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Design and Evaluating a Hydraulic Pelletizing Machine for Producing Feed Pellets from Pistachio Shells

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ABSTRACT

Due to the shortage of water resources and frequent droughts, optimizing the use of food resources to provide feed for animal is an important issue. In this study, pistachio shells were collected and stored in open air environment to reduce their moisture content. Then, they were powdered using a grinder to produce pellets using a developed hydraulic pelletizer, and the mechanical properties of the produced pellets were measured using a biological material testing machine. An experimental design with four factors, including moisture levels of 15 and 20%, particle sizes of 0.6 and 1 mm, mold diameters of 8 and 10 mm, and compression pressures of 6,000, 8,000 and 11,000 kPa, was carried out in a completely randomized design. The density, fracture energy, and toughness of the produced pellets were measured. The results showed that the independent effects of moisture, mold diameter, and compression pressure were significant on all the above properties ($P \leq 0.05$), and the effect of particle size was significant on the density and toughness of the pellets ($P \leq 0.05$). Additionally, some of their interactions had a significant effect on the density, fracture energy, and toughness of the pellets ($P \leq 0.05$). The coefficient of variation and determination coefficient were 1.92% and $R^2= 0.83$ for density, 25.42% and $R^2= 0.49$ for fracture energy, and 66.23%, $R^2= 0.41$ for pellet toughness, respectively. Therefore, producing pellets from pistachio shell waste can be a good option to reduce transportation costs, produce Animal feed, and reduce environmental pollution.

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INTRODUCTION

More than 70% of meat production costs stem from procuring livestock and poultry feed. The integration of advanced technologies in feed production enhances livestock efficiency, yet suboptimal execution of these processes results in escalated final product costs (Abdollahi et al., 2013). In recent years, leveraging agricultural waste in animal nutrition has emerged as a successful strategy for diminishing feed expenses, mitigating environmental pollution, and facilitating the cost-effective reintroduction of these materials into the natural cycle (Soleymani et al., 2022; Vasta et al., 2008). Given that pistachio production in Iran reached 472 thousand tons in 2013, the estimated residues from pistachio harvesting in Iran surpassed 755 thousand tons (Taghavi et al., 2020). These residues encompass outer soft hull, cluster stems, leaves, minimal amounts of hollow and half-kernel pistachios, and woody shells (Shakeri et al., 2017). A multitude of research findings underscores the substantial value of pistachio residues, presenting a viable potential for dry and silo storage in ruminant diets (Ghasemi et al., 2012; Shakeri et al., 2017).

Presently, pistachio hull residues undergo silo storage (Shakeri et al., 2017). However, considering the challenges inherent in silo methods for preserving pistachio green hull residues, such as low volumetric density, methane gas production, spoilage, storage intricacies, limited shelf life, and transportation expenses, widespread adoption of this method for preserving these residues is not feasible. Consequently, it is preferable to employ alternative methods such as drying, packaging, utilizing preservation technologies, or converting pistachio green hull residues into feed pallets for livestock to ensure the high quality and durability of the product.

Spoilage due to high moisture content, low volumetric density, high transportation costs, and storage issues are obstacles to utilizing agricultural waste as animal feed (Tumuluru et al., 2011). Challenges such as the presence of harmful microbes and bacteria in raw materials and the constraints of using transfer equipment and machinery can be mitigated through this enhanced method (Terrill et al., 2007). The palletizing process, by compacting these materials and implementing pre-palletizing procedures, addresses decay and mold issues. Furthermore, this approach offers additional benefits, including reduced environmental pollution due to the absence of fine particles and dust, along with an augmented nutritional value resulting from compression (Supriya et al., 2012). In a study, the effects of moisture, temperature, and compression pressure on the compressibility of pistachio green hull residues were investigated with a laboratory palletizing device. The results indicated that the produced pallets had good density, breaking energy, and cohesiveness (Laei et al., 2023; Laei et al., 2023). This also leads to an improvement in the palatability and digestibility of pistachio pellets (Laei et al., 2023). The utilization of palletized forage, due to various reasons such as enhanced digestibility, increased appetite, and internal parasite control, amplifies animal performance (Terrill et al., 2007).

Several lignocellulosic biomass sources, such as corn fodder, sugarcane bagasse, and grain straws, possess considerable potential for energy applications (fuel, livestock feed, organic fertilizers), but their low density (wood chips: 220-180 kilograms per cubic meter; packaged plants or grasses: 130-110 kilograms per cubic meter) presents a substantial limitation for loading and transportation Compacting these biomasses through pressure and suitable temperature using compacting systems such as mills, pallets, and presses can increase their density by 4-5 times. Another advantage of biomass compaction is creating a specific size and shape that improves loading, transportation, and reduces storage space (Fig 1) (Tumuluru et al., 2011). Generally, compacted biomass, such as pallets and briquettes, exhibits mass densities of approximately 750-700 kilograms per cubic meter and 450-350 kilograms per cubic meter, respectively (Tumuluru et al., 2015).

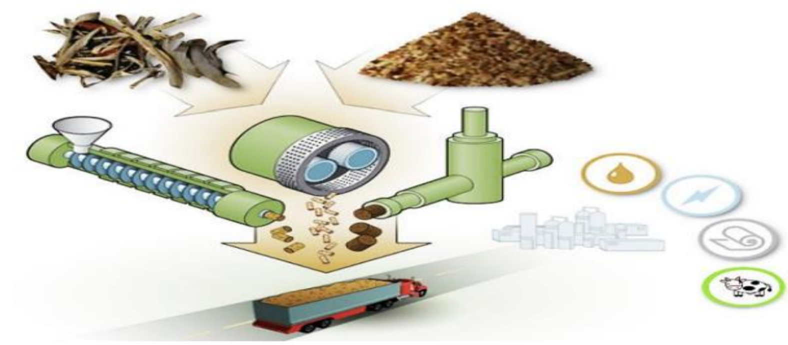

Fig 1. The schematic of lignocellulosic biomass compaction for bio-refinery applications (Tumuluru, 2021)

The residual materials derived from pistachio hulls stand as promising resources for biofuel production, activated carbon, and animal feed. Due to the distinct compressibility behaviors exhibited by different substances, it becomes impractical to extrapolate findings from research on other materials, such as tree bark or rice husks, to residues from pistachio green hulls. In optimizing the compaction process for these materials, meticulous attention must be given to variables like compression pressure, particle size, and rheological behaviors. Consequently, the resulting pallets should demonstrate suitable density and strength, making them effective for deployment as cost-efficient animal feed. The primary objective of this research is to investigate the behavior of residual materials from pistachio green hulls in the palletizing process.

