

# Thermophysical behavior of date palm fiber-reinforced polyvinylchloride /low-density polyethylene/acrylonitrile butadiene rubber copolymer ternary composites

Mohamed Slimani<sup>1</sup>, Ahmed Meghezzi<sup>1</sup>, Yazid Meftah<sup>1,2\*</sup>, Samira Maou<sup>1,3\*</sup>

<sup>1</sup>Laboratoire de Chimie Appliquée, Université Mohamed-Kheider de Biskra, Biskra 07000, Algeria

<sup>2</sup>Ecole Normale Supérieure de Boussaada, Boussaada 28201, Algeria

<sup>3</sup>Département de Chimie, Université Hassiba Ben Bouali de Chlef, Chlef 02180, Algeria

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## ABSTRACT

Date palm tree leaf-reinforced polymer composites have important advantages, such as sustainability and low-cost. In the present study, ternary blend composites of polyvinyl chloride (PVC), low-density polyethylene (LDPE), and acrylonitrile butadiene rubber (NBR) copolymer (LDPE/PVC: C0, LDPE/PVC/NBR:C1) as well as reinforced composites with 10, 20, and 30 wt.% of alkali treated date palm fiber (TDPF) (C2, C3 and C4 respectively) were fabricated using a melt blending extrusion process. TDPF and the NBR copolymer were used to improve the interfacial bonding, compatibility, and thermo-mechanical properties of the composite, yielding the highest tensile strength of 32 MPa for the composite containing 10 wt.% TDPF. Moreover, the morphological analysis showed that the incorporation of the NBR copolymer enhanced the compatibility of the blend. Mechanical tests revealed that the hardness of the TDPF/PVC/LDPE/NBR composite increased in the order C2 (450 MPa) < C3 < C4 (540 MPa). In addition, the flexural and tensile moduli of the composite increased with increasing TDPF content, with the highest values (534 and 1585 MPa, respectively) observed for composite C4. Thermal analysis revealed increased  $T_{\text{onset}}$  and  $T_{10\%}$  values, indicating an improved thermal stability of the composite. This study clearly demonstrates that the (DPF/PVC/LDPE/NBR) composites can be used in various high-tech engineering applications, which require excellent properties. **Polyolefins J (2023) 10: 225-233**

**Keywords:** Polyvinylchloride; low-density polyethylene; acrylonitrile butadiene rubber; alkali treated date palm fiber.

## INTRODUCTION

Over the past few decades, fibers derived from plants, such as date palm [1, 2], jute [3], and Aloe vera [4], have attracted considerable research attention owing to their various economic, technical, and environmental benefits [5, 6]. Natural fibers play important roles in daily life, with various applications in the construction sector [7]. Date palm tree leaves represent a renewable, nonabrasive, and abundant lignocellulose source not only in Algerian oasis agriculture, but also in all Saharan countries in northern Africa [8, 9]. The annual trimming

of trees results in many new leaves being cut off, which creates a significant amount of waste. The estimated global production of date palm fiber (DPF) is 1.13 million tons [10]. Despite having a low specific weight and cost, these natural fibers show comparable strength and hardness to synthetic fibers, providing excellent mechanical characteristics [11]. In fact, this natural resource can be turned into a value-added product through the manufacture of composites with various plastic materials [12]. As such, DPF may be an interesting

\*Corresponding Author - E-mail: s.maou@univ-biskra.dz  
yazid.meftah@univ-biskra.dz

and eco-friendly alternative for use as a synthetic filler or reinforcement in advanced composites [13, 14]. The accumulation of various plastic materials in the form of waste at landfill sites leads to environmental pollution [15]. Recycling is one of the simplest approaches to minimize pollution [16]. However, the recycled materials exhibit poor behavior and properties, owing to the low compatibility and adhesion among different plastic compounds [11]. More specifically, immiscible polymer blends often exhibit inferior thermal and mechanical properties to neat polymers [12]. Polyvinyl chloride is a flexible material extensively used in the construction and building fields [17] with a high strength and resistance to corrosion and chemicals [18]. PVC has different levels of hardness and softness that allow it to be remade without losing its chemical structure or qualities [19]. Moreover, this material is sensitive to treatments at elevated temperatures, which can lead to dehydrochlorination, altering its thermal and strength properties [20]. PVC starts to degrade at approximately 100 °C, which is a much lower temperature compared to other polymers, and breaks down even in the presence of ultraviolet rays, generating hydrogen chloride (HCl) gas [21]. Melt blending processes can be used for mixing PVC with different percentages of polyethylene (PE) [22], low density polyethylene (LDPE) [23], recycled low density polyethylene (r-LDPE) [24], high-density polyethylene (HDPE) [25], polypropylene (PP), and polystyrene (PS). An efficient strategy to overcome the compatibility and adhesion issues is the introduction of small quantities of a third component used as a compatibilization agent. This component serves as the bridge linking the polymer-polymer interfaces for blend compatibilization and/or bio-reinforcement to the polymer matrix [25, 26], which may markedly alter the mechanical characteristics of the polymer blends. Xu and collaborators [27] investigated the effect of the acrylonitrile butadiene rubber (NBR) concentration (33.5-36.5 wt.%) on the characteristics of a PVC/LDPE blend, as well as its synergism with dicumyl peroxide (DCP). The results showed that NBR not only improved phase dispersion but also enhanced the interfacial adhesion in PVC/LDPE blends. Despite the fact that NBR acts as a compatibilizer in the PVC/LDPE blend and enhances the mechanical characteristics. In this regard, powdery nitrile rubber (p-NBR), dicumyl peroxide, triallyl isocyanurate, and magnesium oxide have been used to improve the interfacial compatibility of PVC/HDPE blends [28]. In addition, Xu et al. investigated the effects of butadiene rubber (BR) on the structure and mechanical behavior of PVC/LDPE

composites, as well as its synergistic effect with DCP [29]. According to some reports, the chemical compatibilizer significantly enhances the compatibility of the PVC/LDPE composites [30-32].

