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RESEARCH

Advancing sustainable materials: characterization of pistachio shell and talc filled polyester composites

İdris Karagöz[1,2] · İlayda Arslan Ocak[3] · Aysu Çavuşoğlu[3] · Harun Sepetçioğlu[4]

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Abstract

This study aims to develop sustainable polyester hybrid composites by incorporating environmentally friendly fillers such as pistachio shell and talc into an orthophthalic polyester matrix. The goal is to produce cost-effective, eco-friendly materials for applications such as exterior cladding and electronic enclosures. The mechanical (tensile, flexural, impact), thermal (FT-IR, TGA, DSC), and physical (water absorption, hardness, density, gloss) properties of the prepared composites were tested. Pure polyester exhibited the highest tensile strength at approximately 50 MPa, while the addition of 40% pistachio shell reduced the mechanical properties by 69%. In contrast, the addition of talc increased the tensile strength by 55% compared to the composite with only pistachio shell. Talc also improved thermal stability (increasing the T5 temperature by 7% and Tmax by 2%) and reduced water absorption by 4%. The combination of both fillers optimized the material properties, providing a sustainable and high-performance alternative. These findings suggest that further optimization of filler content could improve performance and expand material applications.

Highlights

1. Pistachio shell and talc were used to develop polyester-based hybrid composites.
2. Talc improved mechanical strength; pistachio shell reduced it.
3. Pistachio shell increased water absorption and decreased surface brightness due to its hydrophilic nature.
4. Talc improved the thermal stability of polyester composites, as confirmed by TGA analysis.
5. The filler ratio had a significant impact on mechanical, thermal, and surface properties.

Keywords Polyester · Polyester composites · Hybrid composites · Thermal properties · Pistachio shell

Introduction

Over the past decade, the increasing demand for cost-effective and high-performance materials has significantly advanced composite technology. Among these advancements, the combination of thermoset resins with various fillers has emerged as a key approach to enhancing material properties [1]. Thermoset resins, such as epoxy [2], polyester [3], and vinyl ester [4], are widely utilized due to their excellent mechanical strength, thermal stability, and chemical resistance [5]. However, their high cost and inherent fragility limit their broader industrial applications. To overcome these challenges, researchers have focused on incorporating fillers to improve performance and reduce production costs [6–9].

Talc is among the most commonly used fillers in polymer composites, offering enhancements in thermal

✉ İdris Karagöz
idris.karagoz@yalova.edu.tr

[1] Department of Polymer Materials Engineering, Faculty of Engineering, Yalova University, 77200 Yalova, Türkiye

[2] Zamia Composite Research and Development Technology Joint Stock Company, ULUTEK Technopark, Nilüfer, 16110 Bursa, Türkiye

[3] Department of Polymer Materials Engineering, Institute of Graduate Studies, Yalova University, 77200 Yalova, Türkiye

[4] Department of Metallurgical and Materials Engineering, Faculty of Technology, Selçuk University, 42075 Konya, Türkiye

conductivity, mechanical strength, and cost-effectiveness [1, 9–11]. Talc-filled composites are particularly valued for their ability to increase the glass transition temperature, making them suitable for applications requiring higher thermal resistance [12]. However, excessive talc content can negatively impact the processability of polymers and reduce transparency, which restricts its use in certain industries [13, 14].

In addition to mineral-based fillers such as talc, agricultural waste-based fillers have also gained attention due to their sustainability, abundance, low cost, and non-toxic nature [15]. Additionally, composites reinforced with cellulosic fibers exhibit durability, lightness, biodegradability, and are safe for both the environment and human health [16–20]. Turkey, as a major agricultural producer, generates significant amounts of agricultural residues, such as pistachio shells, which remain underutilized [21, 22]. Converting these shells into composite fillers not only addresses waste management challenges but also contributes to the development of eco-friendly and sustainable materials [23]. Pistachio shells, like other agricultural waste fillers, have demonstrated the potential to improve mechanical strength, thermal stability, and toughness in polymer composites.

Several studies in the literature highlight the benefits of agricultural waste fillers. For instance, Mohapatra et al. investigated the impact of pistachio shell additions in kenaf/glass/polyester laminates and observed significant improvements in tensile strength, flexural strength, and impact resistance [24]. Similarly, Thiagarajan et al. reported that incorporating pistachio shell microparticles into glass fiber reinforced composites enhanced tensile and flexural properties, showcasing the potential of these fillers for high-performance applications [25]. Furthermore, Rautaray et al. studied the effects of talc and rice husk fillers on polypropylene hybrid composites and found that increasing filler content improved modulus values while slightly reducing other mechanical properties, highlighting the importance of balanced filler ratios [26]. These findings underscore the viability of agricultural waste fillers in developing sustainable composite materials. Given the growing emphasis on sustainability, the integration of natural-based and hybrid-based polymeric composites has gained importance due to their renewable origin and environmentally friendly production processes [27–30].

This study investigates the mechanical and thermal properties of hybrid composites composed of pistachio shell and talc fillers in an orthophthalic polyester matrix. The primary objective is to explore the synergistic effects of these fillers on the thermal and mechanical performance of the composites, offering insights into their potential applications in diverse industries.

Experimental

Materials and methods

In this research, ILKESTER® P-053 orthophthalic polyester resin, with a density of 1.11–1.12 g/cm^3, served as the matrix material. KP50 MEK-P was employed as the hardener, added at a 2% ratio. Pistachio shells (density 0.35–0.6 g/cm^3, particle size between 149 and 125 µm) were obtained from a local supplier in Gaziantep, and talc (particle size < 44 µm, density 2.72 g/ml) was sourced from Asil Kimya.

The pistachio shells and talc were initially incorporated into the polyester matrix using a Vortex Genie 2 mixer to ensure uniform distribution, followed by homogenization with a Sonics VCX 130 sonicator to achieve a consistent dispersion of fillers. The prepared polyester resin mixture was poured into a metal mold (200 × 200 × 4 mm) with cavities designed for standard test specimens. After curing, the samples were demolded. The production steps of polyester composites are illustrated in Fig. 1, and the prepared samples are shown in Fig. 2. The formulations of the thermoset hybrid composites, containing varying amounts of pistachio shells and talc in the polyester resin matrix, are summarized in Table 1.

Characterization

Tensile tests were conducted according to ISO 527–1 standards on a Zwick Z020 device at a crosshead speed of 5 mm/min. For each tensile test condition, at least five specimens were tested. Three-point bending tests were performed at a bending speed of 1.7 mm/min following ISO 178 standards, and five specimens were tested for statistical reliability. Charpy impact testing was carried out using an Instron 120D device with a 7.5 J hammer, adhering to ISO 179–1 standards. Each impact test was conducted on ten specimens. Shore D hardness was measured with a Loyka M01D device in compliance with ISO 48–4 standards. Hardness values were recorded as the average of five separate measurements per sample.

Density was assessed using the liquid pycnometer technique, in accordance with ISO 1183. For water absorption testing, samples were weighed and immersed in water. The water absorption capacity (WAC) was calculated using Eq. (1):

