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Recycling of LDPE-PVC blends from cable waste: Mechanical characterization and performance optimization

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ABSTRACT

The recycling of polyvinylchloride (PVC) from waste electrical cables in blends with low-density polyethylene (LDPE) is here explored, focusing on the material's mechanical and physical responses. Factors influencing these responses were identified, and reasonable ranges of variability were estimated for each factor. A comprehensive test plan was subsequently devised to develop optimal PVC/LDPE blends. The samples were produced by melt-blending the polymers in a counter-rotating internal mixer followed by compression molding. The effects of suitable coupling additives were also evaluated to enhance phases adhesion. The study investigated the impact of various processing parameters on thermomechanical properties using ANOVA, while a specific focus on optimizing material toughness was pursued. This optimization aimed to maximize both elastic modulus and elongation at break, through the application of genetic algorithms. Introducing a 5 % compatibilizer significantly enhances the interface, resulting in a complex fracture surface facilitated by its presence. Higher mixing temperatures promote better dispersion and distribution of PVC and the compatibilizer within the LDPE matrix, yielding a more uniform and interconnected structure. Increased PVC content correlates with reduced elastic modulus in the blend. The inclusion of a compatibilizer plays a vital role in counteracting the negative effects of PVC particles on stiffness, acting as a bridge to enhance interactions with the matrix and thereby improving interfacial adhesion and overall structure. The study offers insights into enhancing the recyclability of PVC from waste cables and optimizing the mechanical performance of the resultant materials.

1. Introduction

Global plastic consumption has witnessed a dramatic surge, with fossil fuels constituting a significant portion of the feedstock for plastic production. Polyvinyl chloride (PVC), a widely used thermoplastic polymer, presents a particular challenge due to the substantial waste generated from applications like electrical cables. Annual PVC production surpasses 35 million tons, accounting for nearly 10 % of global plastic production [1,2]. Stricter environmental regulations and a growing focus on sustainability necessitate the development of effective recycling strategies for PVC to minimize landfilling and resource depletion. Traditional cable recycling has primarily focused on metal recovery, neglecting the potential of polymeric sheath. Thermochemical conversion methods, while seemingly attractive, pose environmental risks due to the potential generation of harmful byproducts like hydrogen chloride, dioxins, and furans [3]; [4]. This necessitates exploring alternative recycling pathways that prioritize both environmental and economic benefits. Recent research advancements offer promising avenues for PVC cable waste valorization. The European Regional Development Fund (POR CALABRIA 2014–2020) funded a project investigating the repurposing of PVC from electrical cables into secondary raw materials for civil engineering applications. This project, spearheaded by R.ED.EL. SRL, explored the incorporation of recycled PVC into urban tiles and cementitious mortars. The findings demonstrated the feasibility of utilizing PVC waste in these applications, achieving satisfactory mechanical performance while offering additional benefits such as improved thermal insulation and reduced permeability. Understanding the composition and behavior of recycled PVC is crucial for optimizing its utilization in novel applications. Janajreh et al. [5] employed thermogravimetric analysis to characterize the thermal stability and residual content of PVC waste derived from electrical cables. Their study provided valuable insights for devising suitable processing conditions for recycled PVC. Subsequent mechanical testing confirmed the feasibility of integrating recycled PVC into sustainable manufacturing processes. Challenges remain in directly blending unmodified PVC with other polymers due to incompatibility

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issues. Diaz et al. [6] investigated the use of unpurified electrical cable sheath material in rotational molding blends with virgin polyethylene. While the study demonstrated the feasibility of incorporating up to 35 % recycled content without significant performance reduction, limitations were evident at higher inclusion levels. Overcoming these compatibility challenges is a key focus in PVC recycling research. Czarnecka-Komorowska et al. [7] addressed this issue by incorporating recycled LDPE and a compatibilizer into PVC waste. Their results indicated that recycled polyethylene (rLDPE) effectively serves as a secondary phase in the blend, enhancing tensile modulus and flexural strength compared to blends consisting solely of PVC. To improve component homogenization within the matrix, the researchers added 5 % by weight of maleic anhydride grafted polyethylene (PE-*g*-MAH) as a compatibilizer for the PVC blend. They found that the optimal solution for cable waste management involves producing composites through homogenization using an internal mixer, incorporating 20 % by weight of rLDPE and 5 % by weight of PE-g-MAH into the plastic cable waste. This approach resulted in improved mechanical properties compared to blends containing only PVC. These findings highlight the potential of modifying the recycled PVC matrix to enhance its compatibility with other polymers.

Building upon this knowledge base, this study delves deeper into the influence of the LDPE/PVC ratio on the mechanical properties of the blends. A design of experiments (DOE) approach is employed to systematically analyze the impact of this critical processing parameter. This comprehensive approach aims to identify key interactions between processing variables and their influence on the resulting material characteristics. Furthermore, the study seeks to establish empirical equations that correlate processing conditions with the final mechanical properties. The successful development of LDPE/PVC blends with optimized mechanical properties would represent a significant advancement in PVC cable waste valorization. Such blends offer a sustainable solution for reusing waste PVC in engineering applications, promoting resource conservation and aligning with the growing emphasis on circular economy principles in the construction industry. Ultimately, this research contributes to mitigating the environmental impact of plastic consumption while fostering advancements in sustainable material utilization and construction practices.

2. Materials and methods

2.1. Materials

PVC granules recovered from waste electrical cables were provided by Salvadori S.p.A. (Rovereto, Italy).

The low-density polyethylene (LDPE) utilized in this study was sourced as Flexirene® CL10. It was obtained from Versalis S.p.A. (San Donato Milanese, Italy) in granular form and possesses a density of 0.918 g/cm3, a melting temperature of 120 °C, and a melt flow index (MFI) of 2.6 g/10 min at 190 °C and 2.16 kg.

The compatibilizer used was a linear low-density polyethylene blend modified with maleic anhydride, known as Compoline CO/LL05, provided by Auser Polimeri (Coreglia Antelminelli, Italy). This general-purpose coupling agent is commonly used in polyolefin compounds. Compoline CO/LL05 exhibits a melt index of 1.5 g/10 min at 190 °C and 2.16 kg, a melting point of 120 °C, and a density of 0.92 g cm^{-3}. The maleic anhydride functional groups in the polyethylene graft onto the PVC or rubber molecules create a stronger bond and promote better dispersion of the components within the blend.

2.2. Sample production

This study aimed to enhance the mechanical properties of PVC waste without relying on the pollutant and hazardous chemicals typically used as consolidants (isocyanates). Instead, a combination of LDPE and a compatibilizer was employed through melt mixing and hot pressing. Careful consideration was given to material selection and parameter choices to maximize the degree of improvement. Four key parameters were selected for investigation: PVC content (PVC), compatibilizer content (COMPO), mixing temperature (TM), and compression temperature (TC). By optimizing these parameters, we aimed to enhance the mechanical properties of the PVC waste material. To investigate how these variables influence the mechanical properties of the investigated compounds, a 2^4 full factorial design [8] has been used, whose factors and levels are given in Table 1. Each factor varies between two levels, normalized between -1 and $+1$.

Federov's exchange algorithm is a mathematical method used for experimental design and optimization [9]. The compositions prepared were selected using Federov's exchange algorithm, resulting in a D-efficiency of 0.824. This experimental design is presented in Table 2. According to the parameters of Table 2, PVC, compatibilizer, and LDPE, in a concentration equal to 100-x1-x2, were melt mixed by a compounder Thermo-Haake Polylab (Vreden, Germany) equipped with a mixing chamber of 50 cm^3. The melt mixing was performed at the temperature ×3 and 60 rpm for a total of 10 min. The prepared materials were compression molded into sheets of approximately 2 mm thickness using a Carver hot press 4122 (Wabash, IN, USA) at the temperature ×4 and a pressure of 3.9 MPa for 5 min. Specimens for mechanical characterization were cut out of the compression molded sheets with a laboratory-scale Carver punch die in the shape of ISO527 1BA.

2.3. Characterization techniques

2.3.1. Preliminary characterization of waste material

Particle size analysis was conducted by analyzing the optical pictures of the material (Fig. 1) through the ImageJ software. In particular, the projected area of about a thousand particles are measured and their diameter is calculated by assuming a spherical shape.

The density of waste PVC material from electrical cable was measured using a helium pycnometer, Micrometrics Instrument Accupyc 1330 pycnometer (Georgia, USA) at a temperature of 23 °C. To take into account the possible inhomogeneity of the material supplied, 5 samples were tested, and 30 measurements were taken for each sample.

Thermo-gravimetric analysis (TGA) consists of the continuous measurement over time of the mass change of a sample of material as a function of temperature under controlled environmental conditions. This test was carried out with a TA Instrument TGA Q5000 thermobalance (Delaware, USA) in a flushed nitrogen atmosphere of 100 ml/min in a temperature range from 30 °C to 700 °C at a heating rate of 10 °C/min. TGA can provide insights into the thermal stability and potential reactivity of the waste material during recycling or disposal processes. This knowledge is crucial for determining appropriate processing conditions and understanding the potential environmental impact of the waste material.