MATERIALS AND METHODS

Preparation and Conditioning of Pistachio Green hull Residues

The raw materials, residues from pistachio green hulls, were obtained from processing terminals in Damghan County, Semnan Province (Fig 2). They were left exposed in an open space for one month to reduce their initial moisture content. Subsequently, the pistachio green hull residues were transferred to the laboratory of the Agricultural Engineering Department, Faculty of Agricultural Technology (Abureyhan Campus), University of Tehran, for processing and palletizing.

Fig 2. Green pistachio shell residue

The obtained pistachio residues comprised, on average, comprised 62% green hulls, 26% clusters, 11% leaves, and 1% kernels and hard shells. Employing an advanced hammer mill, the particle length was reduced to a geometric mean of 0.6 and 1 millimeter (mesh 16 and 30). The particles were layered on top of each other in the shaker device with large hole sizes arranged to small (Fig 3). An electric laboratory sieve shaker (Model KG 531, Iran) was employed to measure the geometric mean particle size. Initially, 100 grams of pistachio green hulls were poured onto the top sieve, and after 30 seconds of vibration, the remaining amount on each sieve was measured with a digital scale (0.01-gram accuracy). The geometric mean particle size was then calculated using equation (1) (ASABE, 2006).

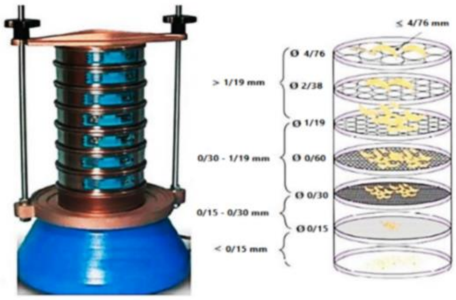

Fig 3. The electric sieve shaker used to determine the geometric mean length of particles

$$d_{gw} = \log^{-1}\left[\frac{\sum_{i=1}^{n}\left(w_i \log \bar{d}_i\right)}{\sum_{i=1}^{n} w_i}\right] \quad (1)$$

where d_{gw} is the geometric mean of particle length (mm), W_i is the mass on the sieve (gr), n is the number of sieves plus one, and d_i is the pore size of the sieve (mm).

To enhance the adhesiveness of pistachio green hull residues, bentonite, wheat, urea, and molasses were utilized at the respective rates of three, six, four, and five kilograms per 100 kilograms of pistachio residues.

Determining the Initial Moisture Content of Raw Materials

The recommended standard method (AACC, 1999) was employed to measure the initial moisture content. Firstly, the initial moisture content of the pistachio hull was determined. Subsequently, the moisture content was standardized to 15% and 20% based on standards. To achieve these moisture levels, the required amount of water was calculated using equation (2). Distilled water, measured based on the calculated requirement, was then added to the pistachio green hull using a water spray. The samples were then stored in zip-lock plastic bags in a refrigerator at four degrees Celsius for 48 hours to ensure uniform moisture distribution throughout the samples.

$$m_w = \frac{m_i(M_{wf} - M_{wi})}{١ - M_{wf}} \quad (2)$$

where m_w is the weight of added water, m_i is the wet-based initial weight, M_{wf} is the wet-based final moisture content and M_{wi} is the wet-based initial moisture**.**

Determining the Bulk Density

To determine the bulk density, the milled pistachio green hull was poured into a specified container until it reached the brim. Subsequently, the excess material was carefully removed by zigzagging a ruler over the surface of the container, ensuring that the container was filled with uncompacted material. Taking into account the dimensions of the container, the volume was calculated, and the mass of the material inside the container was measured using a digital scale (Model LUTRON GM-300P, Germany) with an accuracy of 0.01 grams. The bulk density was then calculated for the pistachio residues, resulting in a value of 449 kilograms per cubic meter using equation (3).

$$p = \frac{m}{v} \quad (3)$$

where p is the density of the sample (kg/m^3), m is the mass of the sample in kg, and v is the volume of the sample in m^3.

Designing the Mold

Continuing the investigation, molds of various dimensions (10 millimeters in diameter and 50 millimeters in length; 8 millimeters in diameter and 55 millimeters in length) were designed and fabricated with the aim of producing pallets for animal feed (Fig 4) (ASABE, 2007). Additionally, an appropriately sized heat belt was employed, delivering a temperature of 65 degrees Celsius to heat the materials within the mold, facilitated by an advanced heating system and a type K thermocouple.

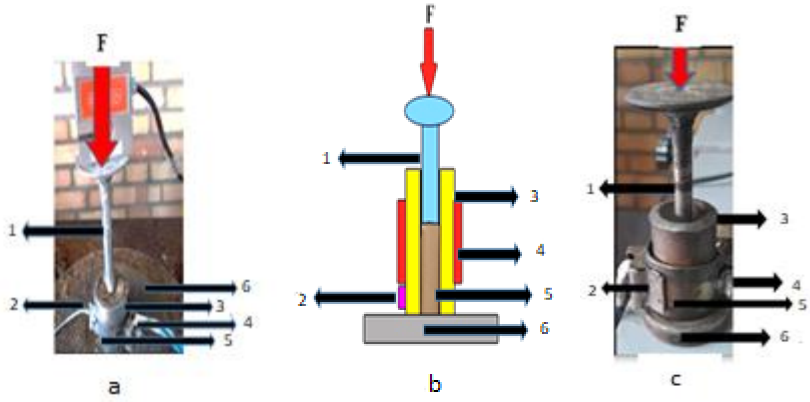

Fig 4. a) Actual depiction of a 10mm diameter mold, b) Pattern of the mold, and c) Actual depiction of an 8mm diameter mold. 1- Piston, 2- Thermocouple, 3- Compression mold frame, 4- Heat belt, 5- Material compression area, 6- Mold bottom stopper

Production of Pallets Using a Hydraulic Palletizer (Single)

The hydraulic palletizer machine, as illustrated in Fig 5, comprises a fixed jaw, for placing the mold, and a movable jaw which moves with a hydraulic cylinder. The hydraulic pump of this machine provides the necessary speed and pressure for the movement of the movable jaw. The force required for compressing the sample is applied to the piston by the movable jaw, and the applied force is measured with a load cell and recorded in the device's data logger. The machine has the capability to adjust the incoming compression pressure. To produce pallets, the compression pressure was applied at three levels: 6000, 8000, and 11000 kilopascals for 10 seconds on the samples.

