UFSM

Ciência Florestal

ISSN 1980-5098
OPEN ACCESS

Ci. Fl., Santa Maria, v. 35, e88280, p. 1-24, 2025 • https://doi.org/10.5902/1980509888280
Submitted: 17th/07/2024 • Approved: 13th/11/2024 • Published: 30th/05/2025

Articles

Eco-friendly composite with matrix of recycled low-density polyethylene reinforced with wheat waste

Compósitos ecologicamente corretos com matriz de polietileno reciclado de baixa densidade reforçado com resíduos de trigo

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ABSTRACT

The study investigated the effects of replacing varying amounts of straw and wheat husk residues on the properties of composites with a recycled low density polyethylene (LDPE) matrix. The composites were produced through the extrusion process, employing the following proportions: 0%, 10%, 20%, and 30% of wheat waste as reinforcement in the polymeric matrix. The agricultural wastes were reduced in particles and characterized in natura. The composites were shaped from pressing processes and their physical, mechanical and microstructural properties were evaluated. The results have shown an increase in water absorption for each 1% of wheat waste inserted in the composite of the order of 0.018%. The density of the composites decreased with the replacement of wheat waste by 4.8 g/cm^3 for each 1% of replacement. The substitution of wheat waste increased the burning speed (flammability) when compared to recycled polymers (LDPE100%), indicating shorter fire spread time. There was a decrease in strength, modulus of elastic and tenacity, obtaining a material with high deformation.

Keywords: Lignocellulosic reinforcement; Polymeric matrix; Wheat straw and bark; Sustainable materials

RESUMO

O estudo investigou os efeitos da substituição de quantidades variáveis de resíduos de palha e casca de trigo nas propriedades dos compósitos na matriz reciclada de polietileno de baixa densidade (PEBD). Os compósitos foram produzidos através do processo de extrusão, empregando as seguintes proporções: 0%, 10%, 20% e 30% de resíduo de trigo como reforço na matriz polimérica. Os resíduos agrícolas foram reduzidos em partículas e caracterizados in natura. Os compósitos foram moldados a partir de processos de prensagem e suas propriedades físicas, mecânicas e microestruturais foram avaliadas. Os resultados mostraram um aumento na absorção de água para cada 1% de resíduo de trigo inserido no compósito da ordem de 0,018%. A densidade dos compósitos diminuiu com a substituição do resíduo de trigo em 4,8 g/cm3 para cada 1% de substituição. A substituição dos resíduos de trigo aumentou a velocidade de queima (inflamabilidade) quando comparado aos polímeros reciclados (PEBD100%), indicando menor tempo de propagação do fogo. Houve diminuição da resistência, módulo de elasticidade e tenacidade, obtendo-se um material com maior deformação.

Palavras-chave: Reforço lignocelulósico; Matriz polimérica; Palha e casca de trigo; Materiais sustentáveis

1 INTRODUCTION

The low degradability of polymeric waste has been recognized as a major environmental problem in the face of the high development of industries in this sector. The high demand and consumption of polymers in daily activities, such as in packaging and storage applications, inevitably lead to the generation of approximately 300 million tons per year of waste worldwide (Jha; Kannan, 2021).

The Low-Density Polyethylene (LDPE) is one of the most widely used polymers in the world (Jia; Zhang; Zhang, 2022). It presents properties of interest for several applications, such as good process ability, low cost, flexibility, toughness, impact resistance, aqueous solvent chemical resistance and good electrical properties. Their applications include films for industrial and agricultural packaging, food, pharmaceutical and hospital packaging, toys and household utensils, wire and cable sheathing, pipes and hoses (Mark, 1999). These products, after their lifespan, represent 70% of solid waste in landfills. Therefore, the use of polymers, such as recycled LDPE, is growing worldwide (Bello *et al.*, 2021). Plastic waste represents a promising source of raw material for manufacturing materials as it is available in large quantities (Rodrigues *et al.*, 2023).

According to the National Supply Company (2023), Brazilian wheat production may reach 9.77 million tons in 2023, a growth of 27.2% more than in the 2021/22 harvest. However, the increase in production implies a greater potential generator of waste, since during wheat production the straw is generated, the main agricultural waste, corresponding to 50% of the plant's weight (Ferreira-Leitao; Gottschalk *et al.*, 2010). A study conducted by the Brazilian Association of Industries Biomass Bioenergy Bioelectricity and Pellets (2011), shows that the waste from the wheat agroindustry is equivalent to a percentage factor of 60%. However, it is believed that high rates of these wastes are improperly disposed of in the environment. Thus, wheat waste is an option for use in polymeric matrices.

Researchers have directed their efforts to studying the effect of replacing lignocellulosic waste in polymers. This combination has the potential to develop a material with good mechanical properties and lower environmental impacts, aiming to meet the social, environmental and economic context (Gomes *et al.*, 2021). The recycled polymer and lignocellulosic composites are considered sustainable materials of high quality, low cost and flexible regarding the final physic-chemical properties (Rowell, 2006).

