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ORIGINAL ARTICLE

The Effects of Moisture Content, Temperature, and Compaction Pressure on the Compressibility of Animal Feed Pellets Produced From Green Pistachio Shell Residues

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A R T I C L E I N F O

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A B S T R A C T

Pelleting is a promising, cost-effective method to optimize the use of garden wastes as animal feed production. Shortage of animal feed and increasing costs are the main reasons to produce feed from garden wastes like green pistachio shell residues. In this study, green pistachio shell residues were gathered and stored in the open air to reduce moisture content, then the dried residues were hammered and sieved to make pellets using a hydraulic pellet maker machine. A factorial experiment with three factors was performed at temperatures of 50 and 65℃, moisture content levels of 15 and 20%, and compaction pressure with a single hydraulic pellet machine at 6000, 8000, and 11000 kPa using a 10 mm mold to investigate the possibility of pelleting green pistachio shell residues. Toughness and fracture energy are the important parameters for optimal pellet-making conditions. The produced pellets were investigated in terms of density, fracture energy, and toughness. The results showed that the effect of compaction pressure on the attributes was significant at the 1% level. The highest values of these attributes were obtained at the highest pressure of 11000 kPa. It was observed that the interaction effect of moisture and temperature on pellet density was the most significant level (1308.13 kg m^{-3}) at temperatures of 65 ℃ and 15% moisture content. Also, the highest fracture energy and toughness (0.0228 J and 1.44×10^{-14} J m^{-3}) were observed at temperatures of 50°C and 20% moisture content. Therefore, pellets made of green pistachio shell residues have sufficient density, fracture energy, and toughness, which makes pelleting a viable option for reducing transportation volume and costs in animal feed production.

Introduction

Fungi germination and growth can damage pistachios and other dried fruits. *Aspergillus flavus* germinates on pistachio or other dried fruit and produces aflatoxin under optimal growth conditions. Aflatoxin is poisonous and carcinogenic if exceeding certain concentrations (Fallah Tafti, 1999). Pistachio has a

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major potential source for the growth and germination of this fungi since it mainly grows on pistachio green shells abundantly found in pistachio farms. This is while the desert nature of the region, the lack of animal feed, and the increasing cost of animal feed evidently indicate the necessity to produce feed from garden waste (Aleyki, 2000). The World Food Organization statistics have indicated that the agricultural product waste in Iran could feed 15 million people per year, which is 25 times that of developed countries, ranking Iran as the top country in the waste of garden products (FAO, 2014). The recent studies on the changes in the extension of pistachio farms show the growing trend of this product. Iran is a major producer of pistachio, with a total area of 460,000 hectares of cultivated land (Laei, 2021). Every year, a large portion of agricultural and garden products are wasted in different stages. Many countries take proper planning and management measures to optimally benefit from such waste. Evidence indicates that Iran generates about 400,000 tons of pistachio waste per year (Shakeri *et al*., 2004). Due to the mass production of pistachio and its production in a short period (2–3 months), currently, there is no suitable use for this waste (Foroogh Ameri, 1997). The pistachio waste is usually burned and buried by farmers (Salihoglu *et al*., 2018). A large portion of the pistachio waste consists of peeling residues, which can be used optimally by planning and acquiring relevant technology (Golmohammadi, 2012). Agricultural and garden wastes can be managed without harming the environment by converting them into high-added-value products, such as animal food and fertilizer (Ahmed *et al*., 2002). These measures can improve the economic situation of farmers and help deal with environmental concerns (Rouissi *et al*., 2013). It is difficult to use these wastes in their natural form due to their bulkiness, wetness, non-uniform size and shape of particles and their dispersion, and it causes many problems in transportation, storage, and transfer of these materials in unprocessed form (Ghasem and Chayjan, 2019). The pelleting process is a mechanical action to compress small particles into a limited volume with pressure, heat, and humidity (Falk, 1985). Pelleting is one of the common methods in animal husbandry that aims to reduce the volume of bulk materials with low density to facilitate transportation, storage, and adding nutrients. Pelleting is a process in which the milled product is forced to pass through many holes (with or without steam) and become compressed pills. The most important difference between the storage of the pelleted product and the unprocessed raw materials is its low humidity content, which limits the growth of microorganisms. If the pelleted product is used to feed animals, it can be enriched with a uniform and certain ratio of nutritional supplements (Tumuluru, 2020). Sahoo *et al*., (2021) investigated the use of garden and vegetable waste as a source of sustainable and environmentally friendly animal feed to determine the nutritional quality of fresh fruit and vegetable waste and include them in the diet of sheep. The results indicate that fruit and vegetable waste can potentially feed ruminants. Siddiqu *et al*. (2021) investigated the pelletizing process of recycling food waste to produce bird feed and liquid fertilizer products. The obtained extract from the pelleting process was found to have high concentrations of nutrients, making it a safe replacement in hydroponic systems. Tabatabaei Kolor *et al*. (2020) investigated the effect of bran-to-molasses ratio, temperature, and compaction pressure on pellet resistance, density, and strength. The results showed that the highest axial and radial compressive strength was achieved in the bran-to-molasses ratio of 1.50 to 1 and compression force of 1300 N. The pellet resistance increased as the temperature increased from 50 to 70 ℃. Increasing the temperature and compaction pressure increased the density and stability of the pellets. Zainuddin *et al*. (2014) investigated the effect of moisture in four moisture content levels (35%, 40%, 45%, and 50%) on the volume density, pellet density, brittleness, and porosity of pellets. They used pineapple recycling waste to produce animal feed. They found that moisture content in the range of 35%–50% had no significant effect on the physical properties of the pellet except its actual density. The compressibility and durability of pellets produced under pressure depend on factors such as the chemical structure and material dimensions, transformation temperature, initial volumetric weight, moisture percentage, loading speed, pressure, and process duration (Amiri *et al*., 2012). These properties can be vital in optimizing the pelleting process, recognizing the pressing mechanism, designing pressing equipment with sufficient energy, and determining the effect of different variables on the density and durability of pellets. Filbakk *et al*., (2010) investigated the effect of the moisture content of Pine bark on the quality parameters of pellets produced from its wood and bark. The results showed that the pellets produced (larger size particles) were less durable than those produced from pure pine tree bark (smaller size particles). It was observed that the cost of livestock feed increased with increasing demand for livestock inputs despite Iran's consecutive droughts, causing production decline and financial crisis in some animal husbandry units. Pelleting pistachio shell residues is a potential solution to overcome such problems and convert waste into animal feed pellets with increased density and energy per unit volume, fracture energy, and toughness.

