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Pelletization of Refuse-Derived Fuel Fluff to Produce High Quality Feedstock

Charley Sprenger

Department of Chemical and Biological Engineering, University of Saskatchewan, Canada, email: charley.sprenger@usask.ca

Lope Tabil

Department of Chemical and Biological Engineering, University of Saskatchewan, Canada, email: lope.tabil@usask.ca

Majid Soleimani

Department of Chemical and Biological Engineering, University of Saskatchewan, Canada, email: mas233@mail.usask.ca

Joy Agnew

Prairie Agricultural Machinery Institute, Humboldt, SK, Canada, email: jagnew@pami.ca

Amie Harrison

Prairie Agricultural Machinery Institute, Humboldt, SK, Canada, email: aharrison@pami.ca

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ABSTRACT Due to its primarily organic composition municipal solid waste (MSW) is a suitable feedstock for thermochemical conversion. Current technologies process the MSW into refuse-derived fuel (RDF) fluff before conversion. Bench and pilot-scale densification trials were conducted to determine the parameters required to produce a higher quality feedstock from the MSW RDF material in a pellet form. Characterization MSW-RDF fluff sample showed that the composition of the material was approximately 35% paper, 22% plastics, 14% fabrics, 6% organics/wood, and 23% fines by weight. The RDF was densified, as well as the biodegradable (paper and wood) fraction of the RDF stream to compare quality of pellets for the two material compositions. A single pelleting trial was

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conducted to examine the compaction parameters that would produce high quality pellets: sample material, grind size, moisture content, temperature and pelleting pressure. It was determined that quality pellets, for both materials, were formed at a grind size of 6.35 mm at 16% moisture under pelleting conditions of 90°C and 4000 N applied load. Pilot-scale pelleting was then completed to emulate industrial pelleting process utilizing the parameters from the single pelleting operation that were deemed to produce quality pellets. All of the samples produced durable pellets (88-94%), with the ash content around 20% for all samples. A techno-economic feasibility study determined that 6.35 m diameter pellets could be produced for an average cost of $38/Mg, although the aggressive process of the size reduction required indicates that it may not be a technically feasible option.

Keywords: densification, moisture content, density, durability, ash content, higher heating value, bio-processing, biofuels, pellets, techno-economic study

INTRODUCTION There is potential for the utilization of municipal solid waste (MSW) as an advanced biofuels feedstock suitable for thermochemical conversion processes in the form of refuse derived fuel (RDF). This application would enable diversion of waste from landfill operations, the traditional destination for single-stream waste. A state-of-the art project at the Edmonton Waste Management Centre (Edmonton, Alberta, Canada) sees the production of methanol from MSW RDF through low-severity gasification technology in a collaboration with Enerkem Alberta Biofuels (Enerkem Alberta Biofuels 2015). Municipal solid waste (MSW) is a very heterogeneous waste product and its composition and properties vary by source location and season. The primary organic components are plastics, paper, textiles, and food/wood waste, combined with inorganic metals, glass, and various composites. The current feedstock is in the form of a 50.8 mm (2-inch) fluff, however, densification of this material would produce a higher quality feedstock that is more durable, easier to handle, and more uniform. A first quality fuel pellet must contain less than 1% by weight ash and have a calorific value greater than 18.6 GJ/t of fuel (www.evergreenbioenergy.com). Municipal solid waste RDF has a higher ash content, approximately 10-22% (NETL 2015); in addition, the inorganic elements of the waste feedstock create challenges in the conversion processes including slagging and loss of efficiencies. Improving these characteristics would also increase the potential of RDF as a quality fuel feedstock (RAEFS 2011).

