Customized and Value-added High Quality Alfalfa Products: A New Concept

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ABSTRACT

This article presents a comprehensive summary of research performed in the area of postharvest fractionation and processing of alfalfa crop. The aim was to develop alfalfa products that could cater to diverse demands of the market as well as improve their quality. A novel process of fractionation (separation of leaves and stems) was explored to improve dehydrated and sun-cured alfalfa pellet and cube quality. Fractionation and dehydration of alfalfa was achieved by modifying a small-scale industrial three-pass rotary drum dryer. Fractionated leaves and stems were later combined in different proportions and densified to form pellets and cubes. Various physical characteristics such as density, hardness, durability and colour of pellets and cubes were determined. Regression equations were derived by considering these physical characteristics as dependent variables, while leaf content, grind size (for pellets), chop pre-heat temperature (for cubes), moisture content, applied pressure, die temperature and holding time were the independent variables. Studies were also conducted to determine volatile organic compounds (VOCs) emitted during industrial drying of alfalfa crops as a function of drying temperature, time and specific plant fractions (leaf, stem or flower).

Keywords: Alfalfa, fractionation, dehydrated, sun-cured, pellets, cubes, rotary drum dryer, volatile organic compounds (VOC), pellet mill, hardness, durability, colour, density.

1. INTRODUCTION

From fresh alfalfa plants in the field to a processed forage product for consumption, alfalfa undergoes various stages of processing to attain final customized product form such as pellets and cubes. The chain of processes includes harvesting, drying and densification of alfalfa.

Drying is an important operation in the forage processing industry. It is one of the important operations that controls the quality and cost of the final product. Dried alfalfa can be obtained in two different forms: 1) sun-cured alfalfa; 2) dehydrated alfalfa. Sun-cured and dehydrated alfalfa chops differ with each other in their postharvest processing methods. To obtain sun-cured alfalfa, the crop is harvested and left in the field to dry under sun. Sun-cured alfalfa is than baled and brought to the processing plant, where they are stored and later chopped using tub grinders and dried to the final moisture content using low temperature rotary dryer and further subjected to processing. On the other hand, dehydrated alfalfa chops are obtained from alfalfa plants that are cut and chopped simultaneously in the field during harvesting (using special harvesting machines) and dried in high temperature rotary drum dryers (fig. 1).

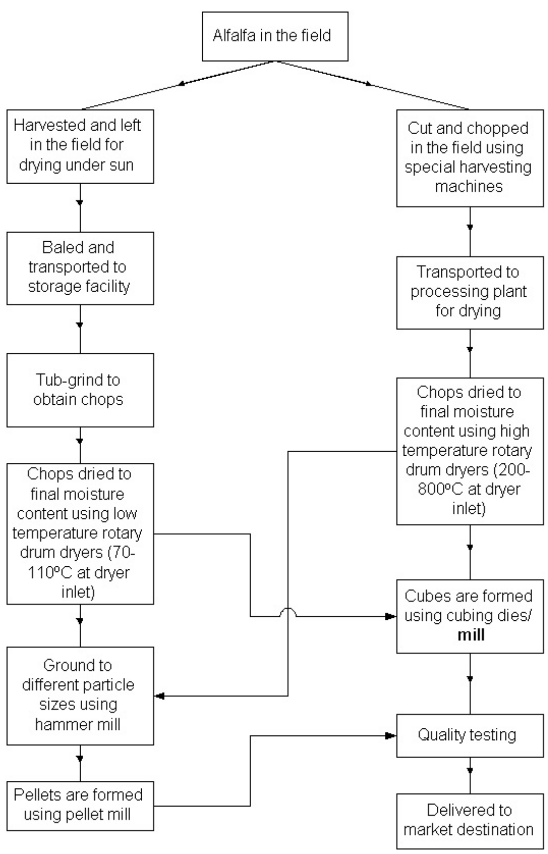

Figure 1. Block diagram for alfalfa drying and processing.

The Canadian forage industry suffers a competitive disadvantage because of the need for high-temperature artificial drying due to climate and seasonal constraints. High-temperature drying is typically done in rotary drum dryers, where air temperatures are maintained in the range from 200°C to 800°C (392°F to 1500°F) at the inlet to 60°C to 95°C (140°F to 210°F) at the outlet (Adapa *et al.*, 2004a; Sokhansanj *et al.*, 1998). Pneumatic drying/conveying in a rotary drum dryer does not closely control heat and holding time resulting in under-dried stems and over-dried leaves. This results in loss of nutritious leaf fractions. A uniform moisture content of the dried product is necessary for good quality alfalfa products, because it influences the mechanical stability during handling. During drying, it is especially important not to over-dry and possibly burn the leaves of alfalfa chops as this result in the generation of smoke, odour and increased particulate emission beside the loss in product quality (Adapa *et al.*, 2004a; Khoshtaghaza *et al.*, 1995; Sokhansanj *et al.*, 1996; Tabil *et al.*, 1996).

The process of fractionation could be a potential solution for the abovementioned problem. In this project, fractionation is the term applied to the separation of alfalfa into two or more component parts (usually leaves and stems). This process enables a later, controlled recombination of these components to achieve specific market nutritional requirements for animal feeds or the potential use of the more valuable leaf material in the rapidly expanding neutraceutical and herbal markets. Leaf meal can be used as poultry and swine feed, protein supplement for ruminants or in the pharmaceutical industry for human consumption. Stems are high in fibre and can be used to feed ruminants, feedstock for paper and hardboard manufacturing and energy production (biofuel/ethanol) (Koegel and Straub, 2000). The aim is to increase crop usefulness and create products that can more than offset the cost of processing. Fractional drying of alfalfa leaves and stems is required because alfalfa leaves and stems dry at significantly different rates resulting in over-dried leaves and under-dried stems (Adapa *et al.*, 2004a; Arinze *et al.*, 2003; Bilanski *et al.* 1989; Bilanski, 1992; Menzies & Bilanski, 1968).

Besides drying of alfalfa chops, handling, storage and transportation of low bulk density alfalfa crop to market destination, are major concerns. Densification of alfalfa is an effective solution to these problems and can reduce material waste. Densified alfalfa may appear in various product forms such as pellets, cubes and compressed bales (Hill and Pulkinen 1988; Tabil and Sokhansanj, 1996a).

Ground alfalfa is densified in a pellet mill to make pellets. The densified pellets results in lower transportation and storage costs especially for export. Breakage susceptibility of pellets during handling is a major concern. It has been reported that 20% to 30% losses in the form of fines are found in bulk product at the user level (Adapa *et al.*, 2004b). Testing and, if required, improving the durability of pellets is important for the industry to evaluate pellet quality and minimize losses during handling and transportation. Besides durability of pellets, colour of the final pelleted product determines their marketable value. Colour is one of the primary considerations in the quality evaluation of fresh food and feed products (Patil *et al.* 1994; Sokhansanj *et al.* 1994; Walton, 1983).

Cubes are preferred over pellets in the cattle and dairy industry as they contain more intact fibres, which are good for digestion and reduce bloating (Adapa *et al.*, 2005a; Sokhansanj *et al.*, 1996). Compressed bales could be a better option; however, transportation cost overseas is high because of their low bulk density compared to cubes. Alfalfa cubes are composed of chopped leaves and stems compressed into a block, typically 30 x 30 mm in cross-section.

Cube quality is an important parameter in the manufacture and marketing of alfalfa products. Desirable qualities of an alfalfa cube include: a natural green colour, a high content of long fibres, high durability and palatability/hardness. Colour is associated with the nutritional quality of a cube and has been used as an unofficial grading criterion (Adapa *et al.*, 2005a; Sokhansanj *et al.*, 1996; Tabil and Sokhansanj, 1996). Therefore, the preservation of green colour in forage during processing and storage is important.

The main objective of this research was to develop an innovative approach for artificial drying of chopped alfalfa leading to the separation of leaf and stem fractions. The long term goals of such an approach were to minimize objectionable odours due to over-drying and high product temperatures, minimize volatile organic compound (VOCs) emissions from the processing plant and produce high quality fractionated products (for both dehydrated and sun-cured alfalfa) with good colour, odour and storage stability. A number of sub-objectives were defined to achieve customized and value-added high quality alfalfa products. They are:

i) to achieve both drying and aerodynamic separation (fractionation) of chopped alfalfa into leaves and stems in a single operational step, using a small industrial three-pass rotary drum dryer;
ii) to improve and establish relationships for pellet quality and investigate the pelleting characteristics of grinds in terms of change in pellet density, hardness, durability and colour with variation in grind size and leaf content of sun-cured and dehydrated alfalfa chops;
iii) to improve and establish relationships for cube quality and investigate the effect of chop moisture content, leaf-to-stem ratio, chop preheat temperature, cubing die temperature, applied pressure and chop holding time, on the cubing characteristics of sun-cured and dehydrated alfalfa chops; and
iv) to establish relationships between the volatile organics compounds (VOCs) emission from alfalfa as a function of drying temperature, time and specific plant fractions (leaf, stem or flower).