$$\mathrm{WAC} = \left(\frac{F_w - I_w}{I_w} \right) \times 100 \qquad (1)$$

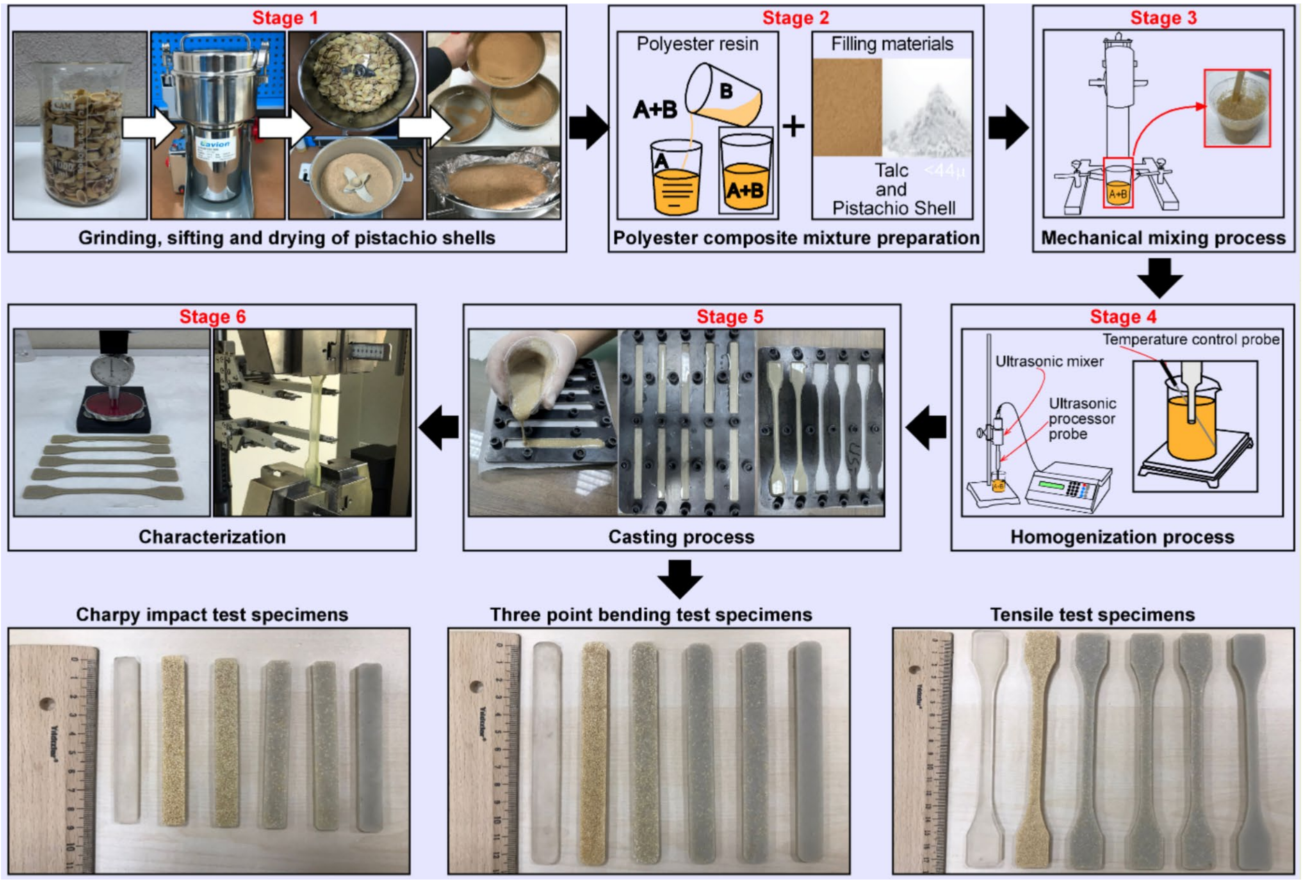

Fig. 1 Step-by-step production process of polyester composites

where F_w is the final weight, I_w is the initial weight, and WAC represents the water absorption capacity (%). Three specimens were used for water absorption measurements. Measurements were taken after the first hour and intervals over 744 h.

Surface gloss measurements were performed at a 60° angle using an Elcometer micro-gloss meter, following ASTM D523 standards. Gloss measurements were repeated three times for each sample to ensure reproducibility. FT-IR spectra were acquired with a Perkin Elmer Spectrum 100 within the range of 650–4000 cm^{-1} (ASTM D6348). Differential scanning calorimetry (DSC) was conducted using a Setaram DSC131 Evo device at a heating rate of 10 °C/min under a nitrogen atmosphere, in line with ASTM D3417. Each DSC analysis was performed on at least three specimens to confirm repeatability. Thermogravimetric analysis (TGA) was performed on a Seiko Exstar TG/DTA 6300 device up to 600 °C at a heating rate of 10 °C/min, following ASTM E1131. The activation energy (E_a) was calculated using the Coats-Redfern method (Eq. (2)):

$$ln\left(\frac{g(\alpha)}{T^2}\right) = \ln\left(\frac{AR}{E_a}\right) - \frac{E_a}{RT} \tag{2}$$

Here, T is the absolute temperature (K), R is the gas constant (8.314 J/mol·K), A is the frequency factor, Ea is the activation energy, and α is the fractional mass loss. By plotting $\ln(g(\alpha)/T^2)$ against 1/T, the slope and intercept were used to determine Ea and A [31, 32].

Scanning electron microscopy (SEM) analysis of impact-fractured surfaces was performed with a Zeiss Evo LS10. Before imaging, a 100 Å gold coating was applied to enhance conductivity. SEM analysis focused on identifying fracture surface characteristics and filler dispersion.

Results and discussion

The tensile test and flexural test results

Figure 3 compares the tensile test results, while Fig. 4 compares the three-point bending test results. The pure polyester samples exhibited the highest tensile and flexural strength.

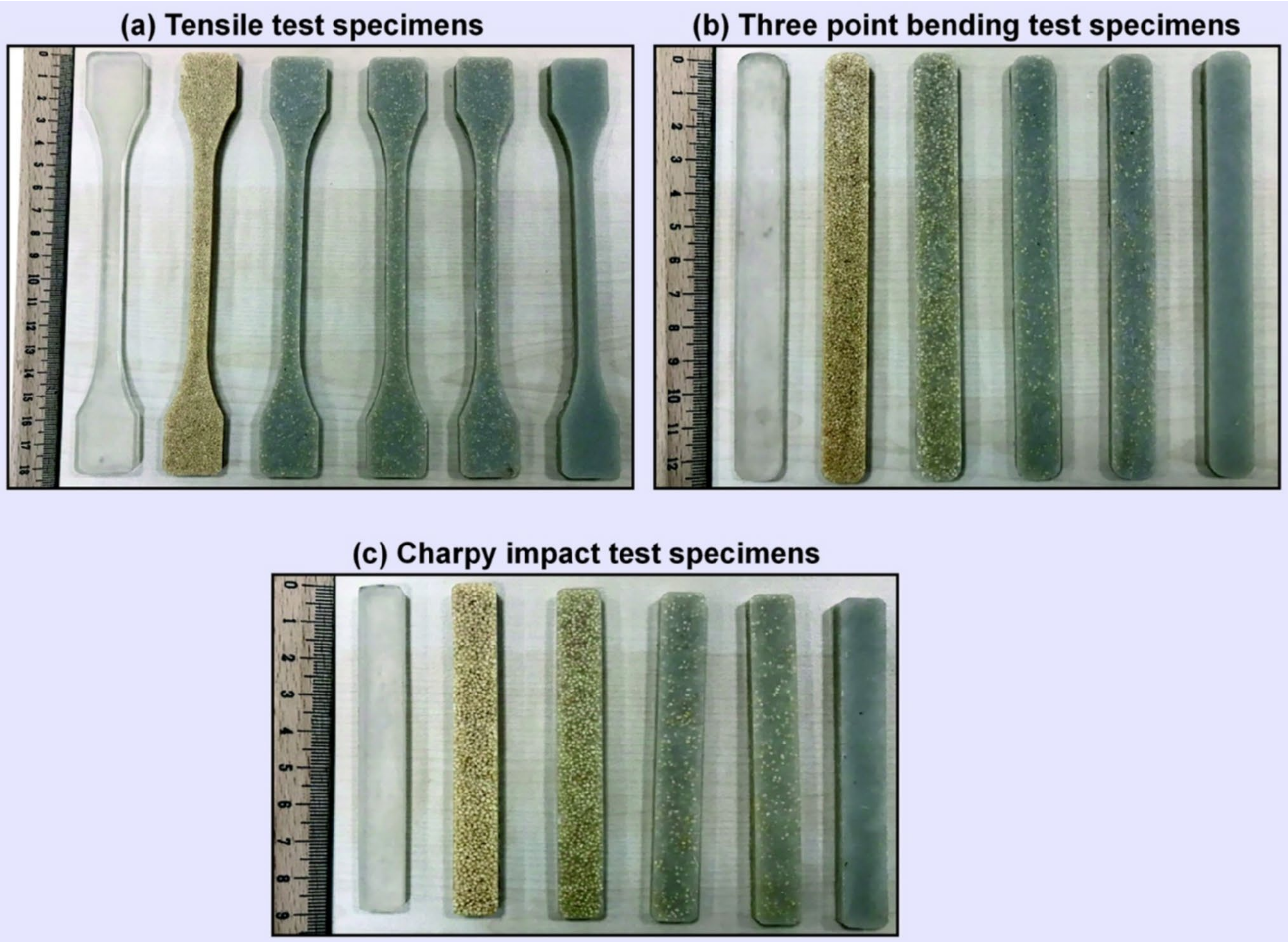

Fig. 2 Images of the prepared samples

Table 1 Formulation and codes used in the study

Codes	Polyester (wt.%)	Pistachio shells (wt.%)	Talc (wt.%)
PST1	100	-	-
PST2	60	40	-
PST3	60	30	10
PST4	60	20	20
PST5	60	10	30
PST6	60	-	40

Among the composites, the PST6, which contains 40% talc, displayed the highest tensile and flexural strength. However, the addition of pistachio shell and talc to the polyester composite resulted in a general reduction in these mechanical properties, with pistachio shell contributing to a more significant decline compared to talc.