Recently, green composites have attracted much attention and found numerous applications owing to their improved mechanical, morphological, and thermal properties [33]. To fabricate efficient green composites, it is important to enhance the bonding adhesion between plastic polymer blends and natural fibers [34]. Another important strategy for improving the behavior of green composites is to enhance the compatibility between the natural reinforcer and the polymer matrices. Alkaline modification has been frequently applied to enhance the interfacial bonding as well as the bonding between matrix and fibers by reducing the content of non-cellulosic components, leading to a significant improvement in the fiber surface [35]. To this end, the objective of the present study is to fabricate a green composite using PVC, NBR copolymer and LDPE reinforced with TDPF, via melt blending extrusion. Furthermore, we investigated the different behaviors of the fabricated green composites. The two main goals of this study are: (i) to identify the effects of the alkali surface treatments of DPFs on the thermal and mechanical performance of TDPF/PVC/LDPE/NBR composites; and (ii) to study how the NBR copolymer affects the properties of the resulting TDPF/PVC/LDPE composites.

## EXPERIMENTAL

### Raw materials

PVC 4000 M with a K value 67-2, and bis (2-ethylhexyl) terephthalate (DOP) and LDPE pellets (melting point = 129°C, specific enthalpy of melting = 106 J/g) were supplied by the “National Petrochemical Company (ENIP)” in Skikda, Algeria. Ca/Zn stearate was purchased from Nanjing OMYA Fine Chemical Ind. Co. Ltd. (Nanjing China). NBR copolymer with an acrylonitrile (AN) content of 32 wt.%, sodium hydroxide (NaOH), and acetic acid (CH<sub>3</sub>COOH), were purchased from Sigma Aldrich, France. Date palm tree leaves were collected from the local Sidi-Okba oasis in southern Algeria.

### Preparation of DPFs

The collected DPFs were immersed into a large glass beaker filled with deionized water at 75°C for 2 h to remove dust, wax, and impurities. The DPFs were

dried under sunshine for 5 days. The dried DPFs were crushed into small particles (<1mm) using a coffee blender, sieved and stored in polyethylene bags for further compounding.

### Alkali modification of DPFs

The DPFs were pre-treated by soaking them in a 2L glass beaker filled with NaOH solution (5 wt.%) for 1 h at 80°C. Then, the sample was fully washed with deionized water and neutralized with an acetic acid solution. The TDPFs were then filtered and dried in an oven at 60°C for 2 days.

### Preparation of TDPF/PVC/LDPE/NBR composites

PVC with 5wt.% Ca/Zn and 20wt.% DOP, NBR, and LDPE were added slowly and simultaneously in a laboratory twin screw extruder, with a processing temperature ranging from 165°C to 180°C and a speed of 60 rpm. The melt blending temperature was increased to 170°C to obtain a homogenous blend. The dried TDPFs were added slowly to this polymer blend during the melt mixing process. The composite sample was cooled to room temperature and ground using a grinding machine. The composite samples were obtained using a compression molding press at 170°C under a pressure of 200 bar for 5 min. The sample codes and compositions of the composites are presented in Table 1.

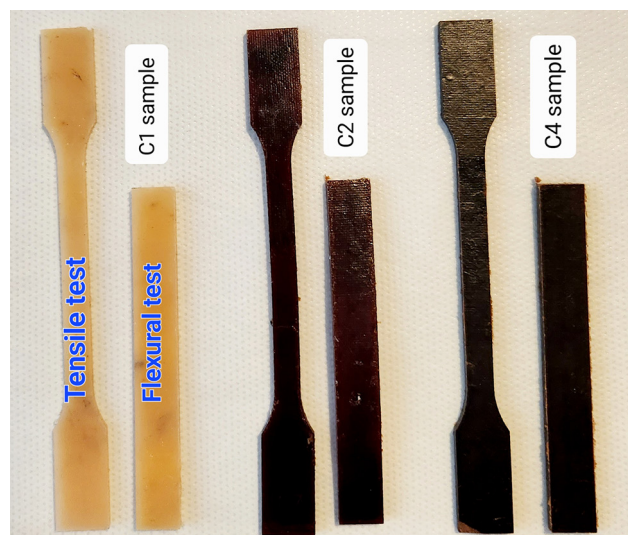
### Characterization

#### Mechanical tests

The tensile and flexural properties of the blend and composites were measured using an MTS Synergy RT1000 machine under ambient conditions. The tensile samples were tested according to the ISO 5272 standard at a crosshead speed of 3 mm/min. Three-point flexural tests were conducted according to the ISO 14125 standard at a crosshead displacement speed of 1.5 mm/min. Similarly, the Shore-D hardness test was carried out for the blend and TDPE/PVC/LDPE/NBR composites according to the ASTM D 2240, (2016) standard. At least five samples were tested for each formulation. Figure 1 shows the geometry of the

**Table 1.** Sample code and compositions of TDPF/PVC/LDPE/NBR composites.

Sample	Composition
C0	PVC/LDPE 20/80
C1	PVC/LDPE/NBR 20/80/10
C2	TDPF/PVC/LDPE/NBR 10/20/80/10
C3	TDPF/PVC/LDPE/NBR 20/20/80/10
C4	TDPF/PVC/LDPE/NBR 30/20/80/10



**Figure 1.** Geometry of the specimens for tensile and flexural testing.

specimens for tensile and flexural testing.

