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Machine performance in pelletizing poultry litter

Kümes hayvanı altlığı peletleme işleminde makine performansı

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ABSTRACT

Objective: This research investigates the pelletizing performance of the machine used to process poultry litter. Fresh poultry litter poses challenges due to its high moisture content and volume per unit weight. Handling large volumes at low density over long distances is both difficult and expensive.The objective of this study is to employ a simple machine to transform poultry litter into the desired shape and volume weight, thereby improving storage, transportation, and off-site utilization.

Material and Methods: The research aims to assess the impact of five different moisture content levels (11%, 17%, 26%, 34%, and 47% d.b.), four die diameters (4 mm, 6 mm, 8 mm, and 10 mm), and three auger speeds (1.2 m/s, 1.8 m/s, and 2.4 m s^{-1}) on pelletizing efficiency (%), broken pellets (%), and pelletizing capacity (kg h^{-1}).

Results: The results indicate that optimal pelletizing efficiency (%) and minimum broken pellet percentage (%) were achieved at a moisture content of 26%, an auger speed of 2.4 m s^{-1}, and a die diameter of 4 mm. Maximum pelletizing capacity (kg $h^{=1}$) was attained with a moisture content of 47%, screw auger speed of 2.4 m s^{-1}, and a die diameter of 10 mm.

Conclusion: Therefore, it is recommended to operate the simple machine at an auger speed of 2.4 m s^{-1} for optimum results.

Keywords: Machine, pelletizing, poultry litter, recycling

ÖZ

Amaç: Bu araştırma, kümes hayvanı gübrelerini işlemek için kullanılan makinelerin peletleme performansını araştırmaktadır. Taze kümes hayvanı altlığı, yüksek nem içeriği ve birim ağırlık başına hacmi nedeniyle zorluklara neden olur. Büyük hacimlerin düşük yoğunlukta uzun mesafelerde taşınması hem zor hem de pahalıdır. Bu çalışmanın amacı, kümes hayvanı altlığını istenen şekil ve Hacim ağırlığı kazandırmak için dönüştürmek için basit bir makine kullanarak. depolama, taşıma ve saha dışı kullanımı iyileştirmektir.

Materyal ve Yöntem: Ayrıca araştırmada, beş farklı nem seviyesi (%11, %17, %26, %34 ve %47 d.b.), peletleme diskinin dọrt farklı delik çapı (4 mm, 6 mm, 8 mm ve 10 mm) ve üç farklı helezon (vida) (1,2 m s^{-1}, 1,8 m s^{-1} ve 2,4 m s^{-1}) hızının peletleme verimliliği (%), kırık peletler (%) ve peletleme kapasitesine (kg h^{-1}) etkisi incelenmiştir.

Araştırma Bulguları: Sonuçlar, %26'lık bir nem içeriğinde, helezon vidası hızı ve peletleme diskinin 10 mm delik çapında bir peletleme diski delik çapı çapında optimum peletleme verimliliğine (%) ve minimum kırık pelet oranı (%) ulaşıldığını göstermektedir. Maksimum peletleme kapasitesine (kg h^{-1}) %47 nem içeriği, 2,4 ms^{-1} vida hızı ve 10 mm peletleme diski delik çapı çapıyla ulaşılmıştır.

Sonuç: Bu nedenle, optimum sonuçlar için peletleme makinası 2,4 ms^{-1} vida hızında çalıştırılması önerilir.

Anahtar sözcükler: Makine, peletleme, kümes hayvanları altlığı, geri dönüşüm

INTRODUCTION

Poultry (*Gallus gallus domesticus*) represents the fastest-growing agricultural sub-sector in developing countries (Mottel & Tempio, 2017). In Egypt, poultry production is poised to rise in tandem with increasing domestic consumption. Poultry litter, comprising manure, feathers, spilled feed, and bedding material, poses a significant solid waste challenge, with broiler chickens generating an average of 43 kg of fresh litter per 1000 kg of live weight each day (Alkis & Celen, 2009). Addressing this issue is crucial for effective waste recycling.

Poultry litter emerges as an excellent resource for organic fertilizer production (Kyakuwaire et al., 2019), contributing to enhanced soil physical-chemical conditions (Lima et al., 2021). Its applications extend to supporting the fattening of ruminants (Adli et al., 2017) and exploring energy recovery options (Lee et al., 2017). Not only does it improve soil fertility and aeration, but it also enhances soil water-holding capacity (Li et al., 2021), with ruminants capable of metabolizing it into essential amino acids for growth and maintenance (Adli et al., 2017).

Moreover, research by Yangin-Gomec et al. (2020) and Zhao et al. (2021) has delved into energy recovery options for poultry litter, providing insights into various technologies such as pyrolysis, biochar production, combustion, gasification, anaerobic digestion, and others.

Poultry house litter is periodically removed and stored in covered facilities or outdoors until it is transported and applied to the field, typically done in winter or during the dry season before tillage. However, storage often poses challenges, leading to litter being dumped as waste. Improper storage or field application of fresh poultry litter can result in contamination issues, including nitrogen emissions to the atmosphere, chemical and microbiological contamination of water bodies, carrier insects, and odor nuisance (Janczak et al., 2017; Ranadheera et al., 2017; Kabelitz et al., 2021), along with additional concerns such as transportation costs and handling (Gilbert et al., 2009).

The inefficient use of poultry litter has caused many to view it as a problematic waste (Suppadit et al., 2008). Pelletizing emerges as a promising approach to alleviate these issues. The manufacturing process of poultry litter enhances the physical-mechanical properties of the feedstock material, facilitating easier handling, transportation, and storage (Gilvari et al., 2019).

Several researchers (Yang et al., 2016; Gong et al., 2019; Pampuro et al., 2020) have explored the impact of compression force during material forming. Their findings indicate that pressure significantly affects the material's qualities by increasing particle density. The physical characteristics of pellets formed from poultry litter are mainly influenced by their moisture content (Brunerova et al., 2020).

