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Principal component modeling of energy consumption and some physical-mechanical properties of alfalfa grind

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Abstract

The objectives of this study were determining the relationships between physical (bulk density) and mechanical properties (cohesion, coefficient of internal friction, adhesion and coefficient of external friction) and their effects on specific energy consumption for alfalfa grind. Alfalfa chops were ground using a hammer mill with three screen sizes of 2.38, 3.36 and 4.76 mm at moisture content of 8% (w.b.) and passed through sieve sizes of 18, 15 and 12 mm. The energy consumption during grinding in hammer mill was measured with a watt-hour meter. According to the correlation coefficients (Pearson's matrix), it was found that all the physical and mechanical properties significantly (P<0.001) correlated with together. Coefficient of internal friction and coefficient of external friction on polished steel was negatively (-0.84 and -0.59 respectively) correlated with the specific energy consumption. The highest correlation coefficient (0.99) was observed between bulk density and coefficient of internal friction. Principle component analysis identified one component which explained 78% of the total variation among physical and mechanical properties.

Keywords: alfalfa grind, internal friction, physical properties, modeling, specific energy

Abbreviations:

C= cohesion, (kPa)
C_a = adhesion, (kPa)
d_{gw} = geometric mean of particle diameter (mm)
E_{sc} = specific energy consumption (kJ/kg)
GMD= geometric mean diameter
GML= geometric mean length
MSE = mean square error
N = force unit (Newton)
τ = shear stress (kPa)
PCA = principal component analysis
R^2 = coefficient of determination
r = coefficient of correlation
S_{gw}= geometric standard deviation of particle diameter by mass (mm)
SS = screen size (mm)
w.b. = wet basis (%)
μ = coefficient of internal friction
μ_s = coefficient of static friction
σ = normal stress (kPa)

Introduction

Alfalfa (*Medicago sativa, L.*) contains digestible fibers and useful range of minerals, vitamins and protein in animal feed (Haiqing, 2004). Alfalfa leaves are high in protein and carotenoids, low in fiber and are useful to feed mono-gastric animals such as poultry and swine or as a protein supplement for ruminant ration. Fiber of alfalfa stems are high and can be used for paper production, ruminant feed, hardboard, and energy production (biofuel/ethanol) (Adapa et al., 2007). Physical and mechanical properties of alfalfa grind are required for optimum design of equipments which are being used in transporting, processing and storage. Measuring the energy requirement for reduction of alfalfa size would be useful in developing the strategies to reduce input energy in process of converting to bio-energy. Particle size, shape, true density, bulk density, moisture content of particles after grinding are important for downstream processing (Manlu et al., 2006). Tabil (1996) obtained consumption of specific energy for alfalfa pellet mill at two hammer mill screen sizes of 2.4 and 3.2 mm using a watt-hour meter with a data logger attachment and sampling time of 15 s. Specific energy consumption of grinding material depends on moisture content, bulk and particle densities, feed rate of the material, particle size distribution (initial/final particle size) and machine variables (Lopo, 2002). Several models such as Kick (Henderson and Perry, 1970), Rittinger (Henderson and Perry, 1970) and Bond (Bond, 1961) have been used to predict the required specific energy consumption for grinding agricultural materials. They explained that size reduction process depends on initial and new surface area. Energy consumption of alfalfa grind may be depends on physical and mechanical properties of biomass, bulk density, cohesion and coefficient of internal friction. Geometric mean diameter and particle size distribution of biomass grind are important factors affecting on binding characteristics. These factors also

Table 1. Geometric mean diameter (GMD) of alfalfa chops and alfalfa grind

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

[a] 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	μ_s	C_a
2.38	0.71±0.01[a]	6.87±0.09	0.26±0.01	1.54±0.32
3.36	0.77±0.01	5.68±0.39	0.26±0.00	1.42±0.16
4.76	0.88±0.01	4.80±0.11	0.27±0.00	1.16±0.09