Fourier transform infrared spectroscopy, abbreviated as FT-IR, is an absorption spectroscopic technique commonly used in the field of analytical chemistry and materials characterization for the study and characterization of chemical bonds. This test was performed using a PerkinElmer Spectrum One (Burladingen, Germany) in a wavenumber range between 4000 cm^{-1} and 650 cm^{-1} with a KBr beamsplitter. Its resolution ranges from 0.5 cm^{-1} to 64 cm^{-1} and 4 scans were acquired for each specimen.

Table 1
Experimental parameters and extremes considered for a 2^4 Experimental Design in investigating PVC/LDPE blends.

Factor	Level	−1	+1
PVC	PVC content (vol%)	10	90
COMPO	Compatibilizer content (vol%)	0	5
TM	Compounding temperature (°C)	120	190
TC	Compression temperature (°C)	120	190

Table 2
Experimental design according to Federov's exchange algorithm.

Sample	PVC concentration, PVC (vol %)	Compatibilizer concentration, COMPO (vol %)	Compounding Temperature, TM (°C)	Pressing temperature, TC (°C)
1	10	0	120	120
2	90	0	120	120
3	10	5	120	120
4	90	5	120	120
5	10	0	190	120
8	90	5	190	120
9	10	0	120	190
12	90	5	120	190
14	90	0	190	190
15	10	5	190	190

2.3.2. Compression molded sample characterization

The samples' density was determined using Archimedes' principle in ethanol at a temperature of 23 °C. A Gibertini E42 precision digital balance (Modena, Italy), with a sensitivity of 10^{-4} g, was employed for the measurements.

FESEM analysis was conducted to examine the morphology of LDPE/PVC blends on cryofractured surfaces. Prior to observation, all specimens underwent coating with a platinum/palladium alloy (Pt/Pd 80:20) for 20 s and were then examined using a Carl Zeiss AG Supra 40 microscope (Oberkochen, Germany).

The thermal conductivity (λ) was determined using the formula $\lambda = \alpha \rho c_p$, where α represents the thermal diffusivity, ρ denotes the density of the sample, and cp stands for the specific heat capacity. To measure the thermal diffusivity, a laser flash technique was employed using a Netzsch LFA 467 HyperFlash instrument (Selb, Germany) operating at room temperature under an inert N2 atmosphere. Prior to conducting measurements, a thin layer of graphite was spray-coated onto both surfaces of the samples. Subsequently, a light pulse (generated from a Xenon lamp) with a roughly rectangular intensity profile and a duration of 0.6 ms was applied to the front surface of the sample. The temperature rise at the rear surface was recorded using an InSb IR detector. The diffusivity of the sample was determined by averaging five measurements. The specific heat capacity of the specimen was determined using a Netzsch standard, while the density was measured using the Archimedes principle.

Quasi-static tensile tests were conducted using an Instron 5969 (Norwood, USA) testing machine in accordance with ISO 527 standards. The tests were conducted at room temperature using dumbbell-shaped specimens of type 1BA. The testing machine was equipped with a 10 kN load sensor. The elastic modulus (E) was measured at a rate of 0.25 mm/min using an extensometer (Instron 2603, Norwood, USA) with a gauge length of 12.5 mm, with a maximum deformation set at 1 %. The elastic modulus was calculated as the secant modulus between deformation levels of 0.05 % and 0.25 %. Ultimate tensile stress (UTS), stress at break (σb), and strain at break (εb) were determined without the use of the extensometer, with a crosshead speed set at 10 mm/min. Each sample was tested using at least five specimens to ensure reliability of the results.

The results obtained from the characterization of the compression molded samples were analyzed using the response surface methodology (RSM) technique to derive empirical models for various properties, including density, thermal conductivity, elastic modulus (E), ultimate tensile stress (UTS), stress at break (σb), and strain at break (εb). RSM is a statistical method introduced by George E. P. Box and K. B. Wilson in 1951, which explores the relationships between multiple explanatory variables and one or more response variables [10]. The fundamental concept behind RSM is to conduct a sequence of designed experiments to optimize the response. While the model generated by RSM is an approximation, it proves to be highly valuable as it is easy to estimate and implement, even when limited information is available about the underlying process. This methodology allows for the evaluation of the effects of various factors and their interactions on the response variables [8]. In our study, we employed a full quadratic response surface to model the influence of the considered factors on the mechanical properties of the fibers, as described by Equation (1):

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} \beta_{ij} x_i x_j + \epsilon \tag{1}$$

where y is the measured output, β_0 is the y-intercept which is the value of y when all other parameters are set to 0 (independent variables and

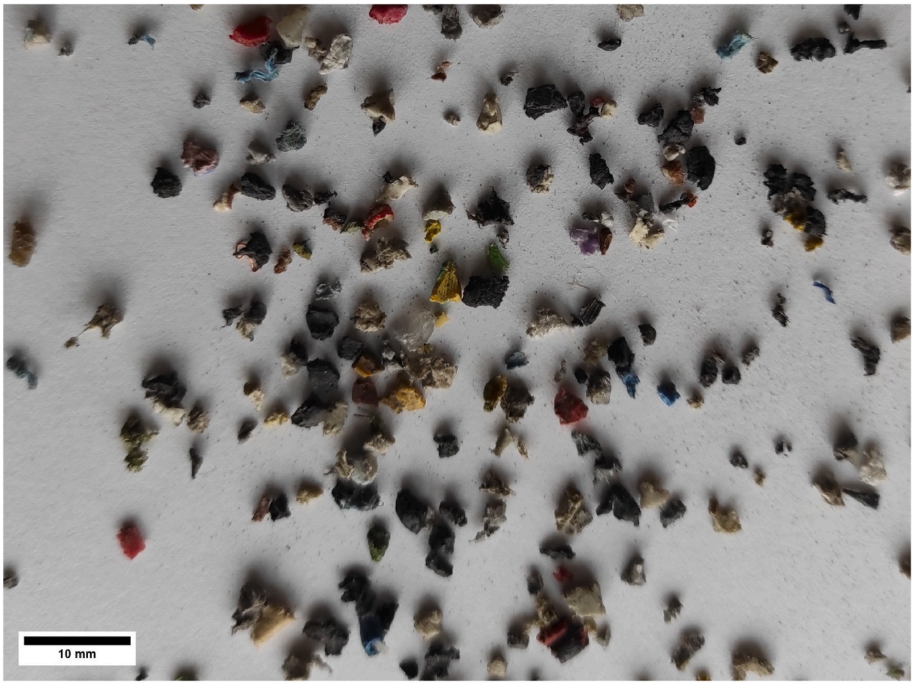


Fig. 1. PVC waste particles, one of the images taken for the determination of dimensions.

error term), x_i is the designated input variable, β_{ij} is the regressor coefficient and ε is the error term. Following this procedure, an analysis of variance (ANOVA) was conducted to assess the significance of each term concerning the measured responses. Terms exhibiting a high F value (Fisher test) and correspondingly low probability value (P-value <0.05) were identified as highly significant, whereas terms with larger P-values (P-value >0.05) were deemed non-significant. To determine the optimal process parameters, specifically the combinations that maximize both elastic modulus and strain at break, we employed the multi-objective non-dominated sorting genetic algorithm (NSGA2) optimization technique [11]. Genetic algorithms (GA) operate based on the principles of natural selection outlined in Darwinian theory, whereby the most robust species survive and proliferate, while less successful ones fade away. NSGA2, introduced by Deb et al. [12], is a widely recognized and potent multi-objective evolutionary algorithm. NSGA2 has been established as a strong method among the numerous methods of multi-objective optimization in many fields of material science [13]; [14–16].

3. Results and discussions

3.1. Preliminary characterization of waste material

The PVC waste granules are shown in Fig. 1, which represents an example of the several photos used to determine the average size of the PVC granules. The PVC particles have a complex shape. The volume of each particle was measured and the diameter x of a sphere of the same volume was used as an indication of the particles size. The analysis of the diameter distribution of the particles revealed that it did not follow a Gaussian distribution, as evidenced by the Shapiro-Wilk test (p-value $<2.2 \times 10^{-16}$). Instead, a better fit to the experimental data was achieved using the beta distribution, the probability density function of which is detailed in Equation (2).

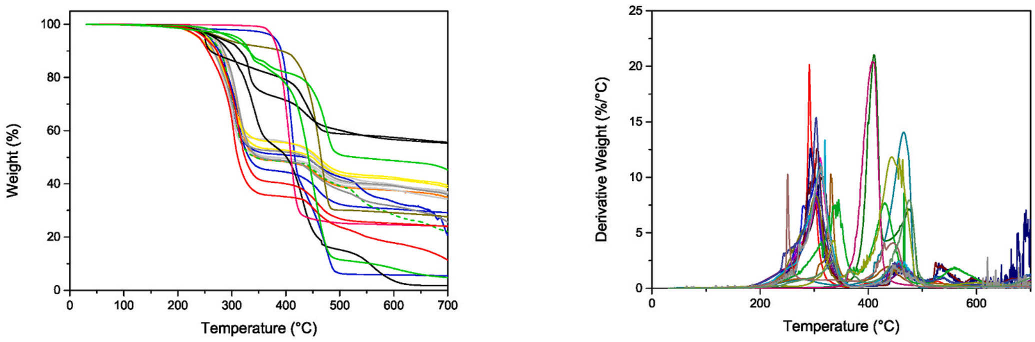
$$f(x;\alpha,\beta) = \frac{1}{B(\alpha,\beta)}\, x^{\alpha-1}(1-x)^{\beta-1} \tag{2}$$

where x is the equivalent diameter and α and β are the fitting parameters. This distribution provided a more accurate representation of the observed particle sizes. Based on the beta distribution, it was determined that the mean diameter of the particles was 2.07 ± 0.15 mm. This metric serves as a central value to describe the average size of the PVC granules. By considering the entire dataset, which includes more than 1000 particles, and employing the appropriate statistical analysis, the beta distribution analysis allowed for a more precise characterization of the size distribution and the estimation of the mean diameter of the PVC waste particles.