The reduction in tensile strength caused by talc is attributed to its brittle and rigid nature, which limits the composite's ability to deform under tensile loads. Moreover, the insufficient bonding between talc and the polyester matrix hinders stress transfer, thereby reducing the composite's overall strength [33, 34]. On the other hand, the pronounced decrease in tensile strength caused by pistachio shell is linked to its irregular and rigid structure, which creates stress concentrations within the matrix [34–36]. Similar findings in the literature indicate that natural fillers with irregular shapes and weak interfacial adhesion can substantially decrease the tensile strength of polymer composites [37]. For instance, walnut shell powder in polyester composites exhibited comparable behavior due to its rigid structure and poor compatibility with the matrix [38].

The effect of filler content on flexural strength showed a similar trend to that observed for tensile strength. As the talc content increased, the resulting stiffness improved the composite's resistance to flexural loads, enhancing its flexural strength and modulus [26]. Conversely, as the pistachio shell content increased, the flexural strength decreased, owing to

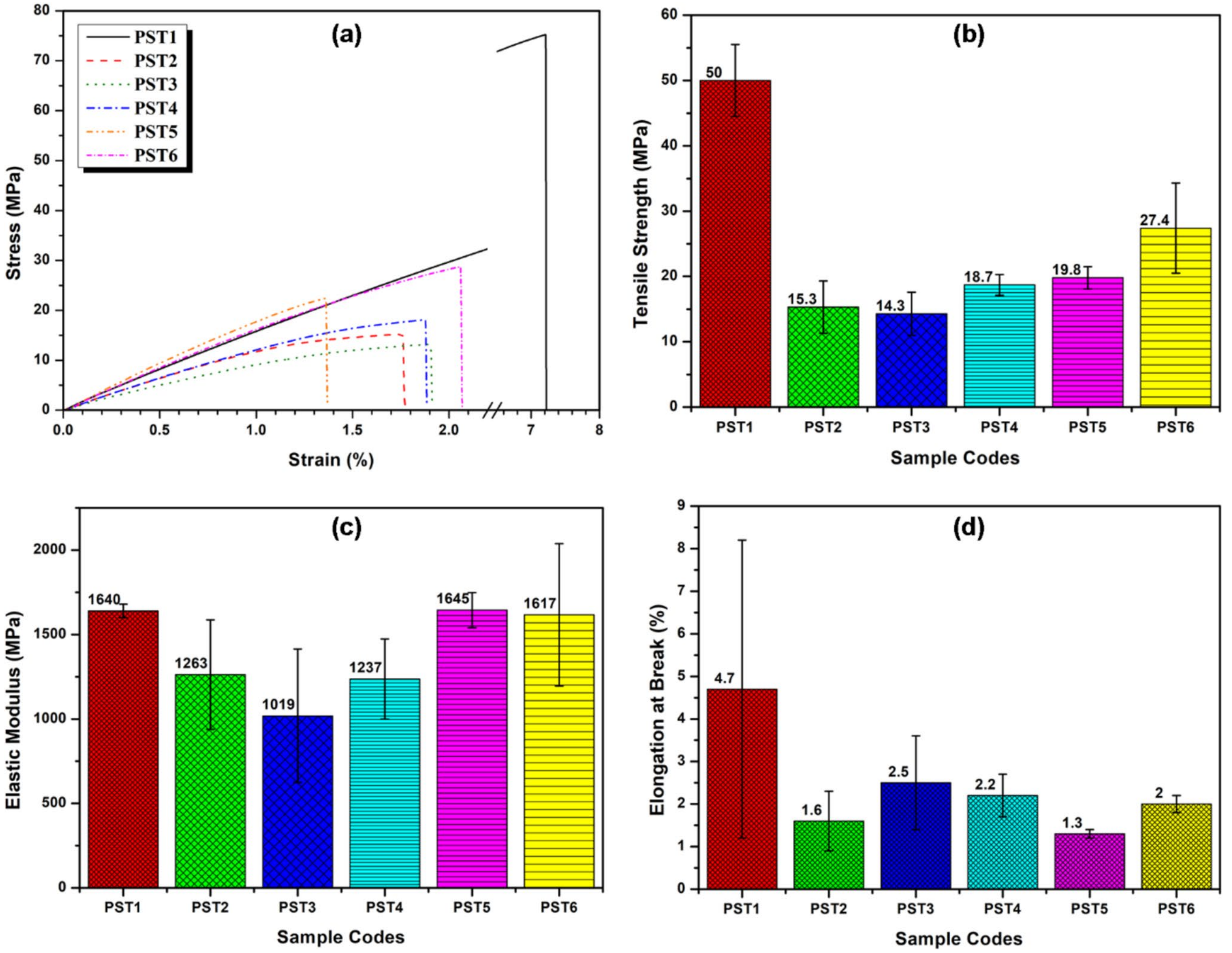

Fig. 3 Graphical comparison of tensile test results for polyester composites (**a**) Tensile curves, (**b**) Tensile strength, (**c**) Elastic modulus and (**d**) Elongation at break

its rigid and incompatible nature, which weakens the matrix-filler interaction and causes stress concentrations.

Charpy impact test results

Figure 5 presents a graphical comparison of the Charpy impact test results for the polyester composites. In the unnotched impact test (Fig. 5a), the pure polyester sample exhibited the highest impact strength at 5.7 kJ/m^2. Conversely, in the notched impact test (Fig. 5b), the PST6 sample, containing 40% talc, showed the highest impact strength at 5.2 kJ/m^2.

The type and amount of filler significantly influence the impact strength of polyester composites. Talc, being rigid and brittle, is expected to make the composite more prone to brittleness as it poorly absorbs energy during impact [26]. This trend is evident in the unnotched impact test results. However, in the notched impact test, talc exhibited a surprising strengthening effect on impact resistance.

This phenomenon can be attributed to energy concentration at the notch. During impact, talc particles may act as barriers, distributing energy more evenly around the notch area and slowing crack propagation. This controlled energy distribution reduces the speed of crack growth, thereby requiring more energy for the material to fracture and increasing the impact strength. Similar behavior has been observed in composites with other rigid fillers like mica and glass fibers, which have been reported to alter crack paths and delay failure [39].

At high filler contents, the pistachio shell's influence on the impact strength becomes more apparent. It's hard and irregular structure creates stress concentrations within the composite, which promote crack formation and propagation during impact [34]. Additionally, the weak interfacial bonding between pistachio shell particles and the polyester

