date packaging factories, are considered a source of waste. Some researchers have suggested methods for the utilization of this waste in animal diets [10, 11] and in the production of activated carbon [12, 13]. Belhachemi et al. [14] found that the activated carbon prepared using date pits was as efficient as the commercial ones used in granular activated carbon (GAC). On the other hand, Azeem et al. [15] reported that date pits can provide high-quality biodiesel due to their physiochemical properties, thus demonstrating the possibility of producing biodiesel from date pits.

Furthermore, date pits are used as a filler in different polymer and building materials. Alami [16] added date pits and olive husk to masonry bricks. The clay with date pits exhibited higher toughness than did the clay mixed with olive husk. Alsewailam and Binkhder [6] added date pit powder to high-density polyethylene and polystyrene matrices and studied the resulting mechanical and thermal properties. While the tensile strength of the high-density polyethylene was not affected by the date pits, the polystyrene tensile strength reduced with the increasing filler content. However, the authors did not measure the thermal conductivity, compression strength, or water retention. A date pit–polyester composite thermal insulation material was developed by Abu-Jdayil and Mourad [17]. Notably, adding date pits to the polyester reduced its thermal conductivity and the prepared composites exhibited a very low water retention rate. On the other hand, Benmansour et al. [18] investigated the use of a composite material composed with natural cement, sand, and date palm fibers as insulating building materials. Water absorption, thermal conductivity, and compressive strength were experimentally investigated. Their results revealed that the incorporation of date palm fibers reduces the thermal conductivity and the compressive strength of the composite and reduces the weight as well. The effect of date palm pit particles on the properties of reinforced polyester was studied by Ameh et al. [19]. Unsaturated polyester resin was reinforced with date palm pits of 0.5, 2.0, and 2.8 mm particle sizes using variable particle loadings of 5, 10, 15, 20, and 25 wt.%. The prepared composites were subjected to various types of mechanical and physical tests in order to assess their performance. The optimum tensile

strength and the lowest water absorption were found for 0.5 mm particle size. Recently, Haddadi et al. [20] evaluated the possibility of using date palm wood in thermoset polymer matrices to obtain a low thermal conductivity composite material. Their results showed that the thermal conductivity of the polymer-based materials decreases with increasing date palm fiber concentration, while the water retention test revealed that the composites have a strong tendency to absorb water, particularly with increasing filler contents. However, the structural capacity of the prepared composites has been not investigated.

The main objective of this research is to produce a polymer–filler composite that can be used as a heat-insulating material. Polystyrene was used as the matrix due to its low thermal conductivity, and it was mixed with date pit powder (DPP) at different percentages (0–50%). The prepared composites were subjected to various thermal and physical tests to determine the thermal conductivity, density, degradation temperature, and water retention.

## 2. Materials and Methods

**2.1. Materials.** The polystyrene used in this research was provided by a national polystyrene packaging factory in Dubai, UAE. The expanded polystyrene bead size was 950  $\mu\text{m}$ . This polymer was used because its thermal conductivity, cost, and water retention are low. The date pits used in this study were obtained from UAE University farm in Al Foah, UAE. Date pits were crushed using a commercial milling machine and then sieved. Only date pit particles less than 300  $\mu\text{m}$  in size were used to produce the composites.

**2.2. Composite Fabrication.** To produce the date pit–polystyrene composites with different filler contents, date pit powder was added to polystyrene, and the resulting material was then heated and compressed. Different molds were fabricated from stainless steel according to the ASTM standards for each test. Date pit powder at various weight percentages was mixed with polystyrene using a HAAKE MiniLab II melt extruder, and the mixture was poured into the appropriate steel mold, depending on the test requirements. To prevent the specimens from sticking to the mold, it was sprayed with a mold release agent. Then, the mold was placed in a hot press under a pressure of 500 kg at 180°C for 20 minutes. Samples were prepared using different date pit powder percentages; see Table 1. The produced samples were used for different physical and thermal tests. For all tests, the results of three samples from each filler content percentage were averaged and reported.

**2.3. Density.** The density is the ratio of the composite's weight to its volume. The weight of the samples was found using four significant digits, and the sample volume was determined using a two-significant-digit caliper. While the pure polystyrene density was measured using the prepared cylindrical samples following the mentioned method, the date pit powder density was determined by finding the weight of a powder sample and dividing it by the volume of the weighted sample.

TABLE 1: Samples abbreviation.