Single-pelleting experiments allow investigation of the effects of different variables known to influence biomass densification; and thus, determine the parameters that produce high quality pellets. Process conditions such as applied pressure, die geometry and temperature, and hold-time are variables that can be altered to improve the quality of pellets, while moisture content, particle size distribution, and biochemical composition are also influential as variations of material properties. Increasing the applied pressure during the densification process results in higher density pellets, while a level at which plastic deformation occurs is necessary for improved strength and durability (Yaman, et al. 2000). A hold-time at maximum load also reduces the effect of 'spring-back' due to elastic deformation. As the operating temperature during densification is increased, the material's resistance to applied load is reduced and the degree of compaction is improved. The die geometry has an impact on pelleting as it indicates the required pressure required to compact the material and overcome the friction of the inner die surface; smaller diameters also increase the power required to produce a pellet due to the increased restriction to material flow. Moisture contents between 8-12% wet basis (w.b.) in cellulosic materials have been shown to produce denser pellets, as water acts as a binder, increasing the contact area available for the formation of van der Waal's forces (Mani et al. 2003). Particle size distribution influences the extent of compaction from particle rearrangement (Adapa et al. 2013). Lignocellulosic feedstocks, traditional biomass, are very resistant to deformation, thus the biochemical composition of the material is influential on the need for any pretreatment steps. The plastic fraction present in MSW provides a variable whose effect on the quality of pellets is currently unknown. The effects of each of these characteristics assist in determining the requirements for effectively and efficiently producing higher quality pellets.

Briquetting of municipal waste has been implemented in numerous regions around the world in order to utilize the biomass as a solid fuel since it has a higher energy density and is easier to handle than raw MSW (Shrestha and Singh 2011). Most of the process development has been driven by the waste-to-energy industry, however briquetting has long been used to make other biomass based-fuel products (Krizan et al. 2011). There has been research conducted on the composition and thermochemical properties of MSW in order to justify its use as an energy feedstock (Gidarakos et al. 2005). However, there is little research available regarding the optimization process for densifying MSW-derived materials in order to efficiently produce quality briquettes or pellets. These types of studies have been conducted for other biomass such as straws, alfalfa, and wood chips, and are important as each material behaves differently when densified and has its own unique set of material and process variables required to produce a quality densified product (Tabil and Sokhansanj 1996b). As such, it is critical to establish experimental determined parameters for producing a densified refuse derived fuel product from MSW.

Objectives The objective of this study is to determine the factors in the production of high quality MSW-RDF pellets and to investigate the feasibility of implementing the production of such pellets in a full-scale operation. This was completed by characterization of the raw RDF-fluff feedstock, followed by pelleting trials, both single and pilot-scale, to determine the effect of pelleting parameters on pellet quality, concluded by a techno-economic feasibility study.

MATERIALS AND METHODS

Materials Municipal solid waste (MSW) refuse-derived fuel (RDF) fluff was supplied by the Edmonton Waste Management Centre (EWMC), Edmonton, AB, Canada in July 2015. The fluff upon receipt had a moisture content of 5.5% wet basis (w.b.) and an average bulk density of 54.6 kg/m3. It is to be noted that the EWMC facility experiences RDF-fluff moisture contents of upwards of 20-30% w.b.

Pelleting characteristics were examined for two different fractions of the RDF-fluff material. The first material utilized the RDF in its raw composition; this consisted of approximately 35% paper, 22% plastics, 14% textiles, 6% wood/organics, and the remainder fines and inerts, determined by a composition sort. The second material consisted of only biodegradable components, wood and paper, after undergoing sorting to remove plastics and textiles.

Each material was ground in two screen sizes, 3.18 mm and 6.35 mm, of the knife mill (Retsch GmbH, Haan, West-Germany). The moisture content of each of the 4 material/grind size samples was determined according to ASABE Standard S358.3 (ASABE 2012), then adjusted to 8%, 12%, and 16%, w.b. Samples were allowed to equilibrate in air-tight containers for a minimum of 3 days prior to the start of the experiment.

Characterization of MSW RDF-Fluff MSW-RDF fluff samples were acquired from the Edmonton Waste Management Centre in July 2015 to use for characterization and densification analysis.