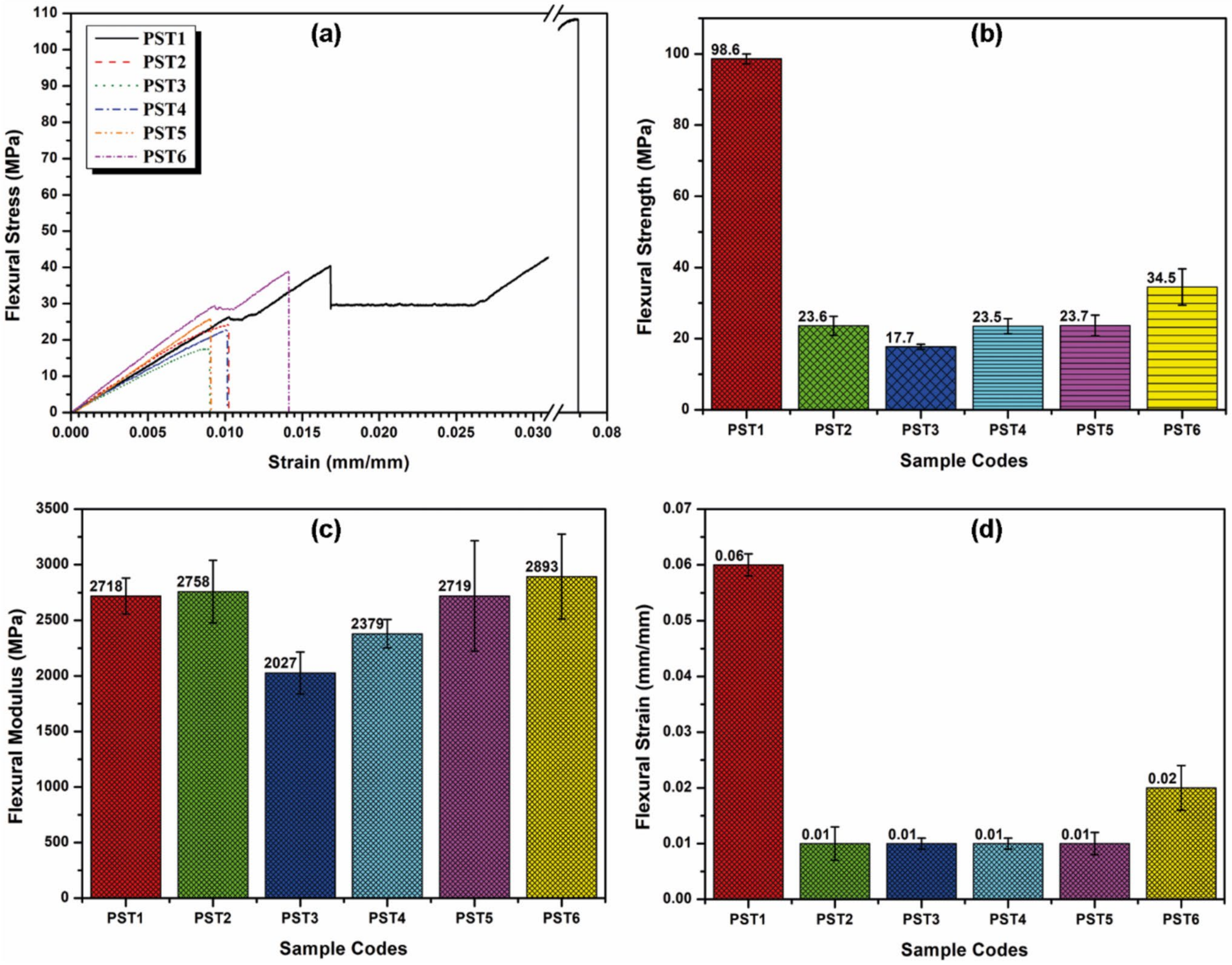

Fig. 4 Graphical comparison of three-point bending test results for polyester composites (**a**) Flexural curves, (**b**) Flexural strength, (**c**) Flexural modulus and (**d**) Flexural strain

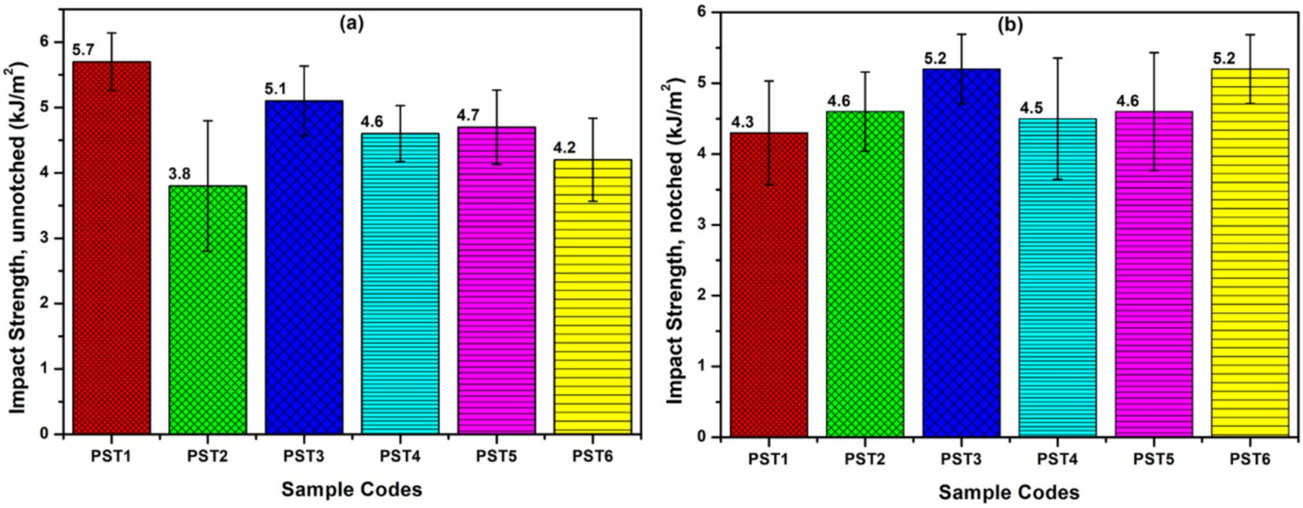

Fig. 5 Comparison of notched and unnotched impact strengths (**a**) impact strength, unnotched, (**b**) impact strength, notched

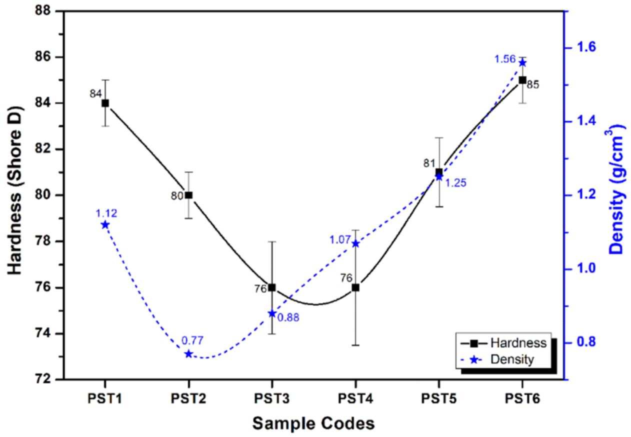

Fig. 6 Graphical comparison of hardness and density measurements for polyester composites

matrix limits efficient energy transfer, further reducing the composite's ability to absorb impact energy [26].

Hardness and density results

Figure 6 presents a comparison of the hardness and density results. The highest hardness values, recorded at 85 and 84 Shore D for the samples coded PST6 and PST1, respectively, were observed in the polyester composites. As the talc content in the structure increases, the matrix becomes harder, and resistance to indentation on the surface improves. This is due to talc's rigid nature, which reduces the flexibility of the polyester matrix, restricting the movement of polymer chains and making the composite stiffer and more resistant to deformation [1, 40]. Therefore, a higher talc content typically results in increased hardness, as the proportion of the hard filler in the composite rises [10, 37].

However, when talc is combined with pistachio shell, a decrease in hardness is observed until the talc content reaches 30%. This reduction can be explained by the interaction between the irregularly shaped pistachio shell and talc. The pistachio shell's rough and uneven surface causes the talc particles to slide over and align parallel to the shell, which limits the reinforcement effect of talc on the composite. This sliding effect reduces the composite's overall hardness, as the two fillers do not bond effectively, and the movement of talc particles become less constrained [1, 37]. Additionally, similar interactions between irregular fillers and rigid particles have been shown to result in lower mechanical reinforcement, as the fillers can cause relative motion rather than contributing to the matrix's rigidity [1].

The densities of the composites were measured as expected. The low-density pistachio shells decreased the composite's overall density, while talc, which has a higher density than polyester and epoxy, increased it. As shown in Fig. 5, this effect became more pronounced as the talc content increased. Literature supports that agricultural waste with lower density generally reduces the density of polymer composites, as seen with other filler systems [41].