The amplification of low environmental impact materials has become an important parameter around the world for human civilization because the addition of waste materials in polymeric matrices, such as vegetable fibers, reduces the problems of waste generation and disposal, since they are biodegradable and renewable (Dubey; Mishra; Sharma, 2021). Therefore, the use of agro-industrial waste as raw material for the production of new materials aims to enable the development of sustainable products, with the aim of minimizing environmental impacts (Duran *et al.*, 2023).

Therefore, the objective of this research was to investigate the effects of the gradual replacement in mass of LDPE by wheat crop waste particles (0, 10, 20 and 30%) in the physical, mechanical and microstructural properties of composites.

2 MATERIALS AND METHODS

The wheat waste, *Triticum* spp., straw and bark, were collected on an industrial farm. The particles, ground in a hammer mill, used for the composites production were selected as the ones passing in the 40 mesh sieve and retained in the 60 mesh sieve. The recycled LDPE was acquired in a recycling industry. The polymeric materials obtained were with dimensions of 1.5 x 4.0 cm, approximately, and the particle size was sufficient to feed the extruder without pre-treatment.

Both materials were oven dried at a temperature ranging from 50 - 75°C. The process was finished when the particles reached a moisture content of 3 - 4%.

2.1 Physical and chemical characterization of the lignocellulosic material

The particles of the wheat waste were characterized according to the analyses and standards: total extractives NBR 14853 (ABNT, 2010); insoluble lignin NBR 7989 (ABNT, 2010); ash content NBR 13999 (ABNT, 2017) and apparent density (ρ) adaptation to NBR 11941 (ABNT, 2003). With the characterization data of extractives, lignin and ash content it was also possible to calculate the holocellulose content (H), as Equation (1):

$$H\ (\%) = 100\ (\%) - \text{total extractives}\ (\%) - \text{lignin content}\ (\%) - \text{ash content}\ (\%) \qquad (1)$$

2.2 Thermogravimetry (TGA) of lignocellulosic material

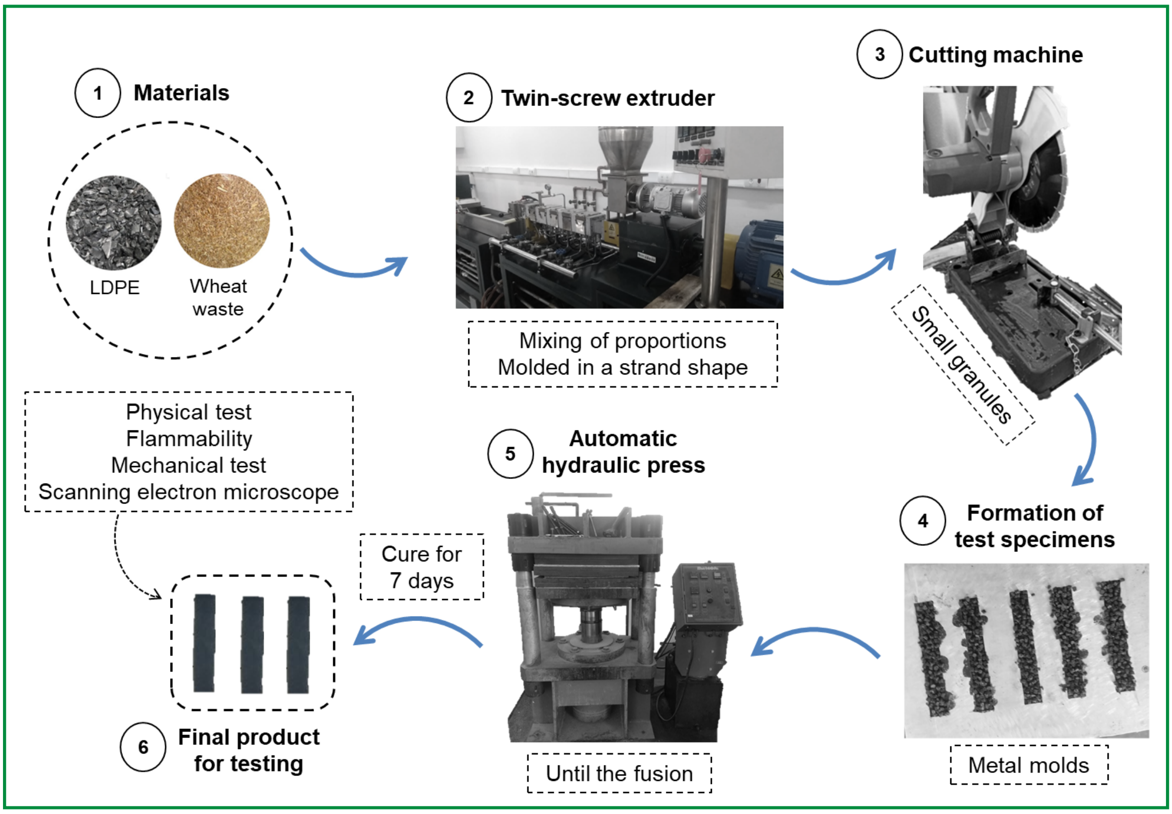
A thermal analysis of the wheat waste was also performed using a TA Instruments Q500 TGA thermal analyzer (Delaware, USA). The samples were heated from 25 to 500 °C in nitrogen flowing at 20 mL/min with a heating rate of 10 °C/min. The degradation temperature was determined from the inflection of the baseline on the differential thermogravimetric (DTG) curve.

