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ARAŞTIRMA MAKALESİ **RESEARCH ARTICLE**

Effect of Die Geometry and Moisture Content on Pelletizing of Palm Pruning Residues

Palmiye Budama Artıklarının Peletlenmesinde Pelet Kalıp Geometrisi ve Peletleme Neminin Etkisi

Hasan YILMAZ[1*], Mehmet TOPAKCI[2], Murad ÇANAKCI[3], Davut KARAYEL[4]

Abstract

Palm pruning residues are potential pellet raw material, which are quite abundant in regions with hot climates. In pelletizing process, raw material properties and pellet machine features are the main factors affecting the final pellet quality. In this study, 5 mm sieve hole diameter milled palm pruning residues was pelleted using two different pellet dies and two different pelletizing moisture. First die (D1) has 25 mm total length, 17° inlet angle and 10 mm inlet depth. The second die (D2) has 35 mm total length, 33° inlet angle and 5 mm inlet depth. The inlet and outlet hole diameter of both die are 11 mm and 8 mm, respectively. Pelleting moisture is fixed at two different levels as 10% (M10) and 14% (M14). The change of production parameters and pellet physical properties were investigated according to the die type and moisture content parameters. Increasing pelletizing moisture had a positive effect on the production capacity and it was obtained as 82.44, 103.1, 134.05, 145.49 kg h^{-1} for D1-M10, D1-M14, D2-M10 and D2-M14 pellets, respectively. The increase in pelletizing moisture caused degradation of the pellet forms, which is more evident in the pellets produced in the D1 die. Pellets produced in the D2 die are more compressed and denser and lower moisture content. The increase in total die length resulted in heavier and denser pellet production, resulting in higher production capacity and low specific energy consumption. Pellet durability index (%, ar) of D1-M10, D1-M14, D2-M10 and D2-M14 were measured as 95.53; 92.29 and 97.74; 98.32, respectively. It was concluded that the longer active die length can tolerate high moisture content pelletizing, and durable pellets can be produced in a wide moisture content range. In addition, die conical dimensions and die length are the factors that needs to be optimized according to different raw materials.

Keywords: Biomass, Pellet die, L/D ratio, Compression, Durability, ENplus®

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Öz

Palmiye budama artıkları pelet yakıtı olarak değerlendirilme potansiyeli bulunan, özellikle sıcak iklimlerde oldukça fazla miktarda ortaya çıkan artıklardır. Peletleme işleminde hammadde özellikleri ve pelet makinesi özellikleri pelet kalitesini belirleyen unsurlardır. Bu çalışmada, 5 mm elek delik çapına sahip çekiçli değirmende öğütülen palmiye budama artıkları iki farklı peletleme nemi ve iki farklı pelet kalıbında peletlenmiştir. İlk kalıp (D1) 25 mm toplam uzunluk, 17° giriş açısı ve 10 mm giriş derinliğine sahiptir. İkinci kalıp (D2) 35 mm toplam uzunluk, 33° giriş açısı ve 5 mm giriş derinliğine sahiptir. Her iki kalıbın giriş çapı 11 mm ve çıkış çapı 8 mm'dir. Peletleme nemleri %10 (M10) ve %14 (M14) olarak belirlenmiştir. Peletleme nemi ve pelet kalıbı değişkenlerine göre üretim parametreleri ve pelet fiziksel özellikleri incelenmiştir. Peletleme neminin artışı üretim kapasitesinde artışa neden olmuş, D1-M10, D1-M14, D2-M10 ve D2-M14 peletleri için sırasıyla 82.44, 103.1, 134.05, 145.49 kg h-1 olarak hesaplanmıştır. Pelet formu peletleme neminin artışıyla bozunmaya uğramıştır, bu durum D1 kalıbında daha belirgindir. D2 kalıbında üretilen peletler daha fazla sıkışmaya maruz kalarak daha yoğun ve düşük nem içerğine sahiptir. Toplam kalıp uzunluğunun artışı pelet kütlesinde artışa neden olarak daha yoğun peletler üretilmesini sağlamıştır. Bu nedenle D2 kalıbında üretilen peletlerin yoğunluğu ve üretim kapasitesi artmış, özgül enerji tüketimi azalmıştır. Pelet dayanıklılık dirençleri (%), D1-M10, D1-M14, D2-M10 veD2-M14 peletleri için sırasıyla 95.53; 92.29 ve 97.74; 98.32 olarak hesaplanmıştır. Çalışma sonunda, kalıp aktif uzunluğunun yüksek nem içeriğindeki peletleme işlemini tolere ederek geniş peletleme nemi aralığında dayanıklı peletler üretilebileceği sonucuna varılmıştır. Pelet kalıbı deliklerinin koniklik ölçüleri ve kalıp kalınlığının farklı hammaddelere göre optimize edilmesi gerekmektedir.