Many researchers have already studied waste pelletization but as the behavior of each material for compression (pelleting) is different, the result of other materials, such as sawdust or rice straw, are not applicable for green pistachio shell residues. This is because some parameters like moisture content, dimensions, and rheological behaviors of the product have to be considered for compression to have a final product with relevant conditions. Also, the required force for rejection of pellet from the mold, changes of dimensions and strength of the pellets are different for different materials. The main goal of this research is to study the behavior of green pistachio shell residues during and after pelleting.

Materials and Methods

Preparation and production of green pistachio shell residues

The green pistachio shell residues were gathered from the pistachio processing terminals of Damghan city, Semnan province, Iran (Fig. 1). The collected materials were kept in the open air for one month to reduce their initial moisture content. They were then transferred to the laboratory of the Agricultural Technical Department of the College of Agricultural Technology (Abouraihan), University of Tehran.

Fig. 1. Green pistachio shell residue.

In the next step, the prepared green pistachio shells were processed by a laboratory hammer mill (KG 531, Iran) to reach a geometric mean particle length of 1 mm. (Fig. 2). The sieves were stacked on top of each other, with the size of the pores from large to small.

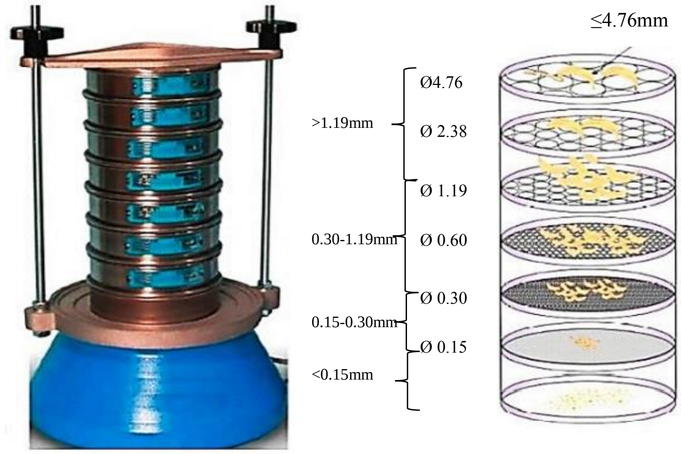

Fig. 2. The electric sieve shaker used to determine the geometric mean length of particles.

In this method, 100 grams of green pistachio shells were poured into the top sieve. The sieves were shaken for 30 seconds, and the amount of green pistachio shell on each sieve was measured using a digital scale (Germany Lutron GM-300P) with a precision of 0.01 gr. The geometric mean of particle length was calculated according to equation 1 (ASAE S319.3; 2006).

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

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).

Physical compounds

The prepared green pistachio shells comprised 62% green shell, 26% cluster, 11% leaf, and 1% kernel and wood shell.