Studies by Behnke (2001) reported that the pelleting process destroys pathogenic organisms, and Kaddour (2003) developed a local pellet-producing machine. Optimal results were achieved with a pelletizing capacity of 362.77 kg h^{-1} and a pelletizing efficiency of 96.092%, using a screw speed of 1.81 m $s^{=1}$, effective hole diameter of 25.5 mm, and 22 holes. Morad et al. (2007) investigated the performance of a pelleting machine, revealing high efficiency (73.15 %) and productivity (422 kg h^{-1}) at a screw speed of 2.11 m s^{-1}.The utilization of poultry litter represents a crucial step in related waste management.

The aim of this study arises from the need to explore efficient methods for utilizing poultry litter to mitigate environmental pollution and nuisances, such as odor and insect proliferation. Despite the availability of machinery for compressing poultry litter, there remains a lack of research focusing on the utilization of such machinery for pellet production. Therefore, this paper aims to investigate the performance of a well-known machine used for pellet production from poultry litter collected and compressed. By evaluating pelletizing efficiency, assessing broken pellets, and measuring machine productivity, the study aims to contribute to the optimization of machine operating parameters for this purpose. Specifically, it seeks to identify the optimal combination of operating parameters that not only maximize pelletizing efficiency and machine productivity but also minimize the percentage of broken pellets. Through this research, we aim to offer practical solutions for sustainable waste management while enhancing the economic viability of utilizing poultry litter for pellet production.

MATERIALS and METHODS

Sample preparation

Samples of fresh poultry litter were acquired from a private poultry house with a capacity of 2000 broiler chickens (Ross). The broiler house is situated at 31° 10' 13" N, 31° 47' 56" E in Meet-Salseel city, El-Dakahlia Governorate, Egypt. An open house with a concrete floor and a stocking density of 10 birds per square meter was utilized for obtaining the poultry litter. At the conclusion of each raising cycle, following the harvesting of the birds, poultry litter is typically accumulated into piles or windrows for mechanized collection using a machine designed by the author. Twenty kilograms per sample were promptly collected, placed in clean bags, and transported to the laboratory. The average chemical composition of fresh poultry litter is presented in Table 1.

Table 1. The average chemical composition of fresh poultry litter

Çizelge 1. Taze kümes hayvanı gübresinin besin içeriği ton başına kilogram olarak

N, kg t^{-1}	P, kg t^{-1}	K, kg t^{-1}
13.1	4.5	3.6

Principles of operation

The primary operational principle of the pelletizing machine involves mechanically forming the output pellet by compacting and pressing it through a die opening, utilizing a die hole with an appropriate diameter. The primary operational principle of the pelletizing machine involves mechanically forming the output pellet by compacting and pressing it through a die opening, utilizing a die hole with an appropriate diameter.

Description of the pelletizing machine

The simple aluminum metal pelletizing machine consist of feeding, pelletizing, power drive, and power transmission units, as depicted in Figures 1 & 2.

Figure 1. *The machine used for pelletizing poultry litter.*
Şekil 1. *Kümes hayvanları altlığının peletlenmesinde kullanılan makine.*

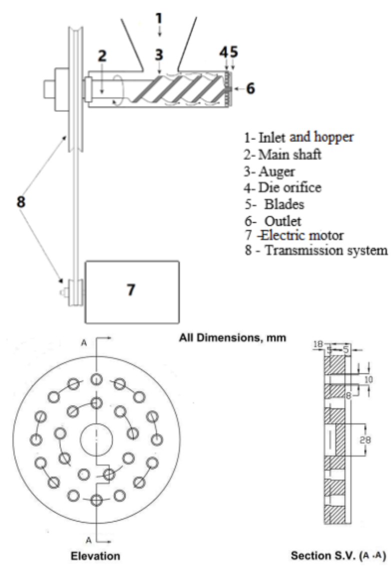

Figure 2. *Schematic diagram for the pelletizing machine.*
Şekil 2. *Peletleme makinesinin şematik diyagramı.*

The feeding unit includes a hopper with a volume of 0.16 m^3, welded to a cylindrical base, facilitating the efficient disposal of poultry litter above the pelletizing machine. The pelletizing unit features an auger (screw conveyor) with a diameter of 10 cm and a length of 45 cm that transports poultry litter from above to a die orifice for pellet creation at a rate of 29 kg/h. The die disc has a total diameter of 15 cm, with the active area (total area of the holes) comprising 47% of the total disc area. The auger subsequently transports the pellets to a cutter knife equipped with four sharp blades, regulating the length of the pellets. Dies with hole diameters of 4, 6, 8, and 10 mm were employed.

A three-phase electric motor with a power rating of 0.56 kW (0.75 HP), operating at 50 Hz, and with voltage options of 190-380 V at a rotational speed of 1400 rpm, powers the machine. Cast iron pulleys and V-belts are utilized to transfer power directly from the motor to the main drive shaft. Adjusting the pulley diameters on the auger shaft to vary the auger speeds (1.2, 1.8, and 2.4 ms^{-1}) requires raising and lowering the electric motor.

Methods

Samples of poultry litter were weighed and introduced into the hopper throat of the pelletizing machine. Under the influence of gravity, the poultry litter descended or was compacted towards the pelletizing chamber of the machine, consisting of a power screw and compression plate. Subsequently, a small motor rotated the power shaft in one direction, enabling the auger to mix and compress the entrapped material before extruding it through the holes in the die plate. Four-bladed knives, spinning against the die plate, were employed to cut the resulting cylinders of material into small lengths upon exiting the die. The process relied on the axial movement of the material within the screw press.

Uniformly sized, shaped, and dense pellets emerged through the holes in the die due to the continuous rotation of the shaft, propelling the screw auger. This rotation facilitated the movement of the compressed poultry litter mixture, subjected to a compression ratio of 10:1, through the die. The poultry litter material is not inherently homogeneous, as it likely contains varying particle sizes and compositions. Therefore, the auger mixes and blends the material before it is extruded through the die. The continuous auger mixing and compression helps create a more uniform and consistent pellet composition. The rotational speed and pitch of the auger are designed to provide sufficient mixing and residence time within the pelletizing chamber to thoroughly blend the poultry litter before it is forced through the die orifices. This mixing and compression process is a key part of the pelletizing operation to ensure the final pellets have the desired characteristics.