Anahtar Kelimeler: Biyokütle, Pelet kalıbı, L/D oranı, Sıkıştırma, Dayanıklılık, ENplus®

1. Introduction

Biomass pellets are a promising fuel type to replace solid fossil fuels. It is defined as cylindrical solid fuels with a diameter of 6-8 mm and a length of 3-40 by compressing the dried and ground raw material in die with conical holes (Döring, 2013).

Due to their low moisture content, regular cylindrical structure and high density compared to coarse biomass, they provide efficient transportation and storage and homogeneous combustion (Gilbert et al., 2009; Kaliyan and Morey, 2010; van der Stelt et al., 2011). In recent years, the production and use of pellets has increased due to the increase in environmental awareness, the renewable energy policies of the countries and the encouragement of domestic fuel use (Liu et al., 2010; Pradhan et al., 2018). World pellet production reached 55 million tons at the end of 2018, an increase of 14% compared to 2017 (Calderón et al., 2019). Forest residues and by-products are the most commonly used raw materials in pellet production because of the well-organized and well-controlled amount of waste, known and sufficient fuel properties, and the availability of appropriate pelletizing technologies. For this reason, pellets obtained from forest products in the world pellet industry are generally called wood pellets. In recent years, pellet fuel characteristics have been tried to be improved by processes such as gasification (Diken and Kayişoğlu, 2020) and co-pelletization (Atay, 2016) and studies have been carried out on different production technologies.

The pelleting process originated with the production of animal feed and as pelleting of biomass became more widespread, pellet machines and their basic components were adapted (Tumuluru et al., 2011). The most important factors in the process of converting the ground biomass into pellet form by compression are the physical properties of the raw material and the properties of the pellet machine and its parts. Appropriate particle size and moisture content of the raw material ensures the production of dense and durable pellets. The basic components of the pellet machine (pellet die and rollers) as well as suitable raw material properties and pelleting conditions are factors that affect the efficiency of the pelleting process. Pellet die geometry is critical for the compaction of the raw material. The pellet die consists of conical holes and the compression ratio (L/D) ratio is used when defining the conicity of the die.

In the biomass pelletizing process, the pellet die is subjected to higher stress and the taper and die thickness have been increased to increase die strength compared to the animal feed industry. (Nielsen et al., 2020). In the pelleting process of biomass, raw material density, moisture content and die L/D ratio are critical for pellet formation (Moon et al., 2014).

Pellet die geometry and accordingly pellet mill load is a factor that determines the production cost by affecting the energy requirement, production capacity, life of the die and rollers (Nielsen et al., 2009).

In the pellet industry, it is known that hard particulate raw materials (hardwood/woody) require more compression force than softwood/herbaceous raw materials (Nielsen et al., 2009). Stelte et al., (2012) stated that in order to determine the ideal die geometry, experimental studies should be carried out on different raw materials under different working conditions.