Water absorption capacity results

The WAC results are shown in Fig. 7. The lowest WAC value was observed for pure polyester, while the highest value was seen in the PST2 sample, which contains 40% pistachio shell filler. The typical behavior of polyester, which serves as the matrix and constitutes the majority of the composite, is evident across all samples. This phenomenon is primarily due to the hydrophobic nature of polyester, which resists water absorption [42]. In contrast, pistachio shells have a tendency to absorb water, a characteristic attributed to the organic components (such as cellulose, hemicellulose, and lignin) within the shells, their inherent porosity, and the weak interfacial adhesion between the polyester and pistachio shells [26, 41]. The hydrophilic nature of these organic components enhances their affinity for water, enabling water penetration into the composite [43]. Furthermore, the porosity of the pistachio shell structure, along with the voids that form at the filler-matrix interface, leads to water retention within the filler material, which increases the composite's water absorption capacity. SEM images could provide further insight into the pore structure and void formation in the composites, showing the relationship between filler distribution and water retention in the matrix.

Similarly to polyester, talc is hydrophobic, which contributes to the lower WAC observed in talc-reinforced samples.

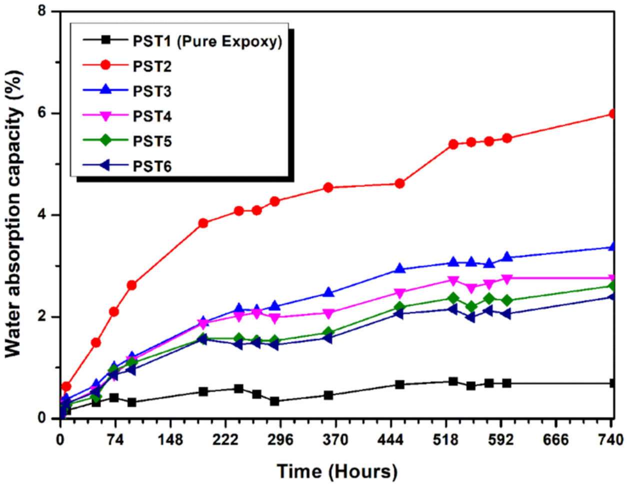

Fig. 7 Graphical comparison of the water absorption capacities of the pure polyester composites

Talc is thought to fill voids within the polyester matrix, which reduces the opportunity for water to penetrate the composite. This is particularly evident in the microstructure, where talc particles appear to occupy voids and limit water movement. As the talc content increases, the compatibility between the filler and the matrix improves, preventing water passage at the interface, as also indicated by FT-IR analysis showing improved interactions between the polyester and talc [32, 44]. The reduced void formation and enhanced interface bonding with increased talc content help to further reduce water absorption.

In summary, an increase in pistachio shell content leads to a higher WAC, while an increase in talc content results in a decrease in WAC. The WAC of all composites varies depending on the proportions of pistachio shell and talc content.

Surface gloss measurements of the polyester composites

Table 2 shows the surface gloss measurement results for the polyester composites. The surface gloss of pure polyester was measured at 57 GU. When 40% pistachio shell was added to the structure, the gloss value decreased to 25 GU. The structural and surface characteristics of the pistachio shells contribute to a more irregular internal structure with micro-voids within the polyester composite, resulting in enhanced light scattering and a more matte finish. Additionally, the natural structure and color of the pistachio shell, which tends to absorb light, may have also contributed to the reduction in gloss [26, 45].

When talc and pistachio shells were used together, the gloss value decreased even further. The combination of talc and pistachio shells negatively affected the gloss value. This could be due to the increased irregularity in the structure and the formation of more micro-voids when both talc and pistachio shells were used together. These voids cause light to scatter unevenly across the surface, leading to a loss of gloss [45, 46]. Microstructural changes, especially the uneven distribution of fillers and the micro-voids they create, result in increased light scattering and thus a higher level of matting. Furthermore, increased surface roughness hinders the smooth reflection of light, contributing to the gloss loss. Literature suggests that the fillers may influence surface roughness, thereby affecting light scattering and gloss loss [47, 48].

Table 2 Surface gloss of polyester composites

Codes	Gloss value (GU 60˚)	Gloss loss (%)	Gloss category
PST1	57 ± 4	-	Semi-gloss
PST2	25 ± 6	56	Satin-like finish
PST3	8 ± 1	86	Velvetlike
PST4	12 ± 2	79	Eggshell-like finish
PST5	13 ± 2	77	Eggshell-like finish
PST6	14 ± 1	75	Eggshell-like finish

As the talc content increased, the gloss value partially increased, although not significantly. The fine structure of talc may have contributed to this by reducing the roughness of the composite [26, 49]. It is known that at very low levels, talc can significantly reduce surface roughness [1]. However, in this study, the high amount of talc used led to saturation, which in turn decreased the gloss value. Higher amounts of talc may reduce light scattering by compacting the structure rather than filling the voids, which can decrease the gloss [50].

FT-IR analysis of polyester composites

The FT-IR results are illustrated in Fig. 8. Figure 8a shows the FT-IR spectrum of pistachio shells. The broad band at 3335 cm^{-1} corresponds to hydroxyl (O–H) groups in lignocellulosic components such as cellulose, hemicellulose, and lignin, reflecting the hygroscopic nature of pistachio shells and the presence of hydrogen bonding. The band observed at 2902 cm^{-1} is attributed to aliphatic C-H stretching vibrations, suggesting the existence of methyl (CH_3) and methylene (CH_2) functional groups in cellulose and hemicellulose [51]. Meanwhile, the peak at 1731 cm^{-1} is indicative of ester or ketone functionalities in hemicellulose, reflecting the presence of carbonyl (C = O) groups. Additionally, the peak around 1646 cm^{-1} corresponds to conjugated double bonds found in lignin or amide functionalities in proteins [52]. Peaks at 1593 and 1504 cm^{-1} reflect the vibrations of aromatic rings in lignin, indicating the presence of aromatic structures. Peaks at 1456 and 1423 cm^{-1} are related to the bending vibrations of aliphatic methyl and methylene groups from cellulose and hemicellulose. The peak at 1374 cm^{-1} is associated with the bending vibrations of methyl groups [48]. The peaks at 1284 and 1240 cm^{-1} are associated with the stretching vibrations of ester or ether linkages present in hemicellulose and lignin. The peak observed at 1157 cm^{-1} is indicative of C–O–C linkages found in both cellulose and hemicellulose. Furthermore, the peak at 1032 cm^{-1} suggests the presence of C–OH and C–O–C bonds within these materials [53]. Additionally, the peak at 896 cm^{-1} is linked to the β-glucosidic bonds in cellulose, while the peak at 828 cm^{-1} reflects deformed C-H vibrations associated with the aromatic rings of lignin [54–56].

Peaks in the FT-IR spectrum of talc (Fig. 8b) at 3658 cm^{-1} and 3673 cm^{-1} are assigned to the vibrations of hydroxyl groups bonded to silicon (Si–OH) and magnesium (Mg-OH),