Physical Properties Moisture content of the MSW-RDF fluff material upon receipt was measured. Approximately 5 g of the original sample was placed in an oven at 105°C overnight. The change in mass was recorded and the wet basis moisture content was calculated. Three replicates were made to determine the average moisture. Ash content was then determined by subjecting the dried samples to incineration in a furnace at 575 ± 25°C for 24 ± 6 h. Crucibles containing the ash sample were then placed in a desiccator to cool. Weight measurements were recorded for the empty crucible and for the crucible containing the sample before drying, before incineration, and after incineration. Percent ash was calculated from the change in mass from the dried sample.

The bulk density of the received MSW-RDF fluff sample was measured using a 5850 mL (cm^3) container. Six replicates were completed to account for the heterogeneity of the material.

Particle size analysis for the received MSW-RDF fluff sample was completed following a variation on the withdrawn ASTM test standard E828-81 (ASTM 1997) from sieving analysis. Deviation from the test method was due to restrictions in testing equipment. A sieve shaker with large rectangular pans (less than 0.5 m^2) in the lab was used to analyze four replicates of approximately 500 g samples of RDF fluff. The sieve sizes in the shaker are 2”, ¾” ½”, ¼”, No.4, and No.14. The shaker was run for 10 min. The mass of the material retained on each sieve was measured and recorded. Four replicates were completed for this analysis.

Material Composition Composition of the MSW-RDF fluff was determined by hand sorting using the categories used by the Edmonton Waste Management Centre: paper, film plastic, rigid plastic, fabric, metal, glass/ceramic and organics. An extra category for fines and indeterminables was added to account for the fraction of the material that could not be evaluated as to its composition. Three sorting sessions were completed with sample sizes of approximately 1.5 kg.

Sample Preparation Proposed densification trials were conducted to compare the pelleting outcomes for the raw RDF-fluff material as well as a sorted fraction in which only the biodegradable material (paper and wood) was included.

Particle Size Reduction Each of the samples were ground using a knife mill (Retsch GmbH, Haan, West-Germany). Originally a hammer mill was to be used for the size reduction as this is a machine commonly used for biomass samples due to its high throughput, however, the plastic films in the sample would stretch through the screen rather than being reduced to the desired particle size. Therefore, in order to obtain a uniform sample for the densification experiments, it was decided that a knife mill would provide the necessary size reduction. The screen sizes used for grinding were 6.35 mm and 3.18 mm; these were the grind sizes that had been chosen as a factor in the densification experiment.

ASAE standard S319.3 (ASAE 2008) was followed to analyze the particle size distribution of each ground sample. Three replicates of 100 g samples for each material and grind size was agitated using a large rectangular screen separator for 10 min.

The particle density for each sample (grind size and moisture content combinations) was determined using a gas pycnometer (Multipycnometer, Quantachrome Corp., Boynton Beach, FL), in which the true volume is measured, accounting for the porosity of the sample. Nitrogen was used as the fluid in the closed system.

Sample Conditioning For the single pelleting experiment, moisture content of the material was adjusted to three levels to examine the effect on pellet quality. The moisture content at storage conditions was first determined for each sample. The initial mass of each sample (approximately 3 g) was recorded and then the samples were placed in a vacuum oven at 105°C RDF overnight (24 h), according to ASABE standard, ASAE S358.2 (ASABE, 2012). The difference in mass was measured and moisture content was expressed in wet basis. RDF and biodegradable materials were adjusted to 8, 12, and 16% w.b., by mixing in the necessary amount of distilled water to the material to achieve a 50 g sample and allowing the sample to come to equilibrium inside of a sealed container for a minimum of 48 h at room temperature.

Samples for the pilot-scale experiments were prepared in the same manner, although the samples were 4 kg and rested for a minimum of 72 h once water was added in sealed, large plastic bags at room temperature to reach equilibrium before pelleting.