Additives

To improve the quality and increase the nutritional value of green pistachio shells, 3% bentonite, 6% pure wheat, 4% urea, and 5% molasses, (all based on the dry matter) were used as additives to the wastes. These additives act as a binder to bind the material particles more tightly in the produced pellets.

Determining the moisture content of raw materials

The AACC, 1999 standard was used to determine the initial moisture content. For this purpose, 50 gr of the primary green pistachio shell sample was placed inside the oven at 103°C for 24 hours. Then the sample was taken out from the oven, and its mass was measured using a digital scale (Germany Lutron GM-300P) with a precision of 0.01 gr. The initial moisture content was determined to be 8%. The moisture content was calculated based on equation (2) on a wet basis.

$$MC(\%) = \frac{m_i - m_f}{m_i} \times 100 \qquad (2)$$

where MC is the percentage of moisture content on a wet basis, m_i is the initial mass of the material in gr, and m_f is the final mass of the material in gr.

Next, the initial moisture content of the samples was determined, and the raw materials were classified into 15% and 20% moisture levels (wet basis). In this regard, distilled water was added to green pistachio shell residue using a water sprinkler according to equation (3) to obtain moisture levels. After adding distilled water, the samples were stored for 48 hours at a temperature of 4 in plastic bags in the refrigerator to distribute uniform moisture content in all samples.

$$m_w = \frac{m_i(M_{wf} - M_{wi})}{1 - M_{wf}} \quad (3)$$

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

In order to determine the bulk density of milled green pistachio shells, the container was filled with the desired materials. The additional materials were removed using a ruler with a zigzag movement on the opening of the container without any compression on the material inside the container. Next, the volume of the container was determined based on its dimensions, and the mass of the material inside the container was also measured using a digital scale model (Germany Lutron GM-300P) with a precision of 0.01 gr. The bulk density value for the green pistachio shell (449 kg m^{-3}) was calculated using equation (4).

$$p = \frac{m}{v} \quad (4)$$

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.

Mold design

A closed mold (10 mm thick, 50 mm long) (Fig. 3) was designed and manufactured to prepare animal feed pellets (ASABE, 2007). A thermal belt was used to apply two temperature levels of 50 and 65℃ using an automated heating system connected to the thermocouple k to heat the material inside the mold.

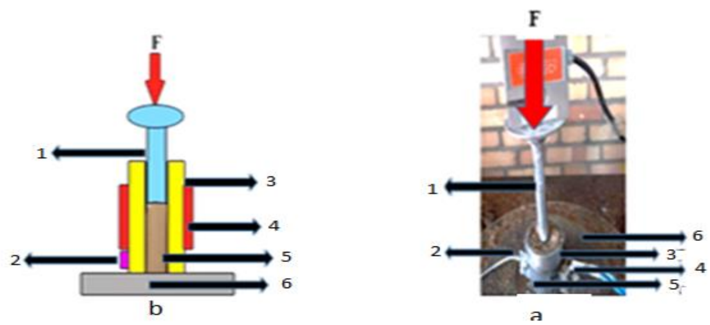

Fig. 3. Mold: the a) real idea of the mold diameter, b) schematic and. 1) piston, 2) thermocouple, 3) compression mold wall, 4) thermal belt, 5) material bulk location, 6) mold bottom blocker

Preparation of pellets using a hydraulic pellet maker machine

The components of the hydraulic pellet maker machine are displayed in Fig. 4. This machine has a fixed jaw (mold placement location) and a movable jaw (hydraulic cylinder). The hydraulic pump of the device provides the speed and pressure required for moving the movable jaw. The force was applied to the compression mold by the movable jaw on the piston, and the load cell's force was measured and recorded in the data reader. Also, the device can adjust the incoming compaction pressure. Therefore, compaction pressure at three levels of 6000, 8000, and 11000 kPa for 10 seconds was applied to the pellet samples for the compression process with this device.

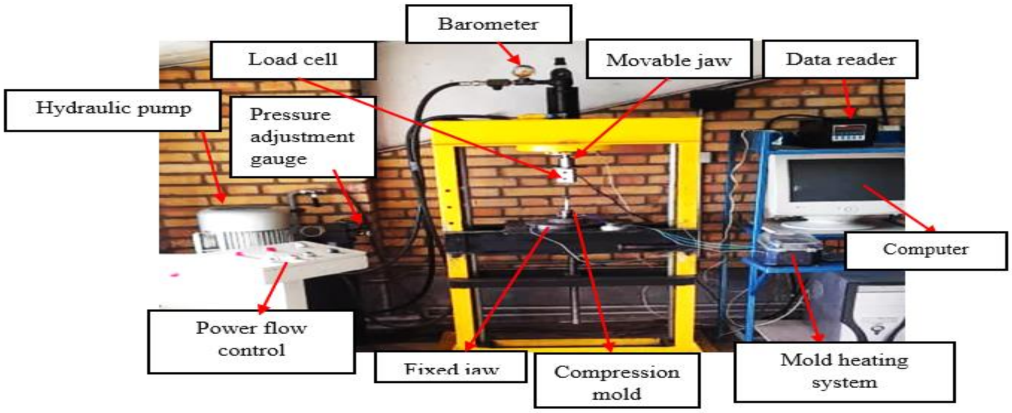

Fig. 4. Hydraulic pellet maker machine.

