QUALITY ASSESSMENT OF BIO-BRIQUETTES OBTAINED FROM NUT FRUIT SHELLS

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Biomass is crucial for Türkiye, which has a large agricultural area and produces 55-60 million tons of biomass waste from its agricultural land annually. In this study, an attempt was made to briquette nut fruit shells (walnut, almond and pistachio) using a prototype briquetting machine and the physical quality parameters of the obtained bio-briquettes were determined. The nut fruit shells were briquetted using a hydraulic piston briquetting machine driven by a PTO (power take-off) and comprising a shredder and grinding or crushing unit with a briquetting pressure range of 0-190 MPa, which was developed as a prototype. The shredding unit of the prototype machine consists of 40 hammers and 16 counter blades rotating at 2550 rpm, and the grinding unit consists of 24 hammers and 58 counter blades rotating at 2200 rpm. The physical and quality parameters of the bio-briquettes, such as density, tumbler and shatter resistance, compression resistance, water-intake capacity, and resistance to moisture- were determined. Overall, the results and factors influencing the subject of the study showed that biomass from nut fruit shells is an excellent feedstock for the production of bio-briquettes and that bio-briquettes produced with a prototype briquetting machine can be used as high-quality fuels.
Key words: Nut fruit shell, bio-briquette, biomass energy, waste

Excessively growing energy demands are the price that is paid for a more comfortable human life. Supplies of non-renewable energy sources (coal, oil, and natural gas) are finite; humans are gradually running out of them, and their prices continue to rise. Nevertheless, they account for about one-fifth of total energy consumption. Since the primary goal of the energy sector is to ensure continued availability of energy at fair prices for a growing population and a developing economy, it is obvious that the consumption of fossil fuels must be reduced and the search for new renewable energy sources must be intensified (Gürdil and Demirel, 2020). This encourages the use of fuels from a variety of sources, especially those that come from renewable and environmentally friendly sources such as biomass. The significance of producing biofuels has consequently increased due to the rising costs of fossil fuels and different environmental effects they have. Over the past 20 years, this production has reached unprecedented levels (Popp et al., 2014)

Biomass is one of the most important renewable energy sources and is promoted as one of the few energy sources with a carbon footprint close to zero, continuous availability and a variety of possible sources. It is estimated that this energy potential is between about 14.6 EJ and 123 EJ and can meet almost 20% of the world energy demand. (Aslantaş, 2018). Direct conversions, such as combustion, and indirect conversions, such as pyrolysis, gasification, and liquefaction, are all methods of obtaining compounds that can be used as fuels (Bajwa et al., 2018). Biomass conversion techniques have become a rapidly growing branch of science and technology aimed at meeting the ever-increasing energy demand while reducing CO_2 emissions by 70 to 90%. (Sohni et al., 2018)

Research on the use of biomass as fuel focuses on producing a solid fuel block called bio-briquette from agricultural waste. It is seen as one of the ways to bridge the growing gap between energy demand and supply, especially given the finite nature of non-renewable energy sources such as fossil fuels. As for their properties bio-briquettes are durable, but density is their main drawback. However, density can be increased by applying a modest amount of energy, which can facilitate storage and transportation. a. (Saeed et al., 2021). In general, bio-briquette fuel has better energy parameters, higher density, higher calorific value (especially per volume unit) and lower moisture content as compared to the raw materials. Bio-briquette production consumes different types of materials and uniform fuel is obtained from mixtures of materials (agricultural residues and energy plants) (Chou et al., 2009b; Kwasniewski et al., 2008). In a study, rice straw with 12.1-12.6% moisture content, 3 different particle sizes (5-10 mm, 2-5 mm, >2 mm) and 16.1 MJ/kg heating value and rice bran with 12.5% moisture content, 250 - 450 µm particle size and 20.5 MJ/kg heating value were used as briquette raw materials. The experiments were conducted at different mixing ratios, particle sizes and pressing temperatures. The briquette densities obtained in the study were varied between 0.82-1.03 g/cm^3(Chou et al., 2009a). In another study, Turkish lignite coal dusts were blended with some biomass samples such as pine cone, olive waste, sawdust, paper mill waste and cotton waste, and these different mixtures were used in briquette production. Blends were subjected to briquetting pressures between 50 and 250 MPa; the ratio of biomass to lignite varied between 0 and 30 wt.%. The results indicated that shatter index (16-120), compressive strength (0.8-1.1 MPa) and water resistance (45-160 min) increased as the briquetting pressure increased (150-250 MPa) (Yaman et al., 2001). Purohit et al. (2006) found that an F-Grade coal had a calorific value of 14 MJ/kg, while the calorific values of briquette made from coconut, coffee, rice husk, cotton and corn stalks were 18.81, 17.56, 13.38, 17.85 and 15.23 MJ/kg, respectively. According to these values, it was reported that the calorific values of agricultural wastes were close to or even higher than those of coal. In the briquetting study using corn cobs it was determined that the density of the briquette raw material obtained from the cobs with a moisture content of 10.4% was 163.9 kg/m^3 and the density of the briquettes obtained varied between 817.8-1030.7 (Kaliyan and Morey, 2010).