#### Morphological properties

Fracture surfaces of the blend and composites were prepared by liquid nitrogen freezing followed by manually breaking down the frozen samples onto thin gold films. Scanning electron microscopy (SEM) images were recorded with JEOL JSM-6031 instrument.

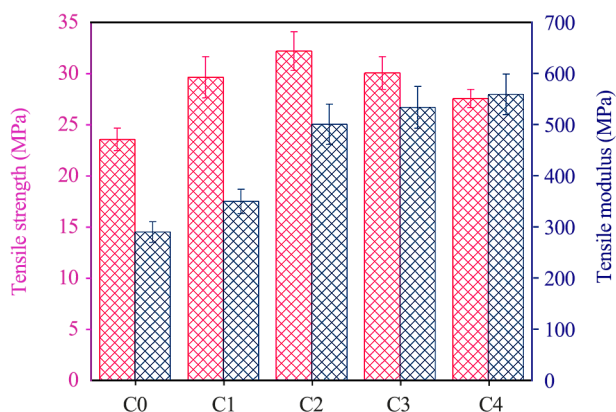
#### Thermogravimetric analysis (TGA)

Thermal decomposition of the blend and composites was performed on a thermogravimetric analyzer (TGA/DSC STARE, Mettler Toledo/ TA Instruments) in the temperature range of 25 to 600°C, at a heating rate of 10°C/min under nitrogen atmosphere.

## RESULTS AND DISCUSSION

### Mechanical properties of TDPF/PVC/LDPE/NBR composites

Figures (2-4) show the mechanical properties of the PVC/LDPE, PVC/LDPE/NBR, and TDPF/PVC/LDPE/NBR composites containing 10, 20, and 30 wt.% TDPF. As shown in figure 3, the addition of NBR to the PVC/LDPE composite improved its tensile strength and tensile modulus. This indicates that the NBR compatibilizer successfully enhanced the phase dispersion between PVC and LDPE. However, the addition of NBR as a compatibilizer has the potential to increased tensile strength of the blend from 23.6 to 29.69 MPa (20%) and its tensile modulus from 290.56



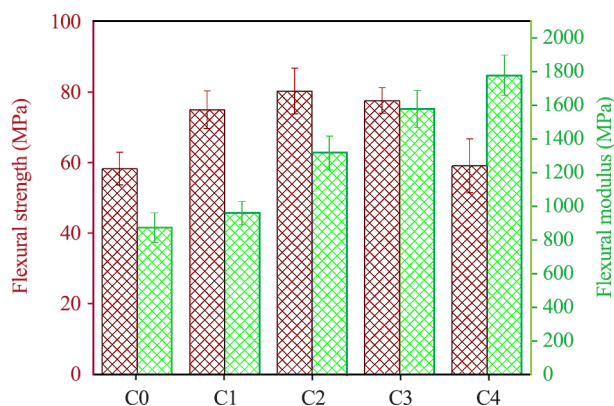
**Figure 2.** Tensile properties of TDPF/PVC/LDPE/NBR (C0, C1, C2, C3 and C4) composites.

to 350.69 MPa (17%). According to Fang et al. [31], in reactive blending, chlorinated polyethylene (CPE) or NBR can be used as compatibilizers to improve the mechanical properties of PVC/LDPE composites.

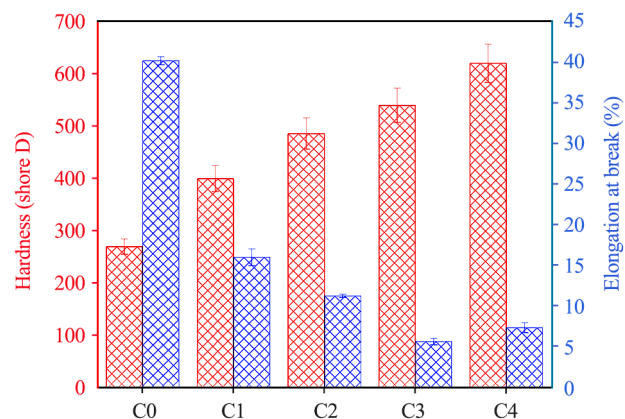
Figure 3 reveals that the flexural strength and flexural modulus increased by 16.7 and 86.94 MPa, respectively, after the addition of the NBR compatibilizer, which enhanced the interfacial adhesion between PVC and LDPE, resulting in improved dispersion. At the same time, the interfacial tension decreased, resulting in efficient stress transfer [32].

As shown in Figures 2 and 3, the tensile and flexural strengths of the C1 sample increased by 2.56 and 5.3 MPa, respectively, after reinforcement with 10 wt.% date palm fiber (sample C2). The addition of 30 wt.% TDPF (samples C4) reduced the tensile strength of the composites by 5.33 MPa, owing to the weakening of the matrix-DPF interface [32].