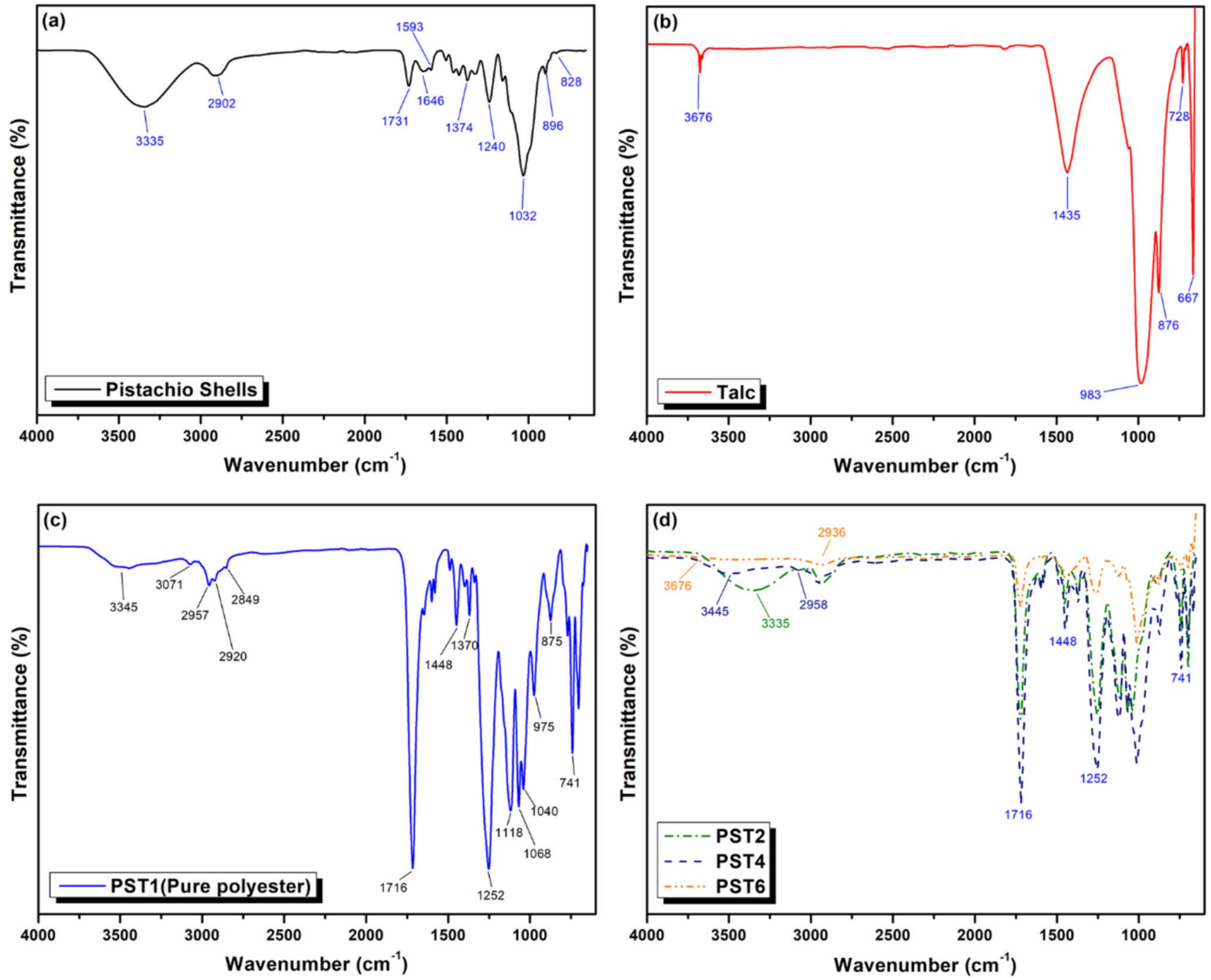

Fig. 8 FT-IR spectra of polyester composites: (**a**) pistachio shells, (**b**) talc, (**c**) pure polyester and (**d**) polyester composites coded PST2, PST4, and PST6

respectively [1]. The peak at 1435 cm^{-1} corresponds to bending vibrations of aliphatic C-H bonds and may also reflect vibrations of minerals present in talc [57]. Peaks at 983, 876, 728, and 667 cm^{-1} indicate the magnesium silicate structure of talc. The peak at 983 cm^{-1} reflects Mg-O bond stretching, while the peak at 876 cm^{-1} represents bending vibrations of Si–O bonds, showing the mineral structure of talc [1]. The band at 728 cm^{-1} corresponds to bending vibrations of Si–O-Si bridges, indicating silicate networks. The peak at 667 cm^{-1} represents deformed vibrations of Si–O bonds [58].

Figure 8c presents the FT-IR spectrum of pure polyester (PST1). The peak at 3344 cm^{-1} corresponds to water content or free OH groups in polyester. Peaks at 3071, 2957, 2920, 2849, 1448, 1397, 1370, 1139, 957, 875, 771, and 703 cm^{-1} reflect stretching and bending vibrations of aliphatic C-H bonds, representing aliphatic groups and structural features of polyester [59]. Peaks at 1716, 1252, 1118, 1068, and 1040 cm^{-1} show C = O and C-O bonds in ester groups, indicating key chemical components of polyester. Peaks at 1647, 1600, 1580, 1489, 741, 703, and 675 cm^{-1} represent C = C and C-H bonds in aromatic rings [59–61].

Figure 8d shows the FT-IR spectra of polyester composites coded PST2, PST4, and PST6. These spectra not only display the characteristic peaks of polyester but also those specific to pistachio shells and talc. The positions and intensities of these peaks vary depending on the type and rate of additives used. The interaction between the polyester and the pistachio shell components can be observed through changes in the peak intensities and shifts in the positions of certain bands. Specifically, the presence of pistachio shells leads to a noticeable increase in the intensity of the hydroxyl group (O–H) band at 3335 cm^{-1}, which may indicate an interaction between the pistachio shell components and the polyester matrix, potentially through hydrogen bonding. This could suggest that the pistachio shells are influencing the polyester's molecular structure, possibly leading to changes in the composite's mechanical and thermal properties. Moreover, the shifts in the C = O stretching band around 1716 cm^{-1} may be indicative of interactions between the ester groups in polyester and the functional groups present in the pistachio shell components, such as the carbonyl (C = O) in hemicellulose [62].

The FT-IR spectra also show the presence of talc in the composites. The talc-related peaks, including the bands at 983 cm^{-1} and 876 cm^{-1}, are present in the composite spectra, indicating that talc is well integrated into the matrix. The increase in the intensity of the Si–O related bands suggests that the talc may be influencing the overall structure of the polyester composite, leading to changes in its physical properties, such as surface roughness and thermal stability [1, 50]. Additionally, the interactions between the talc and polyester may also affect the polymer's crystallinity, as evidenced by changes in the peak positions associated with the aromatic structures of polyester.

These variations in the FT-IR spectra provide evidence of the presence and interaction of all components within the composites. Changes in peak positions and intensities can offer insights into how the additives influence the overall properties and performance of the polyester composites. The relationship between the FT-IR spectra of the polyester and pistachio shell can be further analyzed in comparison to other similar composite systems in the literature to better understand the interactions and effects of these natural fillers [50, 59].

DSC analysis of polyester composites

The DSC curves for polyester composites are presented in Fig. 9, and the numerical data from the DSC test are provided in Table 3. The glass transition temperature (Tg) of pure polyester was found to be 54.83 °C. This result appears to be consistent with similar studies reported in the literature [63–65]. In the composite containing 40% pistachio shells (PST2), the Tg was recorded as 56 °C, while in the composite with 40% talc (PST6), the Tg was 50.17 °C. PST1 exhibited the highest ΔH value (0.329 J/g), indicating the

Table 3 Numerical data derived from the DSC analysis

Code	ΔH (J/g)	Onset (°C)	Tg (°C)	Endpoint (°C)
PST1	0.329	47.50	54.83	58.71
PST2	0.234	52.76	56.00	63.35
PST3	0.276	48.73	53.33	60.50
PST4	0.172	48.36	54.00	56.85
PST5	0.103	45.65	48.50	56.00
PST6	0.192	45.31	50.17	56.72