Composite samples	Polystyrene (wt. %)	Date pit powder (wt. %)
Pure	100	0
10-DPP	90	10
20-DPP	80	20
30-DPP	70	30
40-DPP	60	40
50-DPP	50	50

**2.4. Thermal Conductivity.** Samples with dimensions of 110 mm × 110 mm × 3 mm were produced using a special mold. The thermal conductivity of each sample was measured using a LaserComp FOX-200. This instrument uses the steady-state method to determine the thermal conductivity by measuring the temperature gradient and the input power. The ASTM C1045-07 standard was followed.

**2.5. Scanning Electron Microscope (SEM) Test.** The microstructure of samples was investigated by means of scanning electron microscopy (FEI ESEM Quanta 200). All samples were coated in gold using gold sputtering before each test.

**2.6. Optical Microscopy.** An optical microscope, model Olympus DP22, was used to investigate the morphological characteristics and voids of the composites.

**2.7. Water Retention.** Cylindrical samples with a diameter of 25 mm and a height of 15 mm were produced using a different mold design to perform two different water retention tests according to the ASTM D570-98 standard. Since the samples were less dense than water, they were attached to a heavy weight using a plastic string for complete immersion. The two tests were conducted at room temperature water and in hot water (50°C) for different time intervals. During the 24 immersion tests, the samples were removed from the water at frequent intervals, dried with a dry cloth, and weighed to the nearest 0.001 g. The weighing was repeated till no change in the sample weight was noticed. This time was enough to reach the saturation equilibrium condition.

**2.8. Thermogravimetric Analysis.** A Q50 thermogravimetric (TGA) analyzer from TA Instruments was used to perform the thermal analysis. A heating rate of 10°C/min was used to increase the temperature from 30 to 850°C under nitrogen flowing at 20 ml/min.

**2.9. Thermal Conductivity Models.** Several theoretical and empirical models have been proposed in the literature to predict the thermal conductivity of polymer composites [21–23]. In this work, the simplest approach is followed to model the thermal conductivity data, where it has two limiting cases: linear mixing rule (parallel conduction model, equation 1) and inverse mixing rule (series conduction model, equation 2):

$$k = (1-\varnothing)k_p + \varnothing k_f, \quad (1)$$

$$k = \left[ \frac{(1-\varnothing)}{k_p} + \frac{\varnothing}{k_f} \right]^{-1}. \quad (2)$$

Here,  $k$ ,  $k_p$  and  $k_f$  are the thermal conductivity of the composite, polystyrene, and DPP, respectively, and  $\varnothing$  is the volume fraction of DPP.

A widely used model to describe the effect of filler particles on the thermal conductivity of a randomly dispersed particle in a polymer matrix was proposed by Hashin and Shtrikman [20, 24]:

$$\frac{k}{k_p} = \frac{1 + (d-1)\varnothing\beta}{1-\varnothing\beta}, \quad (3)$$

where

$$\beta = \frac{k_f - k_p}{k_f + (d-1)k_p}. \quad (4)$$

The above three models were used in this work to fit the experimental thermal conductivity data.

### 3. Results and Discussion

**3.1. Composite Morphology.** The morphology of the polystyrene-DPP composite prepared with 10, 20, 30, and 50 wt.% filler loading of date pit powder is shown in Figures 1–4, respectively. In general, the date pit particle is well embedded in the polystyrene matrix. However, it can be seen that there is some degree of detachment between the filler particle and the polymer which causes the formation of small voids or gaps within the matrix of the polystyrene-DPP composite. The formation of these gaps between the filler and the polymer matrix can be attributed to two factors, namely, the poor compatibility between the natural fillers and the matrix and the agglomeration of the natural fillers (see Figure 4). Specifically, the hydroxyl groups (–OH) that are present in natural fillers make them hydrophilic, whereas the polymers are hydrophobic, resulting in poor compatibility [25]. Mohammed et al. [26] reported in their review that because of pendant hydroxyl and polar groups in natural fiber, this leads to extremely high moisture absorption of fiber, resulting in weak interfacial bonding between the fiber and the hydrophobic matrix polymers. In addition, the presence of hydrogen bonds between the particles of natural fillers leads to particle agglomeration [27]. The second factor is supported by the morphology of the 50-DPP composite as shown in Figure 4.

**3.2. Composite Density.** The linear mixing rule was used to calculate the theoretical density of the prepared composites [28]:

$$\rho_{\text{composite}} = \left( \frac{w_{\text{matrix}}}{\rho_{\text{matrix}}} + \frac{w_{\text{filler}}}{\rho_{\text{filler}}} \right)^{-1}, \quad (5)$$

where  $\rho_{\text{composite}}$ ,  $\rho_{\text{matrix}}$ , and  $\rho_{\text{filler}}$  are the densities of the composite, polystyrene, and date pits, respectively. In addition,



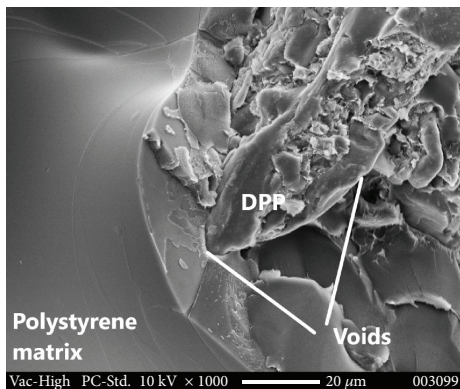


FIGURE 1: SEM of 10-DPP composite.