This article presents comprehensive summary of research performed in the area of postharvest fractionation and processing of alfalfa crop. It is organized in five sections (excluding abstract and conclusions). The second section is about experimental and procedural description of aerodynamic separation and fractional drying of alfalfa into leaves and stems using a small-scale industrial three-pass rotary drum dryer. In addition, performance characteristics for leaf and stem separation were established. A computer model of drying process was developed and simulation results were compared with experimental values. Section three deals with pelleting of fractionated sun-cured and dehydrated alfalfa grinds using a single pelleting unit and pilot-scale pellet mill. Various physical characteristics such as density, hardness, durability and colour of pellets were determined. Regression equations were developed to predict these characteristics. Section four is about determining and predicting cubing characteristics of fractionated sun-cured and dehydrated alfalfa chops using a single cubing unit. Physical characteristics include density, hardness, durability and color of cubes. In addition, specific energy to form cubes at various condition was determined. Statistical models were developed to predict cube physical characteristics and specific energy. Finally, the fifth section presents a study on VOCs emitted during high temperature alfalfa drying conducted on exhaust gases from laboratory scale flow reactor and industrial rotary drum dryers. Effects of drying temperature, drying time and plant fractions were determined using laboratory experiments and later compared with field results from industrial dryers.

2. AERODYNAMIC SEPARATION AND FRACTIONAL DRYING OF ALFALFA INTO LEAVES AND STEMS USING A THREE-PASS ROTARY DRUM DRYER

2.1 The Rotary Drum Dryer

A new approach is presented for combined aerodynamic separation and drying of alfalfa leaves and stems. This was accomplished through relatively simple modifications to an existing small industrial three-pass rotary drum dryer (Vincent Corp., Tampa, FL) Model VVD25SIDEHR (Adapa *et al.*, 2005b). The dryer consists primarily of a direct fired propane gas burner, a feed inlet for the wet material (leaves and stems), three concentric drums (inner, middle and outer (stationary)), two outlets (with sliding doors) on the outer drum for removing relatively dry and heavier material (stems), and a cyclone at the end of the drum to collect light material (leaves). The premise behind our concept is that as the chops pass through a rotary drum dryer, the heavier, mostly stem material, will gravitate towards the outer surface of the drum but the lighter material consisting mostly leaves will tend to remain airborne. The rotary dryer was modified to enable the stems to be collected at the outer drum exit. The lighter leaf material is conveyed pneumatically to the cyclone separator and collected. The lighter material from the drum outlet passes through a cyclone to be separated from the gas stream. The material collected at the cyclone is conveyed to a cyclone exit port by a screw conveyor. The circulating gas and fine particles exit through the fan outlet. For details regarding instrumentation, refer to (Adapa *et al.*, 2005b).

2.2 Experimental Procedure

A series of experiments under different operating conditions were performed to establish the optimum process conditions leading to maximum separation efficiency and leaf purity. The operating variables used during experimentation were the outer drum end gate opening area, material feed rate, gas flow rate and gas temperatures at the drum inlet. The initial moisture content of the alfalfa was determined using ASAE Standard S358.2 (ASAE, 2000). After the drying and separation process, the material was collected at the drum outlet port (mostly stems) and cyclone exit (mostly leaves). The material was subjected to a square sieve analysis (forage particle separator ASAE Standard S424.1, 1999) to determine the quantity of stems and leaves at each outlet. A stack of two sieves was used along with the pan to achieve leaf and stem separation. The nominal opening sizes of the two square sieves were 3.96 mm and 1.17 mm. The material on 3.96 mm sieve was called stems and the material in the pan was called leaves. Leaves could have also contained fine broken stems. The overs on the 1.17 mm were discarded.

2.3 Parameters for Characterizing Stem-Leaf Separation

It is expected that during drying of chopped alfalfa, mostly stems will be collected at the drum exit and mostly leaves will be collected at the cyclone exit. It is important to establish the parameters that can quantify fractionation (stem-leaf separation) process at the drum and cyclone exit. The terms separation efficiency and leaf purity were defined to assess the success of fractionation (Adapa *et al.*, 2005b; Bilanski *et al.*, 1989; Chrisman *et al.*, 1971). Separation efficiency of leaves (η_l) (eq. 1) depends on the amount of leaves collected in the cyclone exit relative to the total amount of leaf present in the material stream entering the dryer. The separation efficiency of stems (η_s) at drum exit is similarly defined (eq. 2).

$$\eta_l = \frac{W_l}{W_l + G_l} \times 100 \quad (1)$$

$$\eta_s = \frac{G_s}{G_s + W_s} \times 100 \quad (2)$$

Where, η is the separation efficiency in %; W is the mass of material at cyclone exit in kg; and G is the mass of material at drum exit in kg. Subscripts *l* and *s* represents leaf and stem fractions, respectively.

A 100% separation efficiency for leaves can be achieved when all the leaves in the fresh material fed into the dryer are collected at the cyclone exit. However, practically it may be possible to achieve high leaf separation efficiency at the cyclone exit while at the same time capturing relatively large quantities of stems at the cyclone. A new term, leaf purity was defined to quantify the proportion of leaves collected at the cyclone. A leaf purity of 100% can be achieved when only leaves and no stems are collected in the cyclone. Purity for stem and leaf components are defined in fractional form as:

$$P_l = \frac{W_l}{W_l + W_s} \times 100 \quad (3)$$

$$P_s = \frac{G_s}{G_s + G_l} \times 100 \quad (4)$$

Where, P is the purity of component in %.

It is important to note that neither separation efficiency nor purity, considered in isolation, measures the performance sufficiently to characterize the quality of the separation process. For example, it may be possible to achieve very high leaf purity at the cyclone exit while capturing only an insignificant amount of the total material flow (very low separation efficiency). In an ideal process, leaf separation efficiency and leaf purity would have a value of 100% (i.e. all leaf material present in the stream end up in the cyclone and all the stem material is collected at the drum exit).

2.4 Experimental Results

Adapa *et al.* (2005b) interpreted results for leaves; however, similar results can be deduced for stems. The experimental results indicated that the outlet moisture content, separation efficiency and leaf purity during fractionation were affected by the outer drum end gate opening area, material feed rate, gas flow rate and gas temperature at the drum inlet. Leaf purity decreased and separation efficiency increased with a decrease in dryer drum end gate opening area. There was no change in leaf purity, however, a decrease in separation efficiency was observed with an increase in material feed rate. On the other hand, leaf purity increased and separation efficiency decreased with a decrease in gas flow rate. The decrease in separation efficiency was most significant at low gas flow rates. No change in leaf purity was observed, however, separation efficiency decreased with a decrease in gas inlet temperature. The highest separation efficiency of 89% was achieved when the drum end gate was 25% open, material feed rate of 42 kg h^{-1}, average drum inlet gas temperature of 421^{o}C and a gas mass flow rate of 0.39 kg s^{-1} were used. The highest leaf purity of 100% was achieved when the drum end gate was 50% open, material feed rate of 43 kg h^{-1}, average drum inlet gas temperature of 404^{o}C and a gas mass flow rate of 0.22 kg s^{-1} were used. Lowering stem moisture levels to an acceptable level of 8% resulted in over-drying of the leaves, leading product quality loss. In all of the experiments, the leaf fraction collected at the cyclone exit had a relatively lower moisture content compared to stems collected at the drum exit (typically 3 to 5 times). This was primarily due to the difference in their structure (surface area and thickness) and aerodynamic characteristics. Ideally, the moisture content of the material collected at the drum and cyclone exits should be same (~ 7-8%) for safe storage. It was determined that the relative difference in moisture levels of stems and leaves at the drum and cyclone exit, respectively, can be averted by re-circulating in the order of 20% of the wet material (stems) from the drum exit back through the dryer inlet. However, this did reduce separation efficiency but not leaf purity. These results show that re-circulation has considerable potential in forage drying and processing, and can be exploited to obtain near uniform drying for forage components.

2.5 Simulation Results

Basic laboratory information on drying and aerodynamic characteristics of whole alfalfa and components are available in the literature. A few field and experimental drying tests (such as those presented above) on specific rotary drum dryers and materials have also been conducted. However, there is a general lack of information on temperature, moisture content, liquid phase changes and aerodynamic separation of solid particles during their movement through a rotary drum dryer. These changes affect the quality and aerodynamic separation characteristics of dried alfalfa components and consequently the quality of the final processed or value-added product. Sampling materials at various intervals along the drum dryer to obtain such information during drying and separation process is extremely difficult and has not been successfully done in rotary drum dryers. Only materials at the inlet and outlet ports can be readily sampled.