The total agricultural area of Türkiye is about 38 089 000 hectares. Of this, 42.16% is arable land (16 062 000 hectares), 8.03% lies fallow (3 059 000 hectares), and the remaining 49.81% is used for the cultivation of fruit and vegetable and other agricultural land. (Tuik, 2021). In Türkiye about 55-60 million tons of waste are generated annually, but this resource cannot be used well enough. Agricultural waste is usually left in the fields, burned after harvesting or used as fuel with very low energy value for heating. (Akpınar et al., 2009). Türkiye occupies an important place in the world in the production of nuts and ranks first in the production of hazelnuts. According to the Turkish Institute of Statistics, the total production of nuts is about 1 384 147 tons, and the production area is 1 311 100 hectares (Table 1). For hazelnuts, almonds and pistachios, 500-550 g, 600-650 g and 400-450 g shells are obtained, respectively, per 1 kg of shelled product. The calorific value of the shells of hard-shelled fruits is close to or even higher than the value of 15.8 MJ/kg of lignite coal. For example, hazelnut shells have a calorific value of 19.2 MJ/kg, pistachios 15 MJ/kg and almond shells 16 MJ/kg (Kongnine et al., 2020).

Table 1: Nut fruit production area and yield in Turkiye

Nut fruits	Production area (ha)	Yield (t)
Hazelnut	735.000	684.000
Walnut	142.000	325.000
Almond	524.000	178.000
Pistachio	369.000	119.355
Chestnut	12.700	77.792
Total	1.311.100	1.384.147

Bio-briquettes are one of the most efficient ways to dispose of this waste. They can provide a cost-effective, certified, environmentally friendly and renewable energy source, dramatically reduce storage and transportation costs, and significantly improve combustion characteristics.

Nowadays, electric powered stationary machines using screw, piston and hydraulic press technologies are used for biomass briquetting (Grover and Mishra, 1996). Various agricultural and other biomass wastes have been used in studies related to briquetting of biomass and the results of these studies have been given, but there has not been sufficient work on briquetting with different types of machines. The grinding and crushing process required for briquetting biomass is carried out in two different machines, and the ground material is then processed into bio-briquettes using immobile, screw, piston, or hydraulic electrically powered press technologies. Tea waste (Demirbaş, 1999), wood processing residues (sawdust, mulch and wood crisps) (Li and Liu 2000), lignite mixed with woody waste (Beker, 2000), rapeseed cake (Karaosmanoğlu, 2000), palm fibers and shells (Husain et al., 2002), cotton and sesame stalks (Kurklu and Bilgin, 2007), various greenhouse plant wastes (Callejón-Ferre and López-Martínez, 2009), straw, reed and hemp stalks (Kaķītis et al., 2011), cotton stalks (Akman and Bilgin, 2012), reed species as energy crops (Bilgin et al., 2014a), sunflower stalks (Bilgin et al., 2014b), various energy crops (*Salix viminalis, Miscanthus sinensis, Rosa multiflora, Polygonum sachalinensis, Helianthus tuberosus, Sida hermaphrodita and Spartina pectinata*) (Urbanovičová et al., 2017), kiwi cuttings (Dok et al., 2018), corn stalks (Dok et al, 2019), hazelnut residues (Gürdil and Demirel, 2020), a mixture of rice husks and pine sawdust (Nino et al., 2020) were briquetted in hydraulic presses, piston or conical screw electric presses under different briquetting pressures, particle sizes or moisture contents.

This study analyzed the quality parameters of bio-briquettes formed from nut fruit shells using briquetting pressures of 190 MPa, moisture contents of 5%-6%, and particle sizes of 0-2 mm in order to assess their potential as solid biofuel made by a prototype bio-briquette machine. Pressure was selected according to studies described by Zhang and Guo (2014) and Krizan et al. (2015).

The objective of this study was to assess the quality and suitability of briquets obtained from nut fruit shells (walnut, almond, and pistachio) for use as solid fuel.