The PVC/LDPE/NBR matrix (C1) exhibited an elongation value of 16%. As shown in Figure 4, when date palm fibers were introduced into the polymer



**Figure 3.** Flexural properties of TDPF/PVC/LDPE/NBR (C0, C1, C2, C3 and C4) composites.



**Figure 4.** Shore D hardness and elongation-at-break of TDPF/PVC/LDPE/NBR (C0, C1, C2, C3 and C4) composites.

matrix, the percent elongation-at-break decreased. The TDPFs deformation is often significantly lower than the PVC/LDPE/NBR matrix; therefore, the TDPFs induces the matrix to deform more than the total deformation of the composites, which causes the elongation-at-break to decrease [36], the addition of TDPF to the blend matrix reduced the softness of the polymer matrix, resulting in a faster fracture process compared to the PVC/LDPE/NBR blend. Hardness is one of the key mechanical properties of polymers, as evidenced by a variety of applications [37]. Owing to the distribution of DPF in the PVC/LDPE/NBR matrix, which increased the rigidity of the composites, the hardness increased significantly upon TDPF addition. The above results illustrate the influence of the NBR copolymer on the mechanical behavior of the PVC/LDPE blend. The incorporation of NBR into the PVC/LDPE blend promotes the phase dispersion of PVC and LDPE and improves the interfacial compatibility. As a result, the NBR copolymer used here is compatible with PVC. Similar behaviors were also observed by Xu et al [29].

### Morphology of TDPF/PVC/LDPE/NBR composites

The morphology of an immiscible blend is influenced by the mixture composition, manufacturing conditions, ingredient viscosity ratio, and surface tension. In most cases, immiscible blends have a coarse morphology that may coalesce during molding or other post-blending procedures. As a result, the inclusion of the appropriate compatibilizer may increase the miscibility of the system, which generally translates into a fine structure unable to coalesce. Figure 5a displays the surface characteristics of a PVC/LDPE blend, which highlight the existence of large PVC agglomerates and holes caused by PVC

**Table 2.** Mechanical properties of blends and composites.

Sample	Tensile strength (MPa)	Tensile modulus (MPa)	Flexural strength (MPa)	Flexural modulus (MPa)	Hardness (Shore D)	Elongation-at-break (%)
C0	23.6 ± 1.14	290.56 ± 20.3	58.6 ± 4.63	878.3 ± 88.6	270 ± 14.6	40.2 ± 0.5
C1	29.69 ± 2.02	350.69 ± 23.6	75.3 ± 5.33	965.24 ± 70.32	400 ± 25.2	16.05 ± 1.02
C2	32.25 ± 2.03	456.36 ± 27.3	80.6 ± 4.96	1280.98 ± 99.3	450 ± 26.3	9.6 ± 0.6
C3	30.1 ± 1.9	501.65 ± 39.6	77.9 ± 6.5	1322.7 ± 100	486.32 ± 30	11.3 ± 0.3
C4	24.36 ± 1.6	534.65 ± 40.9	59.36 ± 3.65	1585.9 ± 110.3	540 ± 33.01	5.7 ± 0.45

particles pull-out during fracture. The actual particle size of the dispersed PVC phase for the PVC/LDPE (20:80) blend was between 3 and 30  $\mu\text{m}$ . This larger size is ascribed to the coalescence of PVC particles, due to interfacial tension with the LDPE domain. A clear lack of adhesion is observed between the PVC and LDPE surfaces. Figure 5a reveals the occurrence of voids with sizes larger than 20 micrometers. This is due to the aggregated PVC particles pulling out during fracture, similar to brittle crack growth, which is a well-known behavior of immiscible blends [38].

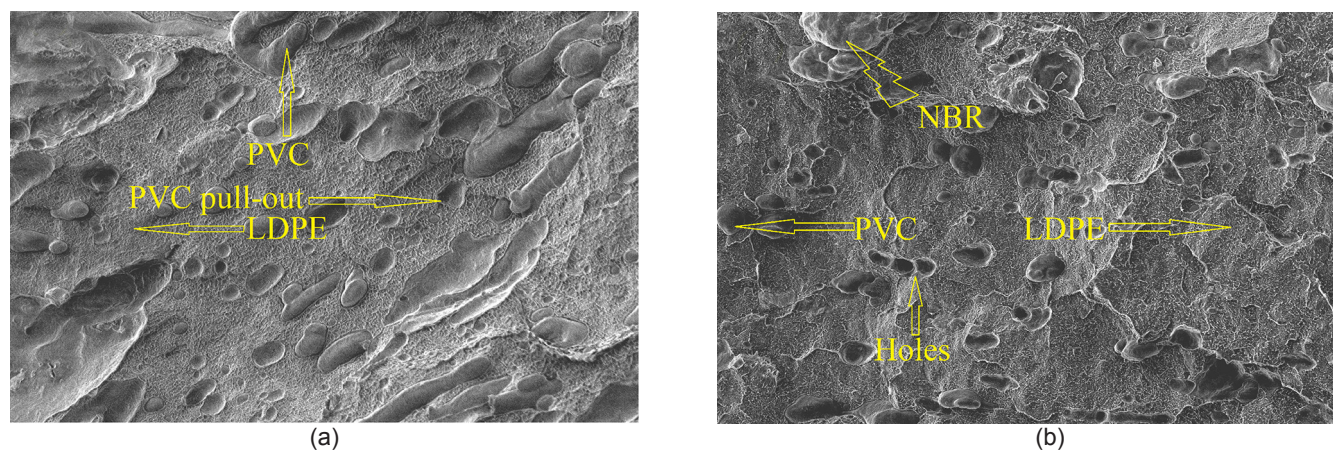
As a result, PVC/LDPE mixtures often have poor mechanical qualities. Figure 5b illustrates the impact of NBR addition on the particle size of the dispersed PVC phase. The average particle size decreased with the introduction of NBR. The decrease in the average particle size of the dispersed PVC phase improved the adhesion between the LDPE and PVC particles. In a compatible system, a decrease in particle size is generally known to be linked to the suppressed coalescence caused by the decreased interfacial tension, which leads to enhanced adhesion [39].