The density measurement using a pycnometer revealed a density of 1.43 ± 0.02 g cm^{-3} for the waste particles. The density of the waste may vary due to the presence of metal particles and other plastic components, resulting in non-uniform density distribution within the material. To quantify the content of these foreign materials, 100 g of waste were immersed in 500 ml of distilled water for 10 days to facilitate the separation of materials with densities greater or less than 1 g/cm^{-3}. At the end of this test, it was found that 1.95 % of the material remained afloat, hence with a density below 1 g cm^{-3}. These granules can be polyethylene or polypropylene due to their density being lower than water. The material with ferromagnetic behavior extracted by means of a magnet is about 0.14 %. Understanding the heterogeneous nature of the waste composition is crucial for further processing and recycling efforts. By identifying and separating the different components, such as metals and non-PVC plastics, appropriate recycling strategies can be implemented to effectively recover valuable resources and minimize waste.

Approximately 20 different granules from PVC waste were examined through TGA, and their corresponding thermo-gravimetric curves are shown in Fig. 2a while the corresponding derivative curves are shown in Fig. 2b. The colors of the curves reflect the colors of the granules analyzed. Upon analysis, it becomes apparent that all the examined granules exhibit no weight loss up to a temperature of 200 °C. This finding indicates an important threshold, i.e. the maximum working temperature at which degradation and the subsequent production of hydrochloric acid (HCl) can be avoided during the thermal decomposition of PVC. By understanding this thermal limitation, it becomes possible to establish appropriate processing conditions for the PVC waste material. Operating within a temperature range below 200 °C ensures that the integrity of the material is preserved, minimizing the generation of hazardous byproducts and maintaining the overall quality of the recycled or processed PVC. Most of the samples showed a two-step weight reduction at around 250 °C and 450 °C, which may correspond to the thermal degradation of PVC [17]; [18,19]. Some samples have shown a single-step weight loss at around 400 °C, which may correspond to the degradation of ABS [20] or aliphatic polymers such as polyethylene or polypropylene [21], confirming their presence as seen in the density separation test. The residual content at 700 °C after polymer degradation can be attributed to inorganic fillers such as talc, carbon black or flame retardants and varies from 55 % to 2 %.

In Fig. 3, 15 FTIR spectra on different particles from recycling of PVC waste are shown and each color represents the color of the granule itself. In the case of the analyzed particles, the presence of characteristic peaks in the FTIR spectrum indicates that a significant portion of the granules can be identified as PVC. These peaks correspond to specific vibrational modes of the chemical bonds and functional groups typically found in PVC molecules. By comparing the obtained spectrum with reference spectra of known materials, the identification of PVC can be confidently made. Absorption bands of PVC are evidenced at 2972 cm^{-1} related to the C–H stretching from CH–Cl, at 2929 cm^{-1} from C–H stretching from CH_2, at 1466 and at 1422 cm^{-1} from wagging CH_2, at 1270 cm^{-1} related to the C–H stretching from CH–Cl, at 1124 cm^{-1} from C–C, at 956 cm^{-1} from the rocking vibration of CH_2, and at 728 cm^{-1} from C–Cl stretching [22]. The presence of oxygenated structures in the PVC chain is



(a) *(b)*

Fig. 2. (a) Thermogravimetric curves for different granules of PVC waste and (b) their corresponding derivative curves.

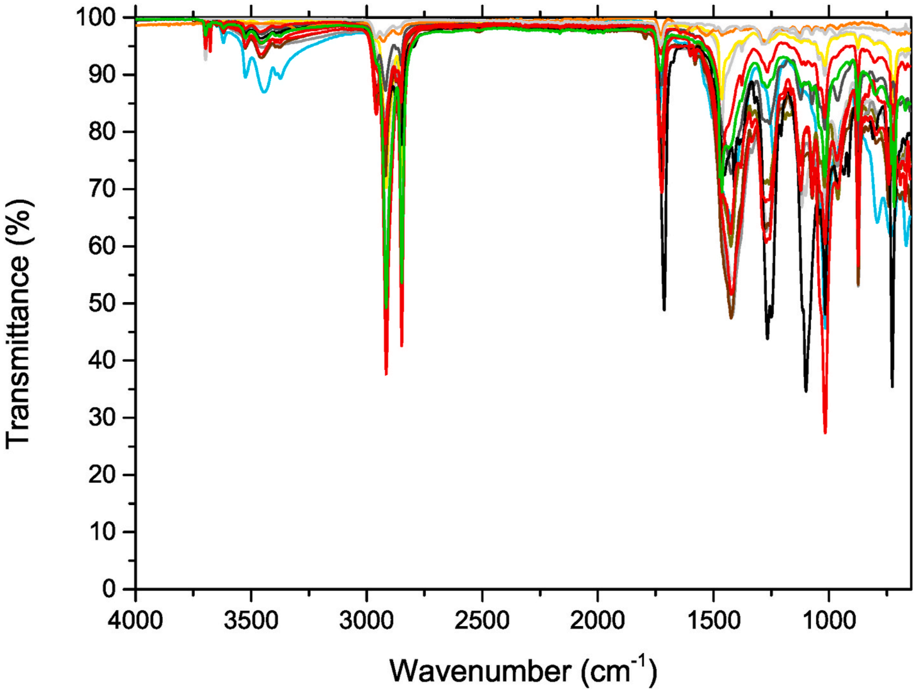


Fig. 3. FTIR spectra of PVC waste particles.

indicated by the absorption observed around 1723 cm^{-1}, which suggests the presence of additives in the PVC product [23]. Some of these granules can be identified as PE [24] or PP [25] based on the presence of characteristic peaks associated with these two polymers. This observation confirms the findings from buoyancy tests, where polymers with a density lower than 1 g cm^{-3} were identified.