The pelletized poultry litter was then cut into small lengths by four-bladed knives made of high-carbon steel with a Rockwell hardness of 55-60 HRC. These knives, spinning against the die plate at 1200 rpm, were employed to cleanly shear the extruded material as it exited the die. The knife blades have a length of 7.5 cm and a thickness of 5 mm, providing robust and durable cutting edges. This knife assembly ensures the pellets are cut to the desired uniform length upon exiting the pelletizing machine. The pelletized poultry litter was then packaged in polythene and stored.

Experimental design and performance evaluation

The experimental design of the test followed a completely random pattern. Moisture content was determined using the oven-dry method, reaching a constant weight at 105 °C for 48 hours, in accordance with ASAE Standard S269.4 (ASAE standard, 2002). The speed of the rotating shaft was measured using a hand speedometer (HT-5100, Ono Sokki Co., Ltd., Japan) with direct reading. The mass of the samples was determined by an electrical digital balance with an accuracy of 0.01 gram. The time required for the execution process was measured using a common stopwatch with an accuracy of 0.01 seconds.

Tested variables:

Three variables were studied :

1) Moisture content (M)

Samples of fresh poultry litter with an initial moisture content of 47% were collected. These samples were allowed to dry, reaching moisture contents of 34%, 26%, 17%, and 11% (d.b.) after 1, 2, 3, and 4 days, respectively. The moisture contents were labeled as M_1, M_2, M_3, M_4, and M_5.

2) Die diameters (D)

Die diameters of 4, 6, 8, and 10 mm (D_1, D_2, D_3, and D_4, respectively) were investigated.

3) Auger speeds (A)

Auger speeds of 1.2, 1.8, and 2.4 m s^{-1} (A_1, A_2, and A_3, respectively) were tested.

Measurements

The experiments were conducted and replicated three times. The following criteria were studied to determine the ideal settings for the machine under study.

Moisture content (M.c.), %.

The moisture content was calculated using the following equation:

$$Mc.,\% = \frac{Mass_{initial} - Mass_{final}}{Mass_{final}} \rightarrow (1)$$

Pelletizing efficiency (η_p), %.

Pelletizing efficiency, expressed as a percentage (%), was determined for one kilogram of poultry litter using the following relationship:

$$\eta_p = \frac{M_o}{M_T} \times 100 \quad \rightarrow (2)$$

Where:

M_o: Mass of output pelletized poultry litter, in grams,

M_T: Mass of total poultry litter input, in grams.

Broken Pellet percentage (B, %)

The percentage of broken pellets (B) in poultry litter pellets is crucial for quality control and assessing the efficiency of the pelletizing process. The percentage of broken pellets (B) is a measure of the proportion of pellets that have broken during the pelletizing process. This measure helps assess the integrity and durability of the pellets, which is important for their storage, transportation, and eventual use.The percentage of broken pellets was determined according to the following relationship:

$$B = \frac{M_b}{M_o} \times 100 \quad \rightarrow (3)$$

Where:

Mb: Mass of broken poultry litter pellets, in grams. This is the amount of pellets that have fractured or shattered during the pelletizing process.

Mo: Represents the total mass of pellets, including both intact and broken pellets. It provides the overall basis for comparison.

The resulting percentage (B) indicates the extent of pellet breakage. A lower percentage suggests a higher quality product with fewer broken pellets, while a higher percentage indicates more breakage and potentially lower quality pellets.

In this study, the following methods were used to measure the efficiency of pellet production, evaluate broken pellets, and measure machine productivity:

Measurement Time (s):

- The product output was measured for 60 seconds during the pelletizing process.
- This duration was deemed sufficient to reliably assess the pellet production rate.

Determination and Collection of Broken Pellets:

- Sieving Method: The produced pellets were sieved using standard sieve sizes (e.g., 2 mm) to separate the broken pellets.
- Manual Collection by Researchers: Additionally, the researchers visually inspected and manually collected the broken pellets.

This metric is essential for manufacturers to optimize their pelletizing process, identify any issues causing excessive pellet breakage, and ensure consistency in pellet quality.

Pelletizing Productivity (PP), kg h^{-1}

Machine productivity was calculated as follows:

$$P = \frac{M_o}{t}, \qquad kg.h^{-1} \rightarrow (4)$$

Where:

M_o: Mass of output pelletized poultry litter, in kilograms,

t: Time of test duration, in hours.

Statistical analysis

The experiments were replicated three times, with each test conducted independently to ensure the reliability and consistency of the results. This replication strategy provides readers with a clear understanding of the experimental design and methodology used in this study.

We employed one-way Analysis of Variance (ANOVA) to assess the effects of the studied factors [moisture content (M) , die diameters (D), and auger speeds (A)] on the response variables: Pelletizing efficiency (ŊP), Broken Pellet percentage (B) and pelletizing productivity (P). The Costat Program (Oida, 1997) was used for all statistical analyses. Statistical significance was established based on a probability level of $p < 0.05$.

For each factor, we compared the means of the response variables across different levels using ANOVA. When significant differences were detected, we conducted post-hoc tests (Tukey's HSD) to determine which specific groups differed from each other.

Prior to analysis, we verified the assumptions of ANOVA, including normality of residuals and homogeneity of variances, to ensure the appropriateness of the statistical method for our data set. This comprehensive approach allowed us to identify statistically significant differences between the levels of each factor for the measured variables.

RESULTS and DISCUSSION

Overall, the initial outcome noted was the effective completion of the densification process, which successfully generated the pellet samples subsequently examined. The pelletized poultry litter, with a moisture content of 26% and auger speeds of 2.4 m s^{-1} using die diameters of 4, 6, 8, and 10 mm, is illustrated in Figure 3.