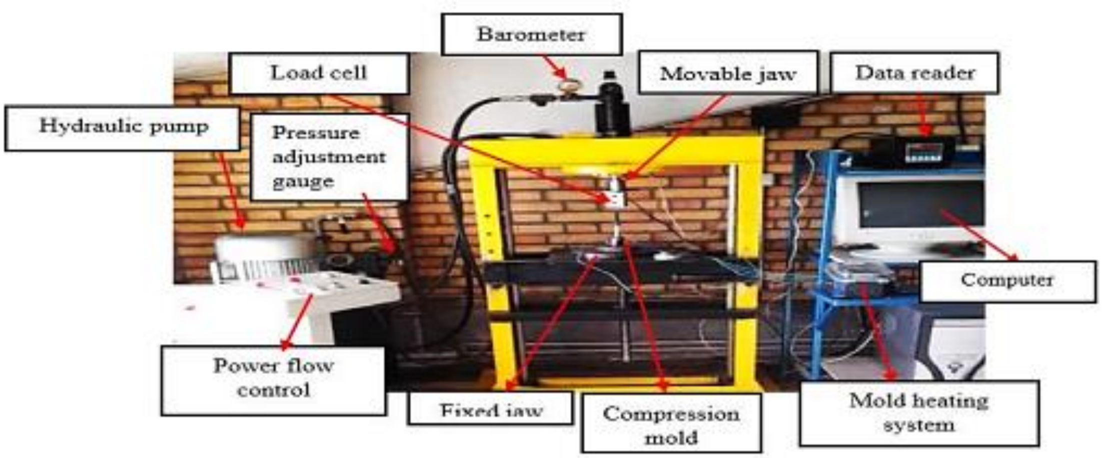

Fig 5. Hydraulic pellet maker machine

Determining Pallet Density

To ascertain the density of the produced pallets, the length and diameter of the pallets were measured using a digital caliper (model CD-6CSX, Mitutoyo Corp, Kawasaki, Japan). Subsequently, the weight of each pallet sample was measured with a digital scale (model LUTRON GM -300P, Germany) with an accuracy of 0.1 grams. Finally, the volume and density of the pallets were calculated using the equations (4) and (5).

$$v_p = \frac{\pi}{4} d^2 l \quad (4)$$

$$p_p = \frac{m_p}{v_p} \quad (5)$$

Biological Material Testing Apparatus

The biological material testing apparatus, depicted in Fig 6, was utilized for measuring the fracture energy, fracture force, and pallet toughness. Developed by the Agricultural Engineering Group at Aboureihan Campus, this device positioned the pallet on the fixed jaw aligned horizontally. The mobile jaw, connected to a load cell, descended at a rate of 25 millimeters per minute until the pallet exhibited either crack or fracture, visible on the force-displacement curve.

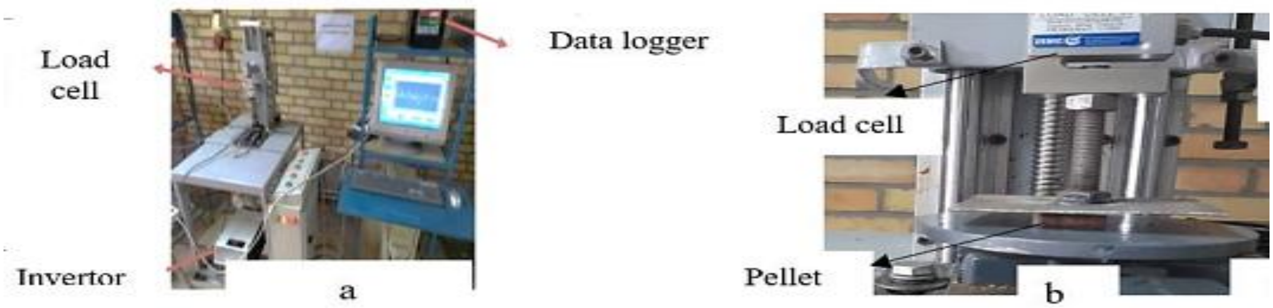

Fig 6. a) mechanical testing device for biological materials; b) how to apply force to the pell*et al*ong the horizontal axis

Fracture Energy and Toughness of Produced Pallets

The biological yield point refers to a point on the force-deformation curve where force momentarily decreases and then increases, indicating the material's failure. Additionally, the area under the force-displacement curve represents the amount of energy required for pallet fracture, calculated using equation (6).

$$E = \frac{1}{2} Fr \times Dr \quad (6)$$

In this regard: E, the energy required for pallet fracture (millijoules); Fr, the maximum force required for fracture the pellets (Newton); Dr, displacement equivalent to the maximum force value (mm).

Toughness is defined as the work done per unit volume of a substance to cause its fracture. Given that the area under the curve represents the work done for pallet fracture, the apparent toughness for the produced pallet was determined using equation (7), considering the estimated volume of the pallets from the previously mentioned formulas.

$$p = \frac{E_a}{v} \quad (7)$$

where p is the toughness in J/m^3, Ea is the absorbed energy by the samples in joules and v is the sample volume in cubic meters.

Statistical Analysis of the First Section

In the initial section, the experimental design was factorial with five factors. These five factors included two levels of temperature (50 and 65 degrees Celsius), two levels of humidity (15 and 20 percent), two levels of particle size (0.6 and 1 millimeter), two levels of mold diameter (8 and 10 millimeters), and three levels of compression pressure (6000, 8000, and 11000 kilopascals). Throughout the experiment, the density, fracture energy, and toughness of the produced pallets were measured. After collecting and organizing the data using SAS statistical software version 9.3 and verifying the normality of the data, data analysis was performed using analysis of variance (ANOVA) and mean comparison using the Duncan test at a 5% significance level. Additionally, three methods, namely coefficient of variation, coefficient of determination, and multivariable regression, were employed to examine the impact of independent variables on dependent variables. The coefficient of variation indicates the extent to which changes in the dependent variable are dependent on changes in the independent variables. The coefficient of determination illustrates how much of the variation in the dependent variable can be explained by changes in the independent variables. Multivariable regression was utilized to simultaneously investigate the impact of all independent variables on the dependent variable.

RESULTS AND DISCUSSION

The results of the analysis of variance and the significance of the independent variables, including humidity, compression pressure, particle size, and mold diameter on the density, fracture energy, maximum fracture force, and toughness of pallets produced from pistachio green hull residues are presented in Table 1. The independent effects of particle size (PS), humidity (M), mold diameter (DM), and compression pressure (CP) on the density of pallets were found to be statistically significant at the 1% probability level.

Moreover, the interactive effects of humidity × mold diameter, particle size × mold diameter, humidity × particle size, particle size × mold diameter × compression pressure, and humidity × particle size × mold diameter × compression pressure on the density of the produced pallets were significant at a 1% probability level. Additionally, the interactive effects of mold diameter × compression pressure on the density of the produced pallets were significant at a 5% probability level.

Considering the information presented, the results indicate that the independent effects of mold diameter and compression pressure on the fracture energy of pallets produced from pistachio green hull residues were significant at a 1% probability level.