2.3 Production of polymeric composites

The polymeric composites were produced with the gradual replacement of the LDPE mass by the particles of the wheat waste (WW), totalizing in four treatments, being them: $LDPE_{100\%}$ (control); $LDPE_{90\%}WW_{10\%}$; $LDPE_{80\%}WW_{20\%}$ e $LDPE_{70\%}WW_{30\%}$.

According to the treatments, proportions of 600 grams of total material (polymer and waste) were processed for each treatment, with 10 test specimens being made from this total value. For this, a twin-screw extruder was used (Figure 1). The replacement of polymer by wheat occurred en masse.

Figure 1 - Flowchart of composite production composite



Source: Authors (2023)

During the extrusion process (2), the material passed between seven hot zones, 120°C; 130°C; 140°C; 140°C; 140°C; 140°C; 150°C, respectively. At the end of the extrusion process, the composite was molded in a strand shape, and then cut into small granules (3) with the help of a cutting machine.

The granules were deposited in metal molds (4) with dimensions 120 x 12 x 3 mm (length x width x thickness), filling the whole area and avoiding empty spaces, to obtain the specimens. Then, the molds were directed to automatic hydraulic press (5), MA 098, for a pressing cycle at 135°C for 15 minutes (Veloso *et al.*, 2021). After pressing, until the fusion was reached, the samples were cooled, demolded (6) and stored in an acclimatized room, free of weather, with temperature of 22 ± 2°C and relative humidity of 65 ± 5% for total curing of the composite, for a period of 7 days. Ten specimens were prepared per treatment to carry out the tests.

2.4 Evaluation of the physical and mechanical properties of polymeric composites

For the determination of the physical and mechanical properties, the composites were tested after reaching 7 days of curing. The tests and standards used in this work to evaluate the composites were: apparent density D-1037 (ASTM, 2012); water absorption immersed for 24 h D-570 (ASTM, 2012); flammability D-635 (ASTM, 2010) and UL 94; traction D-638 (ASTM, 2001). The samples for the mechanical test are dumbbell-shaped with a reference length of 50 mm.

2.5 Scanning electron microscopy (SEM)

To evaluate the tensile rupture region and the interaction between matrix and reinforcement, a microscopic analysis was also carried out after the specimens ruptured in the traction test. For this, the samples of the composites were initially submitted to gold bath and later analyzed in a microscope Zeiss brand Model DSM 940[a], operated at an acceleration voltage of 15 kV, current of 2 nA, no tilt and different magnifications of images and working distances.

2.6 Experimental design

The treatments were analyzed following an experimental design entirely casualized. Linear regression adjustment and variance analysis were performed to verify the influence of the variation in the results of the physical and mechanical properties of the composites and to evaluate the significance (5%), through the comparison between the averages of the treatments.

3 RESULTS AND DISCUSSIONS

3.1 Physical and chemical characterization of the wheat waste

Table 1 shows the average values of the chemical and physical tests performed on the wheat waste.

Table 1 - Average values of apparent density and chemical components of wheat waste

Analysis	Wheat waste
Total Extractives (%)	15.19 (1.29)
Insoluble Lignin (%)	13.65 (0.84)
Holocellulose (%)	60.40 (1.86)
Ash (%)	10.76 (0.55)
Apparent density (g/cm³)	0.18 (0.03)*

Source: Authors (2023)

In where: *Standard deviation in parentheses.

With regard to extractives and lignin, hydrophobic compounds of low molecular weight that can impair the curing of composites, wheat wastes presented, approximately, respective values of 15% and 14%. The values found for lignin were lower than soybean waste (22%) (Borges *et al.*, 2022) and coffee (29%) (Santos *et al.*, 2022). The extractives data of the present research were lower than those obtained in sugarcane bagasse (20%) (Soares *et al.*, 2017) and soybean wastes (14%) (Borges *et al.*, 2022). Therefore, the wheat waste has lower contents of extractives and lignin, when compared to other wastes and literatures, not having significant impacts in polymeric matrixes and dismissing the use of pre-treatment for it is removal.

The holocellulose content found in the present research was 60%, a value compatible with the study of Gomes *et al.* (2022) for the same waste, lower than that found in corn cob (76.7%) (Scatolino *et al.,* 2013) and higher than bean waste (56.6%) (Miranda *et al.*, 2022). Lignocellulosic materials are highly hydrophilic due to hydroxyl groups (OH) present in holocellulose, which can hinder the use of these materials in various applications, due to the negative impact on water and moisture absorption properties (Guimarães Junior *et al.*, 2016). However, in this case, low levels of holocellulose are favorable. However, one of the components of holocellulose is cellulose, which provides good mechanical properties in the material in which they are applied. Therefore, low levels of this component may mean loss in the mechanical properties of composites (Iwakiri; Trianoski, 2020).