Various plant residues around the world have the potential to be used as raw materials for pellet production. Biomass-based residues such as agricultural residues, landscape residues, and municipal residues are sustainable residues in the region where they occur. Residues of palm trees, which are generally grown for palm oil industry and afforestation of landscape areas in regions with hot climates, are biomass products used in various industries. Due to palm oil production and the amount of residues, palm residues are classified as mesocarp fiber, palm kernel shell, palm trunk, palm oil mill effluent, empty fruit bunches and palm frond (Hosseini and Wahid 2014). Previous studies on the evaluation of palm residues were mostly related to palm oil industry residues, and liquid fuel (Ben Hnich et al., 2020), solid fuel in ground form (Ninduangdee and Kuprianov 2015), pellet (Jiang et al. 2016; Na et al. 2013; Si et al. 2016; Ungureanu et al. 2016), biodiesel (Thushari and Babel 2018), biochar (Sun et al., 2013), textile industry product (Chicatto et al. 2018) and building material (Suoware et al. 2019) were obtained from these residues.

Because they grow fast, palm trees require periodic pruning. During pruning, about 35 kg of branches, leaves and fruit residues emerge from each tree (Bourmaud et al. 2017). In cities where palm is used as an ornamental plant, pruned branches are generally disposed of as garbage, causing visual and environmental pollution. In the current literature, besides the use of waste palm pruning residues as pellet raw materials, it has been observed that there is a lack of studies on the basic pelletizing parameters.

The objective of this study was to investigate the effects of die geometry and moisture content on pelletizing of palm pruning residues, as unit energy requirement and physical properties of the pellets are significant factors in pellet production.

2. Materials and Methods

The experiments were carried out in Akdeniz University Faculty of Agriculture, Agricultural Machinery and Technologies Engineering Application Workshop and Biomass Laboratory. The pruning residues obtained from the palm trees in the Akdeniz University campus area were shredded with a PTO driven shredder and left to dry for 4-5 days under sunlight to facilitate grinding. In the natural drying process, pruning residues are mixed at regular intervals in order to prevent decay due to temperature and humidity and for an effective drying process. Dried shredded material was ground with a hammer mill with a PTO driven sieve hole diameter of 5 mm (*Figure 1*).

Pruning process Branch and Leaf Shredded Milled

Figure 1. Preparation stages of raw material

The bulk density value of palm pruning residues in ground form was calculated as 233.5 kg m^{-3}. The particle size distribution of the milled material was determined on a test device with sieves of 0.125, 0.25, 0.50, 1.00, 1.70, 2.36 and 3.00 mm diameter (*Figure 2*).

Ultimate/proximate values and chemical components of ground palm are given in *Table 1*.

Table 1. Ultimate/proximate values and chemical components of ground palm

Raw material	**C (%)**	**H (%)**	**N (%)**	**O[a] (%)**	**HHV (MJ kg^{-1}, ar)**	**LHV[b] (MJ kg^{-1})**	**AC (%)**	**VM (%)**	**FC[a] (%)**	**Lignin[c] (%)**	**Extractives[c] (%)**
PPR	44.29	5.64	1.13	48.94	16.63	16.48	6.30	74.18	19.52	22.53-32.2	4.25-5.08

[a]Determined by difference,[b] Measured with equation developed by Nska et al. 2020; Obidzinski et al. 2019, [c](Mirmehdi et al., 2014)

After drying and grinding, the raw material with a moisture content of 8.4% was divided into two groups and moistened with 10% (M10) and 14% (M14) moisture content. The Equation (1) was used in the moistening process.

$$Q = W_i(M_f - M_i)/(100 - M_f) \qquad \text{(Eq.1)}$$

Equation variables are Q: Amount of water to be added (g); W_i: Initial weight of the material (g); M_i: Initial moisture content of the material (%); M_f: Final moisture content of the material (%)

