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Prediction of specific energy consumption in milling process using some physical and mechanical properties of alfalfa grind

Zahra Ghorbani*[1], Amin Allah Masoumi[2], Abbas Hemmat[2], Mohammad Reza Seifi[3]

[1]Department of Mechanical engineering, Hamedan Branch, Islamic Azad University, Hamedan, Iran
[2]Department of Agricultural Machinery, College of Agriculture, Isfahan University of Technology, 84156-83111, Isfahan, Iran
[3]Department of Agrotechnology, College of Aboureihan, University of Tehran, Iran

***Corresponding author: z.ghorbani90@ut.ac.ir**

Abstract

Estimating energy consumption in milling process of chopped alfalfa using some physical and mechanical properties would be useful and cost effective. The objective of this study was to determine the relationship between specific energy consumption in milling and physical (bulk density) and mechanical properties (cohesion, coefficient of internal friction, adhesion and coefficient of external friction) of alfalfa grind. Rectangular bales (at moisture content of 13.3% wet basis) were chopped with a screen size of 18 mm and divided into three portions. The hammer mill screen sizes of 2.38, 3.36 and 4.76 mm were selected to grind the alfalfa chops at moisture content of 8% (w.b.). Mechanical properties of alfalfa grind were determined using a shear box apparatus. An experimental watt-hour meter was used to measure energy consumption in grinding operation. According to the correlation coefficients (Pearson's matrix), it was found that all the physical and mechanical properties significantly (P<0.001) correlated with the specific energy consumption. Coefficients of internal friction and external friction on polished steel were negatively correlated with the specific energy consumption (-0.839 and -0.593, respectively). The results showed that coefficient of internal friction with a linear regression explained the variations of the specific energy consumption by 70%. After removing coefficient of internal friction from variables, bulk density (ρ_b) explained the variations of the specific energy consumption by 76% with exponential regression. So, bulk density is a key factor to estimate energy consumption in milling process.

Keywords: Alfalfa grind, Specific energy consumption, Coefficient of internal friction,Bulk density.

Abbreviations: C - Cohesion; C_a - Adhesion; d_{gw} - Geometric mean of particle diameter; E_{sc} - Specific energy consumption; GMD - Geometric mean diameter; GML - Geometric mean length; N - Force unit; τ - Shear stress; R^2 - Coefficient of determination; r - Coefficient of correlation; S_{gw} - Geometric standard deviation of particle diameter by mass; SS - Screen size; w.b. - Wet basis; μ - Coefficient of internal friction; μ_s - Coefficient of external friction; σ - Normal stress; ρ_b - Bulk density; LSD - Least significant difference.

Introduction

Alfalfa (*Medicago sativa,* L.) is the most important forage crop species in the world and many researchers have focused on processing technology of this crop. Since 1970, the processing of alfalfa to produce products like pellets and cubes has increased. Alfalfa contains digestible fibres and a useful range of minerals, vitamins and protein in animal feed (Haiqing, 2004). Bulk density can be useful in sizing hoppers and storage facilities. It can also affect the rate of heat and moisture transfer during aeration and drying process (Majdi and Rababah, 2007). Internal friction angle of the stored materials is an important parameter to calculate the lateral pressure acting on storage bin walls. Coefficient of external friction is used to design densification equipment and model the compression behavior of powder materials (Mani et al., 2004b; Majdi and Rababah, 2007). Determining the energy requirement for alfalfa size reduction would help to develop the strategies to reduce the input energy in grinding process. Energy consumption of grinding biomass depends on particle size distribution (initial/final particle size), moisture content, bulk and particle densities, feed rate of the material and machine parameters (lopo, 2002). Energy efficiency of the equipment, bulk density and physical properties such as particle size, shape, distribution, density, and particle surface area are major factors in evaluating the efficiency of size reduction (Mani et al., 2004b, 2006; Wendt et al., 2008; Bitra et al., 2009; Igathinathane et al., 2009; Zhu et al., 2009). Biomass mechanical size reduction, transportation and storage represent between 13% and 28% of the total feedstock production and supply costs (Searcy et al., 2007; Cundiff and Grisso, 2008; Kumar and Sokhansanj, 2007). To enhance packing density of biomass and producing pellets and briquettes, biomass feedstock has to be grounded into 3–8mm particles before compacting the material into a denser product (Mani et al., 2004a, 2006; Shaw, 2008; Felix and Tilley, 2009). In Quebec, Canada, most of the commercial alfalfa and switchgrass pellet mills use hammer mills with the 2.8mm screens to produce a suitable particle size for pelletization (Jannasch et al., 2001). Several models such as Kick, Rittinger (Henderson and Perry, 1970) and Bond (Bond, 1952) explained that energy consumption in size reduction process depended on initial and new surface area. They expressed that the required energy to reduce a specific mass of particles from one size to another fallow as:

$$E = \int_1^2 \frac{dL}{L^n} \quad (1)$$

Table 1. Geometric mean diameter (GMD) the chopped alfalfa and alfalfa grind.

	Chopped Alfalfa			Alfalfa grind		
Screen-sized opening (mm)	18	15	12	4.76	3.36	2.38
GMD (mm)	1.96[a] (1.071)[e]	1.69[b] (1.070)	1.54[c] (1.068)	0.422[a] (0.443)	0.402[b] (0.373)	0.336[c] (0.357)

[e]Numbers in the parentheses are standard deviations (n=3).

Table 2. Coefficient of internal friction (μ), cohesion (C), Coefficient of external friction (μ_s) and adhesion on polished steel (C_a) of alfalfa grind.

Hammer mill screen size (mm)	μ	C (kpa)	μ_s	C_a (kpa)
2.38	0.71[c]±0.01[e]	6.87[a]±0.09	0.26[a]±0.01	1.54[a]±0.32
3.36	0.77[b]±0.01	5.68[b]±0.39	0.26[b]±0.00	1.42[b]±0.16
4.76	0.88[a]±0.01	4.80[c]±0.11	0.27[b]±0.00	1.16[c]±0.09

[e]is standard deviation (n=3)

Where, E is the energy consumption (kJ/kg), dL is the differential size (dimension less), L is size (mm) and C and n are constants. In the Kick model (Henderson and Perry, 1970), it is assumed that the energy requirement is a function of a common dimension of the material, so in Eq. 1: n = -1. The Rittinger model (Henderson and Perry, 1970) assumed that size reduction is essentially a shearing procedure. Consequently, the energy required is proportional to the new surface created, which, in turn, is proportional to the square of a common linear dimension, so "n" in Eq. 1 is equal to -2. In Bond model (Bond, 1952), n = -3/2. Based on the present considerations, no such effort has been made to predict specific energy consumption, using physical and mechanical properties of materials. Therefore, the objectives of this study were determining the correlation coefficient between some physical and mechanical properties of alfalfa grind and predicting the specific energy consumption using physical and mechanical properties of alfalfa grind.

Results and discussion

The particle size distribution

The particle size distribution of alfalfa chops is shown in Fig. 1. For the alfalfa chops which passed through the 15-mm sieve (SS_{15mm}) about 52% was retained on sieve no. 5 (aperture size of 1.18 mm), whereas 53% was retained on pan for those which passed through the 12-mm sieve (SS_{12mm}). Geometric mean length (GML) and geometric mean standard deviation for alfalfa chops and grinds are listed in Table 1. Fig. 2 shows the particle size distribution of alfalfa grind for three hammer mill screen sizes. The grinds which passed through the screen size of 4.76 mm ($SS_{4.76mm}$) had a wider size distribution (geometric mean diameter: 0.422 mm) than those passed through the screen size of 2.38 mm ($SS_{2.38mm}$). Similar results have been reported for peanut hull (Fasina, 2008), wheat straw, switchgrass and corn stover (Bitra et al., 2009) and for corn stover, switchgrass, wheat and barley straw grinds (Mani et al., 2004b). Wider particle size distribution is suitable for compaction process (i.e. pelleting). During compaction, void space of larger (coarse) particles was filled with smaller (fine) particles and produced denser and durable pellets (Tabil, 1996; Mani et al., 2003).