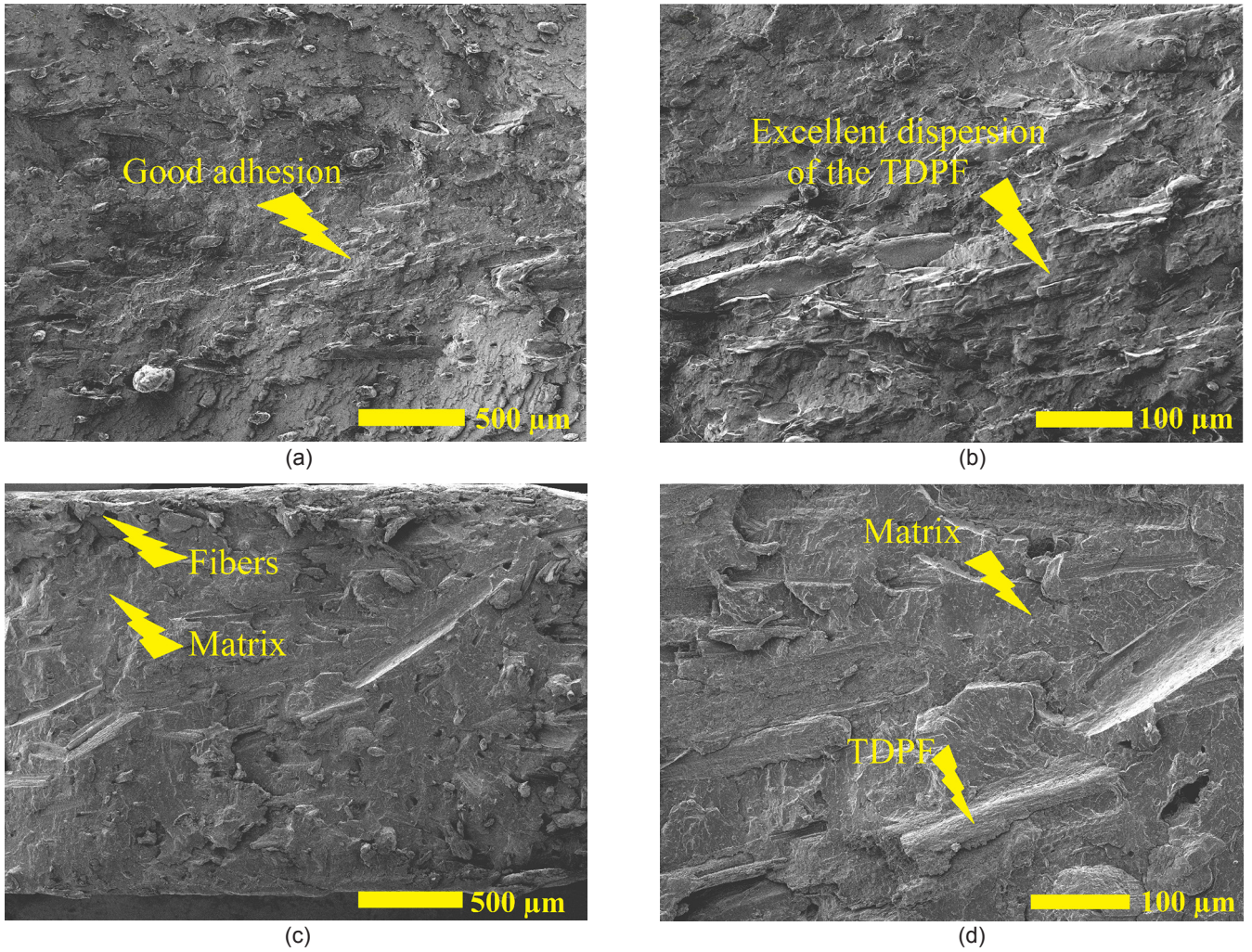
Figure 6 shows low and high magnification micro-topography images of the fracture surfaces of composites incorporating 10 and 30 wt.% TDPF. The morphology of the composite loaded with 10 wt.% TDPF revealed a uniform surface and excellent dispersion of TDPFs. Then, the miscibility between

fiber and polymer was suitably reduced, and TDPF agglomeration was observed in the composite containing 30 wt.% TDPF, as shown in Figure 6A–6D. All SEM micrographs are consistent with the mechanical properties of the present composites.