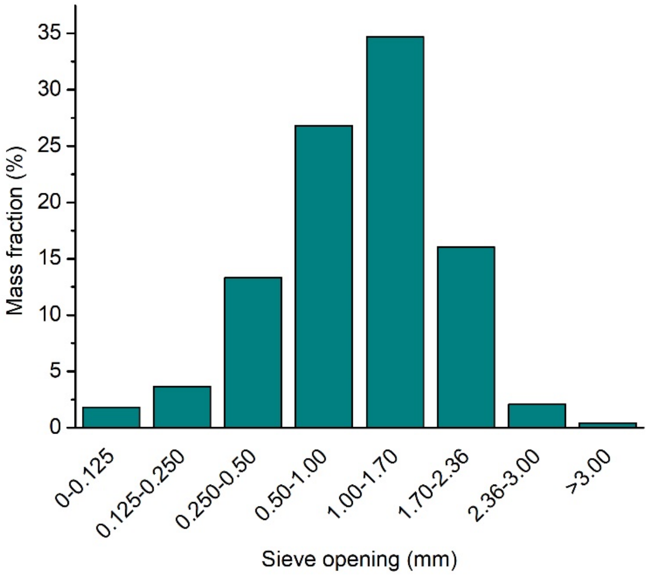

Figure 2. Particle size distribution of 5 mm ground palm pruning residues

A laboratory scale pelletizing machine with a flat die and a motor power of 15 kW was used in the pelleting process. Pellet dies were manufactured by Levent Makine (Turkey, Denizli) from AISI 4140 alloy steel and have a hardness value of 56 HRC. The dimensions and hole geometries of the dies used in the pelleting experiments are given in *Figure 3*.

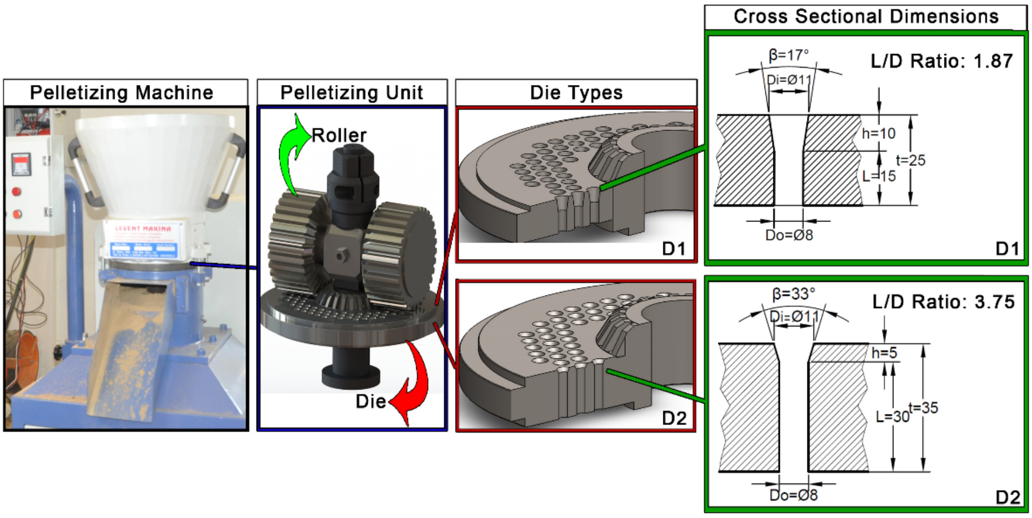

Figure 3. Pelletizing machine and die dimensions used in the experiments

Die geometric parameters are β: Inlet angle, Di= Inlet diameter, Do= Outlet diameter, h= Inlet depth, L= Active length and t= Die thickness.

Raw materials with 10% (M10) and 14% (M14) moisture content were pelleted in D1 and D2 dies and pellets were obtained with the codes D1-M10, D1-M14, D2-M10 and D2-M14. The production capacity (PC) during pellet production was calculated as kg/h by collecting the pellets produced for 60 s in a container. Electrical energy consumption values were measured with a Chauvin Arnoux CA 8332B 3-phase energy analyzer at a recording frequency of 1 second. Electrical energy consumption and production capacity values were taken into account when a constant flow is maintained during pellet production. In order to ensure the pelletizing process under equal conditions, the raw material feeding was carried out in a controlled manner during the trials and the current level of the electric motor was kept constant at 27 (±2) Ampers. The specific energy consumption (SEC) value is calculated as kWh ton^{-1} by dividing the average power consumption (P, kW) by the production capacity (PC, kg h^{-1}). The SEC value is corrected by dry base so that pelleting moisture and die effect can be evaluated.