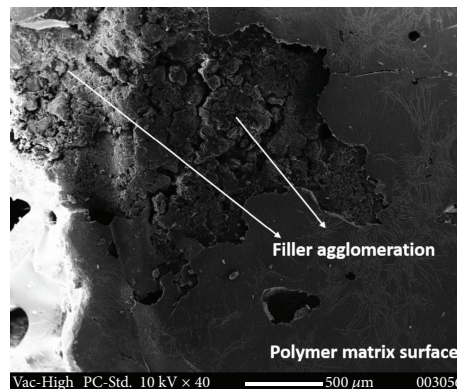


FIGURE 4: Filler agglomeration in 50-DPP composite.

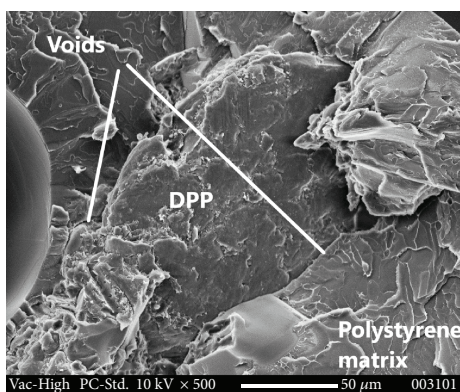


FIGURE 2: SEM of 20-DPP composite.

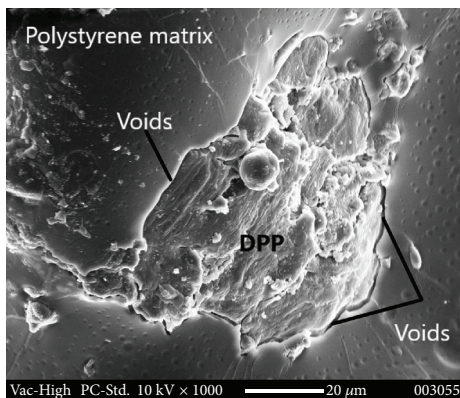


FIGURE 3: SEM of 30-DPP composite.

$w_{\text{matrix}}$  and  $w_{\text{filler}}$  are the weight fraction of polystyrene and date pits, respectively.

Figure 5 shows the comparison between the theoretical and experimental densities of the composites for different filler contents. The experimental density was found by dividing the prepared sample weight by the measured volume. The densities of pure polystyrene and date pits, which were used in equation 5, were measured experimentally to be 457 and 534 kg/m<sup>3</sup>, respectively. The theoretical density increases linearly with the increasing filler content due to the higher density of the filler than that of polystyrene. The experimental

density was higher than the theoretical density for all filler contents, and the rate of increase in the composite density with DPP content was larger than the theoretically predicted increase rate. It is known that the natural fillers induce voids when mixed with hydrophobic polymers, and the fillers agglomerate because of their hydrogen bonds [25, 27], where inducing voids in the matrix lets the experimental density to be less than the theoretical density [29]. In the current case, it seems that the beads of pure polystyrene have some gases, which produced gas voids in the fabricated samples. These voids appear as white spots in Figure 6. On composite fabrication, date pit powder may be agglomerated inside these interesting voids, thereby filling them. As shown in Figure 6 (optical microscope image) and Figure 7 (SEM images), the voids in the 20-DPP composite are noticeably smaller than the voids in pure polystyrene. This could explain the dramatic deviation between the composite density observed experimentally and that theoretically predicted.

Although the composite density increased with the filler content, the density of the 50% polystyrene–date pit composite remains lower than those of some reported composites, such as that of a wood plastic composite date-seed–concrete composite, which was found to be around 1200 kg/m<sup>3</sup> [30]. On the other hand, the density of polystyrene composites filled with 50 wt.% of DPP (630 kg/m<sup>3</sup>) is very less compared to established natural fibres like sisal (1450 kg/m<sup>3</sup>), banana (1350 kg/m<sup>3</sup>), and coir (1150 kg/m<sup>3</sup>) [31], which is an attractive parameter in manufacturing lightweight materials.