Determining the pellet density

The lengths (L) and diameters (D) of the pellets were measured to determine the pellet density, using a digital caliper (CD-6CSX, Mitutoyo Corp, Kawasaki, Japan). Likewise, each pellet sample's weight (m_p) was measured using a digital scale (Germany, Lutron GM-300P) with a precision of 0.01 gr. Volume (v_p) and pellet density (p_p) of the pellets were also calculated using equations (5) and (6).

$$v_p = \frac{\pi}{4} d^2 l \qquad (5)$$

$$p_p = \frac{m_p}{v_p} \qquad (6)$$

The fracture energy and force of the pellets

Research on loading tests of biological materials suggests using a device that can create a constant loading speed for the tests. For this purpose, the mechanical testing device for biological materials (Fig. 5) made by Ghaebi (2009) was used in the Agricultural

Technical Department, College of Abouraihan, University of Tehran. This device can measure the compressive and tensile mechanical properties of biological products under different loading speeds. A biological material testing machine was used to measure the pellets' fracture energy and fracture force. The pellet was placed on the fixed jaw of the machine on the horizontal axis. The movable jaw, connected to the load cell, was moved downward at a speed of 25 mm min^{-1} (Homayoonfar *et al*., 2016). The force was applied to the cylindrical surface of the pellet until a crack or break occurred, which can be seen in the force-displacement diagram as a falling point.

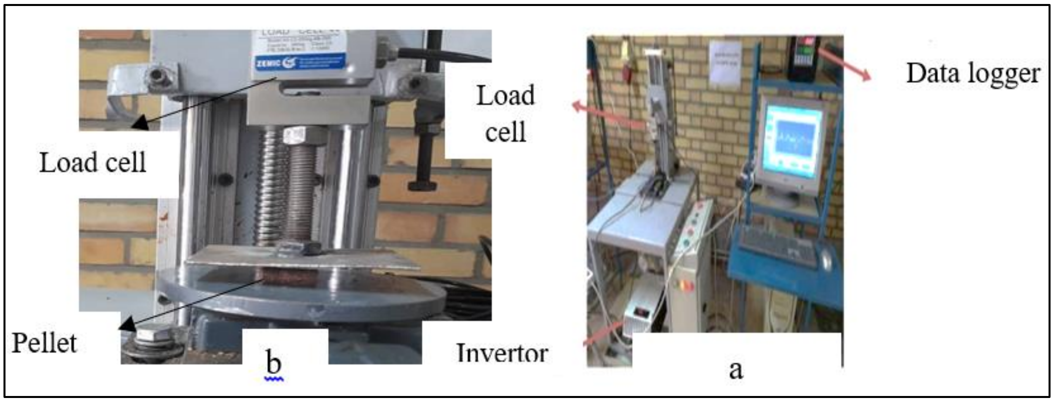

Fig. 5. a) Mechanical testing device for biological materials; b) how to apply force to the pell*et al*ong the horizontal axis.

Pellet Fracture energy and toughness

The biological surrender point is a peak on the force-deformation curve where the force decreases momentarily and then increases. This point expresses a break (rupture) in the material. Also, the consumed energy for the fracture of the pellets was obtained by calculating the area under the force-deformation curve (Ghorbani, 2021).

Toughness is the amount of work applied to the object's volume to break. The area under the curve represents the work done to break the samples. The apparent toughness of the produced pellet was obtained by Equation (7) according to the estimated pellet volume.

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

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

Statistical analysis

A test with a completely randomized design including three factors of moisture content (15 and 20%), temperature (50 and 65°C), and compaction pressure (6000, 8000, and 11000 kPa) was performed with three replications to measure the density, fracture energy, and toughness of the produced pellets. The variance analysis and mean comparison were performed by Duncan's multi-range test at a 5% probability level using SAS 9.3. The graphs were drawn in Excel software.