The obtained pellets were kept on the concrete floor for about half an hour to cool. After the production process, the pellets placed in closed plastic containers were subjected to physical tests 7 days later.

Moisture contents of the pellets were calculated according to ASAE S269.5 (2016) standard by keeping them at 105 °C for 24 h. Moisture contents of pellets and raw material were calculated by keeping them at 105 °C for 24 h. Bulk density was calculated as kg m^{-3} by filling 5 dm^3 container with the method in EN15103, (2010) standard. The particle densities of the pellets were calculated as kg/m^3 by measuring the length, diameter and mass of each of the 100 g pellets and dividing the mass by the volume (EN 16127, 2012). Pellet durability index value was calculated as % of mass loss in pellets before and after the test with the test device manufactured according to EN 15210-1, (2009) standard. The tensile strength (TS) of the pellets was measured with a hydraulic pressure tester advancing at a speed of 1 mm s^{-1}. In this test, the pellet placed between two plates was crushed at a constant speed and the applied load was recorded during the compression. Before the test, the length (L) and diameter (D) values of 10 pellets were measured, the maximum compression force (F) was recorded during the test and the tensile strength was calculated with Equation (2).

$$TS = 2F/\pi DL \qquad \text{(Eq.2)}$$

In the evaluation of the results obtained, 2 x 2 factorial design statistical method was applied with SPSS software. The adequacy of the produced pellets was evaluated according to the (ENplus 2015) standard.

3. Results and Discussion

3.1. Production Capacity and Energy Consumption

The effects of die hole geometry and pelletizing moisture on production capacity and specific energy consumption were found to be statistically significant ($p<0.05$). The increase in pelletizing moisture increased the production capacity for both dies and decreased the specific energy consumption *(Figure 4).*

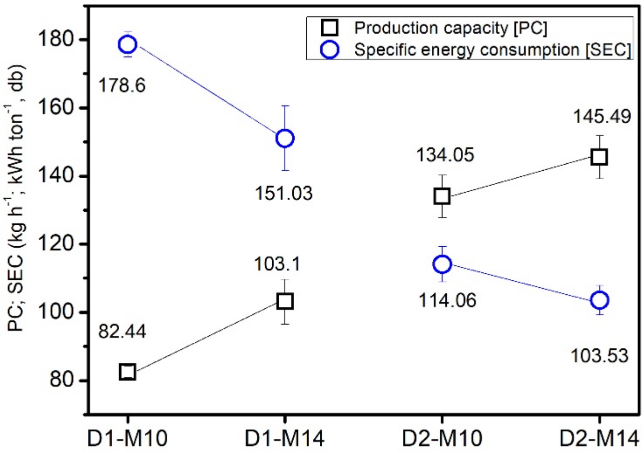

***Figure 4. Production capactiy and specific energy consumption change*s**

The increase in pelleting humidity for both dies increased the adhesion properties between the particles, thus reducing the power required for compaction, reducing the specific energy consumption and increasing the production capacity. It has been reported in studies that raw material moisture has a binding effect and more pellets are produced per unit time by reducing friction (Lehtikangas, 2001; Nguyen et al., 2017; Ungureanu et al., 2018).

Compared to the D1 die, the higher overall length of the D2 die causes longer and heavier pellets to be produced, resulting in a higher production capacity and lower specific energy consumption in the D2 die. In the studies, it has been reported that the die geometry is a factor that directly affects the energy consumption, production capacity and pressure requirement for pellet formation in pellet production (Nielsen et al., 2020; Trezek, 1981).