Furthermore, the independent effects of humidity and particle size on the fracture energy of the produced pallets were significant at a 5% probability level. The interactive effects of humidity × mold diameter, particle size × mold diameter, humidity × particle size × mold diameter, and particle size × mold diameter × compression pressure on the fracture energy of the produced pallets were significant at a 1% probability level.

The interactive effects of mold diameter × compression pressure on the fracture energy of the produced pallets were significant at a 5% probability level. Therefore, according to the results presented in Table 1, it is evident that various factors, such as mold diameter, compression pressure, humidity, and particle size, independently and with their interactive effects, significantly affect the density, fracture energy, and toughness of the produced pallets. These factors must be carefully managed in the compression process of pistachio green skin residues.

Given the information provided, the results of the coefficient of variation and coefficient of determination for density, fracture energy, and toughness of the produced pallets in Table 1 indicate that respectively, these results were 1.92% and $R^2=0.83$ for the coefficient of variation and determination coefficient for density, 42.25% and $R^2=0.49$ for fracture energy, and 23.66% and $R^2=0.41$ for pallet toughness. These findings demonstrate that the variables under investigation have successfully provided a meaningful interpretation of property changes. These results further indicate that the conducted experiment was carried out with precision and appropriate quality.

Table 1. Table 1. Variance analysis of the effect of Moisture content, Mold diameter, particle size and compaction pressure on the density, fracture energy, and toughness of animal feed pellets obtained from green pistachio shell waste

Sources of variation	Mean of square			
	Degrees of freedom	Density	Fracture energy	Toughness
M	1	56584.5156**	0.00013629**	3.396243E-29*
PS	1	11745.1406**	0.00000523^{ns}	2.82569E-29*
DM	1	235588.8906**	0.00088164**	1271300.412**
CP	2	11826.9844**	0.00009238**	6.060231E-29**
CP*DM	2	1053.9531*	0.0000096^{ns}	2.081596E-29*
M*DM	1	8441.0156**	0.00012168**	8.064947E-29**
M*CP	2	601.7031^{ns}	0.00003524^{ns}	5.101918E-30^{ns}
M*PS	1	2197.2656**	0.00000243^{ns}	2.161021E-29^{ns}
M*DM*P	2	567.9844^{ns}	0.00000267^{ns}	8.618127E-31^{ns}
M*PS*DM	1	1.2656^{ns}	0.00059624**	2.381949E-28**
M*PS*CP	2	331.7344^{ns}	0.0000237^{ns}	2.962696E-30^{ns}
PS*DM	1	11209.5156**	0.0005712**	2.04248E-29^{ns}
PS*CP	2	350.2031^{ns}	0.00002989^{ns}	5.07002E-30^{ns}
PS*DM*CP	2	4406.5469**	0.00006315*	1.133701E-29^{ns}
M*PS*DM*CP	2	1721.3906**	0.00004169^{ns}	1.281896E-29^{ns}
Error	139	306.2344	0.00001607	5.91E-30
CV	_	1.92	24.25	23.66
R^2	_	0.83	0.49	0.41

^{ns}, * and ** are non-significant, significant at 5% and 1% levels, respectively

Table 2 illustrates the final regression model for predicting the impact of independent variables such as moisture, compression pressure, particle size, and mold diameter on the bulk density, fracture energy, and toughness of the pallets. In this table, coefficients are encoded and presented with positive and negative signs against each term. The positive and negative signs denote the synergistic and non-synergistic effects of the variables, respectively. Therefore, utilizing the final regression model allows for understanding the relationship between independent and dependent variables, examining the influence of each variable in predicting bulk density, fracture energy, and toughness.

Table 2. Regression model of independent variables on the examined responses with the elimination of non-significant factors

Answer	Regression Model
Density	D=1036.81-7.92M-45.15PS+40.44DM+0.0095CP
Fracture energy	F=0.032+0.00038914M+0.00095269PS-0.00247DM+0.0000004085527CP
Toughness	T=1.76×10-14+1.94×10-16M-2.21×10-15PS-1.07×10-15DM+4.29×10-19CP

The impact of independent variables, including moisture, particle size, mold diameter, and compression pressure, on the density, fracture energy, and toughness of pallets produced from pistachio green hull residues was investigated. The results are presented in Table 3.

The results indicate that an increase in compression pressure from 6000 to 11000 kilopascals leads to an augmentation in the bulk density and toughness of the produced pallets. However, the highest fracture energy is achieved with an increase in compression pressure from 6000 to 8000 kilopascals.

Moreover, a reduction in moisture from 20 to 15 percent results in the highest bulk density of the produced pallets, while for fracture energy and toughness, an increase in moisture from 15 to 20 percent exerts a more significant influence.

Additionally, the findings suggest that a decrease in mold diameter from 10 to 8 millimeters has the most substantial impact on fracture energy and toughness of the produced pallets. Conversely, an increase in mold diameter from 8 to 10 millimeters shows a positive effect only on the bulk density of the produced pallets. Furthermore, a reduction in particle size from 1 to 0.6 millimeters yields the highest values for bulk density and toughness of the produced pallets. However, for fracture energy, the particle size does not exhibit a significant effect.

Table 3. Mean comparison of the effect of Moisture content, Mold diameter, particle size and compaction pressure on the density, fracture energy, and toughness of animal feed pellets obtained from pistachio green peel residues.

Main Effect	Density (kg/ m^3)		Fracture energy (J)		Toughness (J/m^3)	
Mold diameter						
	Mean ± standard error	Grouping	Mean ± standard error	Grouping	Mean ± standard error	Grouping
8	1234.7±5.21	b	0.0232±0.0009	a	$0.143\times10^{-13}\pm0.521\times10^{-15}$	a
10	1315.5±3.58	a	0.0182±0.0005	b	$0.121\times10^{-13}\pm0.296\times10^{-15}$	b
Compaction pressure (kPa)						
6000	1257.8±7.73	c	0.0191±0.0009	b	$0.12\times10^{-13}\pm0.501\times10^{-15}$	a
8000	1279±8	b	0.0216±0.001	a	$0.134\times10^{-13}\pm0.517\times10^{-15}$	a
11000	1288.5±7.8	a	0.0214±0.0009	a	$0.142\times10^{-13}\pm0.561\times10^{-15}$	b
Moisture content(%)						
15	1294.9±5.03	a	0.0197±0.0008	b	$0.127\times10^{-13}\pm0.42\times10^{-15}$	b
20	1255.3±7.05	b	0.0217±0.0007	a	$0.137\times10^{-13}\pm0.456\times10^{-15}$	a
particle size (mm)						
0.6	1284.1±5.49	a	0.0205±0.0007	a	$0.137\times10^{-13}\pm0.461\times10^{-15}$	a
1	1266.1±7.32	b	0.0209±0.0009	a	$0.128\times10^{-13}\pm0.416\times10^{-15}$	b

According to Duncan's multiple range test, the numbers with the same letters in each column are not significantly different

The comparison results of the interactive effects of mold diameter and compression pressure on the bulk density of pallets produced from pistachio green hull residues (Fig 7a) indicate that an increase in mold diameter from 8 to 10 millimeters, simultaneously with an increase in compression pressure from 6000 to 11000 kilopascals, results in an increase in the bulk density of the pallets. These findings align with research on the physical properties of pallets made from sorghum stalks, corn stubbles, and straw, which showed that an increase in mold diameter leads to an increase in pallet density (Theerarattananoon et al., 2011). This suggests that an increase in mold diameter contributes to higher bulk density in produced pallets, and this effect is reinforced with a simultaneous increase in compression pressure and mold diameter. As the mold diameter increases, more material enters the mold, creating greater compression and consequently increasing the bulk density of the produced pallets.