MATERIALS AND METHODS

Bio-Briquetting Procedures

The tests were conducted at Akdeniz University, Vocational School of Technical Sciences, Department of Machinery. The nuts fruits collected in 2022 from a local market in Antalya, Türkiye were used for all the experiments in this study. The shells left after processing of nut fruits (walnut, almond and pistachio) were used, and molasses was utilized as a binder during the briquetting process. For equal treatment of the raw materials to be used in the experiment, 1 kg of molasses was added to the mixture for every 20 kg. For all the experiments to be carried out within the scope of the study, sixty bio-briquettes were randomly selected from one hundred bio-briquettes obtained from each batch. The moisture content of walnut, almond and pistachio shells was reduced to the value of 5% to 6% as prescribed in the standard EN 14774-1. The nut fruit shells were briquetted using a prototype hydraulic briquetting machine with crusher and grinder with a briquetting range of 0-190 MPa (Fig. 1).

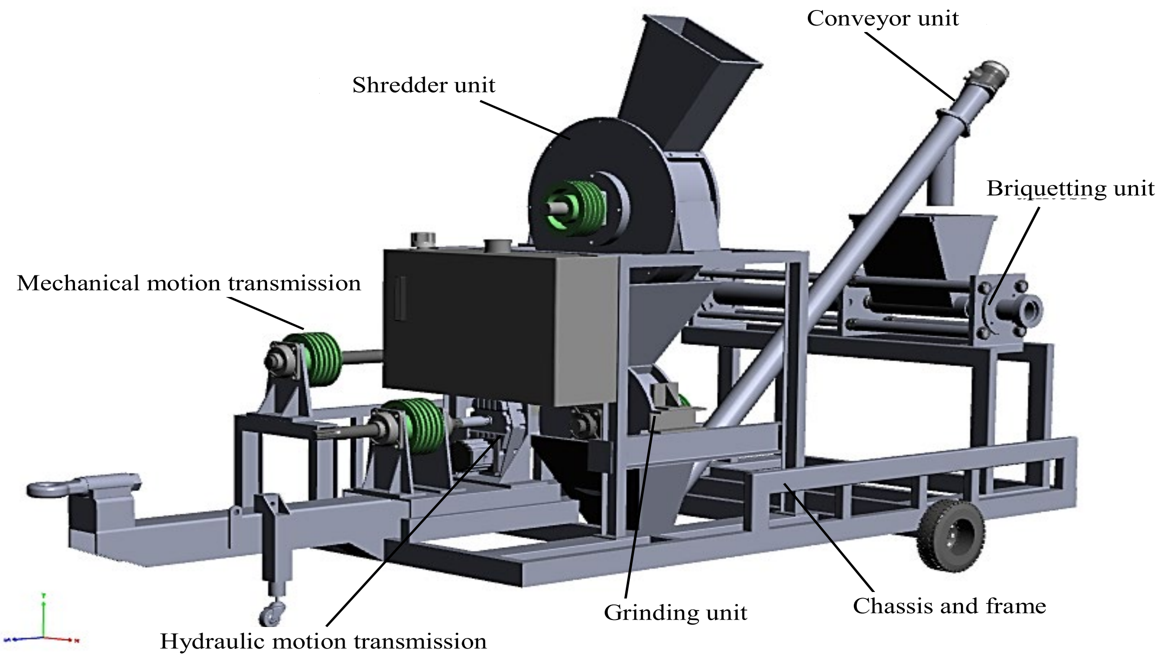

Fig. 1. Prototype mobile hydraulic piston briquetting machine driven by PTO (power take-off)

The materials were initially shredded in the shredding unit of the prototype machine, which consists of 40 hammers made of Hardox® steel and 16 counter blades, which take power from the tractor PTO (power take-off) with the belt-pulley system and rotate at a speed of 2550 rpm. The shredder unit Solidworks (SolidWorks Corporation, Waltham, Mass., USA) drawings are given in Fig. 2, and the isometric assembly drawings in Fig. 3.