Although the L:D ratio is a defining parameter for pellet dies, die design parameters such as taper amount and active die length and variable raw material properties can cause differences in the pelleting process and the compaction ratio of the produced pellets. It is common knowledge about the effect of L:D ratio on pelletizing, increasing the L:D ratio makes it difficulty the compression process, increases friction and results in a denser pellet form (Nielsen et al., 2020). On the other hand, it has been reported that an increase in the L:D ratio in the pelleting process with various agricultural residues reduces the pellet bulk density and durability index value. (Theerarattananoon et al., 2011). The effect of L:D ratio on pelleting parameters and pellet quality may vary according to material type and pelletizing machine components. In this study, low energy requirement and high capacity pelleting process of palm pruning residues were obtained in low inlet angle, high L:D ratio, long die length and high moisture content.

Although production capacity and efficient use of energy are important management elements in the pelleting process, the physical properties of the pellets are a decisive factor for meeting the needs of the end user.

3.1. Pellet physical properties

The effects of die type and pelleting moisture content on all pellet physical properties were found to be statistically significant ($p<0.05$). The appearances of the obtained pellets are given in *Figure 5*. When examined visually, it can be said that pellets produced at low moisture content (M10) have a more uniform cylindrical structure than those produced at high moisture content (M14).

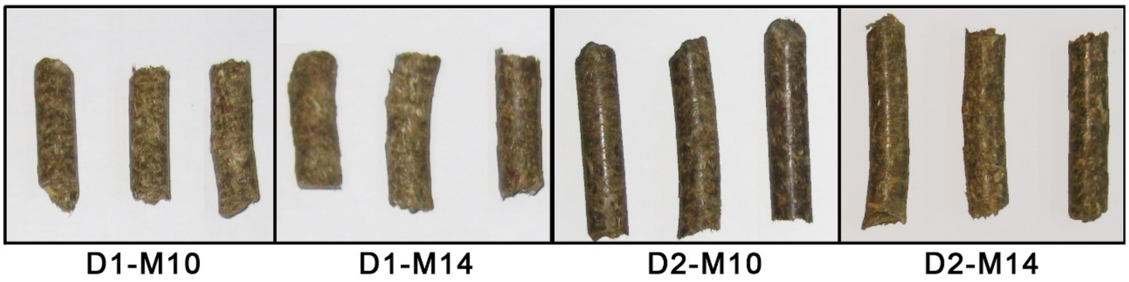

Figure 5. Palm pruning residue pellets produced at different die types and pelletizing moisture

According to *Figure 5*, it is seen that high moisture content distorts the ideal cylindrical shape. The shorter pellets obtained in the D1 die are due to the total thickness of the die. Average pellet length were 30.28 mm and 28.81 mm for D1-M10 and D1-M14, 37.32 mm and 35.47 mm for D2-10 and D2-14, respectively. The increase in pelleting humidity caused gaps between the particles forming the pellet, causing it to break at the ends and obtaining lighter pellets.

Moisture contents were measured immediately after the pellets were produced and allowed to cool on the concrete floor and after they were kept for 7 days at 28 °C (±3) and 65% (±5) ambient conditions (*Figure 6*).

The increase in pelleting moisture caused an increase in pellet moisture. Pellets produced at high moisture content tend to retain their current moisture content, being less affected by environmental conditions. Pellets with low moisture content tend to absorb moisture from the environment, and the pellets with the highest moisture absorption rate are D2-M10 pellets. The low inlet angle value and the short overall length of the D1 die had insufficient compaction in the pellets. For this reason, the pellets produced in the D1 die are more loose and more suitable to absorb moisture from ambient conditions. In previous studies, it has been reported that the increase in friction force in the pellet die increases the temperature of the pellet die (Larsson et al. 2012). The more active compression process in the D2 die increased the temperature caused by friction on the inner walls of the die, causing more moisture to evaporate.