The material ash content was approximately 11%, a value significantly higher than that found for coffee waste (0.6%) (Scatolino *et al.*, 2017), cocoa waste (3.2%) (Veloso *et al.*, 2021) and bamboo fibers (0.2%) (Gomes *et al.*, 2021). This variation between lignocellulosic materials is expected, due to the different growing conditions and climate of the regions where they are found. In addition, ash has no proven impact on polymeric matrices (Iwakiri; Trianoski, 2020). It is important to highlight that burning solid waste can cause greater environmental damage, due to the high ash content.

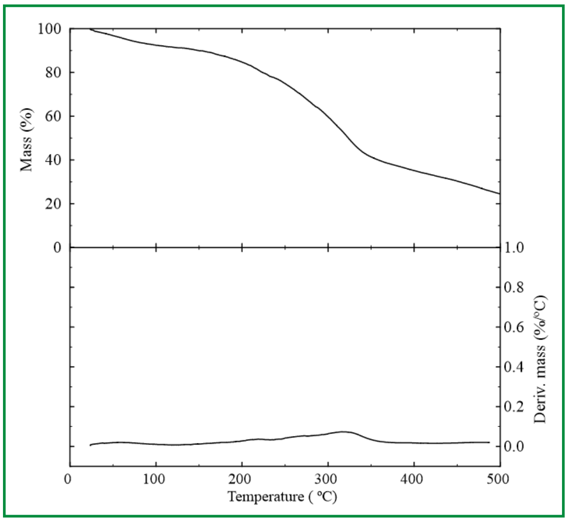
According to Lim and Chung (2002), on the other hand, the lignocellulosic material is considered light, because it has density lower than 0.0005 kg/cm³. The apparent density found in wheat waste (0.0002 kg/m³) was lower also in relation to those found in the literature for vine waste (0.0006 kg/m³) (Wong *et al.*, 2020), bean waste (0.0002 kg/cm³) (Miranda *et al.*, 2022) and natural *Pinus taeda* (500 kg/m³) (Miranda *et al.*, 2022a). According to Iwakiri and Trianoski (2020), the density of the waste for the production of polymeric composite should be low, in order to obtain a light material, generating a gain in the logistics process.

3.2 Thermogravimetry of the wheat waste

Figure 2 shows the thermogravimetric (TGA) and derivative of thermogravimetry (DTG) data of wheat particle. The data show 9% adsorbed water loss below 120°C

(Borges *et al*., 2024). In the TGA graphic, there is a region of hemicellulose and cellulose decomposition, between 200 and 400ºC, corresponding to 50% of its composition. A decomposition peak of these components is noted at ~350°C in the DTG curve. This process is associated with the depolymerization of hemicellulose, pectin and cleavage of glycosides and cellulose bonds (Das *et al.*, 2021). Lignin decomposes between 400 - 500°C, and after this temperature the mass loss is negligible (Sai Revanth *et al.*, 2020). The representation of these lignocellulosic components is compatible with the chemical characterization presented in Table 1.

Figure 2 – TGA and DTG curves



Source: Authors (2023)

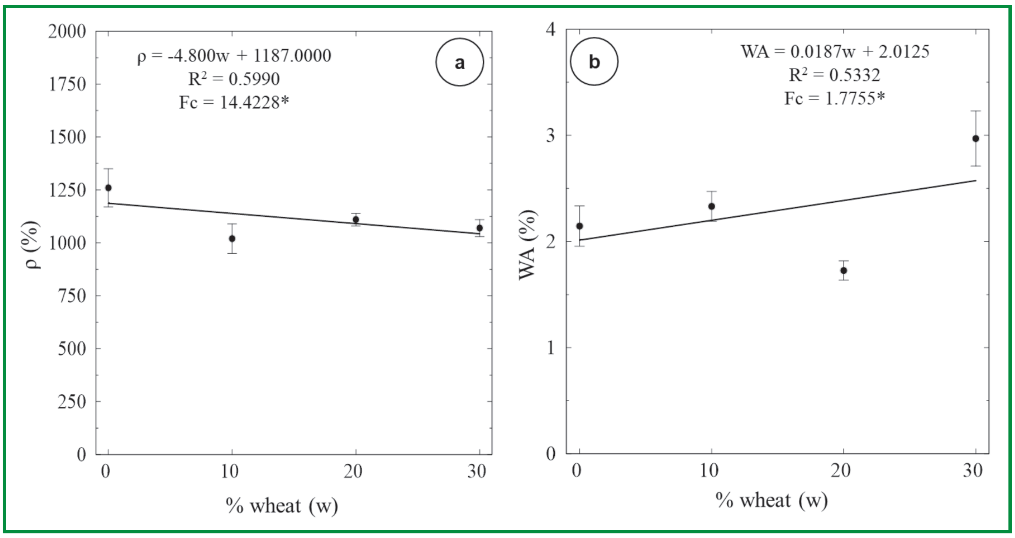
Wheat residue often contains a significant amount of moisture that can affect the manufacturing process, and it is important to remove or control the moisture to avoid processing problems. Furthermore, the amount of solid residues, after burning or heating, may indicate the amount of non-volatile material and may influence the quality of the final product.