To obtain the needed information on physical changes and separation of alfalfa components during rotary drum drying, a mathematical simulation model was developed based on heat and mass balances and transfer rates, as well as experimentally derived aerodynamic characteristics related to separation of stems and leaves (Arinze *et al.*, 2007a). The schematics of the model and inputs and outputs for an elemental or differential control volume of the dryer are shown in Figures 2 and 3.

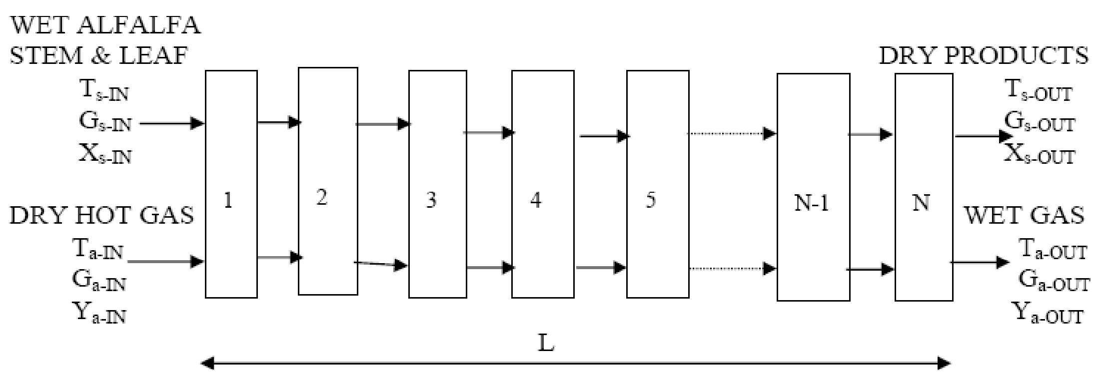

Figure 2: Elemental control volume of the dryer (T, G, X and Y represents temperature, mass flow rate, moisture content and humidity ratio, respectively. Subscripts 'a' and 's' are for gas and solid fractions. L is the dryer length)

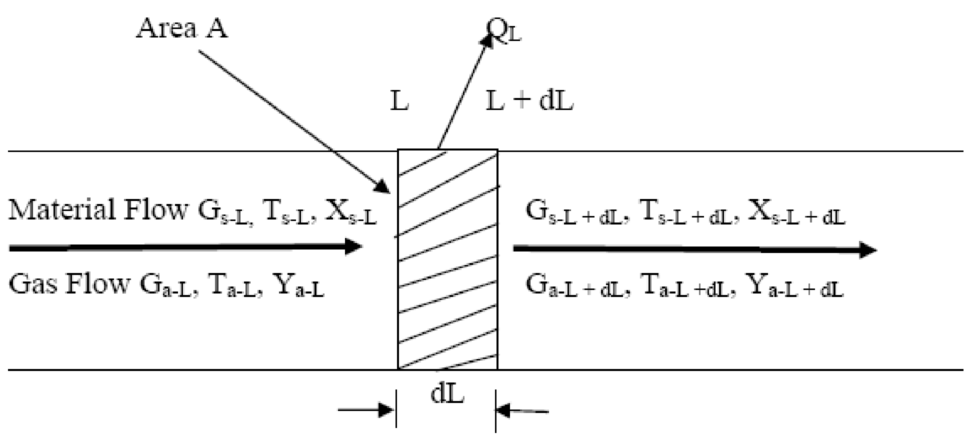

Figure 3: Differential control volume of the dryer (A is the cross-sectional area of the dryer; Q_L is the heat loss through the dryer wall; dL is the differential layer).

For each of the N differential volumes or elements the heat and mass transfer under steady-state conditions for gas and each of the solid components (alfalfa chops, leaves and stems) are provided in eqs. (5) to (8). In these system simulation equations, the independent variable is the space location and the total length for the simulation is the dryer length L. The dependent variables are the gas temperature and moisture content (humidity ratio), T_a and Y_a, and solid fraction (alfalfa chops, stems or leaves) temperature and moisture content, T_s and X_s. The drying rate 'k' is a material property, which is dependent on the drying gas temperature. The other variables, volumetric heat transfer coefficient U_v, solid fraction velocity V_s, latent heat of vaporization h_{fg}, specific heats C_a, C_v, C_{ps}, C_{pw}, dryer free cross-sectional area A, heat loss through the dryer wall Q_L, gas flow rate G_a, and solids feed flow rate G_s, are either constants or related in some ways to the dependent variables. The differential layer dL is sufficiently thin so that the properties of the materials are assumed constant within the short time interval Δt from the inlet to outlet of the layer. For further details, please refer to Arinze *et al.* (2007a).

$$\frac{dX_s}{dL} = -\frac{k}{v_s} \tag{5}$$

$$\frac{dY_a}{dL} = \frac{G_s k}{G_a v_s} \tag{6}$$

$$\frac{dT_s}{dL} = \frac{U_v A(T_a - T_s) + \frac{G_s h_{fg} k}{V_s} - Q_L}{G_s(C_{ps} + C_{pw} X_s)} \tag{7}$$

$$\frac{dT_a}{dL} = \frac{\frac{C_v G_s (T_a - T_s) k}{v_s} - U_v A(T_a - T_s)}{G_a(C_a + C_v Y_a)} \tag{8}$$

The model was programmed in FORTRAN and used to predict the performance of a rotary drum dryer with combined fractions and component separations. The model was validated by comparing model predicted results with measured experimental and field test data obtained from the small industrial rotary drum dryer and a full-scale industrial dryer located in Tisdale, Saskatchewan, Canada. Changes in leaf, stem, and drying gas moisture contents and temperatures were measured and predicted by the model under various drying conditions. The model predicted results agreed closely with the experimental data (fig. 4 and 5). The model was also used to simulate the performance of industrial-type rotary drum dryers under various design and operating conditions. Optimum drying temperature using the small industrial rotary drum dryer was found to be around 300^{o}C for the best level of feed rate of 40-50 kg h^{-1}. Higher feed rates of about 9000 kg h^{-1} are used in full-scale industrial dryers where the optimum drying temperature was found to be 800-900^{o}C.