### Thermal analysis of TDPF/PVC/LDPE/NBR composites

As shown in Figures 7 and 8, TGA and DTG analyses were performed on PVC/LDPE, PVC/LDPE/NBR, and TDPF/PVC/LDPE/NBR composites containing 10, 20, and 30 wt.% TDPF. The pyrolysis of the blends occurred in two stages. The first step was probably caused by the dehydrochlorination of minor quantities of PVC, which produced PVC macroradicals, followed by the dehydrogenation of LDPE, which generated LDPE macroradicals. The second stage was most likely related to the thermal degradation of LDPE by the scission of bonds along its long chains. This resulted in shorter-chain LDPE and further PVC degradation, followed by the formation of long conjugated double bonds or polyene chains. This is consistent with the mechanism of macro-radical generation proposed by Thongpin et al. [40] and Sombatsompop et al. [41] for PVC and LDPE. The temperatures of decomposition are shown in Table 3. The addition of NBR to PVC/LDPE increased the initial thermal degradation temperature ( $T_{\text{onset}}$ ), the temperature associated with

**Figure 5.** SEM micrographs of (a) PVC/LDPE (C0) and (b) PVC/LDPE/NBR (C1) blends.

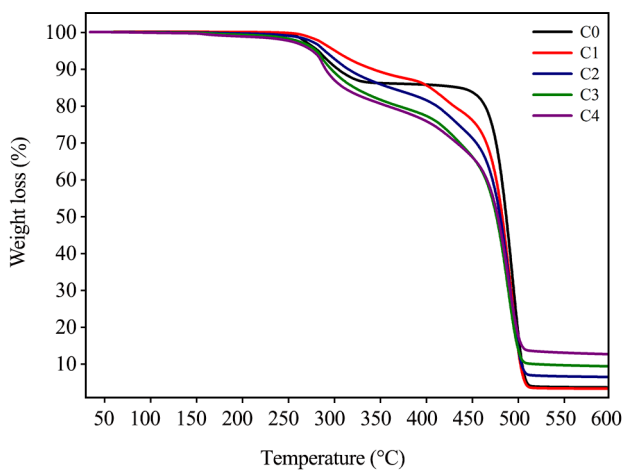


**Figure 6.** SEM micrographs of TDPF/PVC/LDPE/NBR (C2 and C4) composites at high (A,C) and low (B,D) magnifications.

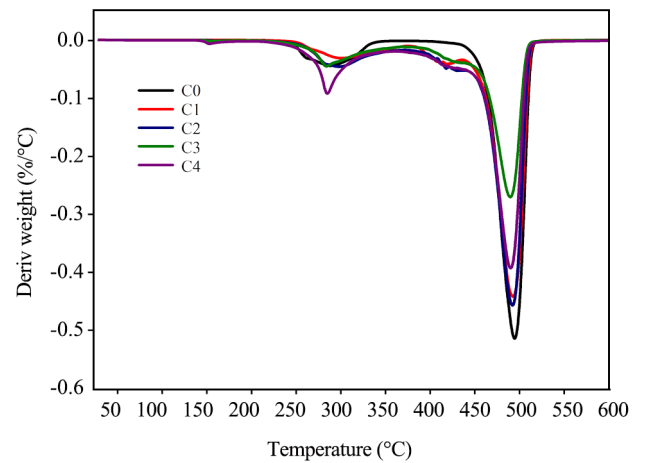
the decomposition of the TDPF/PVC/LDPE/NBR composite at a 10% rate ( $T_{10\%}$ ). The  $T_{onset}$  and  $T_{10\%}$  values increased by 19 and 37°C, respectively. It has

been reported that NBR elastomers can delay the PVC dehydrochlorination [42].

According to Figure 8, the curve of C4 sample



**Figure 7.** TGA curves of blends and TDPF/PVC/LDPE/NBR (C0, C1, C2, C3 and C4) composites.



**Figure 8.** DTG curves of blends and TDPF/PVC/LDPE/NBR (C0, C1, C2, C3 and C4) composites.

**Table 3.** Decomposition temperatures of TDPF/PVC/LDPE/NBR (C0, C1, C2, C3 and C4) composites.

Sample	T <sub>onset</sub> (°C)	T <sub>10%</sub> (°C)	T <sub>20%</sub> (°C)	T <sub>50%</sub> (°C)	T <sub>70%</sub> (°C)	T <sub>85%</sub> (°C)	Residue left (%)
C0	279.84	301	463.12	485.77	494.58	500.82	3.78
C1	298.26	338.91	429.84	482.57	490.74	498.70	3.39
C2	291.53	313.22	411.28	480.65	492.66	498.70	6.57
C3	277.50	294.30	368.40	475.53	489.46	498.15	9.74
C4	273.05	287.67	358.16	478.09	490.10	503.71	12.92

with 30 wt.% fiber loading shows a weight loss of approximately 4% between 100 and 150°C, due to water evaporation. However, the samples with 10 and 20 wt.% fiber contents (C<sub>2</sub>, and C<sub>3</sub>, respectively) are stable in this range. In the second temperature range, between 250 and 500°C, the thermal degradation of all composites is divided into three stages. The initial stage begins at 250°C and continues up to 400°C, resulting in a weight loss of approximately 15%. This step is associated with the thermal decomposition of hemicelluloses and cellulose [43]. The second stage, which occurs at around 420°C, may be attributable to NBR decomposition. The last stage is considerably faster than the first, and the thermal degradation of the composites between 450 and 500°C is attributed to the pyrolysis of the polymer matrix and the noncellulosic constituents of the fiber [44].

## CONCLUSION

In the present work, we successfully fabricated PVC/LDPE/NBR blend and TDPF-reinforced composites. The results indicate that the addition of the NBR copolymer as a compatibilizer enhanced the thermo-mechanical behavior of the PVC/LDPE blend. The NBR copolymer assisted the formation of physical bonds between the PVC and LDPE polymers, and the treated fibers enhanced the interfacial compatibility between TDPFs and the PVC/LDPE/NBR blend matrix. The synergistic effect between the TDPFs and the NBR copolymer (serving as compatibilizer) supported the preparation of environmentally friendly TDPF/PVC/LDPE/NBR composites with excellent thermo-mechanical behavior.