3.3 Physical characterization of the polymeric composites

The average values obtained for apparent density (ρ) and water absorption (WA) are shown in Figure 3. It is observed an increase of water absorption for each 1%

of wheat waste inserted in the composite of the order of 0.018% (Figure 3a) and a reduction of density with the replacement of wheat waste of the order of 4.8 g/cm^3 for each 1% inserted in the composites (Figure 3b).

Figure 3 – (a) Apparent density and (b) water absorption of composites



Source: Authors (2023)

As reported by Veloso *et al.* (2021), the downward trend in the density of the composites was expected, since wheat waste presents significantly lower density than recyclable LDPE. This reduction indicates something favorable, because they reduce the expenses with the maintenance of equipment used, since, during the processing of the composite there will be less tool wear and low processing temperatures will be used (Poletto, 2017). In addition, the material is interesting in civil construction, because the use of lighter materials compared to similar materials used for this purpose, which facilitates its process and handling (Veloso *et al.*, 2021).

The values obtained in this research are still close to those reported in the literature. Santos *et al.* (2022) when replacing soybean waste in relation to the total mass of LDPE in 0, 5, 10, 15 and 20% observed a reduction of 1.01 to 0.81 g/cm³, as well as Rahman *et al.* (2013) that when adding 40 to 70% of sawdust in their composites, obtained a reduction of 1.05 to 0.86 g/cm³ in density.

The water absorption tendency was observed to increase in relation to the increase in the substitution of lignocellulosic waste. This behavior is due to the low density of this material associated with its hydrophilic propensity, can form a porous structure. Raghu and Goud (2020) reported that when replacing 0, 5, 10, 15 and 20% of *Calotropis procera* fiber to the polymeric composite the water absorption increased from 0.5 - 3.5%; as reported by the authors, this increase occurred due to the presence of hydroxyl groups found in the fiber. Santos *et al.* (2022) when replacing LDPE by soy waste (0, 5, 10, 15 and 20%) in relation to the total mass, have observed an increase for WA from 0.55% in the reference sample to 3.45% in the sample with higher replacement. The values achieved in this study were lower than those reported in the literature. According to Veloso *et al.* (2021), this must have probably occurred due to the chemical characteristics of the wheat waste, revealing, however, a positive result, due to the possibility of expanding the use of the composite and possibly reduce costs with additives and pre-treatments.

The reduction in water absorption ($LDPE_{80\%}WW_{20\%}$) can be justified due to the formation of a physical barrier between the polymer matrix and the aqueous medium, preventing water from entering the matrix. Furthermore, the wheat residue may have interacted with the polymer matrix, forming a three-dimensional network that also makes it difficult for water to enter. Indicating that a concentration of 20% waste may be the ideal concentration in reducing this property.

Table 2 presents the burning speed results (s) for the systems under study. The replacement of wheat waste to the systems increased the burning speed when compared to recycled polymers ($LDPE_{100\%}$).

Table 2 – Results of the flammability test

Treatment	Self-extinguishing time after ignition (s)	Was there any dripping?	UL 94 Classification
$LDPE_{100\%}$	405	Yes	H-B
$LDPE_{90\%}WW_{10\%}$	285	Yes	H-B
$LDPE_{80\%}WW_{20\%}$	191	Yes	H-B
$LDPE_{70\%}WW_{30\%}$	155	Yes	H-B

Source: Authors (2023)

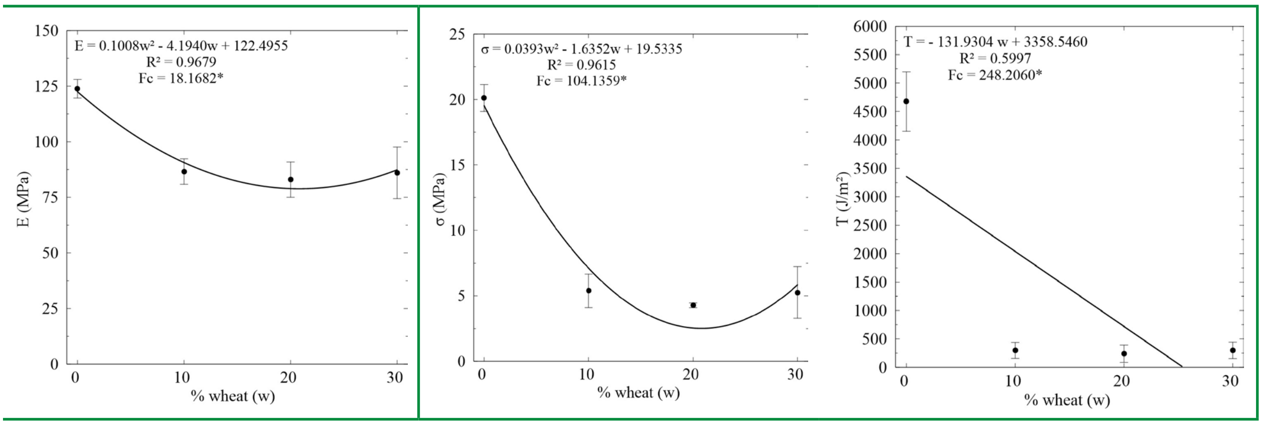
The study by Rodrigues *et al.* (2021) showed reductions in self-extinguishing time of 15 and 25% for the systems with the insertion of cork powder. With the insertion of granulated filler, the composites had reductions of 6 and 23%, indicating that the granulometry is not a significant factor for the combustion process. The reductions possibly indicate that the load acted as a thermal insulator, helping in the process of flame suppression, due to the presence of suberin in the cork composition, which has insulating capacity, capable of preventing the more extensive propagation of the flame and the high difference in the specific heat of the load and the polymer. Therefore, in the present research there was a large spread of flames with a higher percentage of lignocellulosic material, as in other works in the literature.