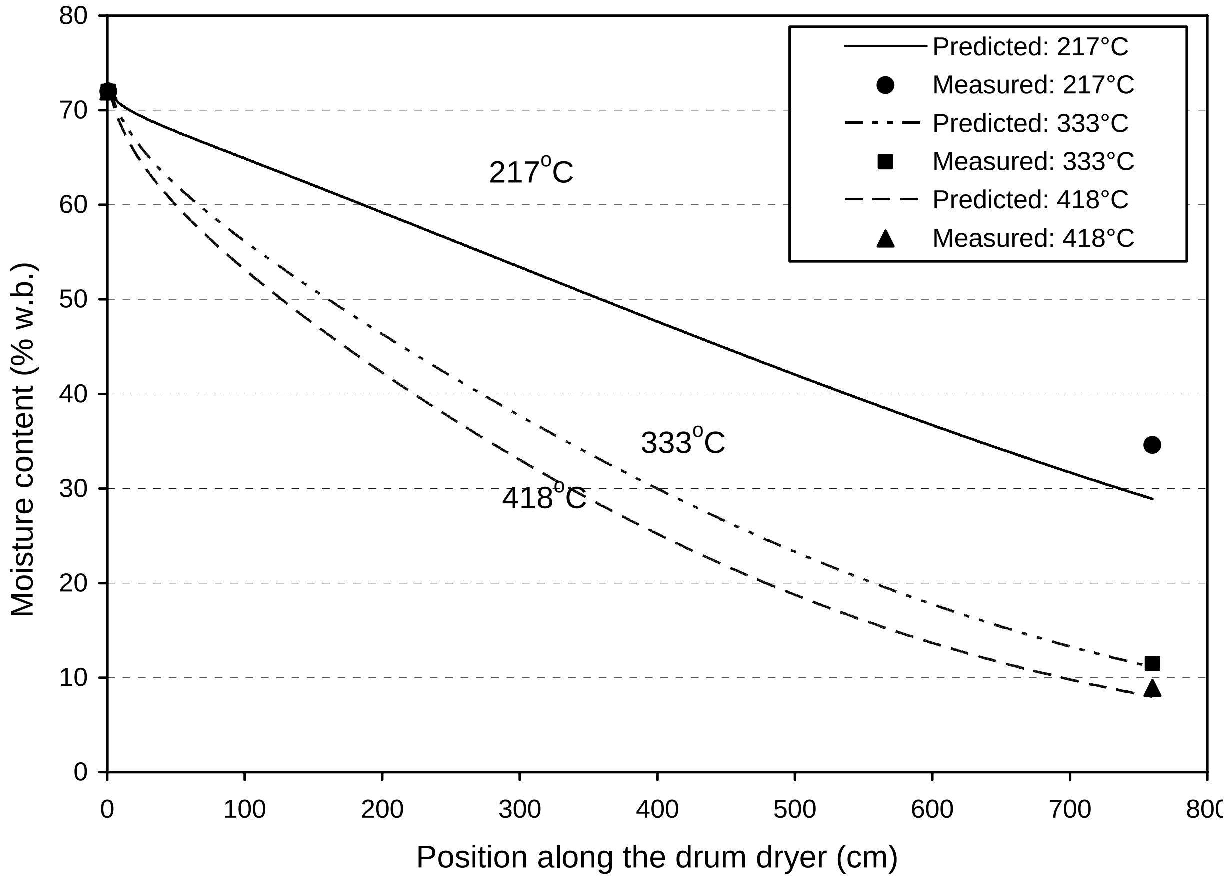

Figure 4: Predicted and measured effects of drying temperature on alfalfa stem moisture content in the small industrial rotary drum dryer with alfalfa chops initial moisture content of 72% w.b., feed rate of 0.039 kg s^{-1} and dry gas mass flow rate of 0.39 kg s^{-1}

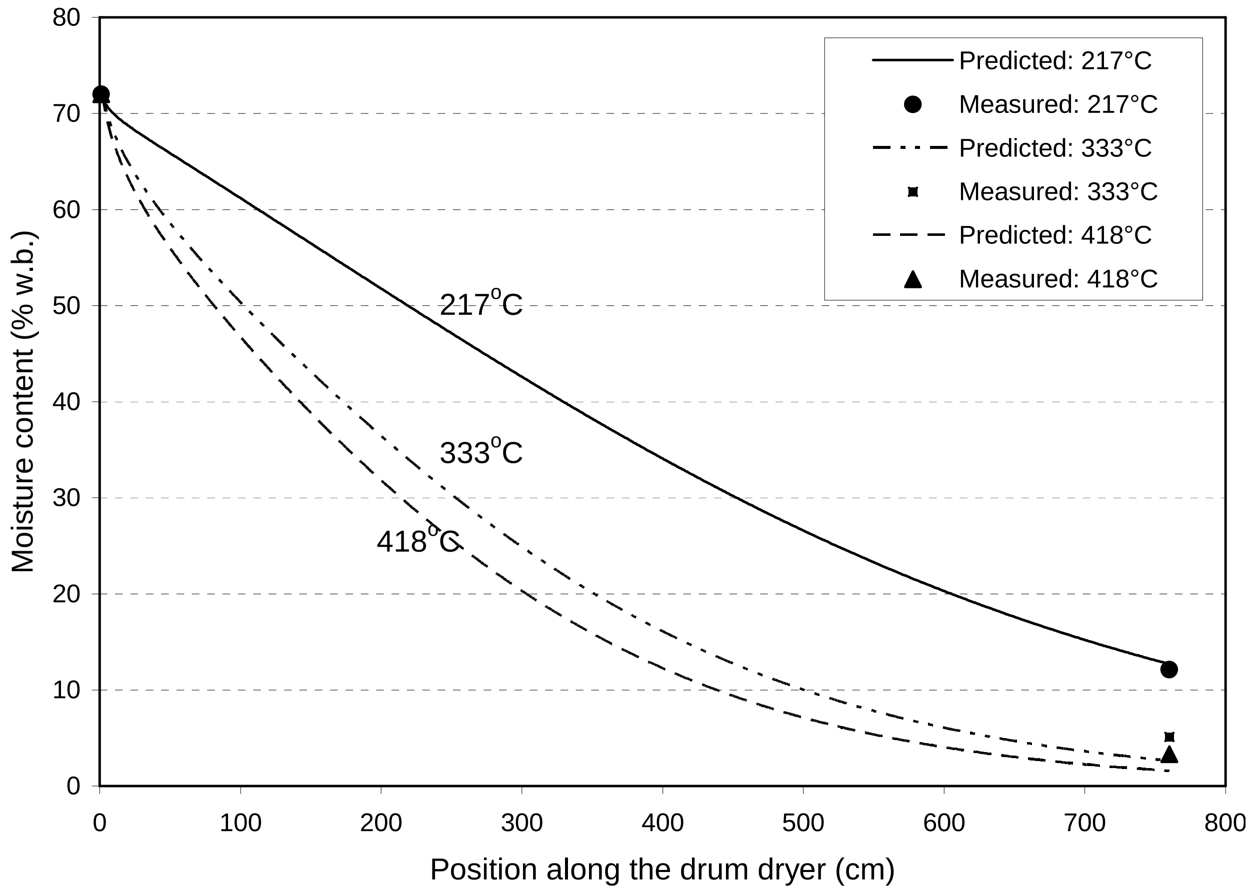

Figure 5: Predicted and measured effects of drying temperature on alfalfa leaves moisture content in the small industrial rotary drum dryer with alfalfa chops initial moisture content of 72% w.b., feed rate of 0.039 kg s^{-1} and dry gas mass flow rate of 0.39 kg s^{-1}

The validated model was extended for simulation of energy consumption for a rotary drum dryer with or without recirculation of partially dried moist particles (mostly stems) (Arinze *et al.*, 2007b). Predicted energy consumption results also agreed well with measured data obtained from the small rotary drum dryer and the full-scale industrial dryer. The extended model was used to simulate the energy consumption in industrial-type rotary drum dryers to determine important energy consumption parameters such as energy savings by recirculation, energy efficiency, thermal efficiency, outlet moisture contents of stems and leaves, and drying uniformity index. Recirculation in rotary drum dryers was found to be beneficial since it leads to a significant energy savings (up to 35%) and greater uniformity in the final moisture contents of stems and leaves.

The model with the extension is useful in obtaining optimum drying and aerodynamic separation and energy consumption parameters, and in the design and redesign of new and existing industrial-type rotary drum dryers.

3. PELLETING OF FRACTIONATED SUN-CURED AND DEHYDRATED ALFALFA GRINDS

One of the major concerns of the forage processing industry is the handling, storage and transportation of the low bulk density alfalfa crop to the market destination, where it is stored or consumed. Densification of alfalfa into durable pellets is an effective solution for the abovementioned problems and can reduce material wastage. Pellet quality is an important parameter in the manufacture and export of alfalfa products. High quality pellets can be produced by the control of the manufacturing operations.

Previous studies have been done on the effect of various control parameters for pellets made from whole alfalfa (which is typically about 50% leaves). However, no work has been reported on the effect of different leaf/stem ratios on pellet quality. More research information on this aspect can open new avenues and potential markets for the forage processing industry.

3.1 Single Pelleting Unit

A close fit cylindrical plunger (6.3 mm in diameter) and die assembly (135.3 mm long and 6.35 mm in diameter) maintained at a temperature of 95-100^{o}C was used to manufacture one pellet in a single stroke of the plunger (Adapa *et al.*, 2002). A layer of copper foil along with a heating element was wrapped on the outer surface of the die to provided uniform heating. The heating element was controlled by a temperature controller. Two type "T" thermocouples were used to measure the die temperature, each located at the top and bottom of the die. A protective cover of fibre glass insulation was used on top of the heating element and die to prevent convective heat loss. The pellet die was fitted on a stainless steel base having a hole matching its outer diameter. This gave stability and allowed the plunger to move straight down with no lateral movement. The plunger was attached to the upper moving crosshead of the Instron Model 1011 testing machine (Instron Corp., Canton, MA).

3.1.1 Pelleting Experiments

Experiments were performed to study compression behaviour of alfalfa grinds subjected to different pressures using the single pelleting unit, which can make one pellet in a single stroke under controlled conditions (Adapa *et al.*, 2002). One year old frozen alfalfa was used due to the unavailability of fresh alfalfa during winter of 2002. Frozen leaves and stems were separated manually and immediately stored in plastic bags to avoid any moisture loss. Initial moisture content of fractionated (separated) alfalfa leaves and stems was 67.8% and 62.2%, respectively. Both alfalfa leaves and stems were further segregated into two sample lots and dried down to 8-9% (wet basis (wb)) and 13-14% (wb) moisture content using a forced-air thin layer dryer. The fractions at two moisture levels were ground in the precision grinder using a screen size of 3.2 mm and mixed into sample lots ranging from 0% leaves to 100% leaves in 25% increments by mass. Compressive forces were applied using the Instron testing machine fitted with a 5000 N load cell. Five preset loads of 500, 1000, 2000, 3000 and 4400 N with respective pressures of 15.8, 31.6, 63.2, 94.7 and 138.9 MPa, were used to compress samples in the die.