[a]standard deviation (n=3)

useful in pneumatic conveyors and cyclones design (Mani et al., 2004a). 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). Coefficient of internal friction is a very important factor in design of storage structures. 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 in design of densification equipment and modeling of compression behavior of powder materials (Mani et al., 2004b; Majdi and Rababah, 2007). Tabil and Sokhansanj (1997) reported, with an increase in particle size from 2.4 to 3.2 mm cohesion of alfalfa grind decreased. Mani et al. (2004a) found that with an increase in particle size, adhesion of ground corn stover on galvanized steel plate decreased. Energy consumption for grinding corn stover, rice straw and wheat straw increased with change in screen opening size from coarser to finer (Arthure et al., 1982). The multivariate statistical technique is known as principal component analysis (PCA) is based on calculation of linear combinations between input variables which explain the most variance of the data. Using this method, data can be reduced to a set of new variables called principal components (Johnson and Wichern, 2001). PCA is one of the most widely applied tools in order to summarize common patterns of variation among variables. The loadings of the PCA are defined as the direction of the greatest variability. All the independent variables were subjected to the principal component analysis to evaluate the relationships among them in order to identify the PC associated with the optimal separation of the grain components (Johnson and Wichern, 2001). PCA was performed using statistical software (SAS, V9, 2008 Institute, Cary, NC, USA). With regard to the present considerations, no such effort has been made to obtain correlation between specific energy consumption and some physical and mechanical properties of alfalfa grind. Therefore the objectives of this study were: (1) measuring specific energy consumption for grinding three sizes of alfalfa chops using a hammer mill equipped with three screen sizes; (2) measuring some physical-mechanical properties of alfalfa grind and (3) determination correlation coefficient between specific energy consumption and some physical-mechanical properties of alfalfa grind using principal component analysis method.

Results and discussion

Size distribution

Fig. 2 shows the particle size distribution of alfalfa chops. For alfalfa chop passed through 15 mm sieve (SS_{15mm}) about 52% was retained on sieve #5 (aperture size of 1.18 mm), whereas for alfalfa chop passed through 12 mm sieve (SS_{12mm}) 53% was retained on pan. Geometric mean length (GML) and related standard deviation for alfalfa chops and grinds are presented in Table 1. Fig. 3 shows the particle size distribution of alfalfa grind for four hammer mill screen sizes. The graph depicts skewness of the distribution. Similar results have been reported for peanut hull (Fasina, 2008) and four biomasses namely corn stover, switchgrass, wheat and barley straw grinds (Mani et al., 2004b). The grinds passed through the screen size of 4.76 mm ($SS_{4.76mm}$) had a wider size distribution with a geometric mean diameter of 0.422 mm than the grinds passed through the screen size of 1.68 mm ($SS_{1.68mm}$) (Fig. 3). Wider particle size distribution is suitable for compaction process (i.e. pelleting). During compaction, void space of larger (coarse) particles was filled by smaller (fine) particles and produced denser and durable pellets (Tabil, 1996; Mani et al., 2003). Particle size distribution in a narrow range with more fines due to the generation of more surface area and pore spaces during fine grinding is suitable for enzymatic hydrolysis of lignocelluloses (Mani et al., 2004b). Geometric mean diameter (GMD) and related standard deviation of alfalfa chops and alfalfa grind are reported in Table 1.

Physical and mechanical properties

The bulk density of alfalfa grind increased with a decrease in geometric mean diameter of the grind. Bulk density varied from 179.9 to 161.6 kg m^{-3} when particle size increased from 2.38 to 4.76 mm. Since larger particles are reduced to small particle size, they occupy less volume and finer particles occupy the void spaces, resulting an increase in bulk density (Mani et al., 2004a). 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 increasing screen size from 2.38 to 4.76 mm. The reduction 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.

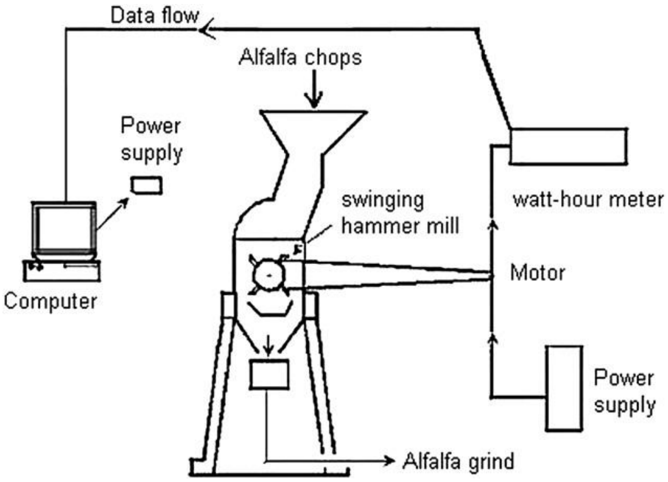

Fig 1. Schematic diagram for power measurement during grinding operation (Ghorbani et al., 2009)