Results comparing the average interactive effects of moisture and mold diameter on the bulk density of pallets produced from pistachio green hull residues (Fig 7b) reveal that a simultaneous decrease in moisture from 20 to 15 percent and an increase in mold diameter from 8 to 10 millimeters result in an increased bulk density of the pallets. The lowest bulk density is achieved for a moisture level of 20 percent and a mold diameter of 8 millimeters. This finding aligns with research on the impact of moisture content in feed on the density of pallets produced from corn stalks, indicating that an increase in moisture content leads to a decrease in pallet density (Tumuluru, 2014). This suggests that reducing moisture within an optimal range, acting as a thin adhesive layer, can increase the amount of material in the pallet. Additionally, an increase in mold diameter allows more particles to enter the mold, and due to the fact that these particles have the highest adhesive properties, it leads to an increase in pallet density.

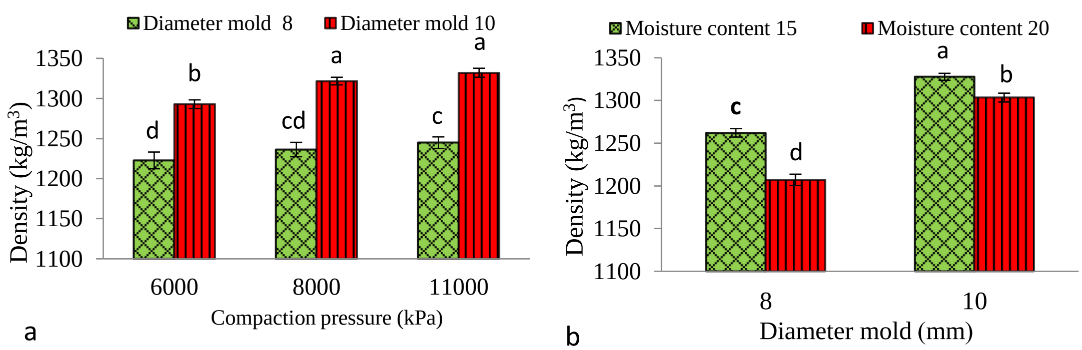

Fig 7. The density of livestock feed pallets derived from pistachio waste residues. a) The effects of mold diameter and compression pressure on pallet density. b) The effects of moisture and mold diameter on density

Results from the comparison of average interactive effects of mold diameter and particle size on the density of pallets produced from pistachio green hull residues (Fig 8a) demonstrate that the highest pallet density is achieved with particle sizes of 0.6 and 1 millimeter, coupled with a mold diameter of 10 millimeters. Conversely, the lowest density is observed with a particle size of 1 millimeter and a mold diameter of 8 millimeters. This indicates that with a simultaneous increase in mold diameter, more material enters the mold. Due to the smaller particle size and less size disparity between particles, compression during the compaction process increases and resulting in elevated density per unit volume of the pallet.

Additionally, the findings in Fig 8b, comparing the average interactive effects of particle size and moisture on pallet density, suggest that the peak density is attained through a simultaneous reduction in moisture from 20 to 15 percent and a decrease in particle size from 1 to 0.6 millimeters. Conversely, the lowest density occurs at a moisture level of 20 percent and a particle size of 1 millimeter. This indicates that a reduction in moisture within an optimal range function as a binder. Simultaneously, with a decrease in particle size, moisture absorption improves, leading to heightened intermolecular and adhesive forces between particles and consequently, an increased density in the resulting pallets. This aligns with analogous research on the influence of moisture on pallet density derived from waste materials, such as peanut shells, highlighting that heightened moisture levels contribute to a diminished pallet density (Fasina, 2008).

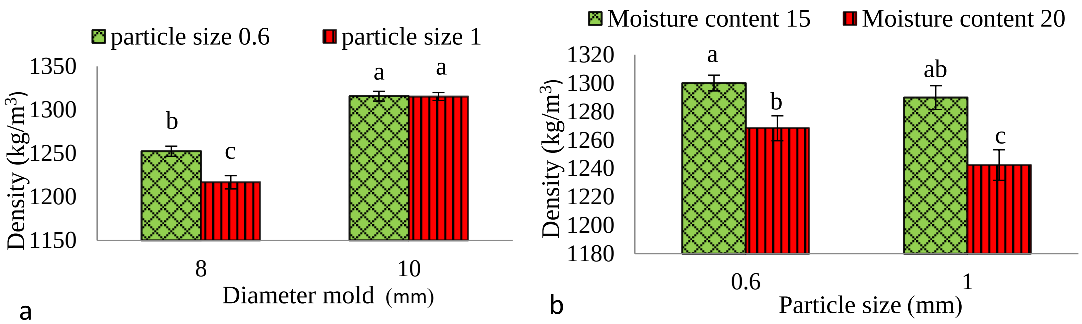

Fig 8. The density of livestock feed pallets derived from pistachio residues. a) The effects of mold diameter and particle size. b) The effects of particle size and moisture

Analyzing the results of the mutual effects of particle size × mold diameter × compression pressure on the density of pallets (Fig 9), it becomes apparent that the highest density is achieved with an increase in mold diameter from 8 to 10 millimeters, compression pressure from 6000 to 11000 kilopascals, and a decrease in particle size from 1 to 0.6 millimeters. Conversely, the lowest pallet density is observed with a particle size of 1 millimeter, mold diameter of 8 millimeters, and compression pressure of 6000 kilopascals. This phenomenon suggests that the interaction of factors, such as increased mold diameter and reduced particle size, results in more material entering the mold. The presence of fine particles leads to an augmented number of contact points between particles, and with the influence of low compression pressure, only particles in close proximity and the unstable arrangement of adjacent particles are subject to rearrangement. However, as the compression pressure increases, particles arrange in a stable and closely conFigd manner, facilitating the flow of particles into available spaces and an augmentation of the contact surface between particles. Consequently, this culminates in an overall increase in the density of the produced pallet (Mani et al., 2006).