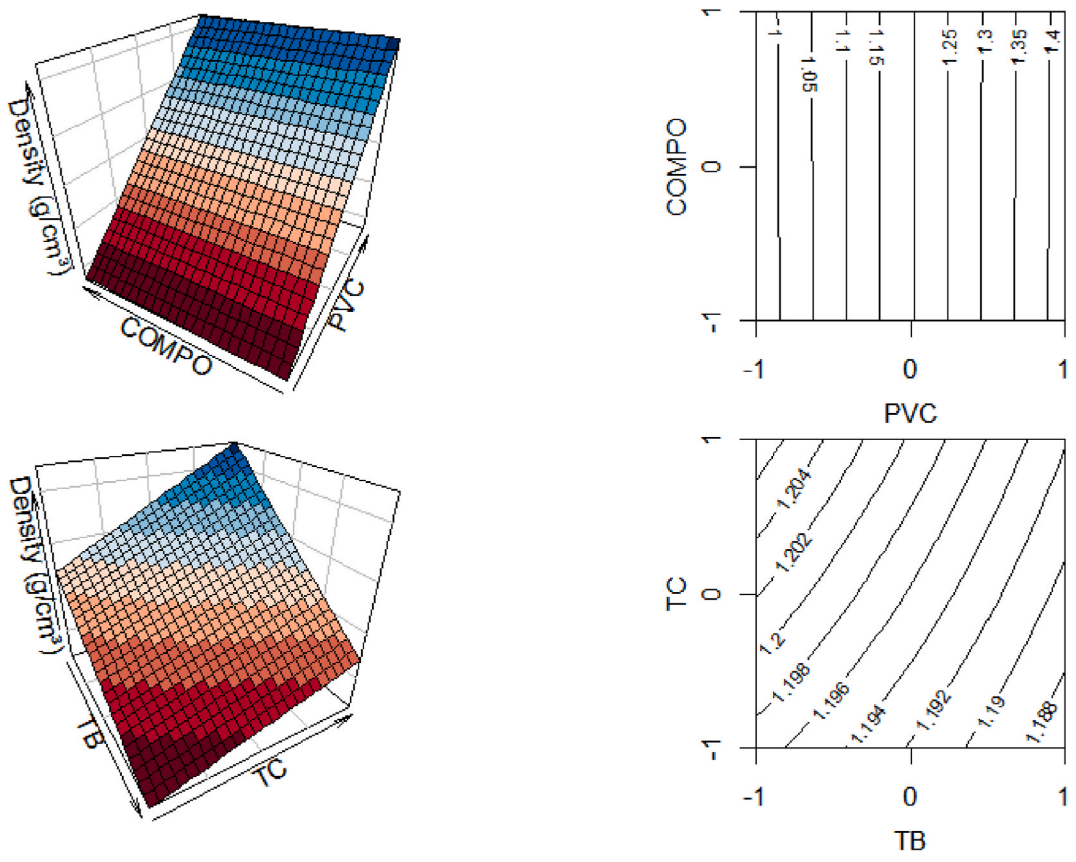
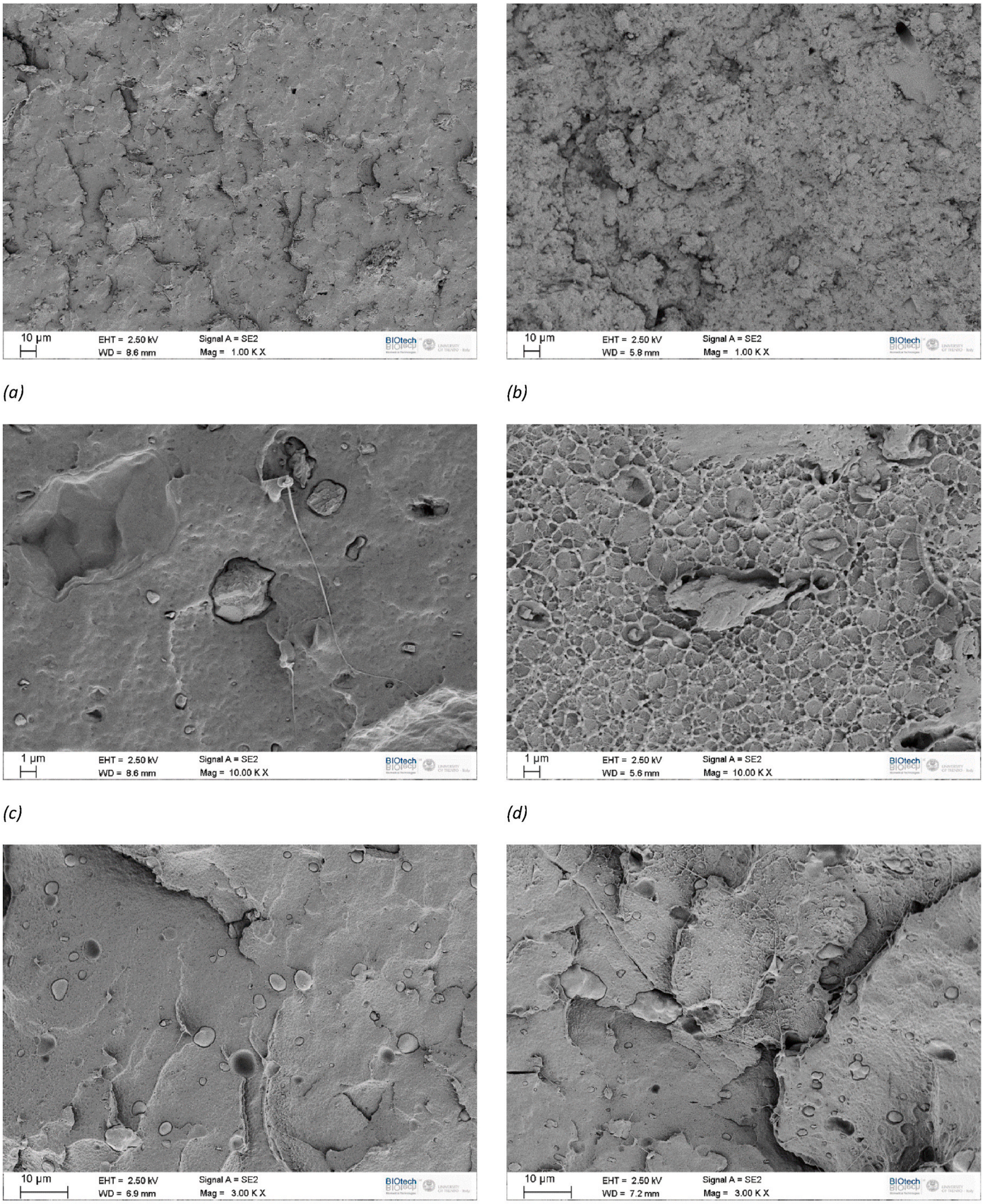


Fig. 4. 3D and 2D plot for the response surface of the density as a function of PVC content (PVC), compatibilizer content (COMPO), blending temperature (TB), and compression temperature (TC).

3.2. *Compression molded sample characterization*

Density was found not only be affected by the amount of PVC (p-value $<10^{-16}$) and so by the density of the PVC that is higher than the one of LDPE but also by the mixing temperature (p-value $= 0.038$), while other parameters did not affect the density of the final material according to ANOVA. In Fig. 4, fitting curves are presented depicting the density of the compression molded materials, with variables that have been fitted to the data. These curves illustrate the relationship between the observed density values and the fitted variables, providing a visual representation of how well the model aligns with the experimental data. Lower value for the mixing temperature provided higher level of densification. The adjusted R^2 value of the fitted surface was determined to be 0.9971, indicating a high level of fit. This signifies that the fitted model accurately captures and explains a significant portion of the variation in the data. The high adjusted R^2 value confirms the reliability

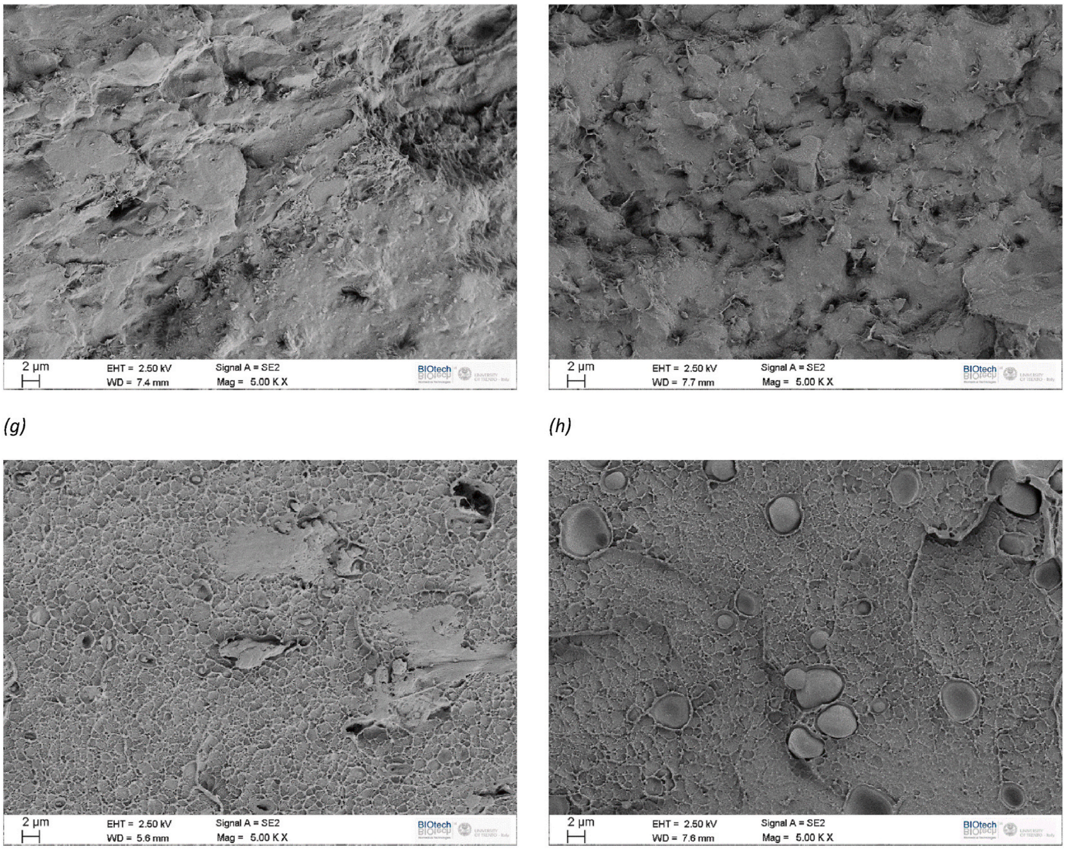


(a) *(b)*

(c) *(d)*

(e) *(f)*

Fig. 5. SEM micrographs of the cryo-fracture surface at different magnification of (a) sample 1, (b) sample 2, (c) sample 1, (d) sample 3, (e) sample 5, (f) sample 9, (g) sample 8, (h) sample 12, (i) sample 3 and (j) sample 15. Refer to Table 2 for sample definition.



(g) *(h)*

(i) *(j)*

Fig. 5. (*continued*).

and goodness of fit of the model, suggesting that it effectively represents the underlying relationship between the variables.