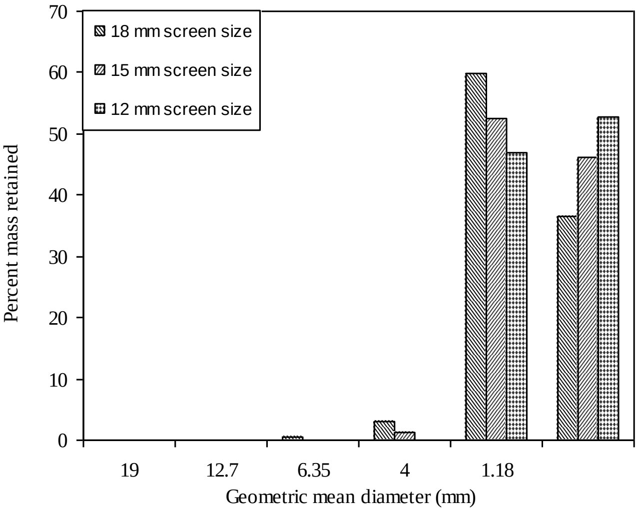

Fig 2. Particle size distribution of alfalfa chops

Energy requirement for grinding

The average specific energy consumption (E_{sc}) for grinding the alfalfa chops is shown in Table 3. Among the three chops sizes, chops from the SS_{18mm} and SS_{12mm} required the highest and lowest E_{sc} for grinding, respectively. As the size of screen on the hammer mill was increased from 2.38 to 4.76 mm, the E_{sc} for grinding of SS_{18mm} chops was decreased by 55%. Comparison of mean values showed a significant difference (P<0.05) between the mean values of E_{sc} at each level of chop, also the highest and the lowest of E_{sc} were obtained when grinding with $SS_{2.38mm}$ and $SS_{4.76mm}$, respectively. In other word, fine grinding requires high E_s. Similar results reported for four biomass namely corn stover, switch grass and wheat and barley straw grinds by Mani et al. (2004b). According to their experiments, E_s for grinding corn stover at moisture content of 6.2% (w.b.) using hammer mill screen sizes of 0.8, 1.6 and 3.2 mm were 79.2, 53.28 and 25.2 kJ kg^{-1}, respectively. A linear relationship between E_s requirement and hammer mill screen sizes for all the three sizes of chops is shown in Fig. 4. The related R^2 values are obtained between 0.93 and 0.99. These results (Fig. 4) proved that the size of hammer mill screen was negatively correlated with E_{sc}, also the highest difference for three sizes of chops was observed after grinding with $SS_{2.38mm}$ whereas any different was not observed when grinding with $SS_{4.76mm}$. This is due to larger size of the screen which caused the similar energy consumption during the grinding of the three sizes of chops. Sitkei (1986) reported a second-order polynomial relationship between the E_{sc} and the mean particle size for alfalfa stem with R^2 value of 0.99. Holtzapple et al. (1989) and Tavakoli et al. (2009) reported that grinding energy greatly increased as the particle size was reduced. Fig. 5 shows a simple linear model between the E_{sc} and the ratio of initial to final size of screens used in size reduction. With increasing ratio of initial to final size of screens, the E_{sc} was also increased. This simple linear model may present as a model for prediction of E_{sc} in milling process. This model is similar to Kick and Rittinger models (Hendersonm et al., 1970).

Correlations between physical and mechanical properties

Table 4 presents the Pearson's correlation coefficients associated with confidence level between physical and mechanical properties. The coefficient of internal friction and coefficient of external friction on polished steel were high significantly correlated (p<0.001) to specific energy consumption (-0.84 and -0.59 respectively). The negative sign means that specific energy consumption increases as coefficient of internal friction and coefficient of external friction on polished steel decreases i.e., high friction coefficients are two important factors in decreasing energy consumption. Crushing or shattering of material in milling process by consecutive hammer impacts, collisions with the walls of the grinding chamber, as well as particle-on-particle impacts, caused high coefficient of internal friction. This is the most important factor in particle-on-particle collisions and high value of external friction coefficient. Correlation coefficients show that the internal friction coefficient had higher effect than the external friction coefficient on specific energy consumption (Table 4). Bulk density and cohesion were positively correlated (p<0.001) to specific energy consumption (r>0.82).