Results

No research was found in the literature about pelleting green pistachio shell residues. In this research first, pre-tests were performed to better understand the wastes (Fig. 6) considering several pelleting parameters, including moisture, temperature, and compression pressure. The results showed that if the value of each mentioned variable is out of a certain range the material cannot be pelleted or the pellet created has low density, fracture energy, and toughness. Hence, the tests were continued to achieve the best results regarding the study parameters.

a b c

Fig. 6. a and b) the produced pellet from the preliminary tests, c) the produced pellet from the results of the preliminary tests on the green pistachio shell.

The maximum density of the produced pellets was 1308.13 kg m^{-3} at 15% moisture content, 65°C temperature, and 11000 kPa pressures, while the minimum density was 1253 kg m^{-3} at 20% moisture content, 65°C temperature, and 6000 kPa pressure. The highest fracture energy observed was 0.022895 J at 20% moisture content, 50°C temperature and 11000 kPa compression pressure, and the lowest fracture energy was 0.01818 J at 15% moisture content, 50 temperature, and 6000 kPa pressure. Also, the highest toughness of the produced pellet was 1.44 $\times 10^{-14}$ J m^{-3} at 20% moisture content, 50°C temperature, and 11000 kPa pressure. Also, the lowest toughness (1.17 × 10^{-14} J m^{-3}) was observed at 15% moisture content, 50 temperature, and 6000 kPa pressure.

Table 1 presents the results regarding the effect of moisture content, temperature, and pressure on the selected parameters. The independent effects of moisture content, temperature, and pressure and the interaction effect of moisture × temperature on the density of the produced pellets were significant at 1%. However, the interaction effects of moisture × pressure, temperature × pressure, and moisture × temperature × pressure on the density of the produced pellets were not significant. Regarding the fracture energy of the produced pellet, the results indicate that the independent effects of moisture content and pressure and the interaction effect of moisture × temperature were significant at 1%. This is while the independent effects of temperature and the interaction effects of moisture × pressure, temperature × pressure and moisture × temperature × pressure on the fracture energy value of the produced pellet were not significant. Finally, regarding the toughness of the produced pellets, the results showed that the independent effect of moisture at 5% and compaction pressure at 1% and the interaction effect of moisture × temperature were significant at 1% level. Nonetheless, the independent effect of temperature and the interaction effects of moisture × pressure, temperature × pressure and moisture × temperature × pressure on the toughness value of the produced pellets were not significant. Agricultural products have raw materials with specific properties and behavior. The factors influencing the quality of the produced pellets are depended on the density, fracture energy, and toughness of the pellets, which are affected by the variables and additives. During the compression process, the mentioned effects caused elastic and plastic deformation of the material particles, thus influencing the quality of the produced pellets in terms of density, fracture energy, and toughness.

Table 1. Variance analysis of the effect of moisture content, temperature, and compaction pressure on the density, fracture energy, and toughness of animal feed pellets obtained from green pistachio shell waste.

Sources of variation	Degrees of freedom	Mean of square		
		Density	Fracture energy	Toughness
Moisture content	1	56584.5156**	0.00013629**	$3.396243\times10^{-29*}$
Temperature	1	8579.3906**	0.0000419ns	3.737323×10^{-30ns}
Pressure	2	11826.9844**	0.00009238**	$6.060231\times10^{-29**}$
Moisture × Pressure	2	601.7031ns	0.00003524ns	5.101918×10^{-30ns}
Temperature × Pressure	2	127.5469ns	0.00001006ns	9.074544×10^{-30ns}
Temperature × Moisture	1	4339.5156**	0.0002726**	$1.185392\times10^{-28**}$
Moisture × Temperature × Pressure	2	182.0781ns	0.0000172ns	2.274201×10^{-32ns}
Error	24	306.2344	0.00001607	5.91×10^{-30}

ns, * and ** are non-significant, significant at 5% and 1% levels, respectively.

Table 2 shows that with the increase of compaction pressure from 6000 to 11000 kPa, the density value, the fracture energy, and the toughness of the produced pellets increased since the independent effect of low compaction pressure provides only close and regular arrangement of particles next to each other. With the increase in compaction pressure, elastic and plastic deformation occurs at higher pressure, causing particles to flow into the empty space, increasing the contact surface between particles (Tumuluru *et al*., 2011), reducing the pores between particles and increasing the density, fracture energy, and toughness of the pellets. The results also showed that the pellets produced had the highest density when the independent influence of moisture content decreased from 20% to 15%, but the fracture energy and toughness of the pellets decreased. However, moisture acts as a thin layer of adhesive that strengthens the bonds between particles. Moisture helps to increase the adhesion of the particles of these materials through van der Waals forces by increasing the contact surface of the particles. This factor helps to increase the density, fracture energy, and toughness of the pellets produced. The results showed that the produced pellet had the highest density when the temperature increased from 50 to 65°C. However, the temperature alone was not effective for the fracture energy and toughness of the produced pellet. In general, it can be concluded that with increasing temperature, pelletization usually activates the natural adhesives inside the materials or the additive adhesives. An increase in temperature also increased the plastic deformation of the material particles. Plastic modification of the particles is very important to achieve permanent bonds. In this study, plastic modification significantly affected the level of pellet density but did not independently affect the fracture energy and toughness. This could be due to the lack of moisture and lack of relevant heat transfer between the particles so that the natural adhesives inside the materials or the additive adhesives of the materials are fully activated. When the moisture content of the raw materials is within the desired range, it generally acts as a bonding agent and heat transfer aid, helping soften the particles to heat and causing the particles to bond in the produced pellet (Larsson *et al*., 2008).