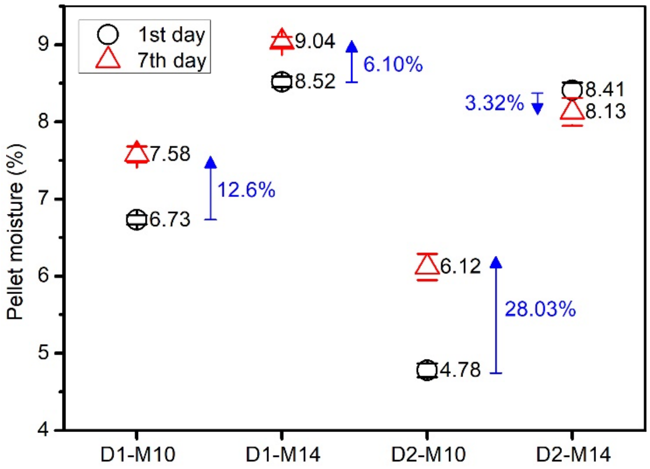

***Figure 6*. Moisture contents of the pellets produced on the first day and at the end of the 7th day**

The particle density, bulk density, pellet durability index and tensile strength changes of the obtained pellets are given in *Figure 7*.

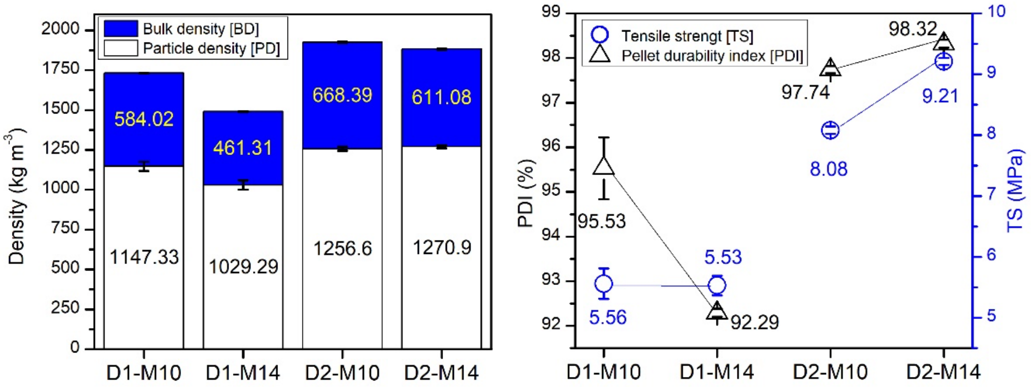

Figure 7. Changes of pellet density and strength indicators.

The active length of die D2 is longer than D1, this ensured that the pellet form was preserved throughout the die. The active length made the compression process more efficient. Therefore, the particle density and bulk density values of the pellets produced in the D2 die are higher than the pellets produced in the D1. The increase in pelletizing moisture caused a decrease in the density values in D1 die. High pelletizing moisture caused insufficient compaction. For this reason, it causes a void structure between the particles and accordingly low density and low durability values. Compared to the bulk density in ground form, the compaction ratios of D1-M10, D1-M14, D2-M10, D2-M14 pellets were calculated as 4.91, 4.41, 5.38, 5.44, respectively. D2-M14 pellets are superior in terms of storability efficiency.

In the pelletizing process in D1 die at 14% pelletizing moisture, the ideal pelletizing moisture threshold was exceeded, resulting in a less dense, low pellet durability index and tensile strength. In D2-M10 and D2-M14 pellets, where high compression was achieved due to the long die length, the increase in pelletizing moisture caused a slight increase in the particle density value, but a decrease in the bulk density value. The possible reason for this is thought to be the porous structure formed in the bulk pellet and the inhomogeneous pellet length. In Monedero et al., (2015)'s the increase in temperature caused by friction in the pellet die resulted in higher density and more robust pellet production. Exposure of the pellet to heat throughout the die increased the binding effect of moisture in D2-M14 pellets, resulting in the production of dense and durable pellets. Miladinovic (2014) reported that the PDI increased with the increase of the die thickness in the pellets obtained in the pellet die with the same exit diameter and 50 mm and 60 mm thickness. In Ginting et al. (2019)'s study the increase of inlet angle enabled sawdust to be compressed in a wider cross-sectional area and to obtain denser pellets.