Physical and mechanical properties

The bulk density of alfalfa grind increased with the decrease in geometric mean diameter of the grind. Bulk density varied from 161.6 to 179.9 kg m^{-3} when particle size increased from 2.38 to 4.76 mm. Since larger particles are transformed to small particle size, they occupy less volume and finer

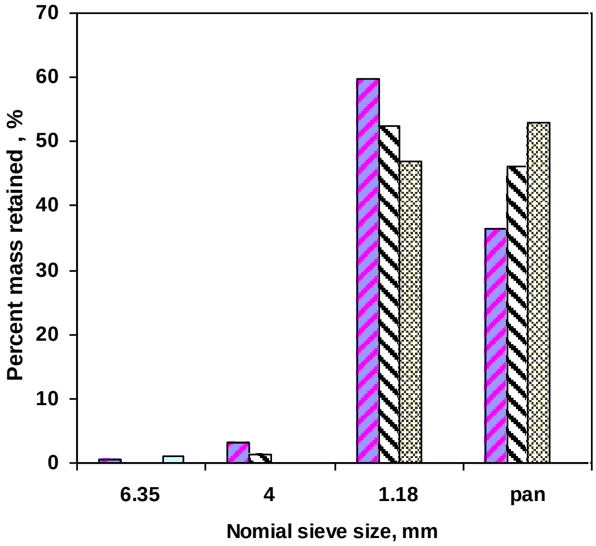

Fig 1. Particle size distribution of alfalfa chops (average of three tests): ▫, 12 mm sieve size; ▫, 15 mm sieve size; ▫, 18 mm sieve size.

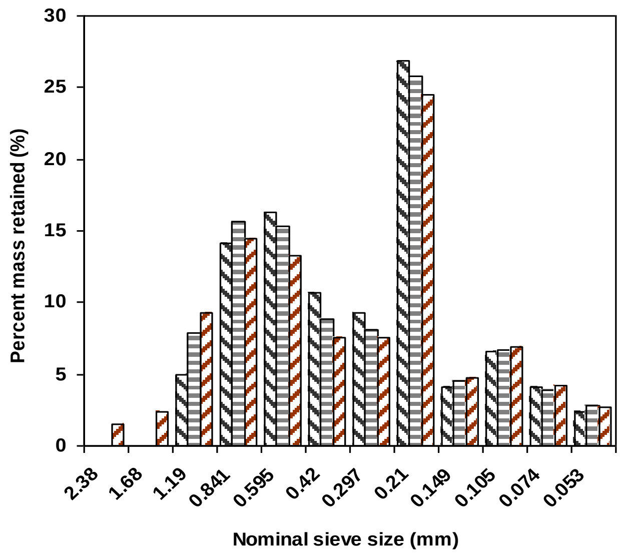

Fig 2. Particle size distribution of alfalfa grind (average of three tests): ▫, 2.38 mm screen size; ▫, 3.36 mm screen size ; ▫, 4.76 mm screen size.

Table 3. Specific energy consumption for grinding chopped alfalfa with chopper equipped with a 18 mm screen and chopped alfalfa passed from 15 and 12 mm sieves.

Geometric mean chopped size (mm)	Hammer mill screen opening (mm)	Geometric mean grind size (mm)	Average specific energy consumption (J/kg)
1.96	2.38	0.336	16220[a]± (0.56) *
	3.36	0.402	12840[b]± (0.99)
	4.76	0.422	7220[c]± (0.56)
1.68	2.38	0.336	13530[a]± (0.97)
	3.36	0.402	10890[b]± (0.22)
	4.76	0.422	6380[c] ± (0.62)
1.53	2.38	0.336	10230[a]± (1.15)
	3.36	0.402	8910[b]± (0.42)
	4.76	0.422	5940[c]± (0.71)

* Numbers in the parentheses are standard deviations. - different letters are statistically different at the confidence level of 95%.

Table 4. Correlation coefficients between physical and mechanical properties.

	E_s(kJ/kg)	ρ_b(g/cm$_3$)	μ	C (kpa)	μ_s	C_a (kpa)
E_s	1	0.827***	-0.839***	0.826***	-0.593***	0.605***
ρ_b		1	-0.949***	0.873***	-0.733***	0.719***
μ			1	-0.945***	0.561**	-0.589***
C				1	-0.552**	0.586***
μ_s					1	-0.937***
C_a						1