The molecular composition and structure of certain lignocellulosic materials provide for the composite the inherent ability to produce thermally stable carbonaceous residues when exposed to fire. At the moment the flame hits the sample, the outer part is covered by a carbonized layer, like an insulating barrier on the surface, preventing the diffusion of oxygen into the material, resulting in improved fire behavior. Therefore, lignocellulosic materials can form a layer capable of slowing down the burning speed of the material, by the barrier effect (Costes *et al.,* 2017). Thus, one can observe that all composites presented lower flame maintenance time than the samples based on pure LDPE, confirming that the wheat waste presents potential application in systems with demand to reduce the flame spread time.

3.4 Mechanical characterization of the composites

The insertion of wheat waste led to a decrease in the values of modulus of elasticity – MOE (E), when com-pared to the reference sample, being quadratic adjustment the most appropriate, being observed a minimum value of 78.93 MPa, with 20% of wheat substitution. After this value, there was an increase of the same (Figure 4a). The E for virgin LDPE varies from 102 to 240 MPa (Coutinho; Mello; Maria, 2003). The E can present variations according to the substitution of lignocellulosic materials in polymeric matrices. The literature has shown that these variations can extend to other mechanical properties and occur mainly due to the structural and chemical differences between the materials used and the type of matrix, virgin or recycled (Poletto, 2017).

Figure 4 – Values of composite properties from the traction test: (a) modulus of elasticity; (b) tensile strength and (c) tenacity



Source: Authors (2023)

A study Kim, Harper and Taylor (2009) found that the inclusion of different wood fibers in a polypropylene matrix resulted in varied MOE (Modulus of Elasticity) values, suggesting that different wood species can alter interfacial adhesion. Another study Georgopoulos *et al.* (2005) observed that the MOE values increased with larger amounts of Eucalyptus and corn cob particles in composites with LDPE. However, when grain wastes were included, there was no significant difference in MOE values, indicating lower mechanical properties compared to other lignocellulosic materials. This was attributed to the low cellulose content present in the waste compared to Eucalyptus and corn cob.

According to the literature (Coutinho; Mello, 2003), the tensile strength of virgin LDPE ranges from 6.9 to 16 MPa. However, when lignocellulosic materials are added as reinforcement in the polymer matrix, a decreasing trend in tensile strength (***σ***) is generally observed. This can be attributed to the low interaction between the fibers and the matrices (Mertens; Gurr; Krause, 2017). This trend was observed in this research, which showed a decrease in tensile strength, with a minimum value of 2.55 MPa, with 20% of wheat substitution in the polymeric matrix. After this value, there was an increase in the same (Figure 4b). A few factors can explain these data, such as the lack of adhesion or inefficient matrix-reinforcement connection, due to anatomical and chemical factors, degradation of the lignocellulosic material in the matrix and processing conditions, such as the extrusion process, which can cause damage to the lignocellulosic structure (Mertens; Gurr; Krause, 2017). Moreover, the low cellulose content of the wheat waste, which is the main component regarding the tensile strength, probably was not enough to act as reinforcement in the matrix.

The size of particles has a significant impact on the tensile strength of composites. Particles with smaller sizes, specifically those that have been sorted on 40 or 60 mesh sieves, tend to result in composites with higher strength. In comparison, composites made with larger particles generally exhibit lower tensile strength (Spear; Eder; Carus, 2015). This suggests that reducing the particle size, as achieved through sorting on finer mesh sieves, can contribute to enhanced tensile strength in composite materials.

Extractives can also directly affect mechanical properties, hindering matrix-reinforcement interaction and curing of polymer composites (Sheshmani; Ashori; Farhani, 2012). The extractives content found in wheat waste (15.2% ± 1.19%) was considered similar when compared to other lignocellulosic wastes such as sugarcane bagasse (16.6%), corn harvest waste (17.5%) and coffee processing (8.6%) (Protásio *et al.*, 2012). According to Sheshmani, Ashori and Farhani (2012), by removing extractives from wood flour, there was a significant improvement in tensile strength due to better adhesion of the matrix-reinforcement interface. Therefore, this component does not become a challenge for valorization of agro-industrial waste for the production of polymer composites.