3.1.2 Physical Characteristics of Alfalfa grinds

Sieve analysis of ground sample lots ranging from 0% leaves to 100% leaves in 25% increments by mass resulted in particle sizes of 0.435, 0.423, 0.424, 0.406 and 0.387 mm, respectively (Adapa *et al.*, 2002 & 2006c). The geometric mean particle diameters decreased with an increase in leaf content, although, the decrease in particle size is insignificant ($P > 0.05$). Alfalfa stems contain more fibrous material than leaves; therefore, grinding of fibrous material is difficult and may have resulted in coarser ground particles.

Negligible change in particle and bulk densities (Table 1) was observed with an increase in leaf content (Adapa *et al.*, 2002 & 2006c). The particle and bulk densities obtained for samples at 8-9% moisture content (wb) were higher than 13-14% moisture content (wb), possibly due to the increase in particle volume of swollen ground leaves and stems at higher moisture content. The particle and bulk densities of the sample at 0% leaf content and 8-9% moisture content had remarkably low values (compared to other leaf content samples at 8-9 % moisture content). The reasons could be lower material moisture content and the presence of fibrous particles, which are difficult to grind and of larger particle sizes.

Table 1. Particle and bulk densities of ground alfalfa sample lots for different leaf content at two moisture levels of 8-9 and 13-14% moisture content.

Leaf content (%)	Moisture content 8-9% (wb)		Moisture content 13-14% (wb)	
	Particle density (kg m^{-3})	Bulk density (kg m^{-3})	Particle density (kg m^{-3})	Bulk density (kg m^{-3})
0	1167	250	1219	217
25	1334	263	1164	217
50	1316	284	1237	207
75	1352	289	1225	206
100	1391	297	1214	192

3.1.3 Pellet Density Prediction

The compression characteristics of fractionated alfalfa grinds were investigated. Alfalfa grinds vary in their response to the compression forces/pressures during pelleting. To a great extent, the strength of manufactured pellets depends on the physical forces that bond the alfalfa particles together (Tabil and Sokhansanj, 1996b). These physical forces come in three different forms during pelleting operations: a) thermal; b) mechanical; and c) atomic forces. The pelleting experiments were completed using a single pelleting unit and a pellet mill. Pellets were formed by subjecting alfalfa grinds to high pressure, wherein the particles are forced to agglomerate. Compaction of grinds is usually achieved in three stages. In the first stage, particles rearrange themselves under low pressure to form close packing. During the second stage, elastic and plastic deformation of particles takes place allowing them to flow into smaller void spaces increasing inter-particle surface contact area. Finally, under high pressure the second stage of compaction continues until the maximum density of particles is reached. During this phase, the particles may reach their melting point forming very strong solid bridges (Ghebre-Sellassie, 1989).

Ground particles behave in different manner under different pressures. Therefore, experiments were conducted to study the changes in compact density and volume under different pressures. Five compaction models: Heckel, Walker, Jones, Cooper-Eaton and Panelli-Filho, were fitted to the pressure-density or pressure-volume data (Adapa *et al.*, 2002; Cooper and Eaton, 1962; Heckel, 1961; Jones, 1960; Panelli and Filho, 2001; Walker, 1923). Among the five compression models studied, the Cooper-Eaton model (eq. 9) had the best fit for the experimental data obtained from all samples at 8-9% moisture content, while the Heckel (eq. 10) and Panelli-Filho (eq. 11) models had the best fit for experimental data obtained from the samples at 13-14% moisture content. It was also concluded that the sample lots of 100% leaf at 8-9% moisture content and 50% leaf at 13-14% moisture content were easier to compress under any applied pressure.

$$\frac{V_0 - V}{V_0 - V_S} = a_1 . e^{-\frac{k_1}{P}} + a_2 . e^{-\frac{k_2}{P}} \tag{9}$$

where,

a_1 and a_2 constants,
k_1 and k_2 constants,
P applied pressure, MPa,
V volume of compact at pressure P, mm^3,
V_0 volume of compact at zero pressure, mm^3, and
V_S void free solid material volume, mm^3

$$\ln\left(\frac{1}{1-\rho_f}\right) = mP + b \tag{10}$$

where,

$$b = \ln\left(\frac{1}{1-\rho_0}\right), \text{ and}$$

$$\rho_f = \frac{\rho}{\rho_1 x_1 + \rho_2 x_2}$$

b and m constants,
P applied pressure, MPa,
x_1 and x_2 weight fraction of components of the mixture,
ρ bulk density of compact powder mixture, kg m^{-3},
ρ_0 relative density of powder mixture, kg m^{-3},
ρ_1 & ρ_2 particle density of components of the mixture, kg m^{-3},

The constants b and m are determined from the intercept and slope, respectively, of the extrapolated linear region of the plot of ln(1/(1- ρ_f)) vs P.

$$\ln\left(\frac{1}{1-\rho_r}\right) = A\sqrt{P} + B \tag{11}$$

where, ρ_r is the relative density of the compact, A is a parameter related to densification of the compact by particle deformation and B is a parameter related to powder density at the start of compaction.

3.1.4 Pellet Hardness Prediction

In terms of rheological properties, hardness represents the rigidity of a material. Hardness may also be expressed in terms of firmness and can be related to the chewability or palatability of many agricultural materials. The term hardness as used in metallurgy is resistance to permanent deformation associated primarily with their plastic properties and only to a secondary extent with their elastic properties. The tensile strength of pellets manufactured using different qualities of alfalfa grinds was determined using the diametral compression test which is widely used in tensile testing of pharmaceutical tablets (Adapa *et al.*, 2006c; Fell and Newton, 1968; Newton *et al.*, 1971; Tabil and Sokhansanj, 1996).

Hardness of manufactured alfalfa pellets changes with material and various processing variables. Regression models were developed to predict hardness of manufactured pellets using fractionated alfalfa grinds. Statistical analysis was performed to establish best-fit regression equations to predict hardness with variation in pressure (5 levels), moisture content (2 levels) and leaf content (5 levels). Analysis indicated that higher moisture content gives significantly higher hardness values, while leaf content is not an important predictor of pellet hardness. It was also observed that hardness prediction can be solely based on applied pressure and moisture content for pelleting (Adapa *et al.,* 2006c).

To develop a regression prediction equation, hardness (H in N) was considered as the dependent variable while pressure (P in MPa), moisture (M in % (wb)) and leaf content (L in %) were considered as independent variables (Adapa *et al.,* 2006c). The model with highest R^2 and all factors significant in the model was selected for prediction regression equations. The following model was selected that satisfied all conditions and R^2 was 0.651.

$$H = 148.4641 + 11.8272\,(P) - 0.1150\,(P)^2 + 0.00035\,(P)^3 + 6.3421\,(M) - 0.8129\,(L) + 0.0078\,(L)^2 \tag{12}$$

Another regression equation that satisfied all the conditions and had comparable R^2 (0.645) but without leaf content was:

$$H = 136.1639 + 11.8504\,(P) - 0.1153\,(P)^2 + 0.00035\,(P)^3 + 6.3736\,(M) \tag{13}$$

This equation is important to consider because it removes the need for measuring leaf content while maintaining similar level of R^2 for hardness prediction purposes.

3.2 Pilot Scale Pellet Processing

A pilot scale investigation was conducted where pellets using ground alfalfa leaf and stem fractions were processed (Adapa *et al.*, 2004b). The objective was to study pelleting characteristics of grinds in terms of change in pellet density, hardness, durability and color with variation in grind size and leaf content of sun-cured and dehydrated alfalfa. Fractionated sun-cured and dehydrated alfalfa chops were used to prepare pellets. Sun-cured alfalfa was obtained in bale form, while dehydrated chops were acquired from an alfalfa processing plant in Tisdale, Saskatchewan. The moisture contents of the sun-cured and dehydrated chops were 8.4 and 9.6% (wb), respectively. A stack of two square sieves with different opening sizes and a pan were used to separate leaf and stem fractions. The leaf and stem fractions were further segregated into two sample lots and ground in a hammer mill using screen sizes of 3.20 mm (1/8 in) and 1.98 mm (5/64 in). The leaf and stem fractions from each sample lot of same grind sizes were combined to get five different samples with leaf contents ranging from 0% to 100% in 25% increments. Average particle sizes of sample lots were determined.