** Correlation is significant at the 0.01 level. *** Correlation is significant at the 0.001 level.

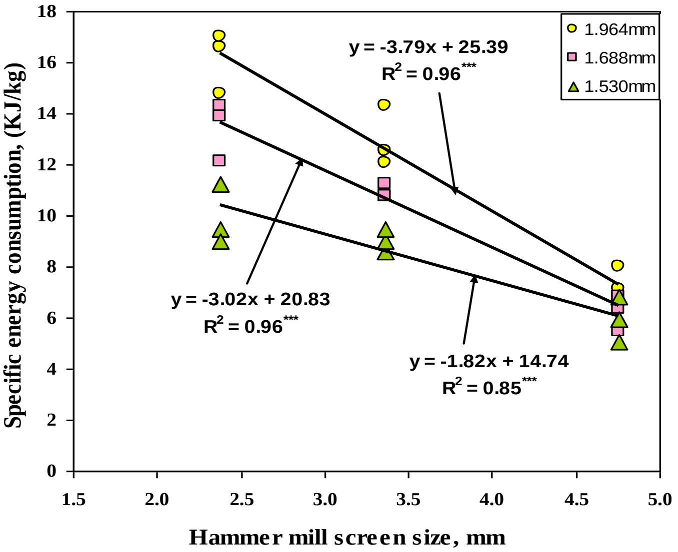

Fig 3. Specific energy consumption (E_{sc}) for grinding of the three sizes of chops.

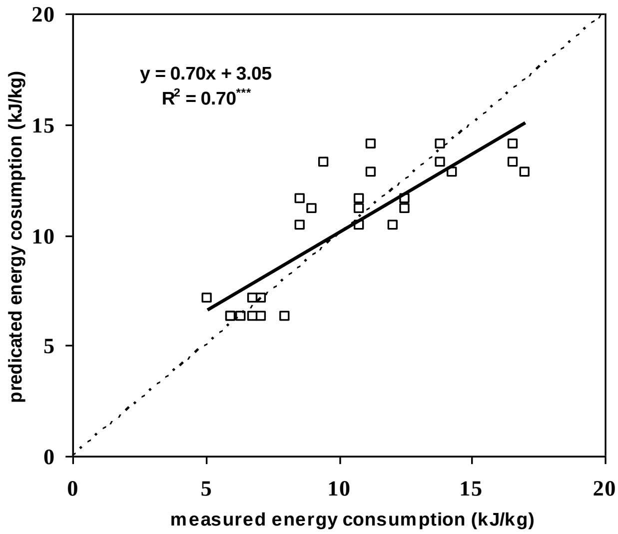

Fig 4. Specific energy consumption predicted with Eq. (2).

particles occupy the void spaces, resulting in an increase in bulk density (Mani et al., 2004a). Miao et al. (2011) found that the bulk density decreased with the increase in the aperture size of milling screens, which resulted in the bigger particles. Adapa et al. (2011) found similar results for bulk density of non-treated and steam exploded biomass grinds. The coefficient of internal friction, cohesion, coefficient of external friction and adhesion on polished steel of alfalfa grind at different particle sizes are given in Table 2. Coefficient of internal friction was increased by 23% when particle size increased from 2.38 to 4.76 mm. This increase in coefficient of internal friction may be due to higher degree of packing. Cohesion decreased with the increase of screen size from 2.38 to 4.76 mm. Similar results were obtained by Afzalinia and Roberge (2007).The decrease of the cohesion at the larger screen size could be related to the reduction of contact area between the larger particles, resulting in smaller specific surface area (surface area per unit volume). External friction coefficient of alfalfa grind varied between 0.26 and 0.27. Similar trend was observed for corn stover grind (Mani et al., 2004a). The adhesion of alfalfa grind decreased from 1.54 to 1.16 when the particle size increased from 2.38 to 4.76 mm.