Through the analysis of scanning electron microscope (SEM) images, we can observe the effect of increasing PVC content in the blend on the cryo-fracture surface morphology. At a lower PVC content, as depicted in Fig. 5a (Sample 1; −1,-1,-1,-1), the PVC particles are finely dispersed within the LDPE matrix. However, with a higher proportion of PVC, as shown in Fig. 5b (Sample 2; +1,-1,-1,-1), individual PVC particles become distinguishable, resulting in a granular and corrugated surface. Moreover, the addition of a compatibilizer has a significant impact on the interface between the PVC particles and the LDPE matrix. As evident in Fig. 5c (Sample 1; −1,-1,-1,-1), without the compatibilizer, poor adhesion is observed between the PVC particle and the matrix. In contrast, the inclusion of a 5 % compatibilizer vastly improves the interface, leading to an intricately woven fracture surface, facilitated by the presence of the compatibilizer according to Fig. 5d (Sample 3; −1,+1,-1,-1). These observations underscore the critical role played by both PVC content and the compatibilizer in determining the morphology and adhesion at the cryo-fracture surface of the polymer blend. The compatibilizer acts as a bridging agent, enhancing the interfacial interactions between the PVC and LDPE phases, resulting in a more homogenous and stronger blend. Regarding the processing temperatures, it was noticed that applying a higher temperature during the mixing phase leads to a more homogenous surface, in contrast to applying a higher temperature solely during the compression phase. Specifically, the cryo-fracture surfaces shown in Fig. 5e (Sample 5; −1,-1,+1,-1) and 5g (Sample 8; +1,+1,+1,-1), corresponding to samples mixed at 190 °C and compressed at 120 °C, exhibit superior characteristics compared to their respective counterparts mixed at 120 °C and compressed at 190 °C Fig. 5f (Sample 9; −1,-1,-1,+1) and 5h (Sample 12; +1,+1,-1,+1). This discrepancy can be attributed to the introduction of a more homogenous and tightly bound material within the mold during the compression phase. The higher mixing temperature is likely to promote better dispersion and distribution of the PVC and compatibilizer throughout the LDPE matrix, resulting in a more uniform and interconnected structure. Conversely, applying a higher compression temperature may affect the cooling rate and material flow dynamics during the solidification phase, potentially leading to less optimal intermixing and adhesion between the components. Fig. 5i (Sample 3; −1,+1,-1,-1) and 5j (Sample 15; −1,+1,+1,+1) provide insight into the influence of increasing the working temperature from 120 °C to 190 °C on the material's morphology. This change in temperature significantly affects the particle shape, particularly leading to a more rounded appearance. At the lower working temperature of 120 °C (Fig. 5i), the particles exhibit a relatively angular and less defined shape. In contrast, at the higher temperature of 190 °C (Fig. 5j), the particles' edges become smoother, and their overall shape appears more rounded. The change in particle morphology can be attributed to the increased mobility of the polymer chains at higher temperatures. This allows for greater molecular rearrangement and relaxation during the mixing and compression phases. As a result, the particles tend to adopt a more spherical shape due to reduced molecular entanglements and chain alignment. Additionally, the temperature-induced changes in the material's morphology and interfacial interactions play a crucial role in determining the final mechanical and thermal properties of the blend.

The data plotted in Fig. 6 showcases the relationship between thermal conductivity and the manipulated variables, shedding light on the intricate interplay between processing parameters and the resulting thermal properties, while in Table 3 are resumed the thermal conductivity results for all the samples prepared. The thermal conductivity was observed to be influenced by several factors, including PVC, COMPO, TB, and TC, with PVC exhibiting the most significant impact, as

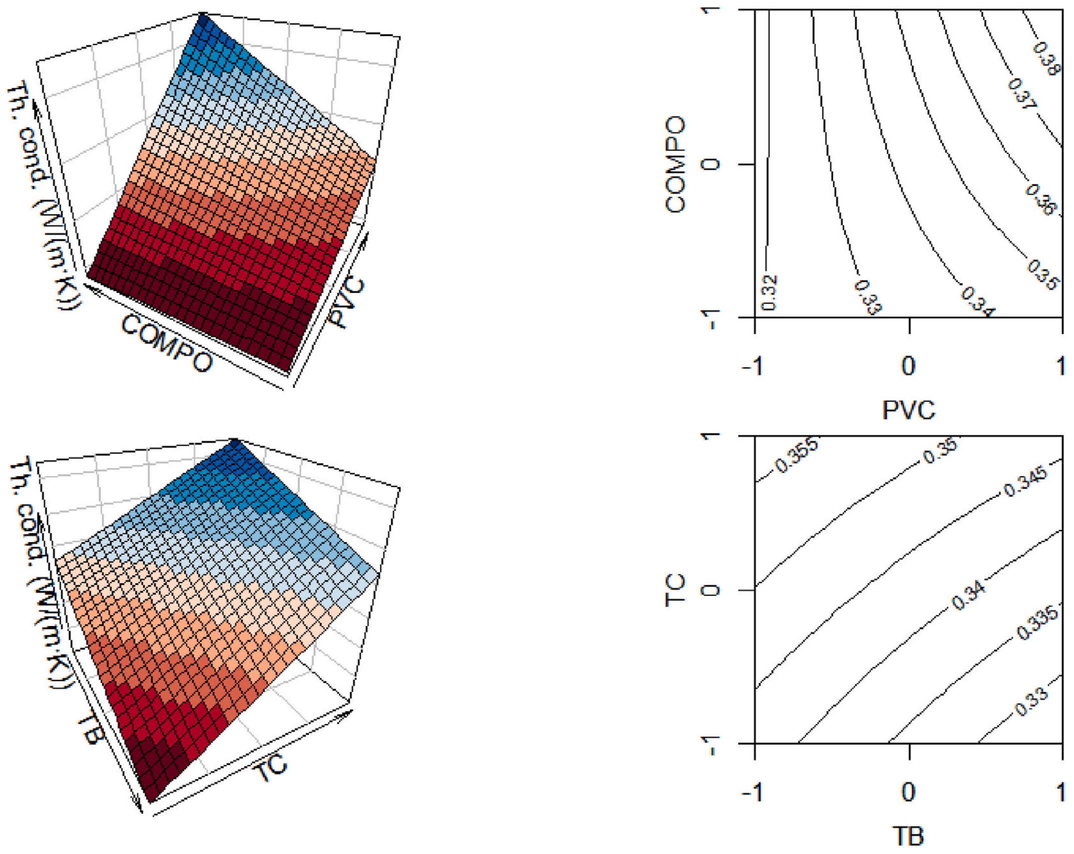


Fig. 6. 3D and 2D plot for the response surface of the thermal conductivity as a function of PVC content (PVC), compatibilizer content (COMPO), blending temperature (TB), and compression temperature (TC).

Table 3
Thermal conductivity value and mechanical properties of the prepared blend of PVC/LDPE according to the developed DOE.

Sample	Thermal conductivity (W m^{-1} K^{-1})	Elastic modulus (MPa)	UTS (MPa)	Strain at break (mm/mm)	Stress at break (MPa)
1	0.318 ± 0.019	132 ± 4	8.2 ± 1.1	4.06 ± 3.20	5.6 ± 3.3
2	0.351 ± 0.012	58 ± 3	1.8 ± 0.2	0.12 ± 0.02	1.3 ± 0.1
3	0.309 ± 0.024	148 ± 18	7.9 ± 1.2	3.00 ± 2.22	4.6 ± 2.7
4	0.389 ± 0.014	55 ± 5	1.8 ± 0.1	0.11 ± 0.01	1.2 ± 0.2
5	0.314 ± 0.012	144 ± 14	7.2 ± 0.6	1.12 ± 0.47	2.1 ± 0.9
8	0.359 ± 0.009	61 ± 11	1.3 ± 0.2	0.06 ± 0.02	0.8 ± 0.5
9	0.320 ± 0.008	114 ± 24	8.8 ± 1.3	5.60 ± 3.44	6.1 ± 3.0
12	0.416 ± 0.017	59 ± 15	2.3 ± 0.2	0.18 ± 0.04	1.2 ± 0.2
14	0.342 ± 0.010	46 ± 5	1.7 ± 0.4	0.26 ± 0.09	0.5 ± 0.3
15	0.326 ± 0.008	156 ± 5	8.3 ± 0.3	2.25 ± 2.15	3.6 ± 2.3

indicated by a p-value lower than 10^{-16}. Additionally, the combined effect of PVC and COMPO, as well as the individual effect of PVC, showed significant associations, with p-values lower than 0.005. These findings highlight the importance of PVC in determining the thermal conductivity, suggesting its dominant role among the examined factors. The thermal conductivity, which is derived from the product of thermal diffusivity and density, was observed to exhibit a correlation with the density trend. Specifically, higher amounts of PVC and lower mixing temperatures resulted in higher thermal conductivity values.

In terms of mechanical characteristics, Table 3 summarizes the key properties derived from the tensile tests conducted on PVC/LDPE blends, as per the Design of Experiments formulated within this investigation.