A laboratory scale CPM CL-5 pellet mill (California Pellet Mill Co., Crawfordsville, IN) was used for processing the fractionated alfalfa grinds into pellets (Adapa *et al.*, 2004b). The pellet mill consisted of a corrugated roller and ring die assembly. The diameter of the roller was 85.0 mm. The ring die size (radius) and length (thickness) were 125.3 mm and 44.6 mm, respectively. The ring hole diameter and length-to-diameter ratio were 6.10 mm and 7.31, respectively. The rotational speed of the pellet mill was adjusted to 250 rpm. All of the above specifications were based upon previous studies performed to achieve high quality pellets (Tabil and Sokhansanj, 1996a; Hill and Pulkinen, 1988). The moisture contents and temperatures of the samples were raised to 10-11% (wb) and 76°C, respectively, in a double chamber steam conditioner prior to the pelleting operation. The temperature of material was further raised to 95°C in the pellet mill due to the friction between its roller-die assembly. Temperatures and moisture contents of samples, after various pelleting stages, were recorded. High durability pellets were produced using fractionated sun-cured alfalfa, irrespective of grind size (except for 100% stems, which was low). Durability fluctuated between high and medium range for dehydrated alfalfa (except for 100% stems, which was low). It was possible to custom re-combine leaf and stem fractions in different ratios and produce high durability pellets. For pellets processed from 100% stems, possible addition of artificial binders is required to improve their durability. Variations in grind size of sun-cured and dehydrated alfalfa had insignificant effects on percentage (high, medium and low) pellet durability. Greener pellets were produced from dehydrated alfalfa, while harder pellets were produced from sun-cured alfalfa. Table 2 shows the process temperatures and meal and pellet moisture contents during pelleting of fractionated sun−cured and dehydrated alfalfa grind from two hammer mill screen sizes. Steam conditioning was used only for sun−cured alfalfa at a grind size of 3.20 mm. Steam conditioning did not work properly on the other samples leading to frequent clogging of pelleter die. The inlet steam temperature was 118°C. The conditioner added 2.0% to 3.5% moisture to the grinds. Once the grind moisture content reached 12% to

13%, it became very difficult to make pellets. Due to higher grind inlet moisture content, pelleting of sun−cured grinds ground at 1.98 mm and dehydrated grinds ground at 3.20− and 1.98−mm screen sizes worked well without steam addition. It was observed that when no steam was added, the moisture content of alfalfa grinds decreased by 2.0% to 3.0% while passing through the conditioning chamber and lost 1.0% to 1.5% while passing through the pellet die (table 2). The loss in moisture at both stages was due to heated surfaces to which the grinds came in contact. Because of the limitations of the vibratory feeder and die−clogging problems, it was difficult to control the feed rate of grinds to the pellet mill.

Similar pellet mill operating conditions were maintained while making pellets from different sample ratios or grinds. It was observed that the pellet mill throughput for dehydrated alfalfa was almost three times higher than sun−cured alfalfa. This difference in residence time could possibly affect final pellet color and its moisture content. It can be observed from table 2 that a decrease in pellet mill throughput decreased the pellet moisture levels. Also it was noticed that throughput increased with a decrease in grind size and dehydrated alfalfa grinds are easy to pellet compared to sun−cured alfalfa grinds.

Table 2. Temperatures, meal and pellet moisture contents during pelleting of fractionated sun-cured and dehydrated alfalfa grinds at two hammer mill screen sizes.

Leaf content (%)	Temperatures (°C) Conditioner Upper	Temperatures (°C) Conditioner Lower	Temperatures (°C) Meal inlet	Temperatures (°C) Pelleter Inlet	Temperatures (°C) Pelleter Outlet	Temperatures (°C) Steam	Meal moisture content (%) Conditioner Inlet	Meal moisture content (%) Conditioner Outlet	Pellet moisture content (%) Pelleter outlet	Pellet moisture content (%) After cooling	Pelleter through-put ($kg\ h^{-1}$)
Sun-cured Alfalfa											
Screen size 3.20 mm (1/8")											
100	105	102	25	76	96	118	8.0	11.9	4.1	4.7	8.0
75	105	102	24	76	96	118	8.0	9.9	3.6	4.4	6.9
50	105	99	25	75	96	119	8.0	10.7	2.9	3.9	7.4
25	105	99	24	74	98	118	8.0	9.3	2.6	4.2	9.1
0	108	105	24	76	96	117	8.0	12.4	3.1	4.7	8.0
Screen size 1.98 mm (5/64")											
100	126	135	23	75	94	NA+	8.7	7.3	5.9	6.5	14.2
75	129	138	24	76	106	NA	8.7	6.3	4.8	5.2	11.0
50	127	134	24	76	104	NA	8.7	6	4.8	5.3	12.5
25	125	133	24	76	116	NA	8.7	5.9	3.5	4.3	15.8
0	123	133	24	77	109	NA	8.7	5.9	3.2	4.8	15.6
Dehydrated Alfalfa											
Screen size 3.20 mm (1/8")											
100	123	131	25	73	99	NA	9.6	8.7	7.4	6.7	27.8
75	121	131	25	76	99	NA	9.6	7.7	6.6	6.6	31.2
50	128	136	28	72	104	NA	9.6	7.2	6.4	6.0	29.0
25	125	135	28	71	106	NA	9.6	7.6	6.4	6.6	28.6
0	124	134	28	71	101	NA	9.6	7.3	5.4	5.8	23.8
Screen size 1.98 mm (5/64")											
100	123	132	27	67	98	NA	9.6	7.9	7.6	7.0	39.3
75	125	134	27	65	98	NA	9.6	7.3	7.2	7.0	44.9
50	128	137	28	66	96	NA	9.6	7.9	7.8	7.0	47.3
25	125	134	28	67	96	NA	9.6	7.9	7.5	7.3	41.4
0	126	134	30	67	95	NA	9.6	7.1	6.9	7.2	44.9

+Not applicable

4. CUBING CHARACTERISTICS OF FRACTIONATED SUN-CURED AND DEHYDRATED ALFALFA CHOPS

Densified alfalfa may appear in various product forms, which includes pellets, cubes, compressed hay and compressed baled hay. Compressed or baled hay could be a better option; however, transportation costs overseas are high because of low bulk density compared to cubes. Alfalfa cubes are composed of leaves and chopped stems pressed into a block typically 30 mm x 30 mm in cross-section and up to 90 mm in length. Cubes are made from alfalfa chops of about 50 mm length.

4.1 Single Cubing Unit

A hydraulic cubing machine having a maximum capacity of 14.0 MPa was used to apply compressive pressures on alfalfa chops (Adapa *et al.*, 2005a; Munoz-Hernandez *et al.*, 2004). The cubing machine consisted of a top and bottom hydraulic driven pistons. Their pressures were adjusted using pressure regulating valves and pressure gauges. Two pressure transducers, one measuring the top piston pressure and the other measuring the bottom piston pressure, were installed. The hydraulic press was capable of making a single cube in one stroke of the plunger. The cubing die consisted of five parts: loading barrel, connect sleeve, top ring, main die and lower die support (Adapa *et al.*, 2005a). The cube die was maintained at a temperature of 90±5^{o}C and 140±5^{o}C, in order to simulate the frictional heating of alfalfa chops during an industrial cubing operation. The mass of chops used for making each cube varied between 22 and 25 g. After compression, the pistons were held in place (holding time) for few seconds, before the cube was ejected from the die. A linear displacement transducer was set up to measure the top piston displacement. During the compression process, a data logger recorded the top and bottom piston pressures, and top piston displacement. Fifteen cubes were made at each combination of pressure and holding time. The mass, length and cross-section of each cube was measured to determine its density.

4.2 Cubing Experiments

A single cubing unit was designed and constructed to study the cubing characteristics of fractionated sun-cured and dehydrated alfalfa chops (Adapa *et al.*, 2005a). The moisture content of dehydrated and sun-cured chops were 6 and 7% (wet basis), respectively. A forage particle separator was used to separate leaf and stem fractions. The leaf and stem fractions were combined to get five different samples each for sun-cured and dehydrated alfalfa with leaf content ranging from 0% to 100% in increments of 25%. The effect of chop moisture content (6, 10 and 14%), leaf content (0, 25, 50, 75 and 100%), chop preheat temperature (50, 75 and 100^{o}C), cube die temperature (75, 90, 150 and 200^{o}C), applied pressure (2.5, 5.0, 7.5, 9.0, 10.0, 12.0 and 14.0 MPa) and chop holding time in the cubing unit (10, 12, 15 and 30 s) on cube quality was studied. Results were subjected to statistical analysis to determine the effect of the processing and material variables on the cube quality.