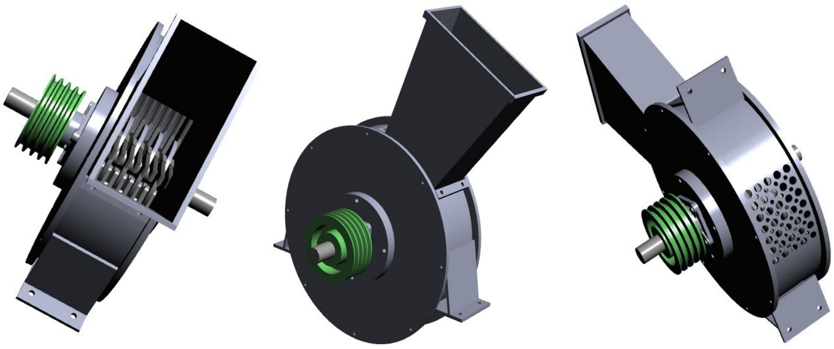

Fig. 2. Shredder unit drawings

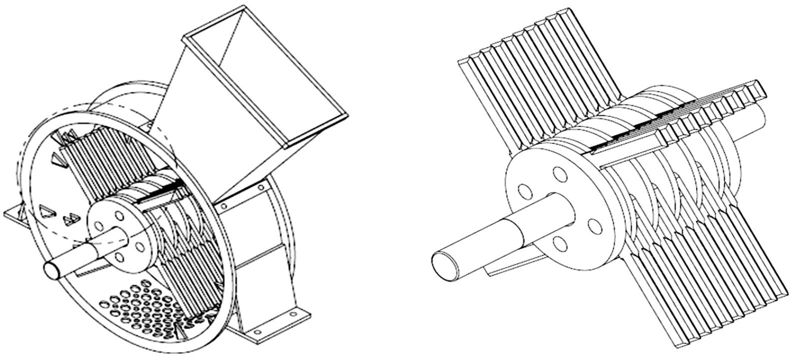

Fig. 3. Shredder unit assembly drawings

Then, the shredded material taken from the shredding unit was brought to the required piece size (0-2 mm) for briquetting in the grinding unit of the prototype machine, which consists of 24 hammers made of Hardox® steel and 58 counter blades rotating at 2200 rpm. The grinding unit Solidworks (SolidWorks Corporation, Waltham, Mass., USA) drawings are given in Fig. 4, and the isometric assembly drawings in Fig. 5.

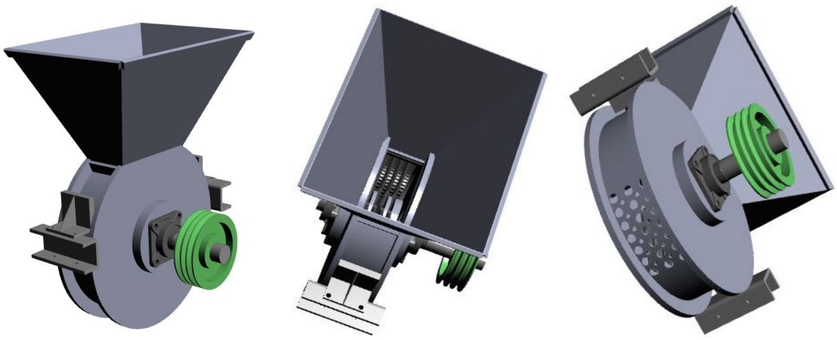

Fig. 4. Grinding unit drawings

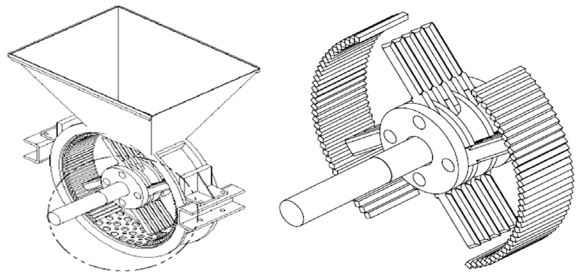

Fig. 5. Grinding unit assembly drawings

A Retsch Vibra AS 200 basic ASTM sieve analysis set (Retsch, Haan, Germany) consisting of 7 sieves with 200 mm diameter, 50 mm depth, 0.125-3.0 mm sieve opening and sieve shaking device was used to determine the particle size distributions of the materials. The properties of nut fruit shells (walnut, almond, and pistachio) used in briquetting experiments are given in Table 2.

Table 2: Properties of walnut, almond, and pistachio shells used in the experiment after grinding

Material	**Density (kg m^{-3})**		**Moisture content (%)**	
Walnut shell	241.27		5.61	
	Sieve analysis and size distribution of material (%)			
	0-1 (mm)	1-2 (mm)	2-3 (mm)	>3 (mm)
	32.68	64.76	1.73	0.83
Almond shell	351.33		6.27	
	Sieve analysis and size distribution of material (%)			
	0-1 (mm)	1-2 (mm)	2-3 (mm)	>3 (mm)
	28.62	62.23	6.47	2.68
Pistachio shell	261.24		5.17	
	Sieve analysis and size distribution of material (%)			
	0-1 (mm)	1-2 (mm)	2-3 (mm)	>3 (mm)
	38.17	58.49	2.21	1.13

After obtaining particles of the requisite sizes (0-2 mm), the particles were briquetted using a prototype mobile hydraulic piston briquetting machine operated by PTO (power take-off) and capable of a briquetting range of 0-190 MPa (Fig. 6).