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## AUTHORSHIP CONTRIBUTION

Mohamed Slimani: Writing-original draft, Methodology.  
 Ahmed Maghezzi: Conceptualization, Supervision.  
 Yazid Meftah: Writing-original draft, Formal analysis.  
 Samira Maou: Writing - original draft, Methodology.

## CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

## REFERENCES

- Awad S, Zhou Y, Katsou E, Fan M (2020) A critical review on date palm tree (*Phoenix dactylifera* L.) fibres and their uses in bio-composites, Springer, Netherlands
- Elseify LA, Midani M, Shihata LA, El-Mously H (2019) Review on cellulosic fibers extracted from date palms (*Phoenix Dactylifera* L.) and their applications. *Cellulose* 26: 2209-2232
- Ovalı S, Sancak E (2022) Investigation of mechanical properties of jute fiber reinforced low density polyethylene composites. *J Nat Fibers* 19: 3109-3126
- Dehouche N, Idres C, Kaci M, Zembouai I, Bruzard S (2020) Effects of various surface treatments on Aloe Vera fibers used as reinforcement in poly(3-hydroxybutyrate-co-3-hydroxyhexanoate) (PHBHHx) biocomposites. *Polym Degrad Stab* 175: 109131
- Chaudhary V, Ahmad F (2020) A review on plant fiber reinforced thermoset polymers for structural and frictional composites. *Polym Test* 91: 106792
- Mahdi E, Ochoa DR, Vaziri A, Dean A, Kucukvar

- M (2021) Khalasa date palm leaf fiber as a potential reinforcement for polymeric composite materials. *Compos Struct* 265: 113501
7. Masri T, Ounis H, Sedira L, Kaci A, Benchabane A (2018) Characterization of new composite material based on date palm leaflets and expanded polystyrene wastes. *Constr Build Mater* 164: 410-418
  8. Meftah Y, Tayefi M, Fellouh F, Chouieur H, Maou S, Meghezzi A (2020) Influence of alkali treatment and dune sand content on the properties of date palm fiber reinforced unsaturated polyester hybrid composites. *Rev des Compos des matériaux avancés* 30: 161-167
  9. Habila T (2023) Thermal and physical properties of hybrid composites made from used PET bottles and date palm fibers filled with unsaturated polyester. *ASEAN J Chem Eng* 23: 94-102
  10. Belakroum R, Gherfi A, Kadja M, Maalouf C, Lachi M, El Wakil N, Mai TH (2018) Design and properties of a new sustainable construction material based on date palm fibers and lime. *Constr Build Mater* 184: 330-343
  11. Bourmaud A, Dhakal H, Habrant A, Padovani J, Siniscalco D, Ramage MH, Beaugrand J, Shah DU (2017) Exploring the potential of waste leaf sheath date palm fibres for composite reinforcement through a structural and mechanical analysis. *Compos Part A Appl Sci Manuf* 103: 292-303
  12. Ghori W, Saba N, Jawaid M, Asim M (2018) A review on date palm (phoenix dactylifera) fibers and its polymer composites. *IOP Conf Ser Mater Sci Eng* 368: 012009
  13. Ray R, Narayan Das S, Das A (2019) Mechanical, thermal, moisture absorption and biodegradation behaviour of date palm leaf reinforced PVA/starch hybrid composites. *Mater Today Proc* 41: 376-381
  14. Awad S, Hamouda T, Midani M, Katsou E, Fan M (2023) Polylactic acid (PLA) reinforced with date palm sheath fiber bio-composites: Evaluation of fiber density, geometry, and content on the physical and mechanical properties. *J Nat Fibers* 20: 2143979
  15. Liu Y, Zhou C, Li F, Liu H, Yang J (2020) Stocks and flows of polyvinyl chloride (PVC) in China: 1980-2050. *Resour Conserv Recycl* 154: 104584
  16. Suresh SS, Mohanty S, Nayak SK (2020) Effect of recycled poly(vinyl chloride) on the mechanical, thermal and rheological characteristics of recycled poly(methyl methacrylate). *J Mater Cycles Waste Manag* 22: 698-710
  17. Ye L, Qi C, Hong J, Ma X (2017) Life cycle assessment of polyvinyl chloride production and its recyclability in China. *J Clean Prod* 142: 2965-2972
  18. Jiang L, He C, Fu J, Xu D (2019) Enhancement of wear and corrosion resistance of polyvinyl chloride/sorghum straw-based composites in cyclic sea water and acid rain conditions. *Constr Build Mater* 223: 133-141
  19. Díaz S, Ortega Z, McCourt M, Kearns MP, Benítez AN (2018) Recycling of polymeric fraction of cable waste by rotational moulding. *Waste Manag* 76: 199-206
  20. Wu J, Tang Z, Liu X, Lin W, Feng M, Lin X, Gu Y, Li Y, Yi G (2020) A facile strategy improving poly(vinyl chloride) stability by introducing unsaturated maleic acid-sorbitol ester and zinc maleic acid-sorbitol ester complex. *Polym Degrad Stab* 181: 109343
  21. Li Y, Wang H, Jiang L, Zhang W, Li R, Chi Y (2015) HCl and PCDD/Fs emission characteristics from incineration of source-classified combustible solid waste in fluidized bed. *RSC Adv* 5: 67866-67873
  22. Bittencourt PRS, Scremin FR (2019) Evolved gas analysis of PE: PVC systems thermodegradation under inert and oxidizing atmosphere. *J Polym Environ* 27: 612-617
  23. Khakberdiev EO, Berdinazarov QN, Toshmamatov DA, Ashurov NR (2022) Mechanical and morphological properties of poly(vinyl chloride) and linear low-density polyethylene polymer blends. *J Vinyl Addit Technol* 28: 659-666
  24. Maou S, Meftah Y, Meghezzi A (2023) Synergistic effects of metal stearate, calcium carbonate, and recycled polyethylene on thermo-mechanical behavior of polyvinylchloride. *Polyolefins J* 10: 1-11
  25. Maou S, Meftah Y, Grohens Y, Kervoelen A (2023) The effects of surface modified date-palm fiber fillers upon the thermo-physical performances of high density polyethylene-polyvinyl chloride blend with maleic anhydride as a grafting agent. *J Appl Polym Sci* 140: e53781
  26. Maou S, Meftah Y, Tayefi M, Meghezzi A, Grohens Y (2022) Preparation and performance of