**3.3. Thermal Conductivity.** The thermal conductivity of the prepared composites was measured at different temperatures from 5 to 50°C. The thermal conductivity coefficients of the composites varied between 0.0470 and 0.0600 W/(m.K) for date pit filler contents ranging from 0% to 50%, respectively. Figure 8 demonstrates the effect of the filler content on the polystyrene thermal conductivity at room temperature. The thermal conductivity of pure polystyrene and pure date pit powder was measured experimentally at room temperature (25°C) to be 0.0515 and 0.0620 W/(m.K), respectively. The thermal conductivity of the 50-DPP composite was 0.0562 W/(m.K), which is only 9.2% greater than that of pure polystyrene. 10-DPP, 20-DPP, 30-DPP, and 40-DPP composites exhibited small increases in the thermal

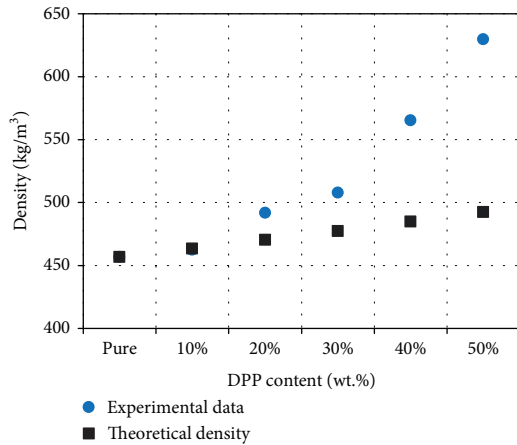


FIGURE 5: Composite density for different filler contents.

conductivity coefficients relative to that of pure polystyrene (i.e., increases of 0.37%, 2.86%, 4.63%, and 8.4% at 25°C). Considering the difference in the thermal conductivity of polystyrene and date pits may explain the slight increase in thermal conductivity with increasing the filler content.

Although increasing the percentage of date pits increases the thermal conductivity of the composite, it was still lower than that of some other developed date pit composites, e.g., polyester–date pit composites [17]. The mean value of the thermal conductivity of pure date palm samples studied by Agoudjil et al. [32] was 0.083 W/(m.K) at atmospheric pressure. The thermal conductivity of the prepared DPP-polystyrene composite materials is very promising when it is compared with the other proposed composites containing date palm fibers (0.075–0.6 W/(m.K)) [18], hemp fibers (0.115 W/(m.K)) [33], and banana fibers (0.117 W/(m.K)) [34]. On the other hand, the thermal conductivity of composites reported here is much less than the thermal conductivity of hemp, jute, and glass fiber-reinforced polyester composites studied by Subba Raju et al. [35], as the thermal conductivity of their composites varied between 0.207 and 0.190 W/(m.K) at 30°C for filler contents ranging between 18 and 36 vol.%. The thermal conductivity of banana/sisal-polyester composites was reported in the range of 0.181–0.213 W/(m.K) [36], which is greater than  $k$  values of the investigated composites.

Moreover, this composite enables replacing 50% of the polystyrene (nonbiodegradable material), which is often used in the thermal insulation industry, with a natural filler derived from waste without significantly increasing the thermal conductivity. Meanwhile, conventional construction walls are made from building bricks, concrete stone, and reinforced concrete, which have thermal conductivities of 0.72, 0.93, and 1.73 W/(m.K), respectively. The overall thermal conductivity without insulation is calculated to be 1.01 W/(m.K) using equation 6:

$$\frac{1}{K_{\text{overall}}} = \sum_{i=1}^n \frac{w_i}{k_i}, \quad (6)$$

where  $K_{\text{overall}}$  is the average thermal conductivity,  $K_i$  is the thermal conductivity of the component, and  $w_i$  is the weight

fraction of the component. If one-third of the wall by weight is made from the 50-DPP composite, the overall all thermal conductivity will be

$$\frac{1}{K_{\text{overall}}} = \sum_{i=1}^n \frac{w_i}{k_i} = \frac{0.667}{1.01} + \frac{0.333}{0.05624} = 6.58, \quad (7)$$

$$K_{\text{overall}} = 0.1519.$$

Thus, using a date pit–polystyrene composite will lead to a huge reduction in the thermal conductivity of the wall, resulting in an overall thermal conductivity of 0.1519 W/(m.K), thus representing a reduction of 84.8%.

The validity of the experimental thermal conductivity of polystyrene-DPP composites with the three theoretical models described in Section 2.9 is shown in Figure 8. For Hashin and Shtrikman mode (Equations 3 and 4), the DPP particles are assumed to be spherical, where  $d$  takes the value of 3 [24, 37]. Both the parallel conduction model and the series conduction model were used here to fit the experimental data as the all linear properties are bracketed by these two values, where the parallel model provides the lower bound and the series model provides the upper bound [23].