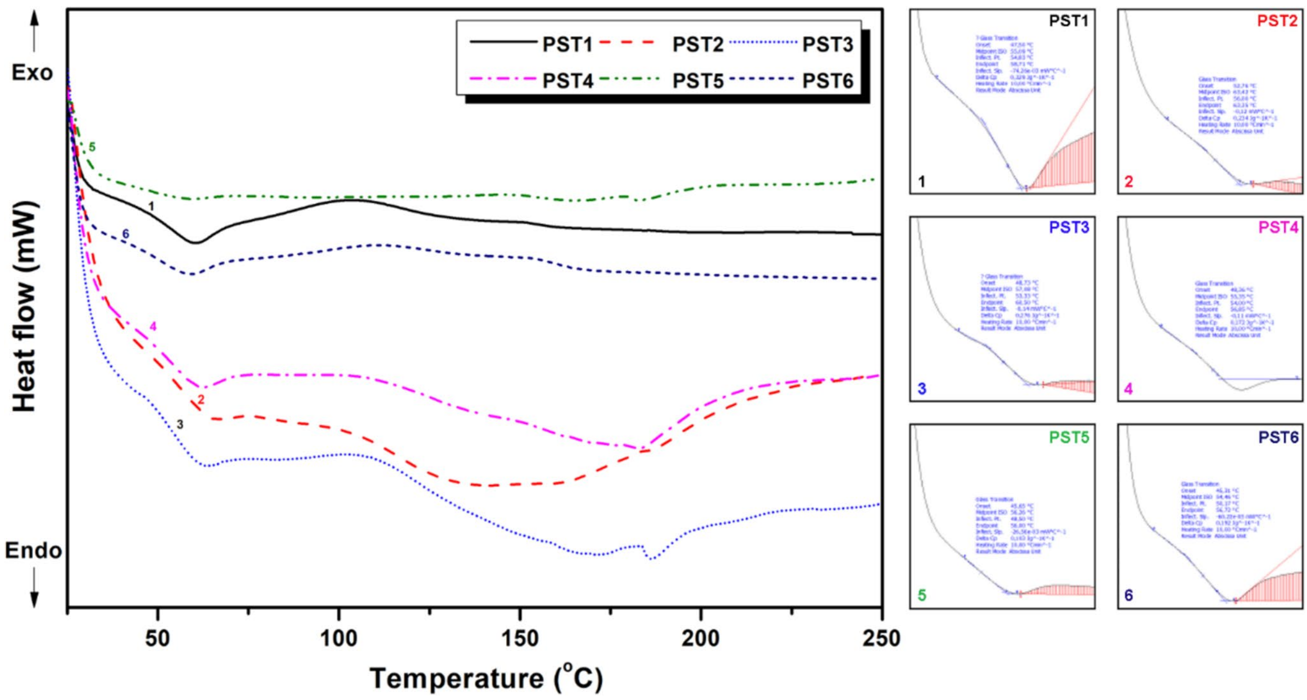

Fig. 9 DSC profiles of the polyester composites

most significant thermal transition, whereas PST5 had the lowest (0.103 J/g). Onset temperatures ranged from 45.31 °C (PST6) to 52.76 °C (PST2), with PST2 showing the highest onset temperature, possibly due to better thermal stability. The inflection temperature, often associated with the peak of the glass transition (Tg), varied from 48.50 °C (PST5) to 56 °C (PST2). The higher inflection point in PST2 suggests a higher Tg, likely due to the pistachio shell filler concentration. Endpoint temperatures, where the thermal transition concludes, ranged from 56 °C (PST5) to 63.35 °C (PST2). The highest endpoint temperature observed in PST2 indicates an extended thermal transition range. Thus, PST2 was identified as the composite with the best thermal resistance (highest Tg) due to its consistently higher temperatures compared to the other samples. In contrast, PST5 and PST6 had lower onset, glass transition, and endpoint temperatures.

The addition of pistachio shells to the mixture increased the Tg of the polymer matrix and enhanced thermal stability. This effect may be attributed to the lignocellulosic structure restricting the mobility of polymer chains, interactions between the fiber and the matrix, and the organic compounds contained within the shell [36]. In the composite containing only talc, the Tg is lower than that of pure polyester and other composites but higher than that of PST5. Generally, the addition of talc to the polyester composite tends to decrease Tg, while pistachio shells tend to increase it. When talc and pistachio shells are used together, their interaction has a complex effect on Tg. The synergistic interaction between talc and pistachio shells appears to alter the mobility of polymer chains, affecting the Tg. As the talc content in the mixture increases, the Tg temperatures decrease. This phenomenon may be due to the increased mobility of polymer chains caused by the higher amount of talc added to the structure [1, 66].

TGA analysis of polyester composites

Numerical results for the TGA tests of pure polyester composites are shown in Table 4, with TG curves in Fig. 10a, and DTG curves in Fig. 10b. Pure polyester (PST1) shows a single sharp peak at around 421.6 °C, corresponding to the primary decomposition step, which represents the rapid degradation of the polyester. The composites coded PST2 (40% pistachio shells) and PST3 (30% pistachio shells + 10% talc) show DTG peaks at lower temperatures (between 400 and 408 °C) compared to pure polyester. As seen in Fig. 9b, the slow decomposition of lignocellulosic components over a lower (earlier) and broader temperature range leads to additional peaks, resulting in a three-stage degradation in the DTG curves of these composites [1].

Table 4 Numerical data derived from the TGA

Code	T_5 (°C)	T_{50} (°C)	T_{max} (°C)	Residue at 600 °C (%)
PST1	362.2	405.0	421.6	3.1
PST2	285.0	360.7	400.8	14.3
PST3	286.9	360.7	407.5	20.5
PST4	346.7	407.3	426.5	24.5
PST5	383.1	411.7	427.6	35.8
PST6	389.2	412.0	427.3	40.6

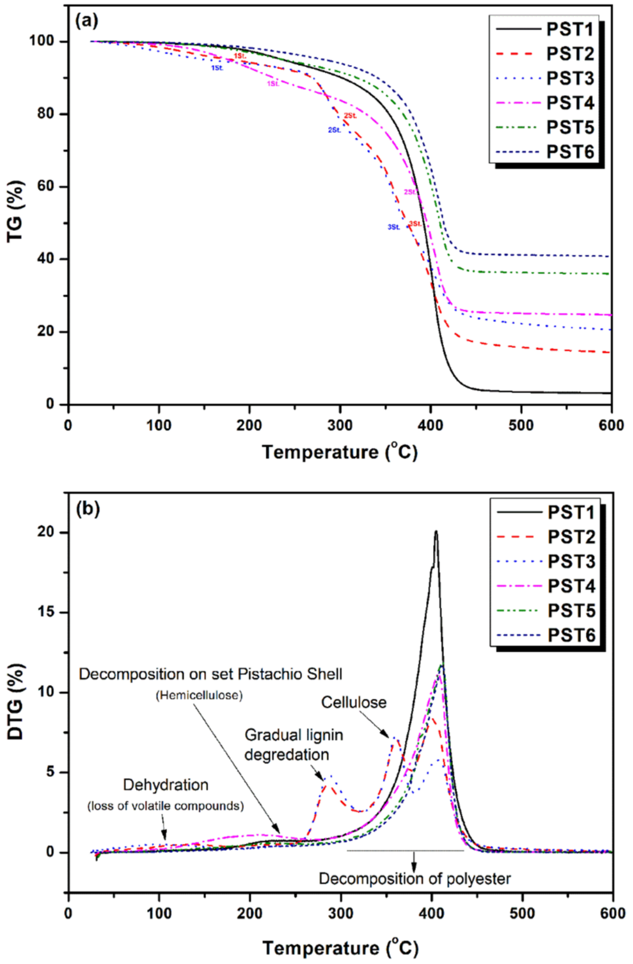

Fig. 10 Polyester composites TGA curves (**a**) TG and (**b**) DTG

The initial thermal decomposition observed in polyester composites reinforced with pistachio shells is primarily due to the breakdown of hemicellulose, cellulose, and lignin. A mass loss between 40 and 150 °C is attributed to the evaporation of water and volatile extractives within the material's structure. The degradation of the pistachio shells begins at 220 °C, initiated by the decomposition of hemicellulose, and progresses to 330 °C, where cellulose degradation becomes more significant. This temperature range reflects the degradation of hemicellulose and cellulose at lower temperatures, followed by the breakdown of lignin at higher temperatures [26, 41].

The fluctuations observed in the early stages of the peaks are caused by the decomposition of pistachio shells and, to a lesser extent, the polyester components. The more prominent peak in the DTG curves corresponds to the degradation of the polyester matrix at a higher temperature [26]. When the talc content in the composite reaches 20% or more, the composites containing talc (PST4, PST5, and PST6) exhibit broader peaks. Due to the stabilizing effect of talc, these peaks are less intense and broader. The results indicate that talc helps maintain the thermal stability of the composite at higher temperatures. This phenomenon can be explained by talc particles acting as a heat barrier within the polyester matrix [67]. It is believed that talc slows down the rate of polymer heating by distributing heat more evenly and reducing heat transfer throughout the composite, which could delay the thermal degradation process when the composite is exposed to high temperatures [68, 69].

The activation energies of polyester composites, calculated using the Coats-Redfern method, are presented in Table 5. Pure polyester exhibits moderate thermal stability, with a single-stage degradation behavior. Composites labeled PST2 and PST3, on the other hand, show multistage degradation behavior. The first stage generally corresponds to the low-temperature decomposition of the components in the pistachio shell. The second stage is associated with the decomposition of the shell's cellulose and lignin contents, while the final stage indicates the thermal degradation of the polyester matrix. The presence of talc makes PST3 more stable compared to PST2. However, since the activation energies in the final stages are similar, there is no significant difference in thermal resistance between these two composites. In the composites labeled PST4, PST5, and PST6, the resistance to degradation increases in the first stage as the talc content rises. The activation energies in the second stage of these composites are fairly similar, indicating that the matrix's degradation tendency does not change significantly with increasing filler content. While the filler's influence is more evident in the first stage, the matrix degradation becomes more dominant in the second stage. Talc is particularly effective in enhancing the thermal stability of the polyester matrix [1]. However, the overall decrease in activation energies during the second stage across all composites suggests that the matrix undergoes faster degradation at this point, with the filler material not stabilizing the degradation process sufficiently. This decrease in activation energy indicates that the filler-matrix interaction in talc-containing composites is not strong enough.