4.3 Physical Characteristics

Geometric mean particle size of sun-cured and dehydrated alfalfa for pure stems and leaves were 62.7 mm and 0.89 mm, and 28.9 mm and 0.82 mm, respectively. For sun-cured alfalfa stems, the amount of stems retained on the top screen exceeded 1% of the total sample mass; therefore, 15 sub-samples/stems were randomly hand picked and measured manually using a vernier calliper and the average length is measured and incorporated in the calculation of geometric mean particle size (Adapa *et al.*, 2005a & 2006b). It was observed that the chop length of sun-cured alfalfa for 0% leaf content was almost double that of dehydrated alfalfa. This could be due to the difference in how sun-cured and dehydrated alfalfa chops are cut and processed; sun-cured chops are from tub-ground bales, whereas dehydrated chops are from cut and chopped fresh alfalfa which are subsequently dried in a rotary drum dryer.

The bulk and particle densities of fractionated sun-cured and dehydrated alfalfa chops at 10% (wb) moisture content are presented in Adapa *et al.* (2006b). Sun-cured and dehydrated alfalfa leaf fractions were mostly in powdered form after fractionation. The bulk and particle densities of sun-cured and dehydrated alfalfa increased with increase in leaf content. The particle density analysis showed that sun-cured alfalfa had smaller particle size compared to dehydrated alfalfa, giving rise to higher bulk densities for sun-cured alfalfa at 75 and 100% leaf content. Best predictor equations were developed with highest coefficient of determination (R^2) with independent variables in the model being significant. Prediction equations for bulk and particle densities as a function of leaf contents are shown in Adapa *et al.* (2006b).

4.4 Cube Density Prediction

The density of dehydrated and sun-cured cubes increased with an increase in pressure, holding time, leaf content and cube die temperature (Adapa *et al.*, 2005a). The increase in cube density is due to a decrease in alfalfa chop particle size and an increase in physical forces that bond alfalfa particles together. Increase in pressure, holding time and cube die temperature, provided enough thermal, mechanical and atomic forces to create strong bonds leading to a better compaction. An increase in leaf content can be interpreted as a decrease in alfalfa particle size. Therefore, more material can be accommodated in a smaller volume, resulting in an increase in cube density.

The compression of fractionated sun-cured and dehydrated alfalfa chops was studied by fitting the compression data to five pressure density equations (Adapa *et al.*, 2005c). In general the Cooper-Eaton model (eq. 9) had the best fit for the data. However, the regression values (R^2 values) obtained were very low. Therefore, new statistical cube compaction models for sun-cured and dehydrated alfalfa were developed. The chop moisture content was 10% (wb), preheat temperature was 75°C and cube die temperature was maintained at 90±5°C based on the results obtained by Adapa *et al.* (2005a). Multiple linear regression analysis was performed, where density (D in kg m^{-3}) was considered as the dependent variable while pressure (P in MPa), holding time (T in s) and leaf content (L in %) were considered as independent variables. New regression values (R^2 values) of 0.846 and 0.592 were obtained for dehydrated and sun-cured alfalfa, respectively. The R^2 values of new equations showed that the new statistical models are a better fit to the experimental data as compared to R^2 values obtained by Cooper-Eaton model. However, R^2 value obtained from the new regression model for sun-cured alfalfa was low (0.592). The reason for variation in cube density could be due to non-uniform mixing of leaf and stem fractions during cubing trials. Also, the sun-cured alfalfa has been previously compressed into bales before tub grinding. Therefore, its compression characteristics may have been altered.

The observed difference in R^2 values between sun-cured and dehydrated alfalfa could be due to the difference in chop size. The average chop size for dehydrated alfalfa (~30 mm) was less than the average chop size for sun-cured alfalfa (~60 mm). More uniform mixing of leaf and stem fractions are expected for dehydrated alfalfa relative to sun-cured alfalfa, henceforth, leading to a better fit or R^2 values.

Dehydrated model ($R^2 = 0.846$):

$$D = 609.27 + 19.29 (P) + 0.91 (T) + 1.84 (L) \quad (14)$$

Sun-cured model ($R^2 = 0.592$):

$$D = 622.32 + 11.65 (P) + 3.23 (T) + 1.34 (L) \quad (15)$$

4.5 Cube Hardness Prediction

In terms of rheological properties, hardness represents the rigidity of a material. Hardness may also be expressed in terms of firmness and can be related to the chewability or palatability of many agricultural materials (Tabil *et al.*, 2002). The term hardness as used in metallurgy is the resistance to permanent deformation associated primarily with their plastic properties and only to a secondary extent with their elastic properties. Hardness of dehydrated cubes increased with an increase in pressure and holding time (Adapa *et al.*, 2005a). This could be due to an increase in the physical forces of attraction between alfalfa particles. An increase in cube die temperature from 90 to 140^{o}C did not show any specific change in cube hardness, except at 75% leaf content. An increase in pressure and die-temperature helps protein and natural binders in alfalfa to reach their melting point, leading to better bonds between alfalfa chop particles and higher hardness values. Hardness of sun-cured cubes increased with an increase in pressure, holding time and die temperature. Hardness of sun-cured cubes decreased with an increase in leaf content (with some exception). For sun-cured cubes, stable bio-compacts or solid lattice structure can be achieved when certain amount of leaf and stem fractions are present. Pure stems give higher hardness values, as the cube is more stable because of mechanical fibre interlocking with additional help from thermal and atomic bonding. However, for pure leaves, the cube is usually formed due to thermal bonding with additional support from atomic bonding. Therefore, to have a good quality cube, some stems in the mix are necessary.

Analysis of hardness values of cubes manufactured from fractionated dehydrated and sun-cured alfalfa chops was performed to determine predictor equations. Hardness of alfalfa cubes was represented in terms of Meyer Hardness to find best-fit regression equations (Adapa *et al.,* 2006b). Separate analysis was conducted for dehydrated and sun-cured experiments. Linear regression equation generated with hardness (H in N) as dependent variable, and pressure (P in MPa), holding time (T in s) and % leaf content (L) as predictor variables. A multiple polynomial regression was fitted to obtain the equation with highest R^2 while assumptions of regression analysis were met. Higher levels and other transformations of variables were tested to develop the final regression equation, with condition that all independent variables in the equation remain significant.

Dehydrated Alfalfa ($R^2 = 0.580$):

$$\ln(H) = -0.0303 + 0.0951\,(P) + 0.0342\,(L) - 0.0029\,(L)^2 + 0.000054\,(L)^3 - 0.00000028(L)^4 \quad (16)$$

Sun-cured Alfalfa ($R^2 = 0.619$):

$$\ln(H) = 0.7444 + 0.0487\,(P) + 0.0097\,(T) + 0.0650\,(L) - 0.0039\,(L)^2 + 0.000063\,(L)^3 - 0.00000032\,(L)^4 \quad (17)$$

where, ln = natural logarithmic

4.6 Cube Durability Prediction

Durability of dehydrated cubes increased with an increase in pressure, holding time and die temperature (Adapa *et al.*, 2005a; Sokhansanj and Crerar, 1999). At 90°C die temperature and a pressure of 14.0 MPa, high durability cubes were obtained, except at 50% leaf content, which was lower. At a pressure of 9.0 MPa, durability fluctuated between medium (70-80%) and high (above 80%) value. As the pressure increased to 12.0 MPa, durability values were mostly high, except for 50% leaf content. Durability followed the same trend as hardness values at 50% leaf content. It is interesting to observe that at a die temperature of 140°C, high cube durability was obtained, even for 50% leaf content. Durability of sun-cured alfalfa also increased with an increase in pressure, holding time and die temperature. At low pressures of 9.0 and 12.0 MPa and at two holding times, high durability cubes were generally produced. However, a leaf content of 100% was the limiting factor, at which either low or medium durability cubes were produced.

Analysis of durability values of cubes manufactured from fractionated dehydrated and sun-cured alfalfa chops was performed to determine predictor equations (Adapa *et al.,* 2006b). A linear relationship was obtained between durability and pressure only. The plot of durability against leaf content showed a higher polynomial response. Higher levels and other transformations of variables (durability (D in %) as dependent variable and pressure (P in MPa), holding time (T in s) and % leaf content (L)) were tested to develop the final regression equation, with condition that all independent variables in the equation remain significant.