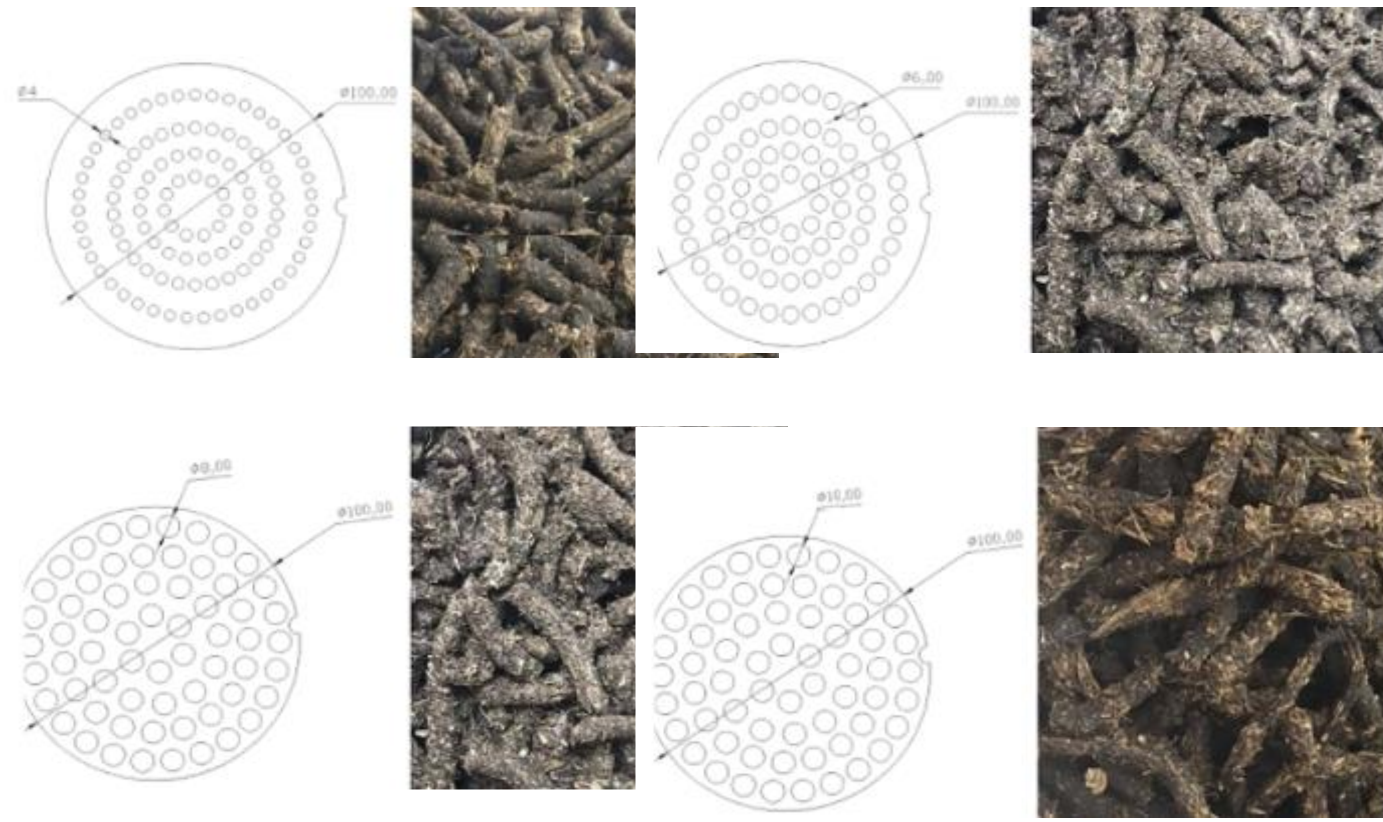

Figure 3. *The organic manure pellets generated from chicken litter.*

Şekil 3*. Etçi piliç altlığından üretilen organik gübre peletleri.*

Factors affecting pelletizing efficiency, %

Figures 4-6 depict the relationships between moisture content, die diameters, and auger speed on pelletizing efficiency. The observations reveal that increasing the moisture content up to 26% enhances pelletizing efficiency, peaking at this moisture level. However, beyond 26%, pelletizing efficiency begins to decline as the consistency of poultry litter becomes less conducive for pellet formation. Conversely, the increase in die diameter negatively impacts pelletizing efficiency due to reduced compressibility. Auger speed, on the other hand, exhibits a positive correlation with pelletizing efficiency. This can be attributed to the enhanced capacity facilitated by higher auger speeds, maximizing the inlet material per unit area at the optimum moisture content (26%).

The highest recorded mean values for pelletizing efficiency were 86.5%, 83.8%, and 81.05%. These top efficiency values were associated with a poultry litter moisture content of 26%, a die diameter of 4 mm, and an auger speed of 2.4 m s^{-1}, respectively. In contrast, the lowest recorded mean values for pelletizing efficiency were 69.25%, 67.07%, and 74.9%. These lower efficiency values corresponded to a poultry litter moisture content of 11%, a die diameter of 10 mm, and an auger speed of 1.2 m s^{-1}, respectively.

The variations in pelletizing efficiency, as indicated by the mean best and mean minimum values, can be attributed to several factors. One significant factor is the moisture content of the poultry litter. When the moisture content is higher (26%), as observed in the cases with higher pelletizing efficiency, the litter material tends to bind together more effectively during the pelleting process. This results in better pellet formation and a higher overall efficiency.