Moreover, a comprehensive review of various studies has consistently indicated an inverse relationship between density and particle size. Furthermore, investigations into the effects of material compositions, moisture content, and mold diameter pressure on the quality of pallets created from pine and spruce sawdust corroborate the current research findings, highlighting that an increase in mold diameter from 17 to 21 millimeters correlates with an improvement in pallet density (Monedero et al., 2015).

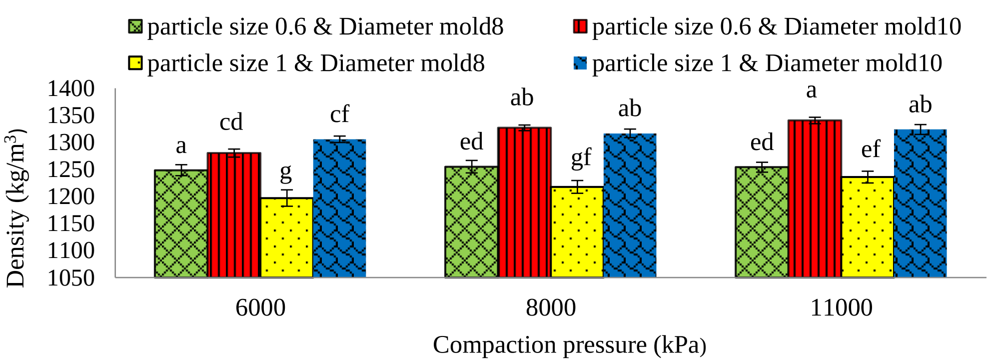

Fig 9. The impact of varying particle sizes, mold diameters, and compression pressures on the density of livestock feed pallets derived from pistachio residues

The comparison of means reveals the interactive effect of moisture × particle size × mold diameter × compression pressure on the density of pallets produced from pistachio residues (Fig 10). The highest pallet density is observed with a simultaneous decrease in moisture from 20 to 15 percent, an increase in mold diameter from 8 to 10 millimeters, particle size reduction from 0.6 to 1 millimeter, and an elevation in compression pressure from 6000 to 11000 kilopascals. Additionally, variations in density among different treatments were within a 1 percent range. The lowest pallet density is associated with the treatment involving 20 percent moisture, 1-millimeter particle size, 8-millimeter mold diameter, and 6000 kilopascals compression pressure. Similar observations in related reports underscore the pivotal role of moisture as a significant factor in the palletization process. Within its optimal range, moisture acts as a binder, influencing intermolecular forces and particle adhesion, thereby affecting the density of the produced pallets (Zafari & Kianmehr, 2014).

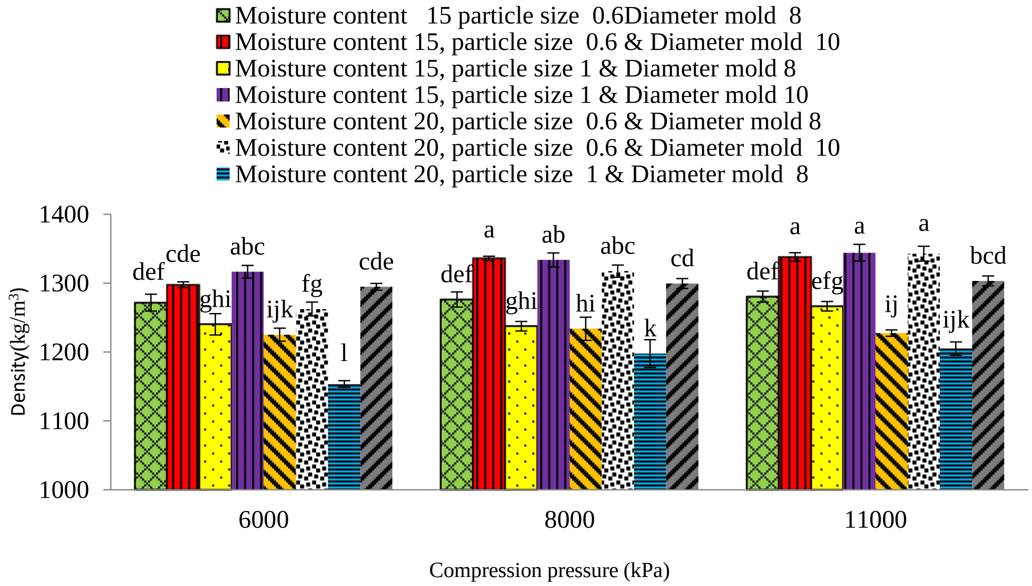

Fig 10. The effects of moisture, particle size, mold diameter and compression pressure on the density of livestock feed pallets derived from pistachio residues

Analyzing the initial results obtained, the first part of the force-displacement curve for the produced pallets from pistachio green hulls is similar to other biological materials, displaying a linear behavior in most cases. Furthermore, the force-displacement diagram for the fracture of the produced pallets (Fig 11) indicates that the force required for pallet fracture increases with greater displacement. This behavior aligns with other biological materials subjected to quasi-static loading.

To determine the mechanical properties of pallets produced from pistachio green hull, various mechanical tests such as fracture, bending, and compression tests should be employed. These tests can provide valuable information about the mechanical properties of pallets and be useful in enhancing the quality and strength of pallets produced from pistachio green hull.

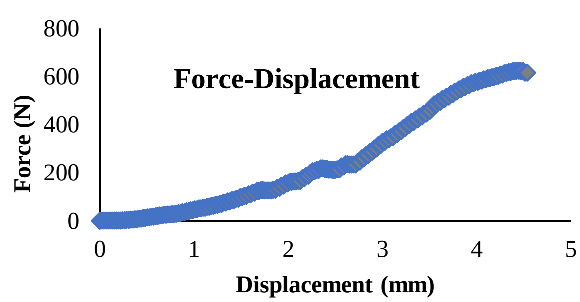

Fig 11. Force-displacement diagram for the fracture of the produced pallets

Comparative results (Fig 12a) indicate that particle size and mold diameter collectively influence the energy required for the fracture of pallets produced from pistachio green hull. The highest fracture energy is observed in the treatment with 1-millimeter particle size and 8-millimeter mold diameter. This result suggests that using smaller particle size (1 millimeter) and a smaller mold diameter (8 millimeters) can lead to the production of pallets with higher resistance to fracture.

On the contrary, the minimum fracture energy is observed in the treatment involving 1-millimeter particle size and a 10-millimeter mold diameter. This finding implies that the utilization of a larger mold diameter (10 millimeters) may result in the production of pallets with lower fracture resistance. Consequently, meticulous attention to particle size and mold diameter is essential for the production of high-resistance pallets, necessitating the determination of optimal conditions for enhanced fracture resistance.