Fig. 7 depicts the response surface model illustrating the relationship between the measured elastic modulus and various factors, including PVC content, compatibilizer content, blending temperature, and compression temperature. The elastic modulus, a critical indicator of stiffness, exhibits a notable dependence on the PVC content, compatibilizer content, and processing temperatures. Specifically, the PVC content demonstrates a significant influence on the stiffness of the blend, as evidenced by the extremely low p-value of less than 10^{-16}. An increase in PVC content is associated with a reduction in the elastic modulus of the blend. This decrease in stiffness can be attributed to the presence of PVC particles, which introduce an incoherent microstructure within the blend. The incoherent microstructure, resulting from the addition of PVC particles, hinders the establishment of a uniform and continuous matrix within the blend. As a result, the overall stiffness of the blend diminishes, reflecting the impact of the PVC content on the mechanical properties. Furthermore, the incorporation of the compatibilizer plays a crucial role in mitigating the adverse effects of the PVC particles on the blend's stiffness. The compatibilizer acts as a bridging agent, enhancing the interfacial interactions between the PVC and the matrix. This improvement in the interfacial adhesion results in a more homogenous and interconnected structure, counteracting the detrimental effects of the incoherent microstructure. Additionally, the blending temperature was found to have a significant influence on the elastic modulus. Increasing the blending temperature led to a more pronounced improvement in the elastic modulus compared to an

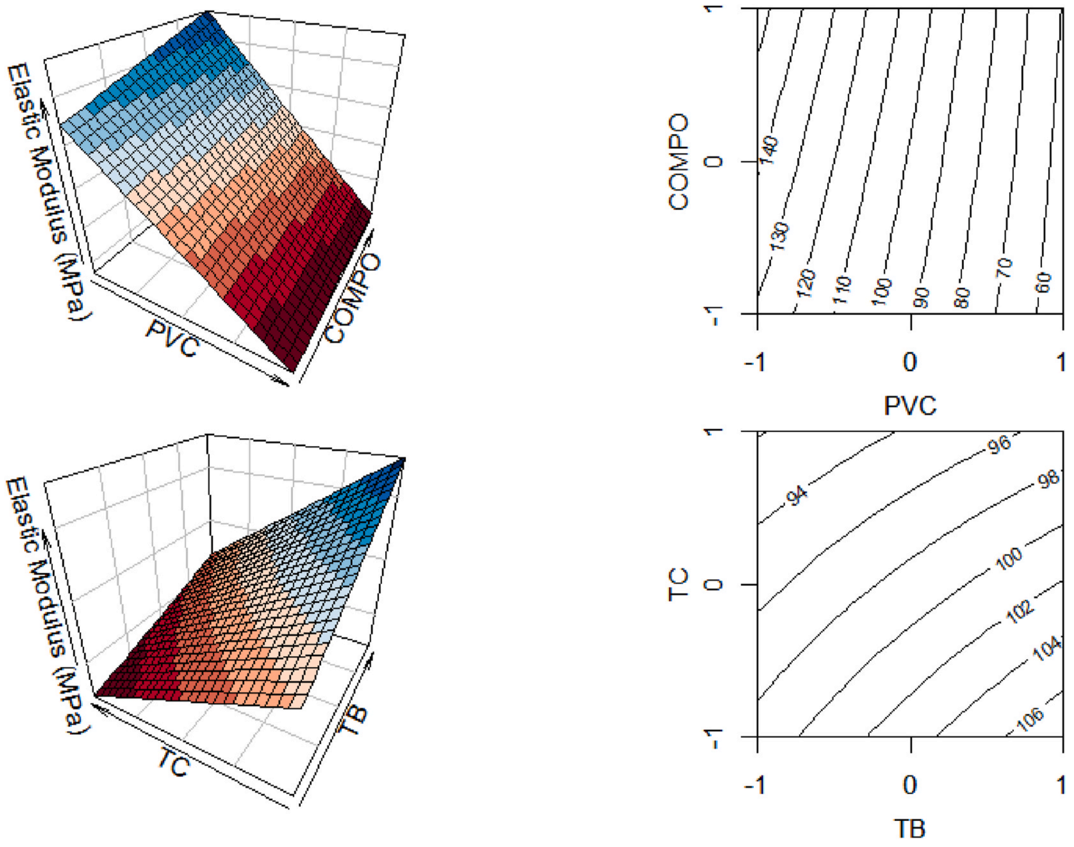


Fig. 7. 3D and 2D plot for the response surface of the elastic modulus as a function of PVC content (PVC), compatibilizer content (COMPO), blending temperature (TB), and compression temperature (TC).

increase in the compression temperature. This observation is associated with the enhanced microstructure achieved by higher blending temperatures. The elevated temperature promotes better dispersion and distribution of the PVC and compatibilizer within the LDPE matrix, fostering a more uniform and interconnected structure, which, in turn, contributes to the improved elastic modulus.

Fig. 8 depicts the response surface model of the ultimate tensile strength (UTS) of the polymer blend. Once again, the influence of PVC content on UTS is evident, as it significantly reduces the ultimate tensile strength. This decrease can be attributed to the formation of an inhomogeneous structure within the blend due to the presence of PVC particles. The poor bonding force between these particles and the surrounding matrix further contributes to the reduction in UTS. Interestingly, the presence of the compatibilizer does not show any statistically significant effect on the UTS of the blend. This suggests that the compatibilizer does not play a significant role in enhancing the ultimate tensile strength in this particular composition. When considering the effect of temperature parameters on UTS, the compression temperature shows a higher level of significance (p-value = 0.001) compared to the blending temperature (p-value = 0.01). This finding indicates that the compression temperature has a more pronounced impact on increasing the UTS. The higher significance of compression temperature can be linked to the increase in density observed in the blend. As the temperature during the compression phase rises, the process of compression becomes more facilitated, leading to a denser and more compact structure in the material. This densification contributes to the enhancement of the ultimate tensile strength.

Fig. 9 presents the response surface analysis of the strain at break in the polymer blend. The investigation reveals the influence of various factors on the strain at break, providing valuable insights into the material's mechanical behavior. The content of PVC emerges as the most significant factor impacting the strain at break. Increasing the PVC content results in a notable decrease in the strain at break. This effect can be attributed to the poor adhesion between the PVC particles and the surrounding matrix, leading to weak interfaces and reduced elongation capacity. Interestingly, the presence of the compatibilizer does not seem to sufficiently compensate for this effect, as revealed by the ANOVA analysis. Additionally, the processing temperatures also exhibit significant effects on the strain at break. Lowering the mixing temperature while simultaneously increasing the compression temperature leads to superior results in terms of strain at break. This observation suggests that a combination of lower mixing temperature and higher compression temperature contributes to the formation of a more robust and well-structured material, enhancing its strain resistance.

Fig. 10 displays the response surface associated with the stress at break measurement in the polymer blend. Although the adjusted R^2 value is relatively low at 0.50, some valuable information about the processing conditions can still be obtained. The analysis conducted using ANOVA indicates that the content of PVC is the most significant parameter influencing the stress at break. As the PVC content increases, there is a noticeable decrease in the stress at break of the material. Furthermore, the blending temperature was also found to exert a significant impact on the stress at break. Interestingly, decreasing the blending temperature resulted in an increase in stress at break. This observation could be attributed to the formation of an incoherent microstructure at lower blending temperatures. Such a microstructure may activate energy dissipative mechanisms, thereby enhancing the strength and stress resistance of the material. Although the adjusted R^2 value suggests that the response surface model may not fully capture all the variation in the data, the identified significant factors provide valuable insights into optimizing the material's mechanical properties. By carefully controlling the PVC content and blending temperature during processing, it becomes possible to tailor the stress at break and ensure that the blend meets specific application requirements.

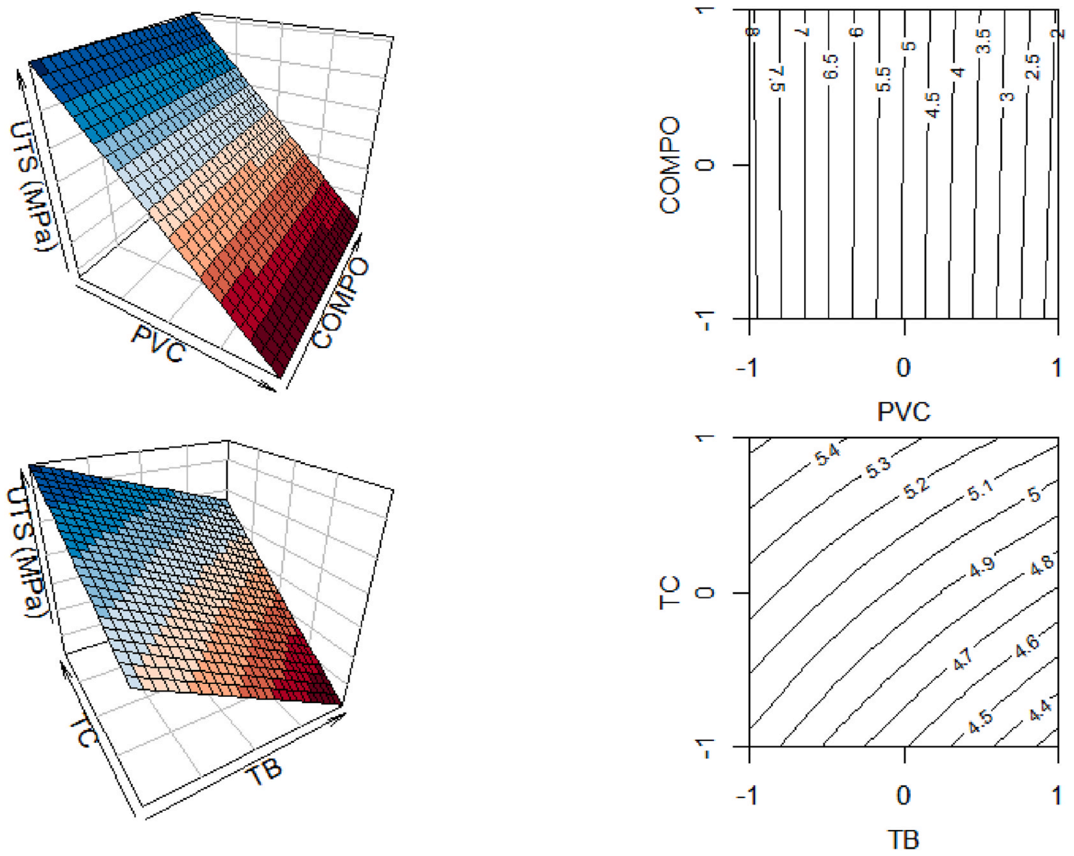


Fig. 8. 3D and 2D plot for the response surface of the Ultimate tensile strength as a function of PVC content (PVC), compatibilizer content (COMPO), blending temperature (TB), and compression temperature (TC).