It may be due to materials with higher bulk density and. An increase in cohesion and contact area between the smaller particles caused increase in specific energy consumption, Also results showed that increase in energy consumption occur when the cohesion coefficient was increased. The bulk density was negatively correlated with internal friction coefficient i.e., with an increase in the internal friction coefficient, bulk density decreased. This may be due to higher increase of packing in the larger particles. This phenomenon caused an increase in internal friction coefficient for larger particles. Due to more volume occupation by the larger particles, bulk density decreased. The adhesion on polished steel was significantly correlated (p<0.001) in negative direction with specific energy consumption (r=0.60). The cohesion value was positively correlated with the internal friction coefficient. Correlation coefficient value was 0.94. This value proved that the relation between cohesion and internal friction coefficient is very important. This result indicated that an increase in one of these parameters caused increase in the other parameter. Study of Bijanzadeh et al. (2010) about effect of herbicides on oilseed rape yield and population and biomass of weeds showed that there was a negative significant correlations between oilseed rape and wild mustard (r=-0.73, p<0.01) at 8 weeks after planting.

Table 3. Specific energy consumption (E_{sc}) for grinding alfalfa chops

Sieve opening size (mm)	Geometric mean of chopped sample (mm)	Screen opening size of hammer mill (mm)	Geometric mean of grind sample (mm)	Average E_{sc} (kJ/kg)
18	1.96	2.38	0.336	$16.71^{a} \pm (0.56)^{*}$
		3.36	0.402	$12.36^{b} \pm (0.99)$
		4.76	0.422	$6.96^{c} \pm (0.56)$
15	1.68	2.38	0.336	$14.01^{a} \pm (0.97)$
		3.36	0.402	$10.78^{b} \pm (0.22)$
		4.76	0.422	$6.67^{c} \pm (0.62)$
12	1.53	2.38	0.336	$10.63^{a} \pm (1.15)$
		3.36	0.402	$8.73^{b} \pm (0.42)$
		4.76	0.422	$5.65^{c} \pm (0.71)$

[*] Numbers in the parentheses are standard deviations; in final Column, Means with different letters are statistically different at 5% probability level.

Table 4. Correlation coefficients among physical and mechanical properties

	E	Bd	μ	C	μ_s	C_a
E	1	0.827^{***}	-0.842^{***}	0.829^{***}	-0.593^{***}	0.605^{***}
Bd		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

E_S: specific energy consumption, Bd: bulk density, C: cohesion, μ: coefficient of internal friction, μ_s coefficient of external friction on polished steel and C_a : adhesion on polished steel. ** Correlation is significant at the 0.01 level. *** Correlation is significant at the 0.001 level.

Table 5. Values of coefficient of factorial matrix

Variable (x)	e_1 (r_{pc1}, X_K)	e_2 (r_{pc2}, X_K)	e_3 (r_{pc3}, X_K)
E	0.407 (0.884)	0.238 (0.221)	0.88 (0.403)
C	0.416 (0.903)	0.348 (0.324)	-0.245 (-0.112)
μ	-0.426 (-0.925)	-0.353 (-0.329)	0.3 (0.137)
Bd	0.443 (0.962)	0.104 (0.097)	-0.273 (-0.125)
C_a	0.378 (0.821)	-0.57 (-0.531)	-0.173 (0.0799)
μ_s	-0.372 (-0.808)	0.599 (0.558)	0.001 (0.000)
Eigen-value	4.72	0.87	0.21
Variance (%)	0.787	0.146	0.035
Cumulated variance (%)	0.787	0.933	0.969

E: specific energy consumption, Bd: bulk density, C: cohesion, μ: coefficient of internal friction, μ_s coefficient of external friction on polished steel and C_a : adhesion on polished steel. Number in parenthesis is correlation coefficient variable with respective factor.

Principal component analysis for physical and mechanical properties

Applying of principal component analysis is based on the significant correlations between physical and mechanical properties of alfalfa grind. In addition, the advantage of this method is simple presentation of results without losses of extra information. Based on correlation matrix for each principal component, the software provides the following attributes: eigen value, proportion of total variance (%) and factorial matrix with the coefficients of polynomial expression among principal components and initial variables.