Single Pelleting Trials The purpose of completing a single pelleting experiment is to examine and analyze the compaction characteristics of densification of the different materials and to determine the effect of several factors on the production of quality pellets.

Experimental Design A four factor factorial design created using Design Expert 9 (Stat-Ease, Minneapolis, MN) was used to evaluate the effect of pelleting parameters on RDF and biodegradable samples. Grind size was compared at two levels: 3.18 and 6.35 mm. Moisture content was compared at three levels: 8, 12, and 16% w.b. Pellet die temperature was compared at two levels: 50 and 90°C (these temperatures are representative of those achievable with the pilot-scale equipment). Pelleting pressure was compared at three levels: corresponding to compressive forces of 2, 3, and 4 kN. This resulted in 36 treatment combinations for each of the RDF and biodegradable materials. Twelve pellets were produced for each treatment combination.

Single Pelleting Unit (SPU) Procedure and Apparatus A single pelleting experiment was first completed to evaluate the compaction and compression characteristics of densifying RDF type material, and to determine the most suitable process parameters to do so. Each sample was densified using a single pelleting unit (SPU) mounted on an Instron testing machine (Model No.3366, Instron Corp., Norwood, MA) to apply the appropriate load. This SPU consists of a cylindrical die with the plunger attached to the moving crosshead of the Instron machine. A heating element is attached to the pelleting die in order to control the temperature of the process, temperatures were compared at 50°C and 90°C. Approximately 0.55 ± 0.05 g of biomass was fed into the die to produce each pellet. The Instron was then used to apply the desired force (2, 3, and 4 kN) to compress the charged material at a rate of 50 mm/min, at which point the plunger was held for 60 s as a retention time to avoid “spring-back” typical of densified biomass. A gate in the platform of the SPU was then opened manually to allow the plunger to eject the newly formed pellet from the die. The same software that was programmed to complete the densification process also recorded the time and force-displacement data for each pellet. Twelve pellets (replicates) were produced for each treatment combination; they were stored at room conditions for analysis after a period of relaxation.

Pellet Density and Dimensional Stability Pellet mass and dimensions (length and diameter) were measured immediately following densification and again after 14 d relaxation in storage. From this, density was calculated to evaluate the change in density of the biomass. Changes in volume immediately following densification (V_o) and after 14 d relaxation (V_{14}) were used to evaluate the volumetric stability of each pellet.

$$Volumetric\ Stability = \frac{V_0 - V_{14}}{V_0} 100\% \tag{1}$$

Moisture Content Moisture content was determined immediately after pelleting and after the 14 d relaxation period to determine the extent of the change in moisture during pelleting and storage. In each case, the initial mass of 2-3 pellets was measured before they were dried at 105°C overnight in a forced-air oven for 24 h, or until there was no change in moisture over a 1 h period. The final mass of the pellets was measured and the wet basis (w.b.) moisture content was determined.

Tensile Strength Tensile strength of the pellets was measured using the diametral compression test, adapted from the pharmaceuticals industry to evaluate the strength of biomass pellets (Tabil and Sokhansanj 1996a). Pellets were cut into approximately 2 mm tablets using a table laser cutter to provide greater consistency in cutting. The diameter and thickness of each tablet were recorded prior to being tested. Tablets were individually placed on their edge on the lower padded (a layer of card stock) plate (Figure 1). The Instron machine was fit with a padded (card stock) upper plunger with a flat face which was used to apply a force to the tablet with a 1000 N load cell at a rate of 1 mm/min until failure. Failure resulting in specimens cracking or breaking in two halves along the loading axis were accepted, with all other failure types being discarded. Applied force was recorded by the Instron software, and the maximum load at failure was used to calculate the tensile strength for the tablet using equation 2, where σ_x is the tensile strength (MPa), F is the load at fracture (N), d is the diameter of the tablet (mm) and l is the thickness of the tablet (mm) (Iroba et al. 2014). Twenty-eight replicates (tablets) from 6 pellets were made for each treatment sample to account for variation in the heterogeneous nature of the pellets.