The mineral components of waste, ash content negatively interfere in the interaction between the raw materials in some applications such as in agglomerated panels. However, according to Fernandes *et al.* (2014), ash does not interfere significantly in the properties of polymeric materials, because they have inert characteristics, acting as a load in composites.

The tenacity (T) corresponds to the capacity of a given material to absorb energy and deform permanently until the occurrence of fracture. The inclusion of wheat waste in the polymeric matrix caused a reduction in this property, and the relationship between tenacity and the different percentages of wheat waste is represented in Figure 4c. The data demonstrated a disadvantage in this property with the incorporation of wheat residues, this fact occurs due to the manipulation of lignocellulosic material by alkaline hydrolysis and mineralization. Therefore, it can be inferred that the specific energy of the compounds in our study is significantly due to the high adhesion rate of residues in the matrix and reduced fiber penetration, which leads to a reduction in specific energy, resulting from the mineralization of the fibers and the densification of the material. The LDPE presents matching values of toughness (Coutinho; Mello, 2003). However, according to Veloso *et al.* (2021), composites with lignocellulosic wastes have a tendency to reduce their toughness values, due to intrinsic factors for both materials and by the matrix-strengthening interaction.

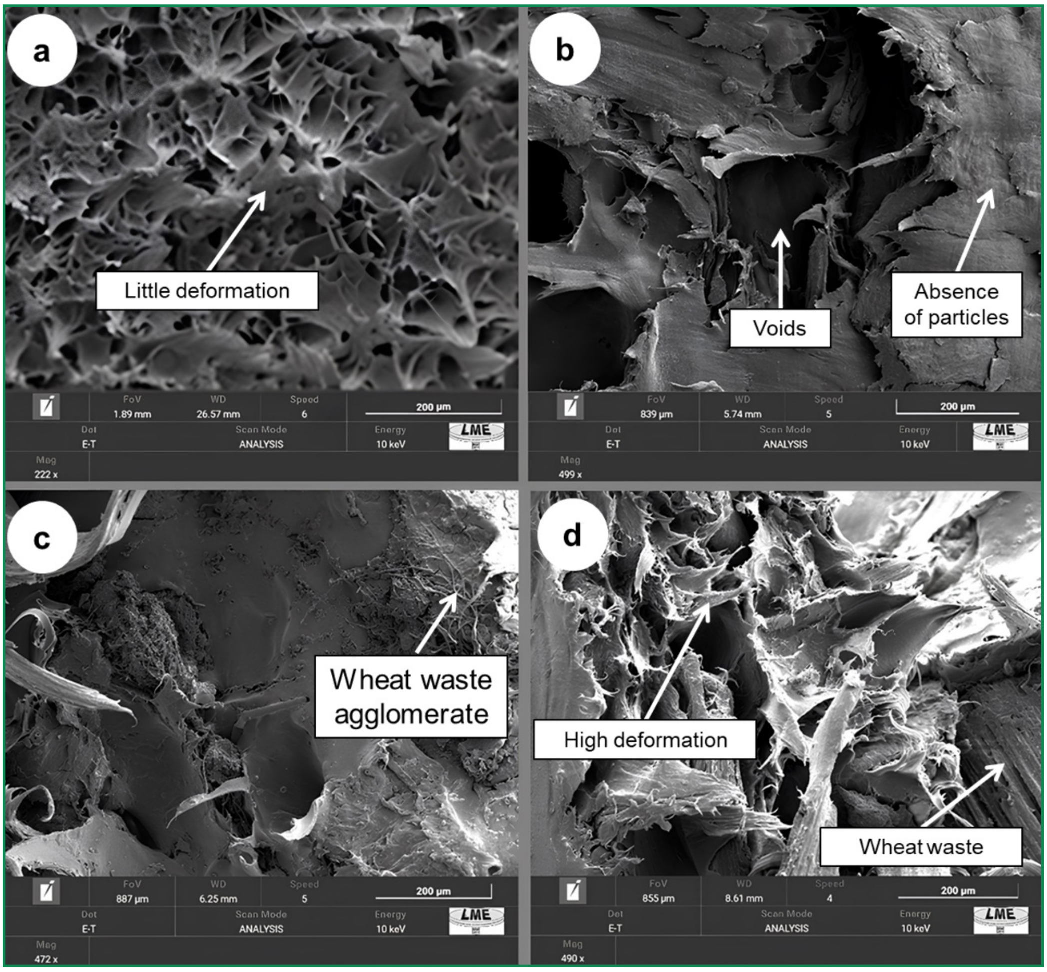
The results of the present research show that toughness complements tensile strength and both followed the same trend. With the increase of the wear percentage, there was a faster and easier rupture, even without the action of large forces. In agreement with Veloso *et al.* (2021), the reduction in strength of polymeric composites has been treated in the literature as a cause of the decrease in their toughness. Pereira *et al.* (2017), when evaluating compo-sites reinforced with green coconut shell fibers in high impact polystyrene (HIPS) matrix, observed reduction in both properties.