Energy requirement for grinding

The average specific energy consumption (Esc) for grinding the alfalfa chops are given in Table 3. Chopped alfalfa with GMD of 1.96 mm consumed the highest E_{sc} to grind in three different hammer mill screen sizes, whereas chopped alfalfa with GMD of 1.53 mm required the least E_{sc}. The E_{sc} to grind chopped alfalfa with GMD of 1.96 mm was nearly 1.5 times as great as those with GMD of 1.53 mm to achieve the same extent of size reduction, except for the hammer mill screen size of 4.76 mm. Requiring high E_{sc} for chopped alfalfa with GMD of 1.96 mm may be due to its larger mean chop size and higher fiber content resulting from the presence of more stems. The comparison of means showed a significant difference (P<0.05) between the mean of E_{sc} and screen opening at each level of chopped alfalfa, such that the highest E_{sc} obtained for grinding with screen size of 2.38 mm and the least for 4.76 mm. E_{sc} for grinding chopped alfalfa with GMD of 1.96 mm decreased by 55% when the size reduction increased from 2.38 to 4.76 mm. In other word, fine grinding required high E_{sc}. Similar results reported for corn stover, switchgrass, wheat and barley straw grinds by Mani et al. (2004a). Miao et al. (2011) found that the energy consumption decreased with the increase in aperture sizes of milling screens for willow and Miscanthus. Adapa et al. (2011) and Ghorbani et al. (2011) found similar results for grinding selected non-treated and steam exploded agricultural biomass. A linear relationship was obtained between the required E_{sc} and hammer mill screen size for all sizes of chops with R^2 values ranging from 0.85 to 0.96 (Fig. 3). From this figure, it can be seen that the hammer mill screen size was negatively correlated with E_{sc}. A second-order polynomial relationship was found between the E_{sc} and the mean particle size for alfalfa stem (Sitkei, 1986).

Correlation coefficients between physical and mechanical properties

Table 4 presents the Pearson's correlation coefficient (r) associated with confidence level between physical and mechanical properties. The bulk density, cohesion and adhesion on polished steel surface were positively significantly correlated (P<0.001) with specific energy consumption (r>0.60). It may be due to the existence of materials with higher bulk density which consume more power in milling process. The adhesion and coefficient of external friction on polished steel were negatively significantly correlated (P<0.001) with specific energy consumption (r> 0.59). This negative correlation suggested that specific energy consumption increased when these two parameters decreased.

Models presentation

A multiple linear regression with a stepwise variable selection was used to find the relationship between specific energy consumption and other variables.

$$E_{sc} = -41.12\,\mu + 42.86 \qquad R^2 = 0.70^{***} \qquad (2)$$

$$E_{sc} = 0.015\, e^{0.03\,\rho_b} \qquad R^2 = 0.76^{***} \qquad (3)$$

$$E_{sc} = 0.357\,\rho_b - 51.39 \qquad R^2 = 0.68^{***} \qquad (4)$$

*** Correlation is significant at the 0.001 level.

Predicated values of specific energy consumption by equation 2 and 4 are shown in figures 4 and 5. From the coefficients of determination, it can be seen that these models are capable of predicting energy consumption with a sustainable accuracy. While the second model showed the best estimation for energy consumption, the first and third model had the linear relationship between E_{sc} and independent parameters. The results showed that bulk density can be the best factor to predict E_{sc} while the coefficient of internal friction had acceptable relationship with E_{sc}. So, the determination of energy consumption with bulk density and coefficient of friction, which can be measured easily, is the advantage of using these models.

Materials and methods

Materials

Rectangular bales of alfalfa were obtained at moisture content of 13.3% wet basis (w. b.) from Isfahan University of Technology Research Station farm, Iran. With a 45 kW chopper (Mashin Barzegar Industrial Products, Hamedan, Iran) equipped with a screen size of 18 mm (SS_{18mm}), operated at 540 rpm and fed at 1.5 t h^{-1}, alfalfa bales were chopped. The alfalfa chops were then divided into three portions. The first portion was left un-sieved, whereas the second and third portions were passed through the sieve sizes of 15 (SS_{15mm}) and 12mm (SS_{12mm}), respectively. These three portions were chosen such that they contained different portions of leaves and stems. The SS_{18mm}, SS_{15mm} and SS_{12mm} contained 36, 46 and 53% leaves, respectively. These three portions represent low, medium and high quality samples. The hammer mill screen sizes of 2.38 ($SS_{2.38mm}$), 3.36 ($SS_{3.36mm}$) and 4.76 ($SS_{4.76mm}$), which are usually used in pelleting process for making poultry and livestock feed, were selected to grind the alfalfa chops at moisture content of 8% (w.b.).