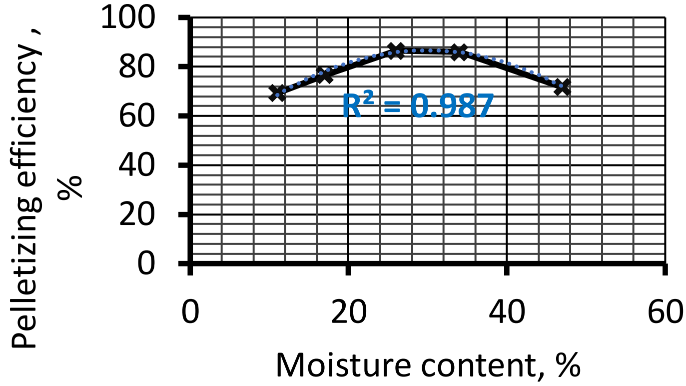

Figure 4. *Effect of moisture content on pelletizing efficiency, %.*

Şekil 4. *Nem içeriğinin peletleme verimliliğine etkisi, %.*

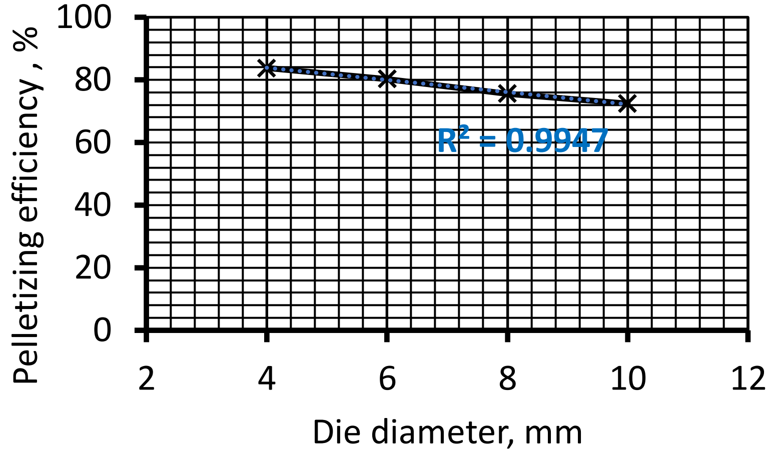

Figure 5. *Effect of die diameter on pelletizing efficiency, %.*

Şekil 5. *Kalıp çapının peletleme verimliliğine etkisi, %.*

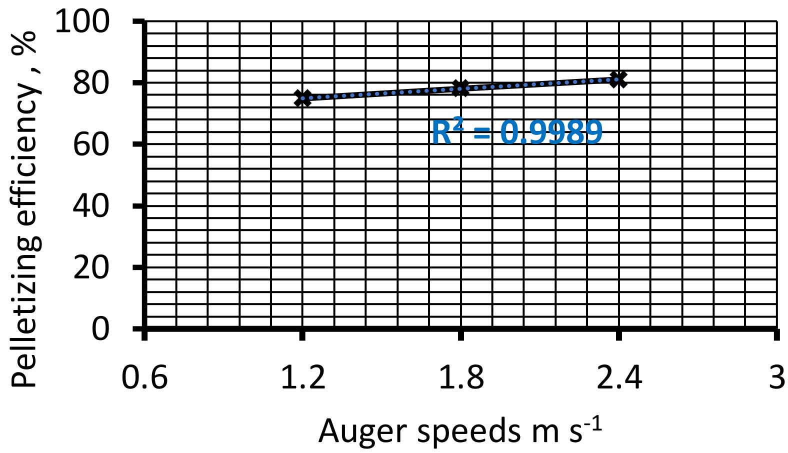

Figure 6. *Effect of auger speed on pelletizing efficiency, %.*

Şekil 6. *Vida hızının peletleme verimliliğine etkisi, %.*

Conversely, when the moisture content is lower (11%), as seen in instances of lower pelletizing efficiency, the litter material may not bind together as well during pelletization. This can lead to difficulties in forming pellets, resulting in lower efficiency.

Additionally, the die diameter and auger speed also play crucial roles in pelletizing efficiency. A smaller die diameter (4 mm) and higher auger speed (2.4 m s^{-1}) seem to facilitate better pellet formation and, therefore, higher efficiency. On the other hand, a larger die diameter (10 mm) and lower auger speed (1.2 m s^{-1}) contribute to lower pelletizing efficiency, likely due to reduced compaction and binding of the litter material.

The obtained regression equations were:

η_P (%)= 75.49 + 0.0941 M

η_P (%)= 91.66 - 1.9470 D

η_P (%)= 68.46 + 5.2800 A

ηP (%)= 79.89 + 0.0941 M - 1.947 D + 5.12 A,

where M is the moisture content, D is the die diameter, and A is the auger speed.

The observed trends in pelletizing efficiency can be rationalized based on the interactions between moisture content, die diameter, and auger speed. The increase in moisture content initially promotes better pellet formation, likely due to improved binding properties. However, excessive moisture leads to a decline in pelletizing efficiency, possibly due to difficulties in material handling and reduced compressibility.

The negative impact of larger die diameters on pelletizing efficiency aligns with the expected reduction in compressibility, making it challenging to form cohesive pellets. This finding emphasizes the importance of selecting an optimal die diameter to balance the pelletizing process's efficiency.

The positive correlation between auger speed and pelletizing efficiency suggests that higher speeds enhance material throughput, particularly when coupled with the ideal moisture content. The optimal combination of factors-moisture content, die diameter, and auger speed-is critical for achieving maximum pelletizing efficiency.

The power regression equations further quantify the relationships between the tested factors and pelletizing efficiency. These equations provide a mathematical framework for predicting pelletizing efficiency based on the moisture content, die diameter, and auger speed. The derived equations offer valuable insights for optimizing the pelletizing process and highlight the significance of balancing these factors to achieve desired efficiency levels.

Factors affecting broken pellets (B), %

Figures 7-9 illustrate the influence of moisture content, die diameters, and auger speed on the percentage of broken pellets. Observations indicate that increasing moisture content initially reduces the mean percentage of broken pellets by up to 26%. However, beyond this point, excess moisture leads to increased percentages of broken pellets due to rapid moisture loss and the formation of cracks in the pellets (Suppadit and Panomsri, 2010). The impact of die diameter is evident as an increase in diameter results in higher mean percentages of broken pellets, attributed to reduced compacting and pressing through the die opening. Conversely, higher auger speeds are associated with decreased mean percentages of broken pellets, indicating improved pellet compaction.

The best values for the mean percentage of broken pellets were recorded at 6.79%, 7.24%, and 7.82%. These optimal values correspond to a poultry litter moisture content of 26%, a die diameter of 4 mm, and an auger speed of 2.4 m s^{-1}, respectively.