$$Tensile\ Strength\ (\sigma_x) = \frac{2F}{\pi d l} \tag{2}$$

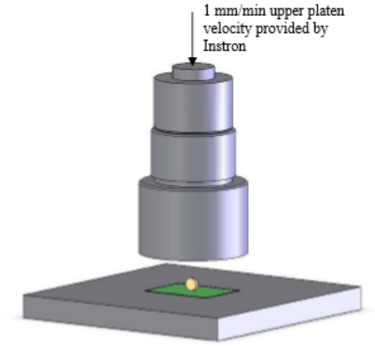

Figure 1. Diametral compression apparatus fit to the Instron machine with tablet loaded on its edge (Shaw, 2008)

Pilot-scale Pelleting Trial Following evaluation of sample pellets prepared with the SPU, a pilot-scale experiment was conducted to emulate an industrial pelleting process. The parameters from the SPU experiment that yielded the best quality pellets were implemented as the treatment combinations for this experiment. Samples ended up consisting of 6.35 mm grind, 16% w.b. moisture RDF produced with either no added heat, or preheated material using the conditioning chamber of the pellet mill. The other sample was 6.35 mm grind, 16% w.b. moisture biodegradables produced with preheated material. A fuel additive known as AK-2 was added as a factor for the pilot-scale experiment. AK-2 (US Patent No. 7,785,379 B2; August 31, 2010) is used as an additive that helps to raise the fusion point of inorganic elements in the sample and to reduce volatile emissions (Emami et al. 2014). This was either added at 0.15% by mass or omitted for each of the above samples; therefore, there was a total of 6 treatment combinations. Each sample consisted of 4 kg of prepared material.

Unit and Bulk Density Length, diameter, and mass of pellets were measured to calculate the unit density of the pellets produced by the pilot-scale pellet mill. Twenty replicates were completed for each sample. Bulk density was determined according to the standard: ASABE S269.4 (ASABE 2012). A 0.5 L cylindrical container was filled with pellets from a funnel and the container was levelled off. The mass of the sample was measured to calculate the density.

Durability Durability of pellets formed from the pilot-scale pellet mill was determined according to ASABE standard ASAE S269.4 (ASABE 2012). The device used was an air-tight tumbler specified in the standard method. A 50 g test sample was first screened with a No. 3½ sieve (5.7 mm opening) to screen to remove any fines. It was then tumbled for 10 min at 50 rpm in the machine. The pellets remaining after tumbling were reweighed to determine the durability (%) according to equation 3.

$$Durability = \frac{mass\ of\ pellets\ after\ tumbling}{mass\ of\ pellets\ before\ tumbling} * 100 \tag{3}$$

Feasibility Study The final investigation into the production of high quality pellets using MSW RDF-fluff as a feedstock was the conduct of a techno-economic feasibility study for a full-scale up utilizing the pelleting characteristics determined in single and pilot-scale trials. The complete study was completed by PAMI, and a final report was generated for analysis and discussion in this project.

The aim was to determine the cost associated with scaling up the process of MSW RDF-fluff densification (Agnew and Harrison 2017). The study was conducted specifically for the context of the Edmonton Waste Management Centre, in terms of existing infrastructure and throughput. The contracted 140,000 Mg/yr of MSW RDF-fluff produced by the EWMC for Enerkem represents the throughput required by the system.

Equipment for both the size reduction and pelletization processes were compared in the report to determine the technical feasibility of each process based on available technologies. Economic feasibility of the scale-up operation was determined by calculating the capital and operating costs associated with the production of MSW RDF pellets on a per tonne basis.