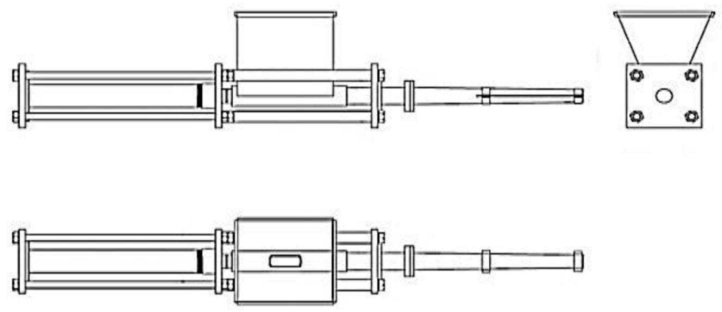

Fig. 6. Hydraulic piston briquetting unit

Briquetting of nut fruit shells was carried out using a hydraulic piston press with a maximum compaction pressure of 190 MPa and during the briquetting process, 1 kg of molasses was used as a binder per 20 kg of raw materials. The compaction pressure of the hydraulic press can be adjusted from 0 to 190 MPa. The conical die has an inlet diameter of 60 mm, an outlet diameter of 55 mm, and a piston diameter of 54.5 mm. To prevent jamming in the die during the briquetting process, the conical die is supported by clamps with spring nuts and bent during pressing if necessary.

Experimental measurements of bio-briquette quality

Measurements were carried out in accordance with European standard EN 13183-1. Moisture content was measured by drying sixty bio-briquettes randomly selected from one hundred bio-briquettes from each of the sources (walnut, almond and pistachio shells at 105 °C in a laboratory dryer for 24 hours. The samples were weighed on a laboratory balance with an accuracy of 0.001 g. Moisture content (MC) is defined as the mass fraction of water contained in the samples according to the formula (Gendek et al., 2018)

$$MC = \frac{m_0 - m_1}{m_0} \quad (1)$$

in which m_0 is mass of initial weight of sample (g), m_1 is mass of final weight of sample (g).
The density is calculated as the ratio of the mass to the sample volume. Thus, bio-briquette density was determined using the stereometric method which is based on the measurement of the dimensions (e.g. diameter, height). The diameter and height of bio-briquettes were determined by a digital caliper gauge in two perpendicular directions (0.01 mm) and the mass of individual bio-briquettes was determined with a digital balance accurate to 0.001 g. The following formula was used to calculate it (Gendek et al., 2018):

$$\rho = \frac{4.m}{\pi.d^2.h} \quad (2)$$

m is the mass of an individual bio-briquette (kg), d is average diameter of a bio-briquette (m), and h is its length (m).
Bio-briquette resistance to impact breakage (Tumbler index) and after falling (Shatter index) were assessed using ASTM D 440-86 and ASAE S269.4 standards, respectively.
In the tumbler resistance test, twenty bio-briquette samples were weighed and placed in the tester for each repetition. The bio-briquettes were then tumbled at 40 revolutions per minute for a period of 3 minutes. After the completion of the rotation process, bio-briquettes were withdrawn from the tester and weighed again. Tumbler resistance was evaluated as a percentage of weight loss that occurred during the test (Fig. 7).

Fig. 7. Tumbler test

Individual bio-briquettes were dropped 10 times onto a concrete floor from a height of 1 m in the shatter resistance test. Before and after the test, each bio-briquette was weighed. Shatter resistance was determined as a percentage based on how much weight was lost during the dropping test. During the shatter and tumbler resistance tests, the broken pieces were screened with a 20 mm sieve, and the pieces remaining on the sieve were not considered as lost (Cra, 1987).

The compression test does not correspond to any technical standard that must be followed. It was determined on the basis of a previous scientific study related to the mechanical properties of pressed materials. (Kabas and Vladut, 2016). The methodology described here was used to determine the hardness of the bio-briquette samples that were examined, modeling their potential damage in practice, such as transportation and storage of bio-briquette. Compression tests of bio-briquettes were carried out in line with ASTM E9-89, with some parts of UNE-EN12504-1 taken into consideration. A universal testing machine (LLOYD LRK Plus; Lloyd Instruments, England) consisting of two compressing plates was used. The bio-briquette sample was pressed between two plates of the testing equipment at a speed of 20 mm min^{-1}.