Table 2. Mean comparison of the effect of Moisture content, temperature, 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($J.m^{-3}$)	
Compaction pressure (kPa)						
	Mean ± standard error	Grouping	Mean ± standard error	Grouping	Mean ± standard error	Grouping
6000	1257.8±7.73	c	0.0191±0.0009	b	$1.20\times10^{-14}\pm5.01\text{x}10^{-16}$	b
8000	1279±8	b	0.0216±0.001	a	$1.32\times10^{-14}\pm5.17\times10^{-16}$	a
11000	1288.5±7.8	a	0.0214±0.0009	a	$1.42\times10^{-14}\pm5.61\times10^{-16}$	a
Moisture content (%)						
15	1294.9±5.03	a	0.0197±0.0008	b	$1.27\times10^{-14}\pm4.20\times10^{-16}$	b
20	1255.3±7.05	b	0.0217±0.0007	a	$1.37\times10^{-14}\pm4.56\times10^{-16}$	a
Temperature (°C)						
50	1267.4±6.41	b	0.0205±0.0009	a	$1.31\times10^{-14}\pm4.83\times10^{-16}$	a
65	1282.8±6.58	a	0.0209±0.0007	a	$1.34\times10^{-14}\pm3.96\times10^{-16}$	a

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

Discussion

Interaction effect on the density of produced pellets from residues

Fig. 7 demonstrates the interaction effect of moisture and temperature on the pellet density produced from green pistachio shell residues. The results showed that the pellet density increased with the increase in temperature and decrease in moisture, while the lowest density of the produced pellets was observed when the temperature increased and the moisture decreased because of the activation of the natural adhesives inside the materials or the added adhesives. In addition, an increase in temperature increased the plastic deformation of the material particles and decreased the empty spaces between-particle. Therefore, softer and stickier materials increase the density of the pellet. Although the moisture and temperature are ideal for the green pistachio shell, they also cause particles to be slippery and lead these materials to slide easily into the hole of the mold, thus compromising the quality of the pellets produced. The materials with lower moisture and temperature, block the mold; any further increase in the moisture beyond the desired range will reduce the forces between the particles, by creating a two-phase mixture (liquid and solid phase). This causes the forces between the particles to be disappeared and the pellet swells and collapses (Zafari and Kianmehr, 2014). Jiang *et al.*, (2016) concluded that increasing the pellet's temperature decreases the particles' modulus of elasticity and increases the flexibility of the pellet's constituent materials. This reduces the empty spaces between the particles and increases pellet density.

Similarly, Zafari and Kianmehr (2014) described moisture as an important factor in the pelleting process, explaining that it acts as a binder in its optimal range. They argued that the attractive intermolecular forces affect the adhesion between the particles of the produced pellets. Fasina (2008) studied the physical properties of pellets produced from peanut skin. They found that with the increase in moisture from 4 to 21%, the mass density of produced pellets from peanut skin decreased from 640 to 600 kg m^{-3}. Their findings are consistent with the results of this research. Rezaeifar *et al*., (2008) studied the physical properties of pelleted cow manure and reported that the density of the pellets increased linearly from 1095 to 1583 kg m^{-3} when the moisture content increased from 6% to 20%. McMullen *et al*., (2005) studied the effects of the physical parameters of chicken manure pellets and found that the density of chicken manure pellets increased from 1390 to 1570 kg m^{-3} when the moisture content increased from 6% to 22%. These results are against the results of this research. This indicates that the behavior of different materials is different in response to the effective variables in the quality of the pellets, therefore, further studies are needed for green pistachio shells.