It is clear that both the parallel conduction model (Equation 1) and the Hashin and Shtrikman model (Equations 3 and 4) provide the best description of the thermal conductivity data of the prepared composites. This result correlates well with the morphology of the prepared composites illustrated in Figures 1–4. In the parallel conduction model (Equation 1), which is a lower-bound equation, the DPP and polystyrene matrix contribute independently to the composite thermal conductivity, in proportion to their relative volume fraction. This model tends to maximize the contribution of the filler phase and accounts for good contact between the DPP particles [23, 24]. When increasing the amount of filler in the polymer matrix, one eventually reaches a point at which particles of the filler begin to contact and form aggregates (which can be seen in Figure 4 for the 50-DPP composite). This kind of aggregates provides good particle-particle interactions that tend to maximize the effect of the filler phase, which is the basic assumption in the parallel conduction model (Equation 1). On the other hand, the Hashin and Shtrikman model (Equations 3 and 4) fits well with the experimental thermal conductivity of the prepared composites as it is considered as a lower-bound model (similar to the parallel conduction model). In addition, this model is used for random distribution of the filler in the polymer matrix, which is the case here. The presence of voids appears in Figures 1–3, having a low effect on the thermal conductivity especially at high filler contents where the number of voids decreased due to the filler agglomeration. This point has been discussed in some details in the previous section.

Figure 9 shows the thermal conductivities of all polystyrene-DPP composites over the studied temperature range (5–50°C), which demonstrates that the thermal conductivity coefficient of the samples linearly depends on the



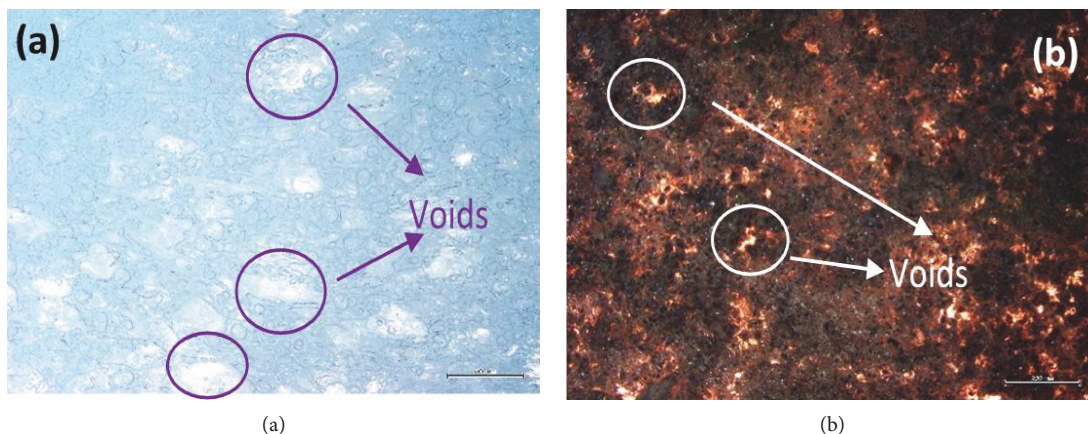


FIGURE 6: Optical microscope image for (a) pure polystyrene and (b) 20-DPP composite sample.

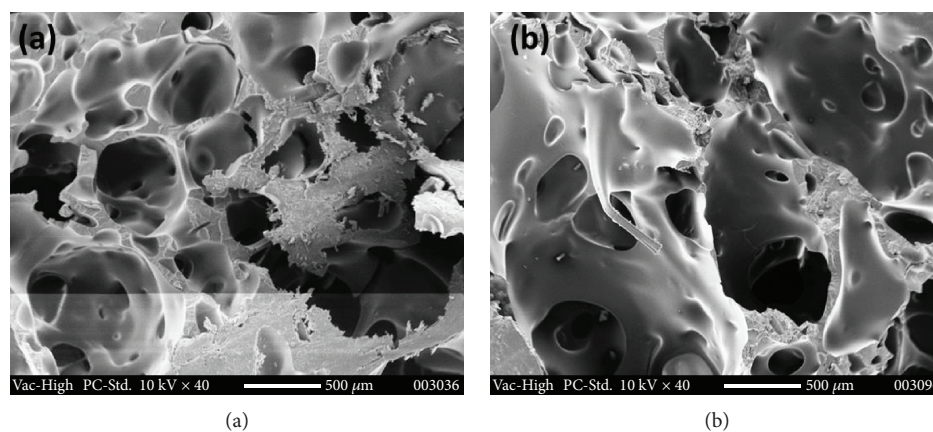


FIGURE 7: SEM for (a) pure polystyrene and (b) 20-DPP composite sample.