The applied compression force increased at a constant rate and continued until the bio-briquette broke, while application forces were monitored during the test. The compression resistance of the bio-briquettes was calculated as N, and the specific compression resistance of the bio-briquettes was calculated as Nmm^{-1} by dividing the pressure resistance by bio-briquette length. (Kaliyan and Morey, 2009; Bilgin et al., 2014a).

The water resistance is traditionally tested in immersion tests. Lindley and Vossoughi (1989) measured the water resistance as the percentage of water absorbed by a bio-briquette when immersed in water. Each bio-briquette was dunked in water at 27ºC for 30 s and the water resistance of bio-briquettes was calculated as a percentage depending on weight increase of bio-briquettes. Also, elongation, swelling and the time elapsed until complete disintegration were recorded for each sample.

Bio-briquettes were stored in a room at a temperature of 20 ºC and a humidity of 50% for 21 days for the equivalent humidity content (humidity resistance) test. Before and after the test, each bio-briquette was weighed. Depending on the weight increase occurring during storage, humidity resistance was determined as a percentage of weight gain of the bio-briquettes (Acaroğlu, 2003; Bilgin et al., 2015)

In order to test all the bio-briquettes to be used in the experiments under the same conditions, they were kept at 20°C and 50% relative humidity for 7 days before the experiments.

All physical and mechanical properties of bio-briquettes were investigated with three replications with twenty determinations for each replication. Variance analysis was carried out between bio-briquettes obtained from the three different nut fruit shells and the difference between the means was evaluated using the LSD test. Mean values were represented with the standard error. Statistical analysis of all the data obtained was performed on the computer using the SPSS® 13 package program (IBM, USA).

RESULT AND DISCUSSION

Moisture content of bio-briquette samples

The moisture content was determined immediately after briquetting the nut fruit shells. The data of the bio-briquette moisture content obtained in the experiment are shown in Table 3.

Comparing the moisture content after briquetting to the one before briquetting, it is found that the moisture content of the samples decreases by about 8.5-12.5%. It was found that the heating of the material by the friction in the mould due to the pressure generated during briquetting effectively reduces the moisture content of the material.

Table 3: Moisture contents of prototype machine bio-briquettes (on average)

Material	Moisture content of ground waste (%)	Moisture content of bio-briquette (%)
Walnut shells	5.61±0.025	4.92±0.030
Almond shells	6.27±0.030	5.64±0.025
Pistachio shells	5.17±0.035	4.73±0.045

Note: ±, standard deviation

As can be seen from the table, the moisture content of the bio-briquettes was generally less than 10%. The highest moisture content was found for the bio-briquettes made from almond shells (5.64%). The lowest moisture content was found for pistachio shells (4.73%). The low moisture content of the obtained bio-briquettes is important for the durability of the briquettes and the quality of the fuel.

There is no difference between the moisture content of bio-briquettes produced with the prototype briquetting machine and the moisture content of bio-briquettes produced with other briquetting machines (piston press and conical screw with electric motor). Results are in line with those of the studies of KURKLU and BILGIN (2007) and KALIYAN and MOREY (2010). KALIYAN and MOREY (2010) documented that briquettes obtained from ground corn cobs had a moisture content of 8.1% in their experiments with hydraulic piston. KÜRKLÜ and BILGIN (2007) found that briquettes obtained from ground cotton and sesame stalks had a moisture content of 4.84% and 4.85%, respectively, in their study with the conical screw with electric motorized briquetting system. GROVER and MISHRA (1996) recommended low moisture content (8-10%) for biomass materials in order to produce strong and crack-free bio-briquettes. In the light of this information, we can say that the bio briquettes produced with the prototype machine in our study are very strong and crack-free because their moisture content is in the range of about 4-7%. Compared to the bio-briquettes produced with other briquetting machines, they seem to be an exceptionally good biofuel in terms of bio-briquette moisture.

Density of bio-briquette samples

In general, moisture content affects density, as shown by other studies (TUMULURU, 2014). Bio-briquette density is a physical property that crucially determines the quality of the bio-briquette, and it is desirable that it is high. (DOK et al., 2019). Table 4 shows the bio-briquette density data from the trials and the results of the analysis of variance. Considering that the raw material density of nut fruit shells ranges from 241.24-351.33 kg m^{-3}, one can see how much the volume of biomass is reduced by briquetting.