Results of principal components analysis for mechanical and physical properties as well as coefficient of correlation matrix are shown in Table 5 and Fig. 6. The first principle component explains 78.7% of the total sample variance. The first two principle components, collectively explain 93.3% of the total sample variance between all measured variables. Finally, sample variation is summarized very well by two principal components and a reduction in the data from 6 variables to 2 principle components is reasonable. Factor 1, was affected by all the variables and proportion of each variable was similar. Given component coefficients and the first principle component represent a contrast between coefficient of internal and external friction coefficients on polished steel (μ and μ_s) with other variables. This comparison between each two parameters was presented in Table 5. In other word, other parameters caused a negative effect between two these parameters. The correlations of variables with first principle component (rpc1, XK) were presented in Table 5. These values confirmed the relationship provided by the component coefficients. The component coefficients of the second principle component showed that there is a contrast between coefficient of external friction on polished steel (μ_s) and adhesion on polished steel (Ca). Khodadadi et al. (2011) determined genetic diversity of wheat genotypes based on cluster and principal component

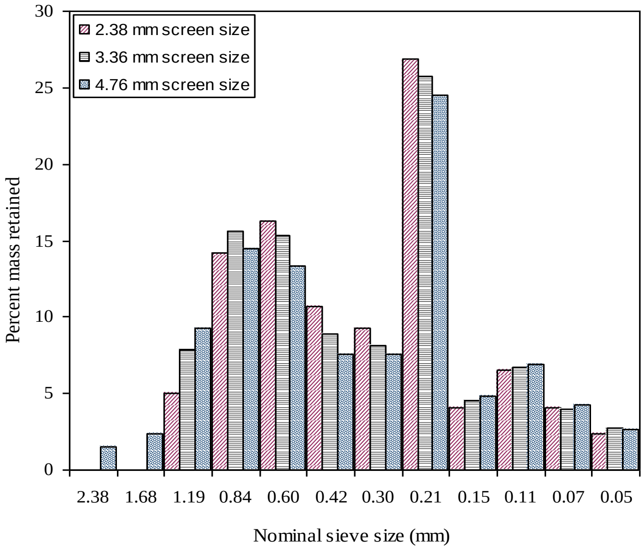

Fig 3. Particle size distributions of alfalfa grind

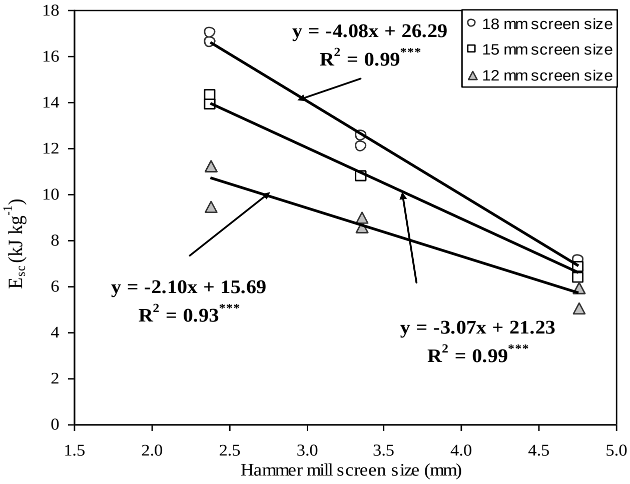

Fig 4. Specific energy consumption (E_{sc}) for grinding three chops sizes, ***: Significant at confidence level of 0.1%

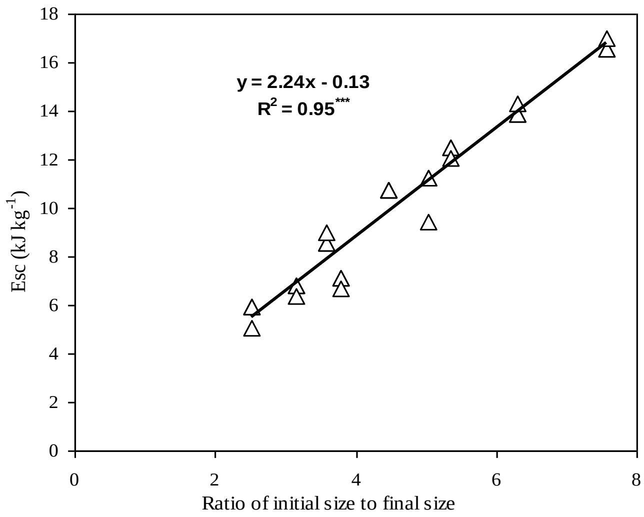

Fig 5. Specific energy consumption (E_{sc}) for combined data. ***: Significant at confidence level of 0.1%