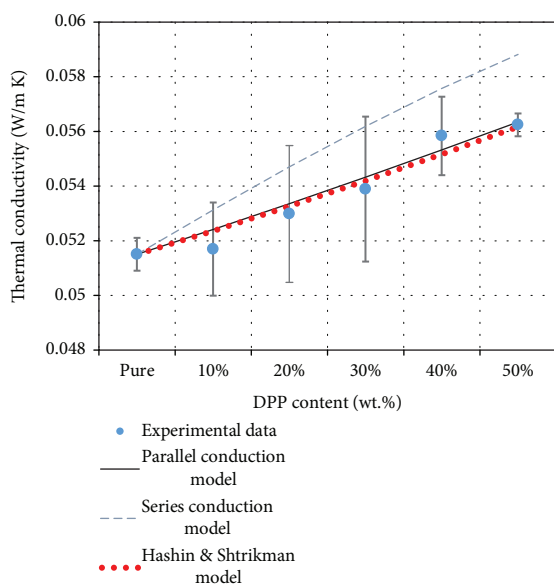


FIGURE 8: Thermal conductivity of composites for different DPP contents at room temperature (25°C).

temperature change. This linear dependency can be expressed by equation 8:

$$k = C + mT, \quad (8)$$

where  $k$  is the thermal conductivity coefficient,  $C$  and  $m$  are constants, and  $T$  is the temperature in kelvin. The extremely small  $m$  values listed in Table 2 show that the thermal conductivity of the date pit-polystyrene composite is weakly dependent on the temperature. This is considered an advantage of the composite since its thermal conductivity coefficient will not change significantly with temperature when used in the construction industry in hot-climate countries. The dependence of the thermal conductivity of polystyrene-DPP composites on temperature is less than that of polyester-based composites such as polyester-clay [28] and polyester-rubber [29] composites.

**3.4. Thermogravimetric Analyses.** Figure 10 shows the weight loss versus the temperature for pure polystyrene, pure date pits, and their composites with varying filler contents from 0 to 50 wt.%. The main TGA results are presented in Table 3. Pure polystyrene showed one principal stage of degradation, while pure date pits showed three stages of

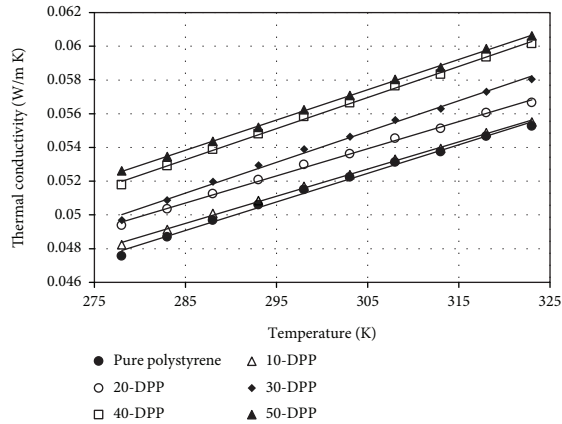


FIGURE 9: Thermal conductivity of composites at different temperatures.

TABLE 2: Parameters of equation 8 as a function of filler content.

Content	C (W/m·K)	$m \times 10^3$ (W/m·K <sup>2</sup> )	R <sup>2</sup>
Pure	0.00078	0.17	0.9974
10-DPP	0.00355	0.16	0.9986
20-DPP	0.00481	0.16	0.9974
30-DPP	0.00085	0.17	0.9959
40-DPP	0.00071	0.18	0.9983
50-DPP	0.00266	0.18	0.9994

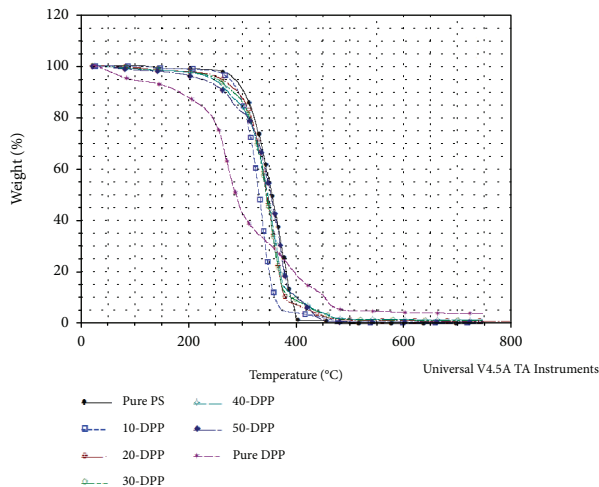


FIGURE 10: Thermograms of date pit-polystyrene composites with different filler contents.

degradation. The first stage in all composites was the loss of the moisture content, which did not show a large weight loss. Date pits mainly consist of three components with decomposition temperatures between 200 and 400°C, namely, hemicellulose, cellulose, and lignin. These observations are in agreement with the results of Wu et al. [38]. Hemicellulose decomposes between 160 and 360°C, and cellulose decomposes between 240 and 390°C. The decomposition temperature range of lignin is wider and higher, i.e., between 250

TABLE 3: Decomposition temperature of the composites.