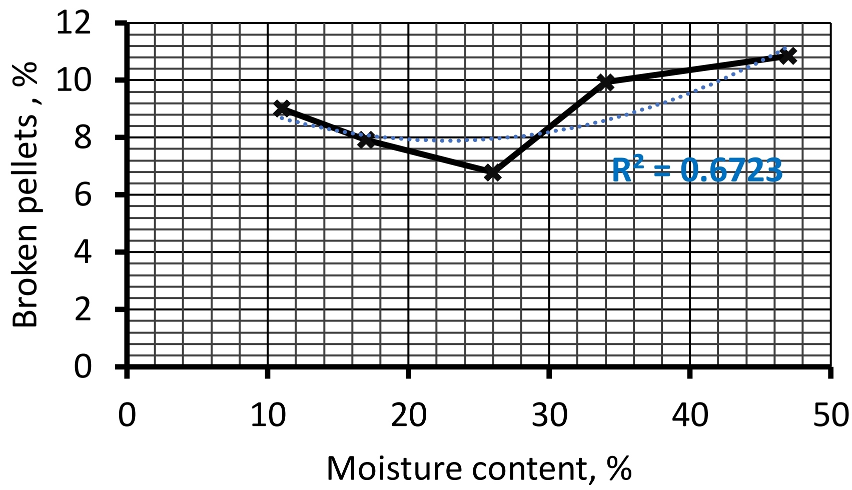

Figure 7. *Effect of moisture content on broken pellets, %.*
Şekil 7. *Nem içeriğinin kırılmış peletler üzerindeki etkisi, %.*

The obtained regression equations were:

B (%) = 7.0090 + 0.070 M

B (%) = 5.2130 + 0.527 D

B (%) = 12.193 - 1.829 A

B (%) = 6.615 + 0.0700 M + 0.5267 D - 1.829 A

The observed trends in broken pellets shed light on the critical factors influencing pellet integrity in the pelletization process. The decrease in the mean percentage of broken pellets with increasing moisture content up to 26% aligns with expectations, as moisture acts as a binding agent, enhancing pellet cohesion. However, the subsequent increase in broken pellets beyond this moisture threshold suggests the presence of challenges associated with excess moisture, such as rapid drying and pellet cracking.

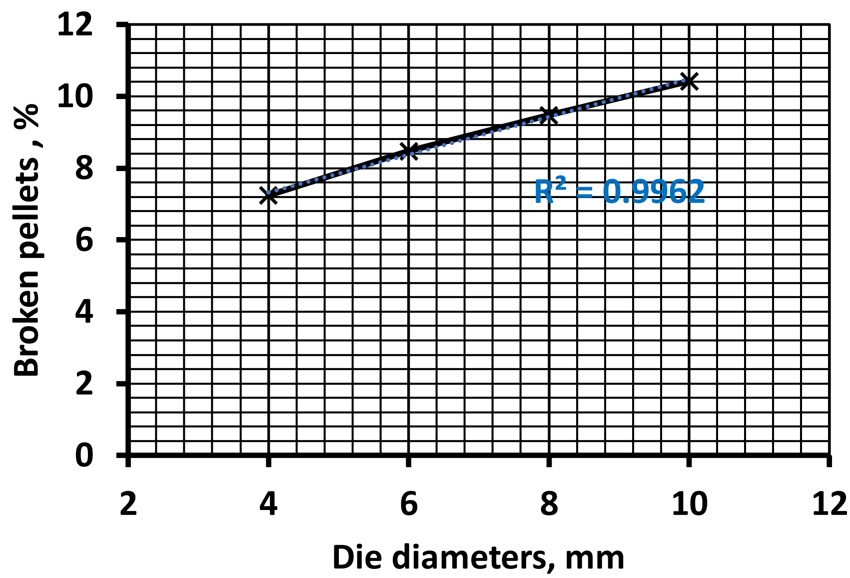

Figure 8*. Effect of die diameter on broken pellets, %.*
Şekil 8*. Disk delik çapının kırılan peletler üzerindeki etkisi, %.*

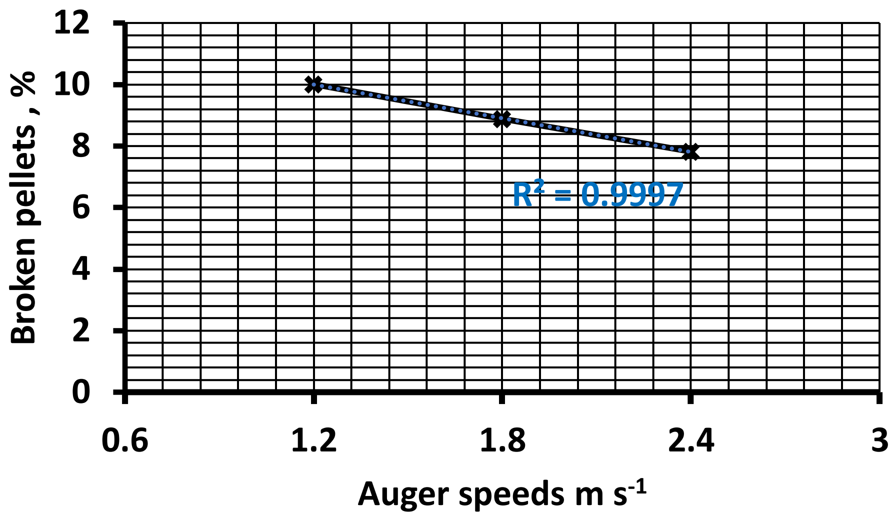

Figure 9. *Effect of auger speed on broken pellets, %.*

Şekil 9. *Vida hızının kırılan peletler üzerindeki etkisi, %*

The impact of die diameter on broken pellets underscores the role of compacting and pressing forces in pellet formation. Larger die diameters result in less effective compacting, leading to higher percentages of broken pellets. This emphasizes the need for a balanced die diameter selection to optimize pelletization and minimize pellet breakage.

The influence of auger speed on broken pellets underscores the importance of pellet compaction in the pelletization process (Spotts et al., 2004). Higher auger speeds contribute to improved compaction, leading to a decrease in the mean percentage of broken pellets. This finding emphasizes the importance of auger speed in achieving desired pellet quality.

The regression equations offer quantitative insights into the relationships between the tested factors and the percentage of broken pellets. These equations provide a mathematical framework for predicting the impact of moisture content, die diameter, and auger speed on broken pellets. The derived equations contribute valuable information for optimizing the pelletization process and minimizing pellet breakage.