Table 4: Density value and variance analysis results of prototype machine bio-briquettes (on average)

Material	Density of ground waste (kg m^{-3})	Density of bio-briquette (kg m^{-3})
Walnut shells	241.27	1198.63±14.41
Almond shells	351.33	1214.27±21.33
Pistachio shells	261.24	1171.44±25.26
Level of significance		n.s

±, standard deviation
ns: The difference between values in the same column is statistically insignificant.

The densities observed in the current study indicate that walnut shell particles had better compaction capacity than almond and pistachio shell particles. It can be observed that the increase of the walnut shell fraction led to an increase in the bio-briquette's density. The difference between the densities of bio-briquettes obtained from nut fruit shells were found to be statistically insignificant. Karaca and Başçetinçelik (2011), Gendek et al. (2018) and Brunerová et al. (2020) used a conical screw, piston, and hydraulic type press briquetting machine for briquetting in their studies. They found the density of bio-briquettes to be 1573.58 kg m^{-3} for groundnut shell waste, 938,55 kg m^{-3} for pinewood waste, and 1022. 44 kg m^{-3} for sugarcane bagasse.

The standard bio-briquette density (acceptable briquette density) was reported to lie between 1000 and 1400 kg m^{-3} (Grover and Mishra, 1996). So, based on these findings, bio-briquette samples made by prototype machines from nut fruit shells were identified as suitable, as they meet the standard bio-briquette density requirement.

Tumbler and Shatter resistance index

These tests are used to determine the bio-briquettes' durability as well as any possible losses that might occur during storage and transportation. The tumbler and shatter resistance indexes of the bio-briquettes obtained in the trials according to the ASAE S269.4 standards are shown in Table 5.

Table 5: Tumbler-shatter resistance indexes and variance analysis results of prototype machine bio-briquettes (on average)

Material	Tumbler index (%)	Shatter index(%)
Walnut shells	97.45a	91.93b
Almond shells	94.78b	92.12b
Pistachio shells	94.65b	97.41a
Level of significance	**	**

**: The difference between the values in the same column is statistically significant at the 1% alpha level.

As seen in Table 5, the tumbler (94.65-97.45 %) and shatter (91.93-97.41 %) indexes were determined for the bio-briquettes obtained with the prototype bio-briquette machine, which shows that the briquettes' durability is quite high. Although the tumbler index of the bio-briquettes obtained from almond and pistachio shells and the shatter index of the bio-briquettes obtained from walnut and almond shells were below 95%, no fragmentation was observed in the bio-briquettes. The highest tumbler index was determined for walnut shell bio-briquettes (97.45 %), and a lower tumbler index was noted for pistachio shell bio-briquettes (94.65 %). When we look at the shatter index, the highest shatter index was determined for pistachio shell bio-briquettes (97.41 %), and a lower shatter index was noted for walnut shell bio-briquettes (91.93 %).

The results obtained in fracture and tumbling resistance tests are evaluated as a percentage between 50 and 100 (Eriksson and Prior, 1990). The closer the results are to 100%, the better the quality of the briquette. According to this information, when Table 5 is examined, it can be said that the bio-briquettes have a very strong structure since the shatter and tumbler resistance values of the bio-briquettes obtained from walnut, almond and pistachio shells are very close to the value of 100%. Similar results were found with the tumbler and shatter index values of the bio-briquettes obtained in other studies by Brunerová et al., (2020) and Saeed et al., (2021) using different bio-briquette machines and compression methods and materials. Along with these, Bazargan et al. (2014) found the shatter index value as 167 in his experiments on briquettes obtained from ground palm kernels. Kalıyan and Morey (2010), reported that the durability value of briquettes obtained from corn cobs ground at 150 MPa compression pressure was between 88.2 and 92.3%. The durability value of the briquette obtained from giant reed and reed plants ground by FENGMIN and MINGQUAN (2011) was found to be between 88.2 and 92.3%.

According to the results of the statistical analysis, the difference between both, the tumbler and shatter index values of the bio-briquettes obtained from nutshells, is statistically significant ($p<0.01$). These findings reveal that bio-briquettes made from various materials have varying levels of resistance.

Compression resistance analysis of bio-briquettes

Compression resistance is a measure of the briquettes' durability and strength against physical impacts. It is desired that the losses caused by stacking the bio-briquettes during storage are at a minimum. The data reflecting bio-briquette compression resistance obtained in the experiment are shown in Table 6.