Samples	T5* (°C)	T50** (°C)	T <sub>max</sub> (°C)	Overall change (%)
Pure	286.0	355.0	402.0	99.87%
10-DPP	274.7	333.0	501.0	99.62%
20-DPP	265.0	345.7	500.0	99.03%
30-DPP	251.0	345.0	497.1	98.74%
40-DPP	246.8	347.4	497.0	98.66%
50-DPP	236.7	352.0	494.5	99.10%
Pure date pits	87.0	289.0	504.0	96.11%

\*Temperature at which 5% weight loss occurs. \*\*Temperature at which 50% weight loss occurs.

and 700°C [39]. Thus, the first peak in Figure 11, which shows the derivation of the weight change of pure date pits (i.e., differential TGA curve), could be due to the decomposition of hemicellulose, cellulose, and lignin. The second peak may be because of the decomposition of cellulose and lignin, and the third peak may be because of the decomposition of lignin. The date pits show an initial loss of 5% at 87°C, 50% weight loss at 289°C, and a total weight loss of 96.11%. Pure polystyrene exhibited initial degradation of 5% at 286°C, 50% weight loss at 355°C, and a total weight loss of 99.87%. The initial degradation of 5% date pit at 87°C is comparable to that of sisal fibers which was reported to be 95.6°C [40].

The thermal behavior of the composite with higher filler contents is closer to that of pure date pits. The composites that contain higher than 20% date pits degrade in four stages; however, the 10-DPP composite and pure polymer degrade in three stages. Briones et al. [41] reported similar results using Deglet-Nour date seed fruit. Table 3 shows that both the initial degradation temperature and the total weight loss decreased slightly with increasing filler content. On the other hand, the results shown in Table 3 indicate that increasing the DPP content from zero to 50 wt.% increased the  $T_{50\%}$  degradation temperature from 402°C to 494.5°C, which is a considerable advantage of incorporating the date pit powder in the polystyrene matrix. In general, it can be said that the thermal stability of the matrix increased slightly with date pit inclusion, which affects the shrinkage of the insulating materials in case of fire.

3.5. *Water Retention.* Distilled water was used to test the water retention properties of the date pit-polystyrene composites, and equation 8 was used to find the water retention (WR%):

$$WR\% = \frac{\text{Sample wet weight} - \text{sample dry weight}}{\text{Sample dry weight}} \times 100. \quad (9)$$

Figure 12 presents the water retention for the different samples at room temperature and in hot water after 24 hr of immersion. The water retention for 10-DPP and 20-DPP composites in the room temperature water was quite low, i.e., around 5% of sample weight. However, for 30-DPP,

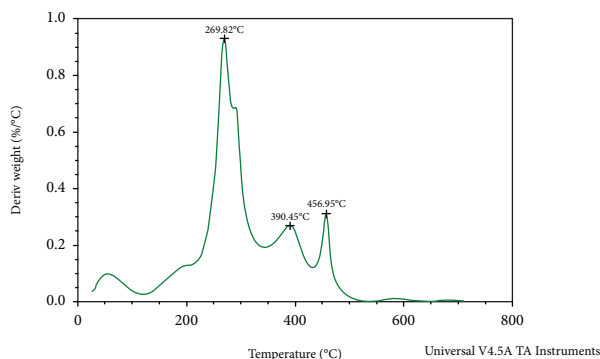


FIGURE 11: DTGA curve of the date pit powder.

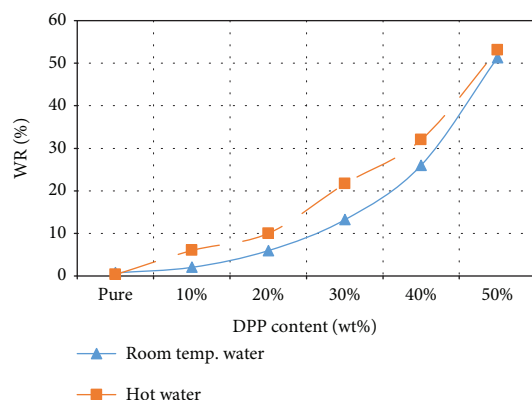


FIGURE 12: Water retention of DPP-polystyrene composites at 24 hr immersion.