Factors affecting pelletizing productivity (P), kg h^{-1}

Direct relationships were identified between the tested factors and the measured pelletizing productivity (%) as depicted in Figures 10-12. The most substantial mean values of pelletizing productivity were recorded at 29.91 kg h^{-1}, 24.38 kg h^{-1}, and 25.9 kg h^{-1} for a moisture content of 47%, a die diameter of 10 mm, and an auger speed of 2.4 m s^{-1}. Conversely, the mean minimum values of pelletizing productivity were 15.97 kg h^{-1}, 21.42 kg h^{-1}, and 23.97 kg h^{-1}, respectively. These values were directly associated with a poultry litter moisture content of 11%, a die diameter of 4 mm, and an auger speed of 1.2 m s^{-1}.

This finding aligns with Rasyid et al. (2018), indicating that increased speed results in higher pelletizing productivity.

Increasing moisture content, die diameter, and auger speed positively impacted pelletizing productivity by maximizing the inlet and outlet of loose material through the augmentation of auger speed and die diameter, respectively.

The obtained regression equations were:

P (kg h-1) = 16.475 + 0.3138 M

P (kg h-1) = 21.430 + 0.5020 D

P (kg h-1) = 22.050 + 1.6100 A

P (kg h-1) = 10.063 + 0.3138 M + 0.5023 D + 1.608 A

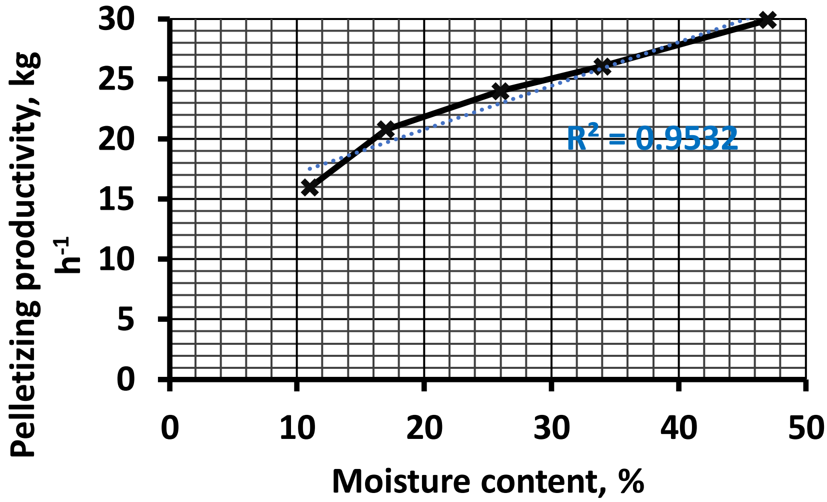

Figure 10. *Effect of moisture content on pelletizing productivity, kg h^{-1}.*

Şekil 10. *Nem içeriğinin peletleme verimliliği üzerindeki etkisi, kg h^{-1}.*

The examination of pelletizing productivity elucidates the interplay between moisture content, die diameter, and auger speed in influencing the efficiency of the pelletization process. The direct relationships observed in Figures 10-12 underscore the importance of these factors in determining the overall productivity of the machine.

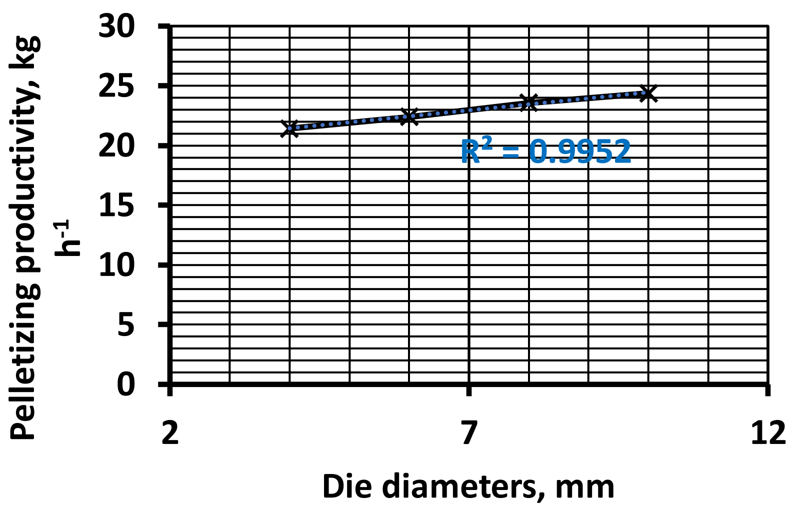

Figure 11. *Effect of die diameter on pelletizing productivity, kg h^{-1}.*

Şekil 11. *Kalıp çapının peletleme verimliliğine etkisi, kg h^{-1}.*

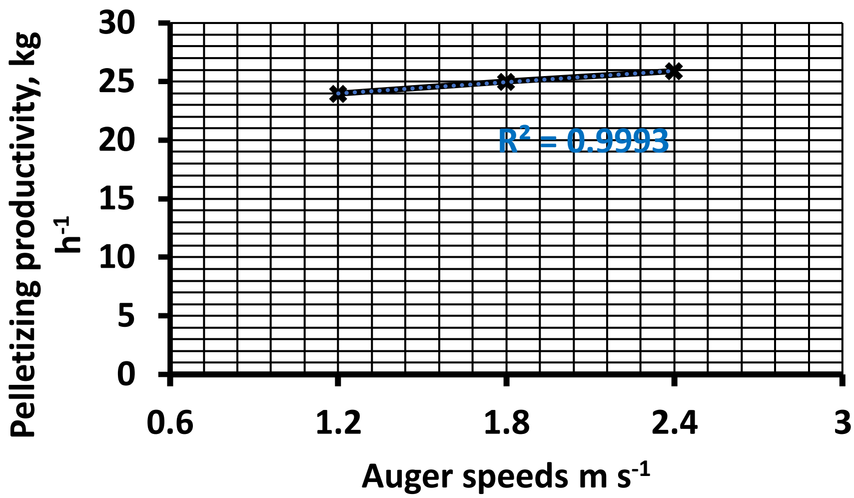

***Figure 12.** Effect of auger speed on pelletizing productivity, kg h*$^{-1}$.

***Şekil 12.** Helezon hızının peletleme verimliliği üzerindeki etkisi, kg h*$^{-1}$.

The highest recorded mean values for pelletizing productivity at a moisture content of 47%, a die diameter of 10 mm, and an auger speed of 2.4 m s^{-1} highlight the optimal conditions for achieving maximum throughput. In contrast, the lowest mean values associated with a poultry litter moisture content of 11%, a die diameter of 4 mm, and an auger speed of 1.2 m s^{-1} indicate conditions where the machine exhibited reduced efficiency.