The properties of stiffness and strain at break frequently exhibit a competitive relationship, making it challenging to achieve the desired material toughness. Nevertheless, when these properties are jointly considered, they provide an initial insight into the material's overall resilience. Particularly for this specific application, it is highly advantageous to obtain elevated values for both stiffness and strain at break, as this indicates improved mechanical performance. To achieve the optimal balance between stiffness and strain at break, a fitness optimization function was formulated. This function combines the regression equations for elastic modulus (Equation (3)), strain at break (Equation (4)) and content of PVC (Equation (5)) to maximize both responses simultaneously. By utilizing a genetic optimization approach, it is possible to identify material compositions or processing parameters that offer enhanced mechanical properties, characterized by increased stiffness and greater elongation at break.

$$E = 98.760 - 42.435\,x_1 - 7.723\,x_2 - 3.402\,x_3 - 4.512\,x_4 - 4.732\,x_1\,x_2 - 5.981\,x_1\,x_3 + 5.525\,x_1\,x_4 + 4.523\,x_2\,x_3 - 1.012\,x_3\,x_4 \qquad \text{[Eq 3]}$$

$$\varepsilon_B = 1.579 - 1.417x_1 - 0.201\,x_2 - 0.650\,x_3 + 0.498\,x_4 + 0.263\,x_1\,x_2 + 0.657\,x_2\,x_3 - 0.366\,x_1\,x_4 - 0.066\,x_2\,x_3 + 0.095\,x_3\,x_4 \qquad \text{[Eq 4]}$$

$$PVC = x_1 \qquad \text{[Eq 5]}$$

This novel function was implemented using R-CRAN software, a versatile platform for statistical computing and graphics, and the optimization process was facilitated through the nsga2R library. By fusing these equations in the fitness optimization function, we gain the capability to identify material compositions or processing parameters that can maximize both the elastic modulus and strain at break simultaneously. This optimization strategy empowers us to pinpoint the most favorable combinations of materials or process conditions that exhibit an improved balance of stiffness and elongation, ultimately enhancing the material's overall toughness. This approach represents a powerful tool in material engineering, allowing for the targeted design and development of polymer blends with enhanced mechanical performance. By accurately optimizing the composition or processing parameters, we can tailor the material's characteristics to meet specific application requirements, thereby enhancing its suitability and performance in practical settings. The integration of advanced optimization methodologies in materials research broadens the scope of possibilities in enhancing mechanical properties, promoting innovation, and fostering progress in various industries. This in-depth understanding of the relationship between stiffness and strain at break offers a solid foundation for further exploration and refinement of polymer blends, leading to the creation of robust and resilient materials that meet the demands of modern engineering challenges. The parameters considered to evaluate the optimal process through genetic algorithm were: population size (3000), size of tournament (2), number of generations (1000), crossover probability (0.9), crossover distribution index (20), mutation probability (0.1) and mutation distribution index (3) [11]. All the variables were left free to move from the lowest to the highest state (−1, 1).

The output of this analysis is a Pareto optimal [26], where no improvement can be made to one of the three output values, i.e., elastic modulus, strain at break or PVC content, without reducing the other. In Fig. 11a, the Pareto front is visualized, depicting a three-dimensional surface that encapsulates the trade-off relationship among three distinct output values. The visualization employs a color palette to signify the corresponding PVC content values associated with each point on this complex surface. The Pareto front constitutes a critical

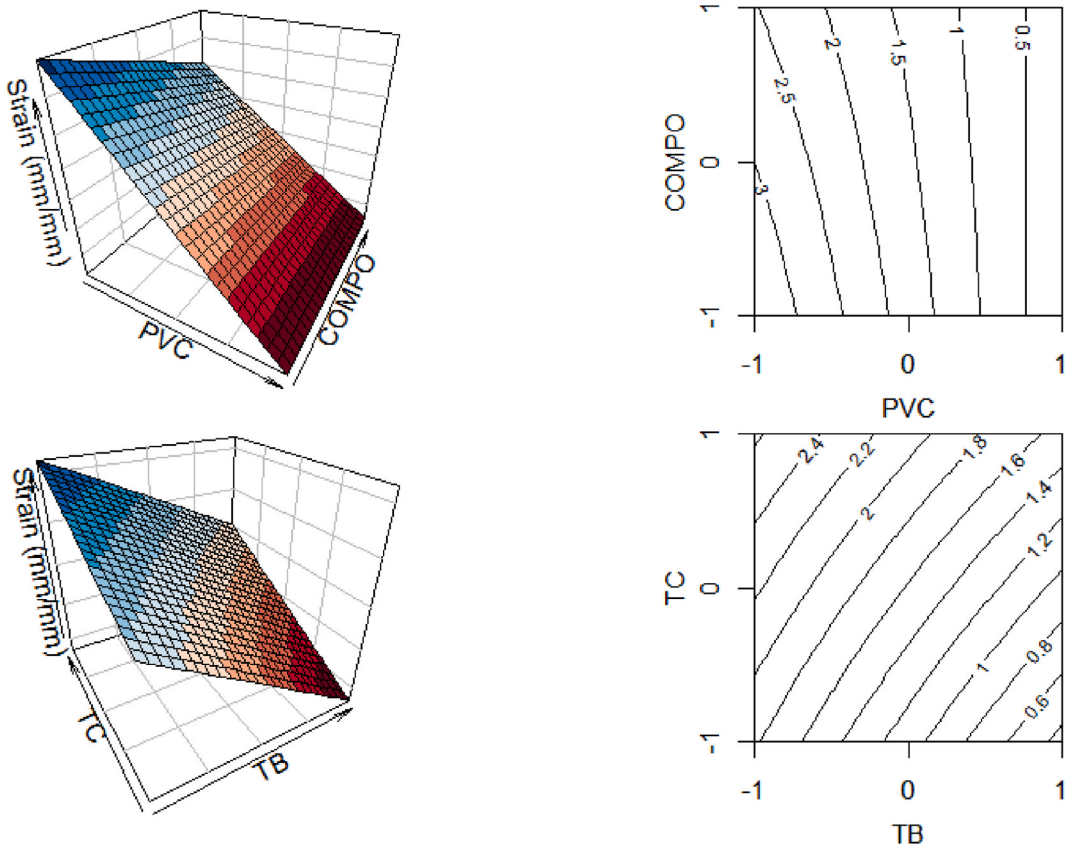


Fig. 9. 3D and 2D plot for the response surface of the strain at break as a function of PVC content (PVC), compatibilizer content (COMPO), blending temperature (TB), and compression temperature (TC).

representation of the optimal solutions achieved through multi-objective optimization, where multiple objectives are simultaneously considered for attaining optimal outcomes. This three-dimensional visualization not only captures the intricate interdependencies among multiple output values but also encapsulates the influence of PVC content, which serves as a key parameter in the optimization process. Each point delineated along the Pareto curve signifies an ideal synthesis of variables, constituting an optimal configuration that delivers balanced and desirable outcomes for all three considered outputs. Fig. 11b complements this representation by projecting the Pareto curve onto a two-dimensional plane. This projection into a more accessible 2D space enhances the interpretability of the data, facilitating a clearer examination of the optimal combinations of variables. The systematic exploration of the parameter space through genetic optimization provides a comprehensive view of how variations in PVC content influence the trade-off between stiffness and strain at break. In this context, it is notable that lower stiffness and strain at break can be achieved with a high PVC content.

Fig. 12 displays the 2D Pareto surfaces resulting from genetic optimization, focusing on the study of stiffness, strain at break, and PVC content. The colors utilized on the graph represent the corresponding process parameters. At lower PVC contents, the Pareto surfaces reveal an opportunity for designers to choose between prioritizing stiffness or enhanced deformability at break by adjusting the compatibilizer content and processing temperatures. This provides valuable insights into how material properties can be finely tuned to meet specific application requirements. However, as the PVC content increases, the influence of other variables diminishes, and PVC content emerges as the predominant factor impacting mechanical characteristics.