The comparative outcomes (Fig 12b) underscore the combined influence of moisture and mold diameter on the fracture energy of pallets manufactured from pistachio green hull. The highest fracture energy is discerned in the treatment with 20% moisture and an 8-millimeter mold diameter. This observation highlights that elevated moisture levels can contribute to the creation of pallets exhibiting heightened resistance to fracture. Furthermore, as the mold diameter diminishes, magnetic force intensifies due to the reduction in interparticle empty spaces, consequently augmenting the fracture energy of the produced pallets. This outcome aligns with analogous studies exploring the mechanical properties of moisture-rich materials. Notably, research has demonstrated that an increased moisture content enhances the strength of pallets derived from sawdust and straw (Stasiak et al., 2017). Additionally, in another study, it was established that heightened moisture content augments the durability of wheat straw briquettes (Smith et al., 1977).

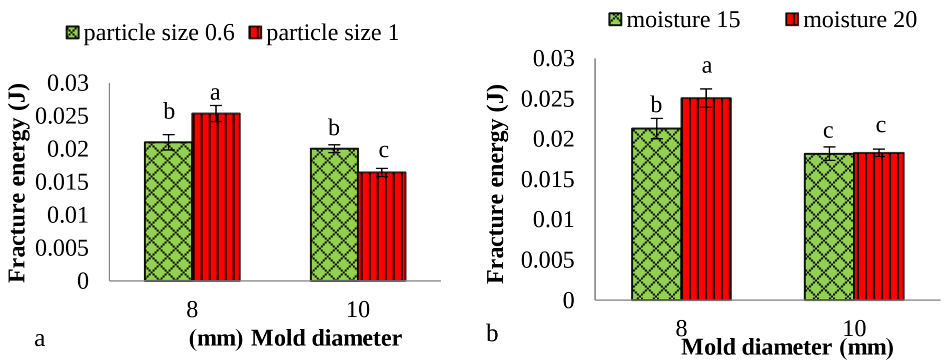

Fig 12. The fracture energy of livestock feed pallets derived from pistachio residues. a) The effects of mold diameter and particle size. b) The effects of mold diameter and moisture

Results from the average comparisons (Fig 13) indicate that particle size, mold diameter, and compression pressure collectively influence the fracture energy of pallets produced from pistachio green hull. The highest fracture energy is observed in the treatment involving 1-millimeter particle size, an 8-millimeter mold diameter, and a compression pressure of 8000 kilopascals. This outcome suggests that the use of larger particle size, smaller mold diameter, and higher compression pressure can lead to the production of pallets with greater fracture resistance. Reduction in mold diameter enhances interparticle bonds, leaving smaller interparticle voids that may enhance particle bonds and increase the fracture energy of the pallets. With increased compression pressure, interparticle bonds strengthen, but the breaking of particles leaves almost no voids between the particles, potentially leading to reduced pallet strength.

On the other hand, the minimum fracture energy is observed in the treatment involving 1-

millimeter particle size, a 10-millimeter mold diameter, and a compression pressure of 6000 kilopascals. This result indicates that the use of larger particle size, larger mold diameter, and lower compression pressure can lead to the production of pallets with lower fracture resistance.

Based on the study results, it was observed that particle sizes larger than 1 millimeter have susceptible crack points in the pallet. While finer particles produce more durable pallets, excessive grinding of particles is economically impractical due to high milling energy consumption. Optimal particle sizes typically offer higher moisture absorption capability and better compaction compared to coarser particles. Moreover, coarser particles side by side create grooves that contribute to the formation of cracks and gaps in the pallets, indicating lower pallet strength (Kaliyan & Morey, 2009).

In light of the previous studies and the present investigation, it can be concluded that increasing particle size can enhance the fracture resistance of pallets produced from pistachio green husk. Additionally, by reducing mold diameter and increasing compression pressure, stronger bonds are formed between particles, contributing to increased fracture resistance of the pallets. Nevertheless, careful attention must be paid to the optimal conditions for producing pallets with greater fracture resistance, considering the constraints related to particle size, mold diameter, and compression pressure in the pallet production process.

Therefore, to improve the quality of pallets produced from pistachio green husk, particle size, mold diameter, and compression pressure should be simultaneously considered, and the best combination of these variables should be selected for the production of pallets with high strength and fracture energy.

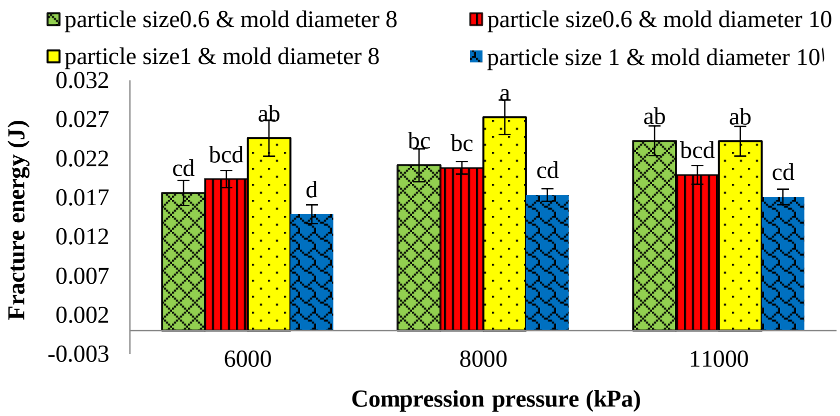

Fig 13. Effect of particle size, mold diameter and compaction pressure on the fracture energy of animal feed pellets obtained from pistachio waste

Results from the average comparisons (Fig 14) indicate that moisture, particle size, and mold diameter collectively influence the fracture energy of pallets produced from pistachio green husk. The highest fracture energy is observed in the treatment involving 20% moisture simultaneously with 1-millimeter particle size and an 8-millimeter mold diameter. This outcome suggests that high moisture, smaller particle size, and smaller mold diameter can lead to the production of pallets with greater fracture resistance.

On the other hand, the minimum fracture energy of pallets is observed in the treatment involving 15% moisture, 0.6-millimeter particle size, and a 10-millimeter mold diameter. This result indicates that lower moisture, larger particle size, and larger mold diameter can lead to the production of pallets with lower fracture resistance. However, considering that the treatment with the highest fracture energy had simultaneously high moisture, smaller particle size, and smaller mold diameter, it can be inferred that a combination of these three factors can have a significant impact on the fracture resistance of the produced pallets.

Taking into account the results of previous studies and the current investigation, it can be concluded that an increase in moisture can improve the fracture resistance of pallets produced from pistachio green husk. Additionally, by reducing particle size and mold diameter, stronger bonds between particles are formed, which can lead to increased fracture resistance of the pallets. Therefore, for the production of pallets with high resistance, optimal selection of moisture, particle size, and mold diameter is essential, and optimal conditions should be determined for the production of pallets with greater resistance to fracture.