The positive impact of increasing moisture content, die diameter, and auger speed on productivity can be attributed to their respective roles. Higher moisture content contributes to improved material flow and compaction, while larger die diameters and increased auger speeds enhance the throughput of loose material. The observed trends align with expectations, emphasizing the need to balance these factors for optimal pelletizing productivity.

The regression equations provide quantitative insights into the relationships between the tested factors and pelletizing productivity. These equations serve as valuable tools for predicting the impact of variations in moisture content, die diameter, and auger speed on pelletizing productivity. The derived equations offer a systematic approach to optimizing machine performance and achieving desired productivity levels.

Analysis of variance (ANOVA) and mean comparisons

The ANOVA analysis revealed significant effects of different levels of moisture content, die diameter, and auger speed on all studied parameters ($p < 0.001$).

The outcomes of the ANOVA analysis underscore the significance of moisture content, die diameter, and auger speed in influencing the measured parameters. The p-values less than 0.001 indicate a highly significant impact of these factors on pelletizing efficiency (ꟼP), broken pellets (B), and pelletizing productivity (P).

Increasing moisture content had a notable impact on all parameters. The mean values for pelletizing efficiency (ꟼP) increased up to a moisture content of 26%, beyond which a decline was observed. Similarly, broken pellets (B) initially decreased and then increased, reaching a minimum at 26%. Pelletizing productivity (P) demonstrated an increasing trend with rising moisture content. The optimal mean values for P were recorded at 29.91 kg h^{-1} for a moisture content of 47%.

Die diameter levels significantly affected all parameters. Larger die diameters were associated with increased broken pellets (B) and reduced pelletizing efficiency (ꟼP) and productivity (P). The die diameter of 4 mm exhibited the highest mean values for B and P, while the 10 mm die diameter led to the highest mean value for ȠP.

Auger speed exerted significant effects on all parameters. Higher auger speeds were linked to improved pelletizing efficiency (ȠP) and productivity (P) and decreased broken pellets (B). The optimal mean values for P and ȠP were associated with an auger speed of 2.4 m s^{-1}, while the lowest mean value for B was observed at an auger speed of 1.2 m s^{-1}.

Table 2. Means and standard errors for measurements affected by studied factors

***Çizelge* 2.** Çalışılan faktörlerden etkilenen ölçümlerin ortalamaları ve standart hataları.

Factors	ȠP, %	B, %	P, kg h^{-1}
M1	69.25±5.12^{b}	9.01 ± 0.03^{a}	15.97± 0.14^{a}
M2	76.67±6.18^{a}	7.92 ± 0.02^{b}	20.81± 0.98^{b}
M3	86.50±5.59a	6.79 ± 0.03^{b}	24.01±0.78^{b}
M4	79.33±7.61^{c}	9.93 ± 0.03^{c}	26.05± 0.88^{c}
M5	71.75±6.43^{b}	10.85±0.02^{b}	29.91±0.48^{b}
p-value	<0.0001	<0.0001	<0.0001
D1	83.80 ± 7.09^{b}	7.24 ± 0.05^{b}	21.42± 0.75^{b}
D2	80.33 ± 5.54^{ab}	8.47 ± 0.04^{b}	22.41± 0.63^{b}
D3	75.60 ± 4.65^{a}	9.47 ± 0.05^{a}	23.58± 0.05^{a}
D4	67.07 ± 5.53^{a}	10.42 ± 0.13^{a}	24.38± 0.13^{a}
p-value	<0.0001	<0.0001	0.0211
A1	74.90 ± 5.57^{b}	10.01 ± 0.07^{b}	23.97 ± 0.46^{a}
A2	78.15 ± 3.79^{a}	8.88 ± 0.09^{a}	24.98 ± 0.69^{ab}
A3	81.05 ± 6.76^{a}	7.82 ± 0.06^{a}	25.90 ± 0.56^{a}
p-value	<0.0001	<0.0001	0.0175

Columns with different superscripts (a-c) are significantly different ($p < 0.05$).

CONCLUSION

In conclusion, understanding the intricate interplay between moisture content, die diameter, and auger speed is essential for optimizing pelletizing efficiency. The findings underscore the importance of selecting appropriate parameters to enhance pellet quality and overall machine performance in poultry litter pelletization processes.

Understanding the factors affecting broken pellets and pelletizing productivity is crucial for optimizing the pelletization process. The findings underscore the importance of moisture content, die diameter, and auger speed in influencing pellet integrity, throughput, and overall machine performance. Achieving an optimal balance among these factors is essential to enhance pellet quality, minimize breakage, and maximize efficiency in poultry litter pelletization processes. The mean comparisons further emphasize the significance of selecting appropriate levels for these factors to ensure high-quality pellet outputs and optimal machine performance.

Future research directions in poultry litter pelletization could explore several key areas. Investigating the long-term effects of different pellet compositions on soil health and crop yields could provide valuable insights for agricultural applications. Studies on optimizing the pelletization process for specific end-uses, such as fertilizer or animal feed, may enhance the pellets' efficacy in these applications. Research into innovative binding agents or additives that could improve pellet durability without compromising nutrient content would be beneficial. Additionally, comprehensive life cycle assessments of poultry litter pellets used as a biofuel could help quantify their environmental impact compared to other energy sources. Exploring potential methods for reducing harmful emissions during the combustion of these pellets also warrants further investigation. Finally, economic feasibility studies across different regions and scales of operation could provide important information for industry adoption and policy-making.

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Data Availability

Data will be made available upon reasonable request.

Author Contributions

Conception and design of the study: MAIAR; sample collection: MAIAR; analysis and interpretation of data: MAIAR; statistical analysis: MAIAR; visualization: MAIAR; writing manuscript: MAIAR.

Ethical Statement

I declare that there is no need for an ethics committee for this research.

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