4. Conclusions

This study focused on the recycling of PVC from waste cables by blending it with LDPE. The factors influencing the material's mechanical and physical responses were identified, and reasonable ranges of variability were estimated for each factor. A comprehensive testing plan was developed to formulate PVC-based blends, which were produced through hot mixing using a counter-rotating internal mixer. These blends were then utilized to create test specimens by compression molding. Additionally, the effects of suitable coupling agents were evaluated to enhance the inter-component adhesion of the material. The obtained test specimens underwent thorough thermal and mechanical characterization. The effects of various processing parameters including PVC content, compatibilizer content, blending temperature, and compression temperature on the mechanical properties were investigated through ANOVA, and an optimization study was conducted to maximize material toughness by simultaneously enhancing the elastic modulus and elongation at break. This was achieved by applying genetic algorithms. The absence of a compatibilizer leads to inadequate adhesion between PVC particles and the matrix. However, introducing a 5 % compatibilizer significantly enhances the interface, resulting in a complex fracture surface facilitated by the presence of the compatibilizer. Higher mixing temperatures promote better dispersion and distribution of PVC and compatibilizer within the LDPE matrix, yielding a more uniform and interconnected structure. Increased PVC content correlates with reduced elastic modulus in the blend. The inclusion of a compatibilizer plays a vital role in counteracting the PVC particles' negative effects on stiffness. The compatibilizer acts as a bridge, enhancing interactions between PVC and the matrix, thereby improving interfacial adhesion and overall structure. Blending temperature significantly affects the elastic modulus, with higher blending temperatures leading to

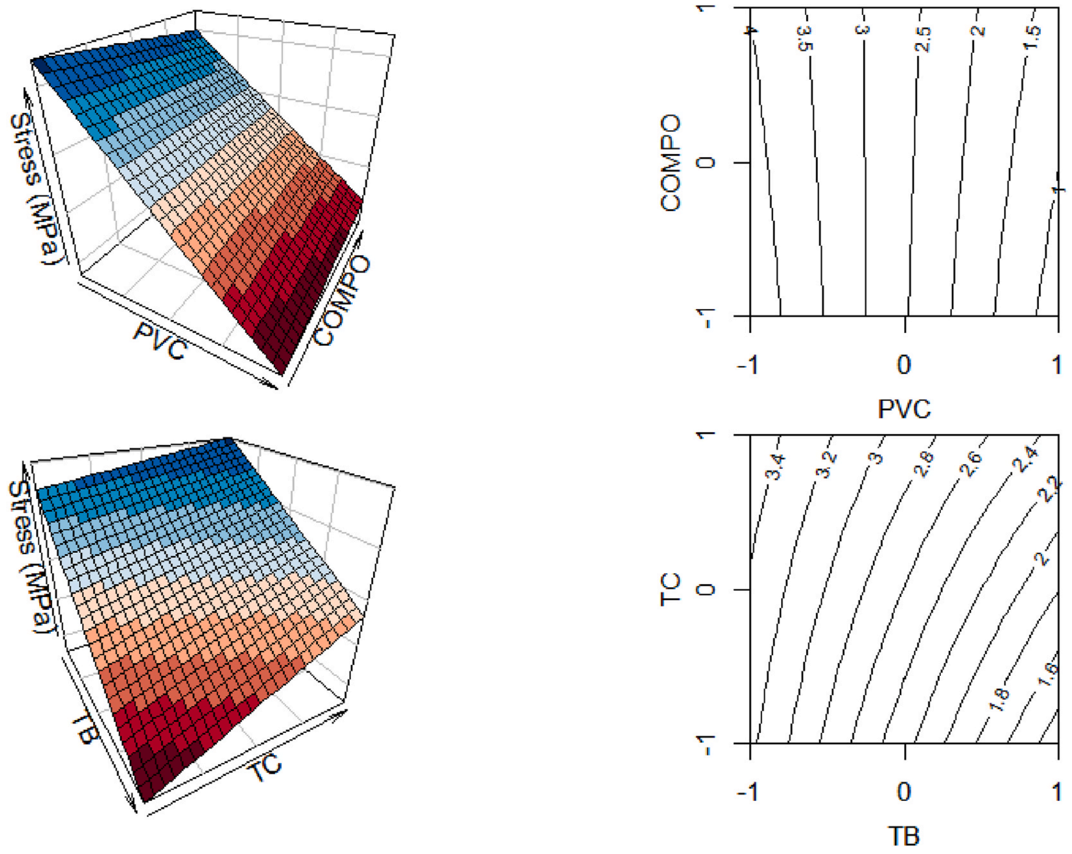
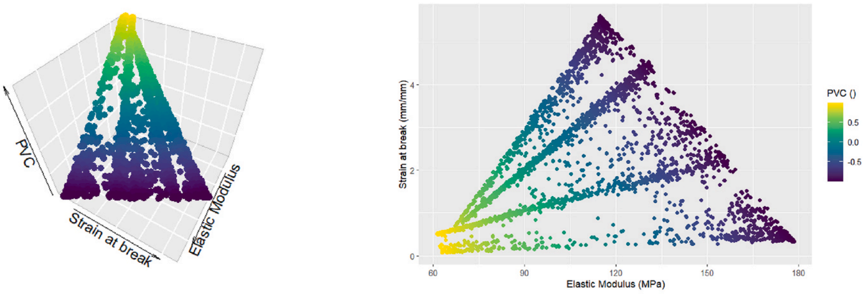


Fig. 10. 3D and 2D plot for the response surface of the stress at break as a function of PVC content (PVC), compatibilizer content (COMPO), blending temperature (TB), and compression temperature (TC).



(a) *(b)*

Fig. 11. (a) 3D representation of the Pareto frontier for the genetic optimization of stiffness, strain at break and PVC content and (b) 2D representation with palette color representing the PVC content.

more pronounced improvements compared to increased compression temperatures. The compatibilizer's presence doesn't fully compensate for this effect. Processing temperatures notably impact strain at break. A combination of lower mixing and higher compression temperatures enhances strain resistance, indicating the formation of a robust material structure. Increasing PVC content leads to a decrease in stress at break. Lowering blending temperatures paradoxically increases stress at break. Stiffness and strain at break often exhibit a competitive relationship, complicating material toughness achievement. Genetic optimization reveals how PVC content influences stiffness-strain balance, showing that higher PVC content results in lower stiffness and strain at break. The study provides insights into optimizing recycled PVC blends, considering factors like compatibilizer, mixing and compression temperatures, and PVC content to achieve desired mechanical properties. Overall, this research contributes to a deeper understanding of the recycling potential of PVC from waste cables, providing insights into the factors influencing the material's behavior and the optimization of its properties. The findings highlight the significance of recycling efforts in promoting sustainability and advancing the circular economy in the realm of polymer materials.

CRediT authorship contribution statement

Daniele Rigotti: Writing – original draft, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Alessandro Pegoretti:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

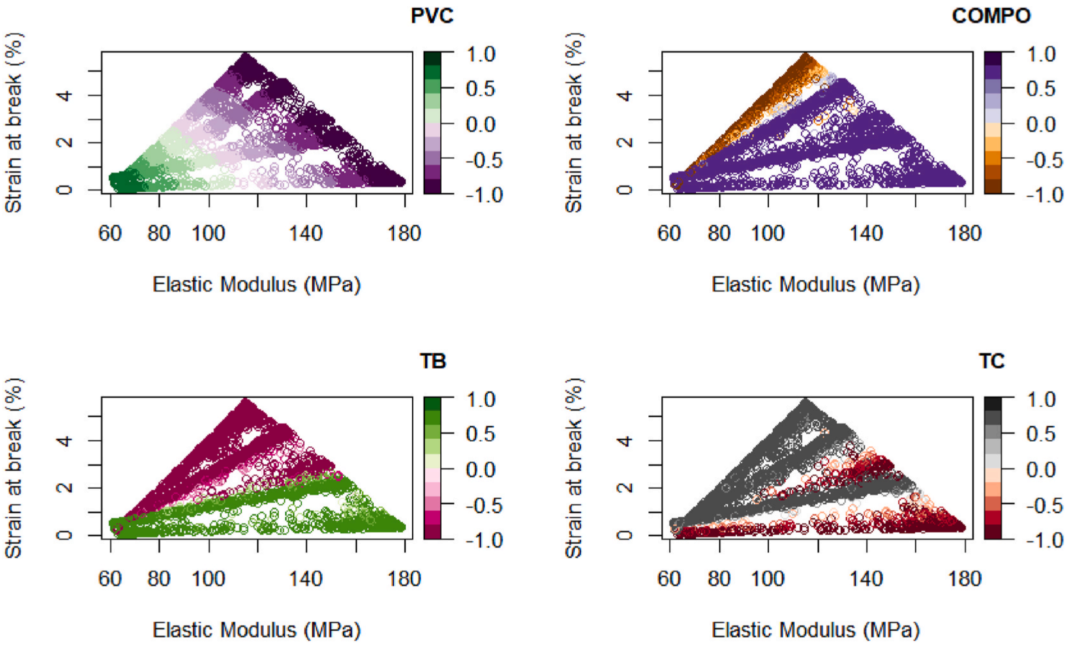


Fig. 12. Pareto surfaces resulting from genetic optimization, focusing on the study of stiffness, strain at break, and PVC content. The colors utilized on the graph represent the corresponding process parameters.

the work reported in this paper.

Data availability

Data will be made available on request.

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