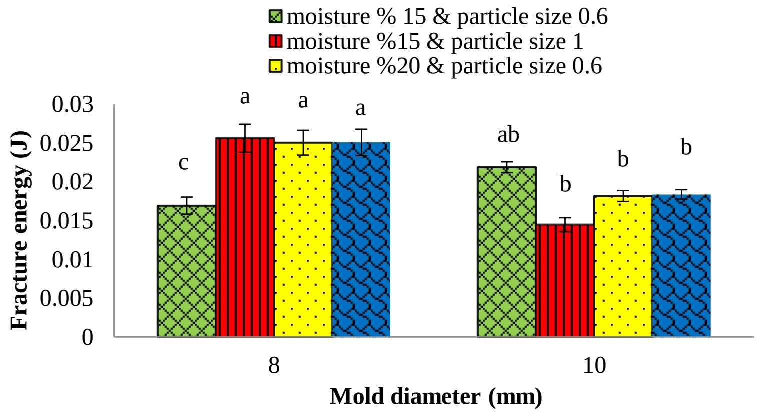

Fig 14. The effects of moisture, particle size, and mold diameter on the fracture energy of livestock feed pallets derived from pistachio residues

Toughness of the produced pallets was investigated concerning mold diameter and compression pressure (Fig 15a). The average comparison results indicated that the highest level of hardness was observed in treatments with an 8-millimeter mold diameter and 11,000-kilopascal compression pressure, exhibiting significant differences compared to other treatments at a 5% probability level. This phenomenon may be attributed to the increased particle connection and reduced inter-particle voids with a decreased mold diameter and increased compression pressure. In other words, the gravitational force between particles intensifies, resulting in enhanced hardness of the produced pallets. Conversely, the minimum toughness was observed in the treatment involving a 10-millimeter mold diameter and 6,000-kilopascal compression pressure. This outcome suggests that, with an increased mold diameter and reduced compression pressure, particle connections decrease, and inter-particle voids increase, leading to decreased toughness of the produced pallets.

This research demonstrated that mold diameter and compression pressure are two crucial factors influencing the quality of produced pallets, and an appropriate combination of these factors can contribute to the improvement of pallet quality.

The influence of moisture and mold diameter on the toughness of pallets produced from the residues of pistachio green hull was also investigated (Fig 15b). The average comparison results showed that the highest toughness level was observed in treatments with 20% moisture and an 8-millimeter mold diameter, exhibiting the most significant difference at a 1% probability level. Furthermore, the lowest toughness level was observed in the treatment involving 20% moisture and a 10-millimeter mold diameter. With increased material moisture, adhesive substances in the material become more active, leading to stronger particle connections. Additionally, reduced mold diameter enhances particle connections, resulting in increased toughness of the produced pallets.

In conclusion, both moisture and mold diameter appear to significantly impact the toughness of pallets produced from pistachio green hull, and this study can be valuable for enhancing the quality and performance of pallets produced from pistachio green hull residues.

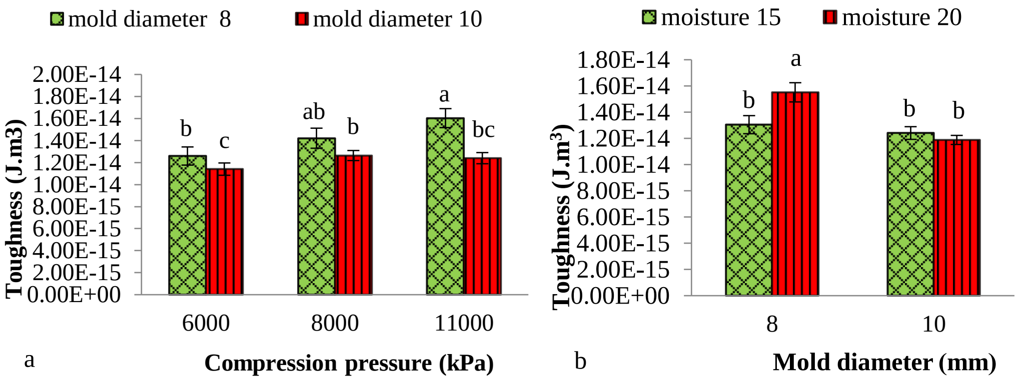

Fig 15. The toughness of livestock feed pallets derived from pistachio residues. a) The effects of mold diameter and compression pressure. b) The effects of mold diameter and moisture

The influence of three factors, namely moisture, particle size, and mold diameter, on the toughness of pallets produced from pistachio green hull was investigated (Fig 16). The average comparison results demonstrated that the highest toughness level was observed in treatments with 20% moisture, 0.6 mm particle size, and an 8 mm mold diameter, exhibiting the most significant difference at a 1% probability level. Additionally, the lowest toughness level was related to the treatment with 15% moisture, 1 mm particle size, and a 10 mm mold diameter.

The impact of all three factors, moisture, particle size, and mold diameter, is interrelated. With increased moisture, reduced particle size, and mold diameter, the gravitational force between material particles becomes stronger, leading to more robust particle connections and, consequently, increased toughness of the produced pallets. In general, it seems that the influence of all three factors, moisture, particle size, and mold diameter, on the toughness of pallets produced from pistachio green husk residues is significant.

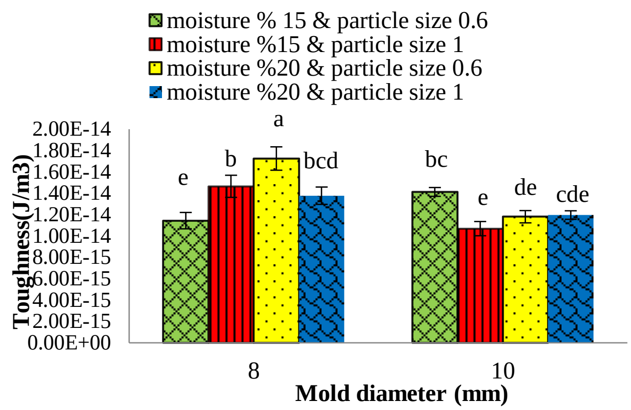

Fig 16. The effects of moisture, particle size, and mold diameter on the toughness of livestock feed pallets derived from pistachio residues

CONCLUSION

Based on the results of the conducted studies, it is evident that moisture, particle size, mold diameter, and compression pressure significantly affect the density, fracture energy, and toughness of pallets produced from pistachio green hull residues. Therefore, optimizing these factors, which play a crucial role in the properties of pallets, is essential for the production of high-quality pallets and increasing efficiency. The use of palletizing methods can be a suitable and sustainable solution for producing livestock feed from pistachio green hull residues, contributing to increased productivity, cost reduction, and environmental conservation.

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