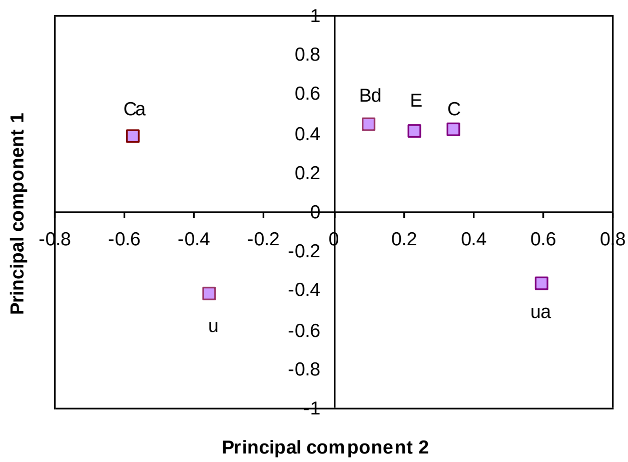

Fig 6. Biplot of the first two principle components

analyses for 36 winter wheat genotypes. Nine components were extracted from the 12 studied traits by PCA analysis. The first five components were explained 97% of genetic variation.

Material and methods

Samples preparation

Rectangular bales of alfalfa were obtained at moisture content of 13.3% wet basis (w.b.) from the Isfahan University of Technology Research Station farm, Iran. Alfalfa bales were chopped using a 45 kW chopper (Machine Brzegar Industrial Products, Hamedan, Iran) equipped with a screen size of 18mm (SS18mm) and operating at 540 rpm and fed at 1.5 t h^{-1}. The alfalfa chops were divided into three portions. The first part was left un-sieved, whereas the second and third parts were passed through the sieve sizes of 15 (SS_{15mm}) and 12 mm (SS_{12mm}), respectively. These parts were chosen based on different parts of alfalfa leaves and stems. The $SS_{18\ mm}$, $SS_{15\ mm}$ and $SS_{12\ mm}$ were contained 36, 46 and 53% leaves. These parts 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 ($SS_{4.76mm}$) were selected to grind the alfalfa chops at moisture content of 8% (w.b.). These sizes are usually used in pelleting process for making poultry and livestock feed.

Particle size distribution

The particle size of alfalfa chops was obtained based on ASAE standard S424.1 DEC01 (ASAE, 2003a) for chops forage materials. Samples of the alfalfa chops were placed into the top screen of the Ro-Tap sieve shaker (Azmon Industrial Products, Tehran, Iran). The experimental sieve sizes were 1, 2, 3, 4 and 5 (nominal openings of 19, 12.7, 6.3, 3.96 and 1.17 mm, respectively). After sieving, the mass retained on each sieve was weighed. Experiments were repeated three times for each chop sample. The geometric mean (d_{gw}) and standard deviation (S_{gw}) of length for the sample were calculated according to ASAE Standard S424.1. Particle size distribution of the grinds after milling was determined according to ASAE Standard S319.3 FEB03

(ASAE, 2003b). About 100 g sample of grinds was placed on the top of a stack of sieves arranged from the largest to smallest opening. Selection of sieve series were carried out based on the range of particles in the sample. For the grinds of $SS_{4.76mm}$, the sieve numbers of 8, 12, 16, 20, 30, 40, 50, 70, 100, 140, 200 and 270 (nominal opening of 2.4, 1.2, 0.85, 0.59, 0.42, 0.30, 0.21, 0.15, 0.01, 0.074 and 0.053 mm, respectively) were used. For grinds of $SS_{3.36mm}$, the sieve numbers of 12, 16, 20, 30, 40, 50, 70, 100, 140, 200 and 270 (nominal opening of 1.2, 0.85, 0.59, 0.42, 0.30, 0.21, 0.15, 0.01, 0.074 and 0.053 mm, respectively) were used. For the fine grinds of $SS_{2.38mm}$, the sieve numbers of 16, 20, 30, 40, 50, 70, 100, 140, 200 and 270 (nominal opening of 0.85, 0.59, 0.42, 0.30, 0.21, 0.15, 0.01, 0.074 and 0.053 mm, respectively) were used. The duration of sieving determined 10 min according to ASAE (2003b). 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

Grain bulk density apparatus was used to measure the bulk density of ground samples (Canadian Grain Commission, 1984). The material were placed on a funnel and dropped at the center of a 0.5 L steel cup, continuously. A rubber coated steel rod was employed to level the cup, gently and then weighed. Bulk density of the grind was obtained using weight per volume in kg m^{-3}.