40-DPP, and 50-DPP composites, the water retention values were 14%, 26%, and 51% of the sample weight, respectively. In addition, water retention increased with the increasing filler content. This may be attributed to the hydrophilicity of date pits due to their hydroxyl groups and to the voids induced by the poor compatibility between the natural filler and the polymer [25]. The approximate percentages of hemicellulose, lignin, and cellulose in typical date pits are 17.5, 11.0, and 42.5% dry weight, respectively [42]. Therefore, the date pit contains high amounts of cellulose molecule that contain the hydroxyl group which attracts water molecules through hydrogen bonding, which in turn leads to water absorption. Plant-based cellulosic fibers contain lumen, a central hollow region which acts as a capillary tube to allow water to be absorbed. Thus, as cellulosic fiber content increases in the composites, more interfacial areas exist leading to an increase in water absorption [43]. Ameh et al. [19] observed a similar water retention behavior, which increased with the increasing date seed concentration in polyester-date-seed composites. Moreover, the water absorption increased with the increasing date pit particle size in the studied composites. In addition, a similar water retention trend was observed when polyester was used with nonnatural fiber (crumb rubber) [29]. In the same context, it was found in oil palm fiber natural rubber composites which increased in the water absorption percentage corresponding to an increase in fiber loading because of the fibers' hydrophilicity [26].

As expected, the water retention in hot water was higher than that in cold water (see Figure 12). Specifically, the water retention values in hot water were 0.3%, 6%, 21%, 32%, and 53% of the 10-DPP, 20-DPP, 30-DPP, 40-DPP, and 50-DPP samples, respectively. Additionally, it was observed that the pure polystyrene samples exhibited negative retention at the early stage of hot water immersion, which means the hot water dissolved some parts of the pure polystyrene matrix.

The equilibrium water content ( $WR_{eq}$ ) is another important parameter to characterize the ability of the composite material for long-term water absorption. This parameter can be determined experimentally if the water retention reaches equilibrium during the measurement, or it can be estimated by fitting the experimental data with a convenient equation if equilibrium is not reached during the measurement [29]. As can be seen in Figure 13, the equilibrium water content and its corresponding equilibrium time increased significantly with the DPP content. While pure polystyrene needs about 1800 hr to reach  $WR_{eq}$ , the 50-DPP composites need more than 4000 hr.

## 4. Conclusions

The obtained results in this work illustrated that date pit powder can be used as a filler in a polystyrene matrix to form insulating composites with low thermal conductivity and low density. Slight increases in the thermal conductivity and density were observed with the increasing date pit content. The properties of the composite, with 40 wt.% date pit powder, are as follows: thermal conductivity of 0.0558 W/(m.K), water retention of 26.0%, and bulk density of 565 kg/m<sup>3</sup>. On the other hand, 10-DPP, 20-DPP, and 30-DPP composites retained relatively less water in both room temperature and hot water immersion. Replacing one-third of the classical construction wall content with DPP-polystyrene composite shows promise for constructive applications as a thermal insulator with 85% reduction in the overall thermal conductivity. The theoretical analysis of the results shows that the thermal conductivity of the prepared composites can be fitted well by lower-bound models. These models tend to account for the agglomeration of the natural filler, which was observed in the SEM monographs. On the other hand, a slight increase in thermal stability of DPP-polystyrene composites with increasing filler content was noted. The hydrophilicity of date pits due to their hydroxyl groups and the presence of voids in the composite matrix induced by the poor compatibility between the natural filler and the polystyrene resulted in remarkable water absorption. However, using date pit powder can compensate for these effects because it reduces the cost of the composite and enhances its biodegradability.

## Data Availability

The physical and thermal data of the developed composites used to support the findings of this study are included within the article.



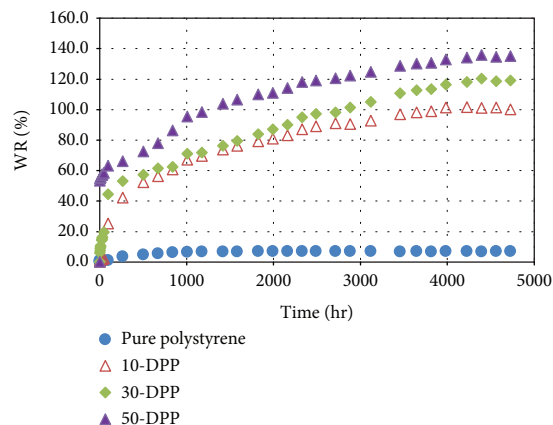


FIGURE 13: Effect of immersion time on water retention of DPP-polystyrene composites at room temperature.

## Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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