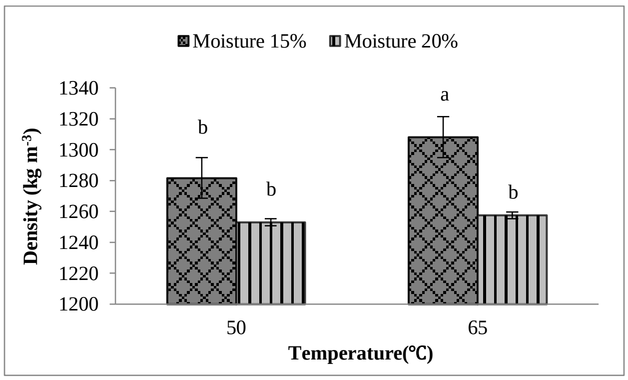

Fig. 7. The effect of moisture content and different temperatures on the density of animal feed pellets created from pistachio residue waste.

Interaction effect on fracture energy and toughness of pellets produced from green pistachio shell residues

In determining the behavior of the pellet produced from green pistachio shells under quasi-static loading, the maximum fracture force of the pellet was measured, and preliminary results indicated that the first part of the force-displacement curve of the pellet is similar to other biological materials and can often be considered a linear range in the initial part and around the turning point. The fracture force-displacement diagram of the produced pellet is shown in Fig. 8.

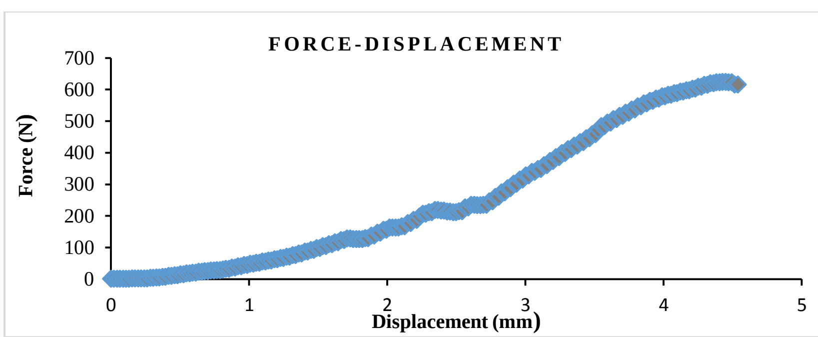

Fig. 8. The force-displacement diagram for the fracture of the produced pellets.

Fig. 9 shows the interaction effect of moisture × temperature on the amount of fracture energy of the pellets produced. The results showed that the fracture energy increased with the increase in moisture content from 15% to 20% and the simultaneous decrease in temperature from 65 to 50°C. Additionally, fracture energy increased with the decrease in moisture content from 20% to 15% and the simultaneous increase in temperature from 50 to 65°C. This is while the lowest fracture energy of the produced pellet was observed at 50°C temperature and 15% moisture content. It can be concluded that a decrease in moisture content and an increase in temperature strengthen between-particle flexibility and adhesion, causing a decrease in the pores between the material particles, creating a strong bond between the particles of the material and a better connection between the particles. Reducing the distance between the particles activates the van der Waals and electrostatic forces play a role in the particles' cohesion and improve the fracture energy of the pellets produced. Kaliyan and Money (2010) stated that the moisture content of biomass materials affects the glass transition temperature of materials during the pelleting process. They also found that at 10 to 15% w.b moisture content for corn stalks, the glass transition temperature decreased, and the bonds between particles were improved at temperatures below 70 to 90 °C. Increasing the moisture content of raw materials significantly decreased the glass transition temperature of lignin, starch, and gluten (Tumuluru *et al*., 2011). Ghorbani (2021) reported the effect of fracture energy for pre-processed livestock feed pellets made of wheat straw compared to samples without ozone pre-treatment from 0.0004 to 0.0007 J. Also, in another study by Amiri (2018), the interaction effect of die roller shaft rotation speed and compost size on the necessary energy required to break produced pellets from compost with particle sizes between 0.3 and 0.6 mm, at speeds of 100, 150, 200, and 250 rpm was reported 87.70, 43.98, 53.45, and 52.95 mj, respectively.

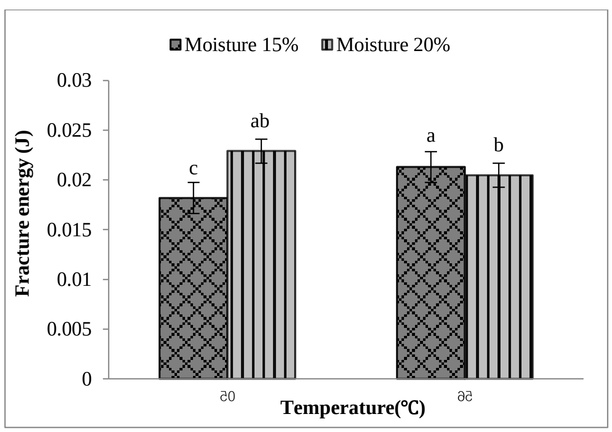

Fig. 9. The effect of moisture content and different temperatures on the fracture energy of animal feed pellets obtained from pistachio waste.