Coefficients of internal friction, adhesion, and cohesion

In this study, the internal (cohesion and coefficient of internal

$$E_{sc} = \frac{\text{Net input electric energy (kJ)}}{\text{Weight of chopped alalfa (kg)}} \quad (1)$$

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). The shear box had a diameter and height of 63.5 and 20 mm, respectively. The half box was pulled at a constant speed of 0.3 mm min^{-1} in the horizontal direction. The shear force and vertical displacement were recorded using two horizontal and vertical gages, respectively.

The cohesion and coefficient of internal friction (strength parameters) of alfalfa grind with screen sizes of 2.38 and 3.36 mm were determined at moisture content of 9.3% for two different ranges of normal loads. The first normal load range was 4.7, 39.5, 158.3 and 316.6 N and the second was 728.3, 1146.4, 1684.8 and 2425.8 N. The shear box was filled with the sample. The same bulk density was used 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, 633.2 and 1266.4 N). The shear tests were replicated three times for each normal load range. The maximum shear stresses were plotted versus the normal pressures for each grind size. The slope of the best fitted line to the data was considered as the coefficient of friction and the intercept of the line was used as the adhesion (or cohesion) of the sample based on Mohr-Coulomb's model. This model express shear strength as a function of normal stress as follows (Chancellor, 1994; Puchalski and Brusewitz, 1996; Lawton and Marchant, 1980).

$$\tau = \mu_s \sigma + C$$

where τ is the shear stress (kPa), μ_s is the coefficient of static friction, σ is the normal stress (kPa) and C is the cohesion (kPa).

Grinding operation

The alfalfa chops were ground using an electric hammer mill (Equipment Laboratory Engineering, England). Particle size of solid materials has been reduced by shear and impact actions using hammer mill. Schematic diagram of the hammer mill which used for grinding alfalfa chops is presented in Fig. 1. It included three swinging hammers, attached to a shaft powered by a 1.1 kW electric motor. The shaft rotated at a speed of 360 rpm. A tapered hopper (with 123 small diameter, 320mm large diameter and 300mm height) was used at the inlet of the apparatus. Since the alfalfa chops were very light and did not flow freely through the hopper, in order to keep continuous flow of the alfalfa 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) for measuring energy consumption in grinding operation. The watt-hour meter was connected to a data logging system. This device was connected to a computer and time-power data was stored. The no load energy values (approximately 4275J) were subtracted from the measured values during grinding. The specific energy consumption for grinding was determined by integrating the area under the power demand curve for the total time required to grind a sample. The hammer mill was started and then a known quantity of alfalfa chops was fed into the hammer mill. Time required 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 (E_{sc}) during milling process was expressed as:

Correlations in multiple- variable analysis

Relationships between some physical and mechanical properties and specific energy consumption obtained from the matrix of Pearson's correlation coefficient (r). This coefficient as well as the *p*-value for the correlation was obtained using the SAS software. The Pearson's coefficient is a correlation index between X and Y variables, also the tendency measure of these variables to decrease or increase together. The value of the coefficient varies from -1 to 1. Value of 1 suggested that there is a linear and positive relation between both variables, whereas a value -1 indicates that the liner correlation between X and Y is negative, e.g. as X increase, Y decreases.

Conclusions

The following conclusions can be drawn from this study:

1. The specific energy consumption was increased when screen opening size was decreased from 4.76 to 2.38 mm.
2. The specific energy consumption with respect to the ratio of initial to final size of screens fitted well using a linear model with a determination coefficient R^2=0.95 and MSE=2.66.
3. Internal and external friction coefficients on polished steel were high significantly correlated ($p<0.001$) to specific energy consumption (-0.84 and -0.59 respectively).

Cohesion and internal friction coefficient were positively correlated with correlation coefficient of 0.94.

4. The first two principle components, collectively explain 93.3% of the total sample variance between all measured variables. Factor 1, was affected by all the variables and influence of each variable was similar.

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