Table 5 Activation energy of polyester composites

Code	Stage	Temperature range (°C)	Activation energy (kJ/mol)
PST1	1st	360–405	107.6
PST2	1st	220–285	112.9
	2nd	330–360	118.6
	3rd	375–405	109.8
PST3	1st	220–285	122.2
	2nd	330–360	119.6
	3rd	375–405	111.8
PST4	1st	220–285	125.5
	2nd	350–425	100.1
PST5	1st	220–285	128.9
	2nd	350–425	100.4
PST6	1st	220–285	130.3
	2nd	350–425	100.6

The morphological examination results of the polyester composites

SEM images of pure polyester (Fig. 11a) and polyester composites are provided in Fig. 11. The fractured surface of pure polyester exhibits a homogeneous and smooth surface structure [25]. After the fracture, small broken fragments and dust particles can be observed on the surface. This smooth appearance confirms that the polyester production process was flawless and successfully executed. In the composite labeled PST2 (40% pistachio shell-filled), the pistachio shells are uniformly distributed throughout the structure. There is excellent interaction between the pistachio shells and the polyester matrix at the interface. The polyester has enveloped the entire surface of the pistachio shells, filling most of the irregularities and voids. Fractures in the composite occurred in a brittle manner, originating from the polyester matrix (Fig. 11b). The pistachio shells acted as barriers to crack propagation within the structure. With the addition of talc (Fig. 11c), the interface between the polyester matrix and the pistachio shells weakened, leading to partial cracking at these points and reducing the overall strength. Additionally, the inclusion of talc led to the formation of small voids within the structure. These voids may have originated from the geometric structure of the talc, its moisture content, or reactions during the curing process. In the composite labeled PST6 (Fig. 11d), which contains 40% talc, the talc is evenly distributed throughout the structure. Compared to pure polyester, the surface has become rougher. Due to the lamellar structure of the talc, the matrix-filler interaction has partially deteriorated. This has resulted in the formation of microcracks within the structure and a reduction in the composite's impact strength [70].

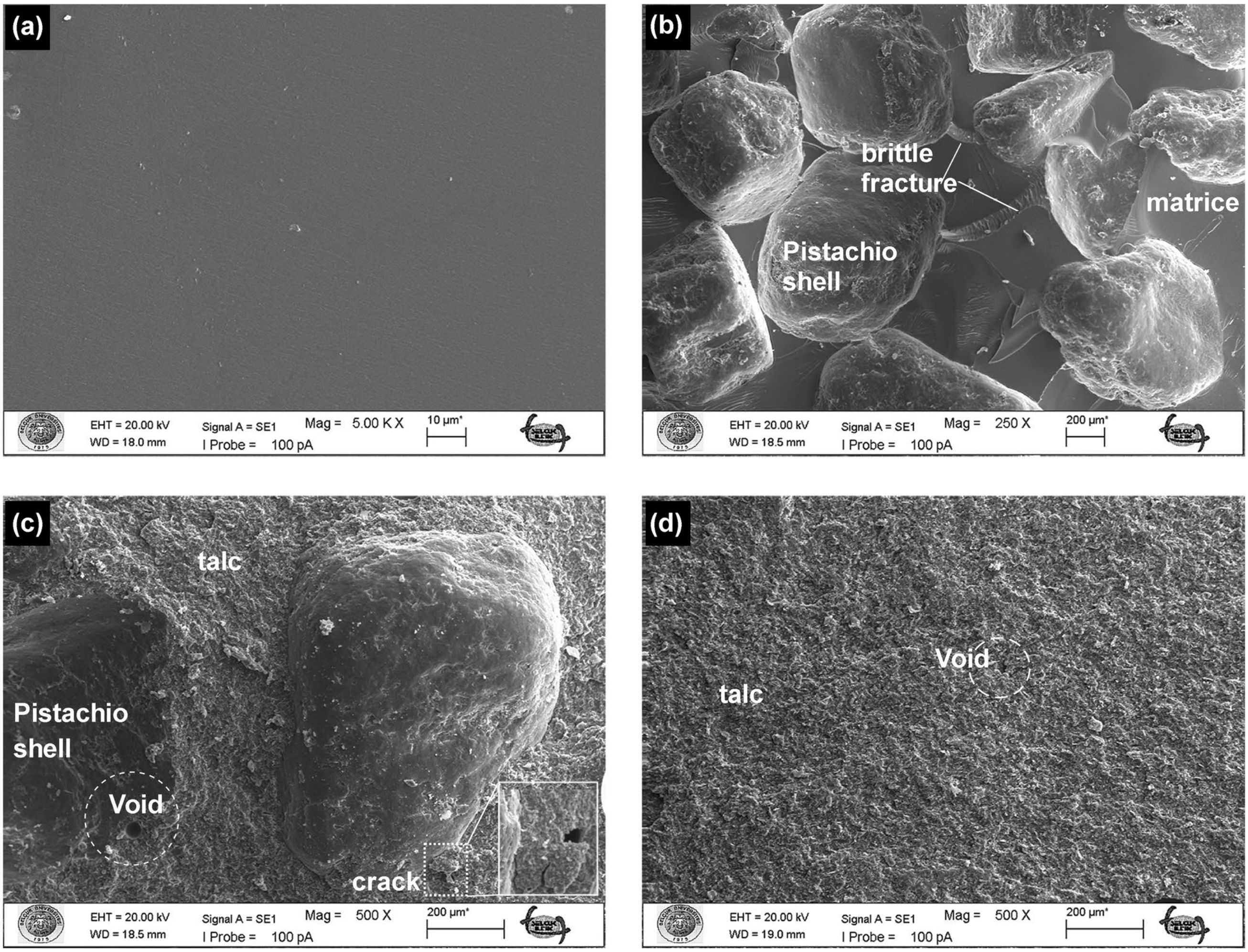

Fig. 11 SEM images (**a**) Pure polyester, (**b**) PST2, (**c**) PST4, (**d**) PST6

Conclusion

In this study, the effects of pistachio shell and talc additives on the physical and mechanical properties of polyester composites were investigated. Tensile, flexural, and Charpy impact tests revealed that pure polyester exhibited the highest strength due to its uniform and defect-free matrix structure. The addition of pistachio shell significantly reduced tensile and bending strength, likely due to poor interfacial adhesion and the brittle nature of lignocellulosic fillers. In contrast, the inclusion of talc partially improved these properties, attributed to its mineral reinforcement effect and better dispersion within the polymer matrix. Due to increased brittleness, the impact resistance of composites containing pistachio shell decreased.

Hardness and density measurements showed that composites with talc had the highest hardness values, whereas those containing pistachio shell exhibited lower hardness levels. This difference arises from the rigid and crystalline nature of talc compared to the relatively soft pistachio shell. Water absorption tests indicated that pistachio shell absorbed more water than talc due to its hydrophilic nature and porous lignocellulosic structure. Surface gloss measurements revealed that pistachio shell reduced the gloss of the composites, while talc had a limited effect on surface gloss.

FT-IR analyses confirmed the chemical structure differences between the additives, highlighting the presence of hydroxyl and aromatic groups in pistachio shell and silicate structures in talc. DSC and TGA tests demonstrated significant effects of pistachio shell and talc on the thermal properties. Pistachio shell reduced thermal stability, likely due to its lignocellulosic composition and lower degradation temperature, whereas talc improved it by acting as a thermal barrier and contributing to char formation.

In conclusion, pistachio shell and talc have notable impacts on the mechanical, physical, and thermal properties of polyester composites, with their effects strongly influenced by filler type, content, and dispersion within the polymer matrix. While pistachio shell can serve as a cost-effective and bio-based filler, its limitations in mechanical and thermal stability should be addressed for broader applications. On the other hand, talc demonstrates its potential as a reinforcing filler for improving both strength and thermal performance. Future studies could focus on optimizing the filler ratios or employing surface modifications to enhance the interfacial bonding and overall composite performance.

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Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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