Fig. 10 shows the interaction effect of moisture content and temperature on the toughness of the pellets produced from green pistachio shells. It was observed that the pellet toughness increased by increasing the moisture content from 15% to 20% and the simultaneous decrease in temperature from 65 to 50°C. In addition, the toughness of the produced pellets increased with a decrease in moisture content from 20% to 15% and a simultaneous increase in temperature from 50 to 65°C. This is while the lowest toughness of the produced pellet was observed at 50°C temperature and 15% moisture content.

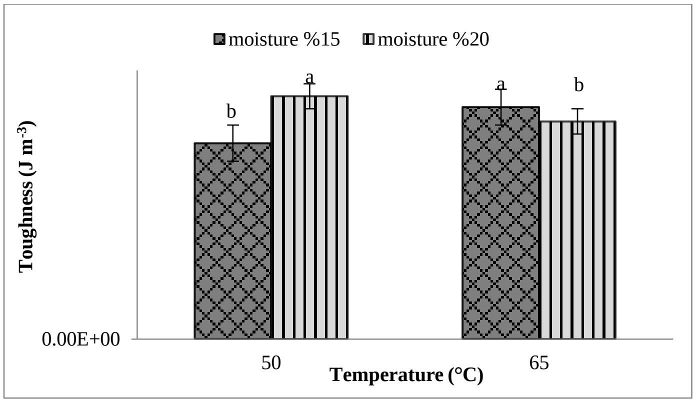

Fig. 10. The effect of moisture content and different temperatures on the toughness of animal feed pellets obtained from pistachio waste.

Increasing the temperature inside the pellet maker in combination with moisture helps soften the material and activate the inherent adhesives or added adhesives, causing more effective bonding and increasing the quality of the pellets (Rhen *et al*., 2005). Moisture and heat lead to many physical and chemical changes, such as thermal accumulation of biomass, protein solvent, gelatinization of starch, and solubilization and recrystallization of sugars and salts (Thomas *et al*., 1998). These physical-chemical changes affect the binding properties of biomass. The optimum biomass density may obtain in moisture content range from 8 to 20% (Kaliyan and Money, 2009). At high moisture content, a coherent pellet may not be produced because the cell structure with high moisture content remains at high moisture levels due to the lack of density of biomass particles (Pickard *et al*., 1961). Several studies on pellets produced from wood show that the durability of wood pellets increases with the increase in temperature until reaching the desired level. Water as moisture in biomass is one of the most useful factors as a binder (cohesive) and lubricant (Kaliyan and Money, 2010). Garcia-Maraver *et al*., (2015) investigated the effect of temperature on mechanical durability, compressive strength, and real and apparent density of pellets produced from different olive tree pruning residues (leaves, pruning, and cuttings). Temperature above 40°C was the best condition for making pellets of the remaining biomass from olive trees. Moisture content is a major property of wood's physical strength and hardness (Nielsen, 2009). Several studies show that the strength and durability of compacted products increase with increasing moisture content until it reaches the optimum value (Kaliyan and Money, 2009). These results are consistent with the results of this research.

Conclusions

The effect of compaction pressure is the most important parameter affecting many properties of the pellets, as this factor significantly affected many properties of the tested pellets. The increasing effect of compaction pressure on all physical and mechanical properties of the pellets was positive. In this study, the optimal compaction pressure for pellet production was 11000 kPa. The interaction effect of moisture and temperature showed that treatment with 15% moisture content at 65°C temperature had the best positive effect on pellet density, while 20% moisture content at 50°C temperature had the best positive effect on fracture energy and toughness. An optimal response was observed when the moisture content decreased and the temperature increased, or vice versa. When the moisture content and temperature increased or decreased simultaneously, the material particles and the density, fracture energy, and toughness properties of the produced pellets improved. From this point of view, compression and palletization can be suitable and economical solutions to remove green pistachio shells from the environment and gain added value. The production of pellets from these wastes increases pellet density, requires less storage space, facilitates transportation, reduces the cost of animal feed, prevents feed spoiling, increases its shelf life, eliminates fine particles and dust, reduces environmental risks, and improves nutritional value due to additives and compaction. The production of pellets from pistachio waste can be a suitable and economical solution to the problems associated with the green shell of pistachios, such as environmental pollution, low density and energy per unit volume, the need for more storage space with limited shelf life, and increased transportation costs.

It is suggested to further investigate the effects of the pellets produced from green pistachio shell residues at different levels of the parameters on the health and quality of ruminant products.

Conflict of interests

The authors declare that there is no conflict of interest.

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