There are several variations in the mechanical properties of composites produced from recycled materials. The study by Keskisaari and Kärki (2018) compared the mechanical strength of composites produced with virgin and recycled polymers, reporting that some properties, as impact resistance, stood out for the recycled composites, in addition to lower material and production costs. The use of virgin and recycled polymers is interesting, providing possibilities of application of the composite, since they are adaptable for various applications, such as domestic artifacts, which do not require great resistance, to elements for civil construction, higher requirements. Therefore, the possibility of choosing low-cost materials that meet the requirements is fundamental as a strategy to boost the development of composites from recyclable materials and lignocellulosic waste.

3.5 Microstructural characterization of the composites

Further scanning electron microscopy (SEM) testing was performed to evaluate the region of tensile failure, interaction between matrix and reinforcement and the presence of pores in the composite. The SEM micrograph analyses of the structure of the composites can be observed in Figure 5, which indicate an increase in the porosity of the polymeric material and, consequently, a decrease in the density and interaction at the interface, corroborating with the tensile strength data (Figure 6b-c-d), which showed a decrease due to the voids and lack of interaction between the wheat waste and the polymer. In a similar way, by developing composites based on PLA (polylactic acid) and natural fibers, Lemos and Martins (2014) observed a drastic decrease in the elongation at break.

Figure 5 – Scan micrograph of composites (a) $LDPE_{100\%}$; (b) $LDPE_{90\%}WW_{10\%}$; (c) $LDPE_{80\%}WW_{20\%}$, and (d) $LDPE_{70\%}WW_{30\%}$



Source: Authors (2023)

The fracture regions of composites often exhibit an uneven distribution of particles within the matrix, resulting in the formation of small agglomerations and weak points. This phenomenon has been observed in several studies, including Mertens, Gurr and Krause (2017). The presence of pores at the interfaces further exacerbates the issue by reducing stress transfer. Additionally, imperfections such as agglomerates can negatively impact the overall strength of the composite. Therefore, it is crucial to minimize the presence of such in homogeneities and imperfections in order to ensure optimal composite strength.

Besides the influence of the chemical composition, due to the polar nature of the plant material and the nonpolar influence of thermoplastics, the low interfacial adhesion between the lignocellulosic reinforcement and the matrix is already expected. To promote adhesion, activation methods, such as the use of coupling or surface agents, are required (Wolcott; Englund, 1999). The insertion of coupling agents improved the mechanical properties of composites produced with high-density polyethylene reinforced with wood particles, especially for tensile strength (Huang; Zhang, 2009). Therefore, the absence of a coupling agent may have been a crucial factor that prevented the proper dispersion of the particles in the composite.

Analyzing the feasibility of the production process is of great importance, as well as the technical efficiency for the use and application of composites. With the use of recyclable materials, the composites can bring benefits with the costs related to the procurement, processing and transportation of these raw materials, especially because they have low densities, revealing a viable process.

The production process of composites, utilizing recycled matrix and reinforcement materials, offers sustainability benefits across social, environmental, and economic aspects. Extensive research, such as Veloso *et al.* (2021), has highlighted the advantages of utilizing waste sources, including reduction of greenhouse gas emissions; conservation of water and energy during production; decreased waste sent to landfills and generation of income and job opportunities. It is essential to explore the potential of replacing primary resources with renewable materials, focusing on the valorization of urban resources and agricultural waste.

4 CONCLUSIONS

The reinforcement of wheat waste in the LDPE matrix increased the water absorption for each 1% of wheat waste inserted in the composite in the order of 0.018%, but at considerably low levels, compared to wood. A reduction in the density of the composites in the order of 4.8 g/cm^3 was observed for each 1% inserted in the composites, resulting in a lighter product, which is beneficial for several applications, such as civil construction. The replacement of wheat waste increased the burning speed (flammability) when compared to recycled polymers (LDPE$_{100\%}$), indicating shorter time of fire spread.

Regarding the mechanical properties, the MOE values were reduced with the replacement of wheat waste, indicating relationship with the decrease of density. The tensile strength of composites produced with matrix composed only by recycled LDPE was 20 MPa, while the insertion of 30% wheat waste reduced this property to 5 MPa. The tenacity indicated less deformation for the polymeric materials with the insertion of wheat waste. Thus, the composite studied can be used to produce materials that require these characteristics, thus replacing virgin polymer.

ACKNOWLEDGMENTS

The authors thank the FAPEMIG, CAPES, CNPq, Graduate Program in Biomaterials Engineering of the Federal University of Lavras.

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How to quote this article

BORGES, I. O.; FURTINI, A. C. C.; MIRANDA, E. H. N.; ARANTES, L. S.; GOMES, D. A. C.; CARVALHO, J. V.; SATIRO, J. S.; OLIVEIRA, B. M. R. G.; MENDES, L. M.; GUIMARÃES JÚNIOR, J. B. Eco-friendly composite with matrix of recycled low-density polyethylene reinforced with wheat waste. **Ciência Florestal**, Santa Maria, v. 35, e88280, p. 1-24, 2025. DOI 10.5902/1980509888280. Available from: https://doi.org/10.5902/1980509888280. Accessed in: day month abbr. year.