Table 6: Compression resistance and variance analysis results of prototype machine bio-briquettes (on average)

Material	Compression force (N)	Compression stress (Nmm^{-2})	Specific compression force (Nmm^{-1})
Walnut shells	3762b	76.60b	40.91b
Almond shells	4021a	82.17a	46.38a
Pistachio shells	3627b	73.09c	40.27b
Level of significance	*	**	*

**: The difference between the values in the same column is statistically significant at the 1% alpha level.
*: The difference between the values in the same column is statistically significant at the 5% alpha level.

As seen in Table 6, the highest value for compression force, compression stress, and specific compression force were recorded in bio-briquettes made from almond shells (4021 N, 82.17 Nmm^{-2}, 46.38 Nmm^{-1}, respectively), whereas the lowest values were observed in bio-briquettes made from pistachio shells (3627 N, 73.09 Nmm^{-2}, 40.27 Nmm^{-1}, respectively). According to the results of the statistical analysis, the difference between the means of compression force and specific compressive force rates on bio-briquettes made from different nut fruit shells were found to be significant ($p<0.05$), and the difference between the means of compression stress rates on bio-briquettes made from different nut fruit shells was found to be significant too ($p<0.01$). Similar results (between 2137-4545 N) were found in studies with machines using other briquetting methods (Supatata et al., 2013; Davies and Davies, 2013). In addition, the overall assessment of the compression strength of the bio-briquettes obtained with the prototype briquetting machine has proven satisfactory when compared to the bio-briquette compression strength data obtained with other machines (Brunerová et al., 2017; Brozek, 2016).

Resistance to moisture-humidity and water-intake capacity of bio-briquettes

The resistance to moisture-humidity, water-intake capacity, and their variance analysis results determined by immersing the bio-briquettes obtained with the prototype machine in water are given in Table 7.

Table 7: The resistance to moisture-humidity, water-intake capacity and variance analysis results of prototype machine bio-briquettes (on average)

Material	Water-intake capacity (%)	Resistance to moisture-humidity (%)
Walnut shells	77.68b	90.47b
Almond shells	78.09b	90.81b
Pistachio shells	82.16a	94.63a
Level of significance	*	*

*: The difference between the values in the same column is statistically significant at the 5% alpha level.

As seen in Table 7, according to the results of statistical analysis, the difference between both water intake capacity and resistance to moisture-humidity of the bio-briquettes was found to be significant ($p<0.05$) both of them being highest for pistachio shells.

In other previous studies, it was stated that the water intake rate of the bio-briquettes should not exceed 50% (Eriksson and Prior, 1990). As illustrated in Table 7, the percentage of increase for the bio-briquettes produced with the prototype machine varied between 17.84 and 22.32 on average. According to the data, it can be said that the bio-briquettes obtained from the nut fruit shells with the prototype machine are quite robust in terms of water intake resistance.

As seen in Table 7, when the equivalent moisture contents of the bio-briquettes were examined, there was not much change in the weight of the bio-briquettes at the end of the 21st day. As a result, properly packed bio-briquettes can be stored under good storage conditions for a long time without structural deterioration.

CONCLUSION

The main objective of this study was to determine whether the production of bio-briquettes from shells of nut fruits with high production value, such as walnut, almond and pistachio shells, is feasible with the prototype of a mobile briquetting machine. Based on the results of all the experiments observed and conducted, the answer to this question is "yes".

It was found that the elasticity and breaking strength of the bio-briquettes were quite high, and that the moisture content and size of the particles were quite acceptable for briquetting. The materials were compacted to a density of about 3-5 times higher. In the resistance to moisture-humidity and water-intake capacity trials it was observed that the water resistance of the bio-briquettes remained relatively stable over a period of time and if properly packaged, they had an even longer shelf life. The technical standard ISO 17225 specifies the requirements for bio-briquettes used as solid biofuel. The tests have shown that the prototype briquetting machine produces bio-briquettes that meet these specifications. In conclusion, it was found that the bio-briquettes produced by the prototype briquetting machine were quite durable based on the results of all tests.

Bio-briquettes produced from nut fruit shells can be used as solid fuel in heating systems, power plants and other equipment. It has also been found that bio-briquettes are of a high standard and suitable to be used in place of fossil fuels for heating greenhouses. Thus, a cost-effective and environmentally friendly fuel was produced. By building briquetting plants in areas where agricultural waste is concentrated, or by using mobile briquetting machines to produce fuel, this waste should be utilized economically.

Therefore, the use of shells of nut fruits (walnut, almond and pistachio) for producing bio-briquettes can be strongly recommended. In general, all measurements and tests carried out in the current research have yielded satisfying results. In addition, this research is expected to improve knowledge of waste management principles, bio-briquetting technology, and the use of all biomasses for the production of solid biofuels that are environmentally sound.

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