Dehydrated Alfalfa ($R^2 = 0.887$):

$$D = 17.9214 + 27.1238\ln(P) + 2.5491\,(L) - 0.1718\,(L^2) + 0.0030\,(L^3) - 0.000015\,(L^4) \quad (18)$$

Sun-cured Alfalfa:

In contrast to dehydrated alfalfa cube experiment, the response of durability did not reach the lowest at 50% leaf content and then significantly increased. Instead, the durability drastically decreased only at 100% leaf content. Higher levels and other transformations of variables were tested to develop the final regression equation, with the condition that all independent variables in the equation remain significant. The predictor equation with highest R^2 (0.851) was:

$$D = 74.9051 + 8.2735\ln(P) + 0.9782\,(L) - 0.0617\,(L^2) + 0.0011\,(L^3) - 0.0000059\,(L^4) \quad (19)$$

4.7 Cube Color

The color index (ΔE) indicates the greenness of a cube, which is an indicator of quality (Patil *et al.*, 1997). The higher the ΔE values, the lower the greenness (Adapa *et al.*, 2005a). Greenness is usually attributed to the presence of chlorophyll and carotenoids, which are more abundant in the leaves and resulted in an increase as the proportion of leaves increased. At a die temperature of 90°C, the color of dehydrated cubes decreased with a decrease in leaf content and holding time. However, at 140°C die temperature, no significant difference in color was observed with change in leaf content, but greenness decreased with a decrease in holding time. The color index of sun-cured cubes decreased with a decrease in leaf content and holding time. Mostly, greener cubes were obtained at 140°C as compared to 90°C die temperature. It was determined that the cube die temperature is the most influential parameter (for any leaf content and holding time) on the color index of dehydrated and sun-cured alfalfa, resulting in chemical changes that might have occurred in the chops during the compression process. Also, for the same process variables, the color index of dehydrated cubes was better than sun-cured cubes. This could be due to the difference in various postharvest processing methods used to obtain dehydrated and sun-cured alfalfa.

4.8 Specific Energy Prediction during Cubing

New statistical models were also developed to predict the specific energy consumption during compaction of sun-cured and dehydrated alfalfa chops into cubes using multiple regression analysis (Adapa *et al.*, 2006a). Specific energy required for compacting alfalfa chops into a cube was determined from the pressure-displacement data (Bellinger and McColly, 1961; Hann and Harrison, 1975; Mani et al., 2004; Mewes, 1959; Reed *et al.*, 1980). The area under the pressure-displacement curve was determined using the trapezoidal rule and expressed in MJ Mg^{-1}. The models considered specific energy (E in MJ Mg^{-1}) as the dependent variable while pressure (P in MPa), holding time (T in s) and leaf content (L in %) were the independent variables. R^2 values of 0.756 and 0.697 were obtained for the sun-cured and dehydrated experiments, respectively.

Dehydrated model ($R^2 = 0.697$):

$$\ln(E) = 1.2935 + 0.0514\,(P) - 0.0003\,(T) - 0.0014\,(L) \tag{20}$$

Sun-cured model ($R^2 = 0.756$):

$$\ln(E) = 1.0663 + 0.0653\,(P) + 0.0047\,(T) - 0.0030\,(L) \tag{21}$$

5. VOLATILE ORGANIC COMPOUNDS EMITTED DURING HIGH TEMPERATURE ALFALFA DRYING

High temperature drying is known to adversely affect the quality of the final product. What is much less understood is the effect of drying temperature on the release of pollutants in the form of volatile organic compounds (VOC's) from alfalfa. Little work has been done in this area. Therefore, establishing relationships between the VOCs released during alfalfa processing as a function of drying temperature, time and specific plant fractions (leaf, stem or flower) is the main focus of the work under this sub-objective. Two sets of experiments were designed to collect VOCs emitted during the alfalfa drying process.

5.1 Laboratory Experiments – Flow Reactor Method

In the first set, laboratory experiments were performed in a controlled environment. A small reactor was designed and constructed to enable exposure of small samples of alfalfa (approx 1 g) to controlled air temperatures for a fixed period of time (Dalai *et al.*, 2006). The setup consists of a cylindrical reactor placed inside a tubular furnace capable of operating to 800^{o}C. During experiments, the reactor was slowly heated to the desired drying temperature under continuous flushing with air at a flow rate of 20 mL min^{-1} and the reactor was allowed to reach a steady state condition. The exhaust gases passing through the samples were collected and injected into a GC-MS (Varian) filled with an ion trap detector. Capillary columns were used to separate and identify the components.

5.1.1 Effect of Drying Temperatures on VOC Emission

The alfalfa chops (leaf and stem) were dried in the flow reactor at temperatures of 60, 150, 250 and 300^{o}C for a constant time period of 5 min. Alfalfa chops over dried and charred when dried at 300^{o}C for 5 min, and produced a burnt odour. On the other hand, drying of chops at 60^{o}C for 5 min caused partial drying of alfalfa samples with moist green residues. At 60^{o}C drying temperature, only a few compounds could be detected. An increase in drying temperature resulted in additional VOCs in the chromatogram, along with those detected at lower drying temperatures (Dalai *et al.*, 2006). The drying of whole alfalfa (both stem and leaf) at 250^{o}C produced as many as 48 VOCs. In addition to other compounds, one of the major components present were derivatives of organic sulphur, which is a matter of concern as they may have some detrimental effect on the environment and human health.

5.1.2 Effect Drying Time on VOC Emission

The alfalfa samples were dried in a flow reactor for time intervals of 5, 20 and 45 min at temperatures of 60, 150 and 250^{o}C. Drying of alfalfa samples at 60^{o}C for 5 min resulted in a very few VOCs. However, after 20 min of drying, some compounds were detected, which were mainly alcohols and aldehydes. Finally, after 45 min of drying at the same temperature, no additional VOCs appeared in the chromatogram. An increase in the intensity (concentration of the corresponding compounds) of the peaks was observed. Similar, observations were made at drying temperatures of 150^{o}C and 250^{o}C. These results suggest that drying time has no significant effect on the type of VOCs emitted, however, the intensity or concentration of VOCs increased with time (Dalai *et al.*, 2006).

5.1.3 Effect of Plant Fractions on VOC Emission

Different fractions of alfalfa plant such as leaf, stem, flower and whole plant were dried separately inside the flow reactor at 250^{o}C for 5 min. The VOCs emitted during drying of the whole alfalfa plant are also present either in the leaf or stem fractions. Separate drying of alfalfa fractions showed that the sulphur compounds were only present in stems (Dalai *et al.*, 2006). The VOCs obtained from drying of alfalfa flowers were mostly saturated and unsaturated aliphatic alcohols and aldehydes.

5.2 Industrial Rotary Drum Dryers

In the second set, field experiments were performed on small and large scale industrial rotary drum dryers to validate results obtained from laboratory tests (Dalai *et al.*, 2006). A small scale prototype three pass rotary drum dryer (Model No. VVD25SIDEHR; Vincent Corporation Inc., Tampa, FL) was used to conduct field drying experiments. Three temperatures were selected to represent the complete range of normal drying temperatures (202, 345 and 480^{o}C). The initial moisture content of fresh alfalfa chops fed into the dryer was 72% (wb). About 15 kg of whole chopped alfalfa (stems and leaves) was fed into the rotary drum dryer at a rate of 1.5 kg min^{-1}. Hot air, generated by burning propane gas, was used to dry alfalfa chops. In a typical rotary drum dryer, alfalfa chops are dried progressively as they move through the dryer. The exhaust gases from the dryer were collected at the cyclone exit. Three replicates of tests were performed at each temperature and the respective exhaust gases were collected using 0.5 L glass sample holders.

Finally, exhaust gas containing VOCs were collected from a large scale dehydration plant situated at Tisdale, SK, Canada. It should be noted that the alfalfa dehydration plant was operated at drying temperature range from 800 to 1000^{o}C. The details of large scale industrial dryers and small scale prototype dryer is reported elsewhere (Sokhansanj *et al.*, 1998; Adapa *et al.*, 2005b).

It was observed that the number of VOCs detected were considerably lower than those obtained during drying of alfalfa chops in a flow reactor. This could be due to the large gas flow rate through the dryer, resulting in dilution of components produced during the drying process and hence the minor compounds could not be detected in the GC-MS spectra. No sulphur compounds were detected.

6. CONCLUSION

A novel process of postharvest drying and fractionation of alfalfa was developed and successfully demonstrated using a small-scale industrial three pass rotary drum dryer. Simulation models were developed and verified using experimental results that could be used to quantify leaf and stem fractions, and predict drying parameters. Fractionated sun-cured and dehydrated alfalfa grinds/chops were later re-combined in different proportions to manufacture good quality pellets and cubes. Regressions equations were developed that could be used to predict pellet and cube quality parameters. These experiments provide a future reference for experimenters and processors as they try to design, develop and implement various processes on a large scale. Present study on alfalfa could be used as a base to develop processing methods for various other crops that are used for the purpose of either feed or fuel.

7. ACKNOWLEDGEMENTS

The authors would like to acknowledge the Natural Sciences and Engineering Research Council (NSERC) of Canada for providing financial support for this research project through the Strategic Research Program. We would also like to thank Mr. Dave Cote, Mr. Jason Bucko and Mr. Bill Crerar for their technical support and valuable input during the experimental work.

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