- an immiscible PVC-HDPE blend compatibilized with maleic anhydride (MAH) via in-situ reactive extrusion. *J Polym Res* 29: 161
27. Xu C, Fang Z, Zhong J (1993) Study on compatibilization-crosslinking synergism in PVC/LDPE blends. *Die Angew Makromol Chemie* 212: 45-52
  28. Fang Z, Xu C, Bao S, Zhao Y (1997) In situ crosslinking and its synergism with compatibilization in polyvinyl chloride/polyethylene blends. *Polymer (Guildf)* 38: 131-133
  29. Xu C, Fang Z, Zhong J (1997) Study on phase dispersion-crosslinking synergism in binary blends of poly(vinyl chloride) with low density polyethylene. *Polymer (Guildf)* 38: 155-158
  30. Ma G, Fang Z, Xu C (2003) Phase dispersion-crosslinking synergism in binary blends of poly(vinyl chloride) with low-density polyethylene: Entrapping phenomenon in PVC/LDPE/DCP blend. *J Appl Polym Sci* 88: 1296-1303
  31. Fang Z, Ma G, Liu C, Xu C (2004) Morphology evolution of immiscible LDPE/PVC blends in the presence of compatibilizer and phase dispersant. *J Appl Polym Sci* 91: 763-772
  32. Prachayawarakorn J, Khamsri J, Chaochanchaikul K, Sombatsompop N (2006) Effects of compatibilizer type and rubber-wood sawdust content on the mechanical, morphological, and thermal properties of PVC/LDPE blend. *J Appl Polym Sci* 102: 598-606
  33. Maou S, Meghezzi A, Nebbache N, Meftah Y (2019) Mechanical, morphological, and thermal properties of poly(vinyl chloride)/low-density polyethylene composites filled with date palm leaf fiber. *J Vinyl Addit Technol* 25: E88-E93
  34. Maou S, Meghezzi A, Grohens Y, Meftah Y, Kervoelen A, Magueresse A (2021) Effect of various chemical modifications of date palm fibers (DPFs) on the thermo-physical properties of polyvinyl chloride (PVC)-high-density polyethylene (HDPE) composites. *Ind Crops Prod* 171: 113974
  35. Berkouk A, Meghezzi A, Chelali H, Soltani MT (2021) Mechanical, morphological, thermal and dynamic study of composites of unsaturated polyesters-date palm leaf fiber DPLF. *Rev des Compos des matériaux avancés* 31: 317-323
  36. Salmah H, Romisuhani A, Akmal H (2013) Properties of low-density polyethylene/palm kernel shell composites: Effect of polyethylene co-acrylic acid. *J Thermoplast Compos Mater* 26: 3-15
  37. Mishra T, Mandal P, Rout AK, Sahoo D (2022) A state-of-the-art review on potential applications of natural fiber-reinforced polymer composite filled with inorganic nanoparticle. *Compos C: Open Access* 9:100298
  38. Zhao X, Niu K, Xu Y, Peng Z, Jia L, Hui D, Zhang L (2016) Morphology and performance of NR/NBR/ENR ternary rubber composites. *Compos Part B Eng* 107: 106-112
  39. Inuwa IM, Hassan A, Samsudin SA, Mohammad Haafiz M, Jawaid M (2017) Interface modification of compatibilized polyethylene terephthalate/polypropylene blends: Effect of compatibilization on thermomechanical properties and thermal stability. *J Vinyl Addit Technol* 23: 45-54
  40. Thongpin C, Santavitee O, Sombatsompop N (2006) Degradation mechanism and mechanical properties of PVC in PVC-PE melt blends: Effects of molecular architecture, content, and MFI of PE. *J Vinyl Addit Technol* 12: 115-123
  41. Sombatsompop N, Sungsanit K, Thongpin C (2004) Structural changes of PVC in PVC/LDPE melt-blends: Effects of LDPE content and number of extrusions. *Polym Eng Sci* 44: 487-495
  42. Khalil AM, Rabie ST (2021) Mechanical, thermal and antibacterial performances of acrylonitrile butadiene rubber/polyvinyl chloride loaded with Moringa oleifera leaves powder. *J Therm Anal Calorim* 143: 2973-2981
  43. Batuer A, Chen D, Xin Q, He X, Zhang J, Huang Z (2020) Mechanical properties of waste cotton and their changes during early pyrolysis. *J Anal Appl Pyrolysis* 149: 104855
  44. Sh. Al-Otaibi M, Alothman OY, Alrashed MM, Anis A, Naveen J, Jawaid M (2020) Characterization of date palm fiber-reinforced different polypropylene matrices. *Polymers (Basel)* 12: 597