Particle size distribution

The particle size of alfalfa chops was obtained based on ASAE standard S424.1 DEC01 (ASAE, 2003a) for chop forage materials. Samples of the alfalfa chops were placed into the top screen of the Ro-Tap sieve shaker (Azmon Industrial Products, Tehran, Iran). Sieve sizes used for the experiment were 1, 2, 3, 4 and 5 (nominal openings of 19, 12.7, 6.3, 3.96 and 1.17 mm, respectively). The mass retained on each sieve was weighed after sieving. For each chop sample, experiments were repeated three times. Geometric mean (d_{gw}) and standard deviation (S_{gw}) of length for samples were calculated according to ASAE Standard S424.1. After milling, particle size distribution of the grinds was determined according to ASAE Standard S319.3 FEB03 (ASAE, 2003b). A 100 g sample of grinds was placed on the top of a stack of sieves arranged from the largest to smallest opening. Based on the range of particles in the sample, selection of sieve series was carried out. Hammer mill screen opening sizes for each grinds are given in table 1. According to ASAE (2003b), the duration of sieving was determined to be equal to 10 min. After sieving, the mass retained on each sieve was weighed. The geometric mean diameter (d_{gw}) and standard deviation (S_{gw}) of particle diameters for the sample were calculated according to the aforementioned standard.

Bulk density

To measure the bulk density of ground samples, grain bulk density apparatus was used (Canadian Grain Commission, 1984). The grinds were placed on the funnel and dropped at

Table 5. Sieve sizes for each grinds.

Grind sizes (mm)	Nominal size opening (mm)
4.76	2.4, 1.2, 0.85, 0.59, 0.42, 0.30, 0.21,0.15, 0.01, 0.074 and 0.053
3.36	1.2, 0.85, 0.59, 0.42, 0.30, 0.21,0.15, 0.01, 0.074 and 0.053
2.38	0.85, 0.59, 0.42, 0.30, 0.21,0.15, 0.01, 0.074 and 0.053

the center of a 0.5 L capacity steel cup continuously. Since the grind was fluffy and did not flow down readily through the funnel, it was stirred using a wire in order to maintain a continuous flow of the material. The cup was leveled gently by a rubber coated steel rod and weighed. The weight per unit volume gave the bulk density of the grind in kg m^{-3}.

Coefficients of friction, adhesion, and cohesion

The internal (cohesion and coefficient of internal friction) and external (adhesion and coefficient of external friction) properties of alfalfa grind were determined using a shear box apparatus (Equipment Laboratory Engineering, ELE, England) with the diameter and height of 63.5 and 20 mm, respectively. The pulling speed of half box was 0.3 mm min^{-1} in the horizontal direction. With two horizontal and vertical gages, the shear force and vertical displacement were recorded. The shear box was filled with the sample and the same bulk density was used for all tests. The strength parameters (cohesion and coefficient of internal friction) were measured at four different normal loads (4.7, 39.5, 158.3 and 316.6 N). The shear box was filled with the sample. The same bulk density was chosen for all tests. To measure the external property of alfalfa grind, a polished steel plate was placed inside the bottom half of the box, the top half was filled with the sample, and the shear force was measured at four different normal loads (39.5, 126.6, 633.2and 1266.4 N). The shear tests were repeated three times for each normal load range. For each grind size, the maximum shear stresses were plotted versus normal pressures. Based on Mohr- Coulomb's model, the intercept of the line was considered as the adhesion (or cohesion) and the slope of the best fitted line to the data as the coefficient of friction of the sample. According to this model, shear strength was expressed as a function of normal stress as follows (Chancellor, 1994; Puchalski and Brusewitz, 1996; Lawton and Marchant, 1980).

$$\tau = \mu_S \sigma + C \quad (5)$$

Where, τ is shear stress, (kPa); $\mu_s$is coefficient of static friction; σ and C are normal stress and cohesion in kPa; respectively.

Grinding operation

The alfalfa chops were ground using an electric hammer mill (Equipment Laboratory Engineering, England) the schematic diagram of which is presented in Fig. 6.This mill included three swinging hammers, attached to a shaft powered by a 1.1 kW electric motor and rotated with the speed of 360 rpm. At the inlet of the apparatus, a tapered hopper (with 123, 320 and 300 mm as small and large diameter and height, respectively) was used. The alfalfa chops were very light and did not flow freely through the hopper, therefore to keep continuous flow of the chops, they were agitated using a helical auger (operating at 30 rpm). An experimental watt-hour meter was manufactured (Agricultural Machinery Engineering Department, Isfahan University of Technology, Isfahan, Iran) to measure energy consumption in grinding operation. It was connected to a data logging system and the