The European Pellet Council is an organization that provides internationally valid certification of pellets used as solid fuel. Compliance of pellets with ENplus standards is a factor that provides confidence in end-user preferences and international trade flow of pellets. Comparison of palm pruning residue pellets produced in the study according to ENplus (2015) standards is given in *Table 2*.

Table 2. Comparsion of produced pellets and Enplus standards

Parameter	**Standard classes**			**Produced pellets**			
	A1	A2	B	D1-M10	D1-M14	D2-M10	D2-M14
Diameter, (mm)	6-8 (±1)			8.52 ☑	8.79 ☑	8.15 ☑	8.06 ☑
Length, (mm)	3.15< L ≤40			30.28 ☑	28.81 ☑	37.32 ☑	34.47 ☑
Moisture, (%)	≤10			6.73 ☑	8.52 ☑	4.78 ☑	8.41 ☑
Bulk density, (kg m^{-3})	600≤BD≤750			584.02 ☒	461.31 ☒	668.39 ☑	611.08 ☑
Durability, (%)	≥98	≥97.5		95.53 ☒	92.29 ☒	97.74 ☑	98.32 ☑
Ash, (%)	≤0.7	≤1.2	≤2.0	6.30 ☒			
Nitrogen (%)	≤0.3	≤0.5	≤1.0	1.13 ☒			
LHV, (MJ/kg)	≥16.5			16.48 ☒			

Pellets that provide all physical qualifications according to Enplus standards are pellets produced in D2 die. Although the increase in moisture content of the pellets produced in D2 die decreased the bulk density, it remained within the standard limits. The durability index of D2-M14 pellets exceeded 98%, allowing the pellets to be in the A1 class physically. The fact that the pellets produced in the D1 die are less compressed than the D2 pellets and their relatively loose structure caused them to be out of standard in bulk density and durability index values.

Ash content and Nitrogen content are above the limit value. The ash content is expected to be low for efficient combustion and long-term use of combustion systems. Nitrogen content is important in terms of preventing the emission of nitrogenous compounds (NO_x) as emissions during combustion. It has been reported in studies that high N content causes NOx gases and reduces combustion efficiency (Cheng et al., 2018; Yilmaz et al., 2020). The high ash content clogs the air flow paths in the combustion systems, reducing the combustion efficiency and causing CO emissions (Juszczak and Lossy, 2012; Liu et al., 2013). The calorific value was slightly below the limit level and could not reach the standard threshold. Palm pruning residues are physically sufficient residues to produce pellet fuel by providing ideal die geometry and pelleting moisture. However, in Enplus standards covering the standardization of pellets to be used in residential heating process, it is seen that palm pruning residue pellets have insufficient combustion properties such as ash content, heating value and nitrogen content.

4. Conclusions

In this study, energy consumption and production capacity values of palm pruning residues milled with a 5 mm sieve hole diameter were maximized at 14% moisture level in low taper and high die length die with the existing pelleting system. The long die length provided the continuation of the compaction process, enabling more dense and durable pellets to be produced. Although higher moisture content is expected to reduce energy consumption and increase production capacity, distortions may occur in the cylindrical formation of pellets produced at high moisture content. In addition to the expectation of high production capacity and low specific energy consumption, pelleting moisture and pellet die geometry are determining factors for the adequacy of pellet physical properties. According to previous studies and obtained results, it has been concluded that besides the unique characteristics of the raw material, die design parameters are of critical importance. Pelleting moisture is a factor that can be changed instantaneously with sprayer systems or conditioners during the process flow. However, considering its high cost and uninterrupted usage conditions, it is necessary to optimize the die hole geometry according to the material to be pelleted.

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