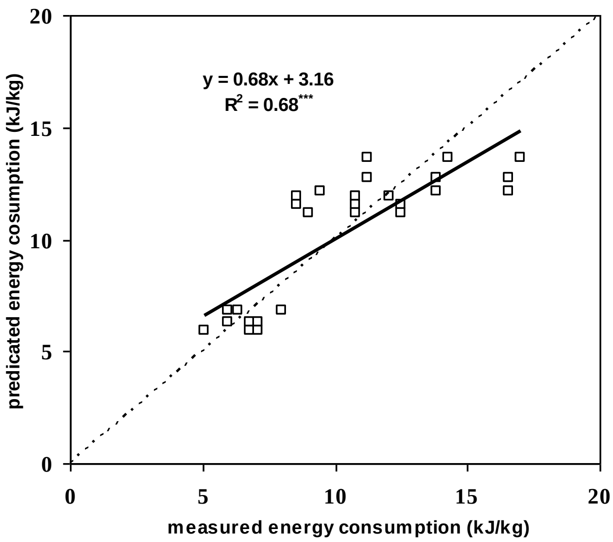

Fig 5. Specific energy consumption predicted with Eq. (4).

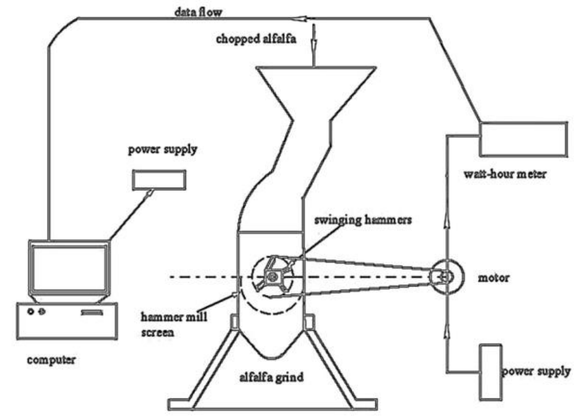

Fig 6. Schematic diagram for power measurement during grinding operation.

time-power data were recorded. The no load energy values (approximately 4275J) were subtracted from the measured values during grinding. By integrating the area under the power demand curve for the total time required to grind a sample, the specific energy consumption for grinding was determined. The hammer mill was started and then a known quantity of alfalfa chops was fed into the hammer mill. The required time for grinding the alfalfa chops along with the power drawn by the hammer mill motor was obtained. Feed rate was measured as 0.11 kg s^{-1}. The specific energy consumption (Esc) during milling process was expressed as:

$$E = \frac{\text{Net input electric energy (kJ)}}{\text{Weight of chopped alfalfa (kg)}} \quad (6)$$

Correlations in multiple - variable analysis

From the matrix of Pearson's correlation coefficient (r), relationships between some physical and mechanical properties and specific energy consumption were obtained.

The presentation of models

A general equation, using standard stepwise linear regression technique of the SPSS software, was used to predict specific energy consumption in milling process of alfalfa from a coarser distribution to the finer one. Bulk density, cohesion, coefficient of internal friction, adhesion and coefficient of external friction on polished steel were defined as independent variables. The investigation of the overall and relative effect of the experimental factors was carried out by testing the statistical validity of including each of the factors in the predicting model of the specific energy consumption. In next step the first selected variable was removed with SPSS software from the data set and the relationships between specific energy consumption and other experimental variables was obtained.

Statistical analysis

A completely randomized design with three replications was used to determine the significance of particle size effects on the physical and mechanical properties of alfalfa grind. Fischer's Least Significant Difference (LSD) was used for multiple mean comparisons. This coefficient and *p*-value for the correlation was obtained using SAS software.

Conclusion

The specific energy consumption was increased with the decrease of screen opening size from 4.76 to 2.38 mm. Internal and external friction coefficients on polished steel were significantly correlated ($P<0.001$) with specific energy consumption (-0.84 and -0.59 respectively). Cohesion and internal friction coefficient were positively correlated (correlation coefficient = 0.94). From the coefficients of determination, it can be seen that the predicting models are capable of predicting energy consumption with a sustainable accuracy. While the second model results in the best estimation for energy consumption, the first and third model have similar results and show linear relationship between E_{sc} and the crop physical proprieties.

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