RESULTS AND DISCUSSION

Characterization of MSW-RDF Fluff

Physical Properties MSW-RDF fluff samples had an average moisture content of 5.5% w.b. as received. This appears to be a relatively low moisture content relative to the values that were presented in correspondence with the Edmonton Waste Management Centre; it was noted that moistures up to 20-30% had been measured at the site, particularly in warmer months where yard wastes were more prevalent. Ash content of the received sample was determined to be 28.3% (dry matter basis). Values above 20% for MSW were expected, however the larger value could be attributed to the observation that the sample provided was very dirty, indicating a high proportion of inorganic dirt which would raise the ash content. The average bulk density of the raw material was measured to be 54.63 kg/m^3.

Particle size analysis was conducted for five replicates of the RDF fluff. Over 40% of the material measured between 1.91-5.08 cm; no material was retained on the 50.8 mm (2 in) sieve, this is consistent with the fact that the RDF material was prepared using a 2-inch disc shredder.

Material Composition

Three sorts were completed for the RDF fluff material that was provided. Table 1 compares the average composition that was provided by the Edmonton Waste Management Centre and the average composition from the manual-sorts that were completed in the lab. It can be reiterated that a category for material that was indeterminable during the sort was created as fines; this material was predominantly less than ¼” in size. All of the other categories are very similar excluding the organics (which could be accounted for in the fines category of the sort), indicating that this MSW-RDF fluff material that was provided is a representative sample of the average Edmonton RDF composition.

Table 1. Municipal solid waste refuse-derived fuel fluff composition comparing the results of the hand sorting in the lab and the averages provided by the Edmonton Waste Management Centre (EWMC)

Material	EWMC Average (%)	Sort Average (%)
Paper	35.6 (1.1) [a]	36.6
Film Plastic	12.7 (0.7)	18.4
Rigid Plastic	9.3 (0.9)	12.8
Fabric	13.5 (1.7)	16.8
Metal	0.3 (0.0)	2.5
Glass/Ceramic	0.0 (0.0)	0.0
Organics/Wood	5.6 (0.3)	12.9
Fines	23.1 (2.0)	n/a

[a] Value in parentheses is standard deviation, n=3.

Physical Properties of Prepared Samples

Particle Size Each material grind size was evaluated by sieve analysis to determine the particle size distribution. The geometric mean diameter, d_{gw}, of RDF material produced using a 3.18 mm and 6.35 mm screen was 0.67 mm and 0.95 mm, respectively; similarly, the d_{gw} of the biodegradable material was 0.50 mm and 1.19 mm, respectively. It can be noted that for each sample, the geometric mean diameter of the particles for the sample is much lower than the grind size; this can be attributed to the heterogeneity of the materials and to the high quantity of fines in the raw sample (**Error! Reference source not found.**). In each case, the majority of the sample by mass does however, appear to be retained within 4 sieve sizes below the maximum expected from the screen size used. In the 3.18 mm samples, there does appear to be material that is larger than the screen size; this could be attributed to the spring-back of particles after grinding, and or agglomeration of material into clumps again.

Table 2. Particle density (kg/m^3) of each sample material prepared for single pelleting trial

Moisture Content (% w.b.)	RDF Material 3.18 mm	RDF Material 6.35 mm	Biodegradable Material 3.18 mm	Biodegradable Material 6.35 mm
8	1248 (12) [a]	1166 (48)	1366 (28)	1279 (6)
12	1221 (45)	1171 (47)	1358 (3)	1292 (78)
16	1235 (22)	1096 (45)	1343 (50)	1279 (47)

[a] Value in parentheses is standard deviation, n=3.

Factors Affecting Pellet Quality Using Single Pelleting Trial Single pelleting unit trials helped to evaluate the compression and compaction characteristics of the different materials under a variety of pelleting conditions.

Pellet Density Density of each material was significantly improved by pelletization; considering the bulk density of the RDF-fluff was 54.6 kg/m^3. The biodegradable material alone achieved the greatest increase in unit density; this can likely be attributed to the fibrous nature of the papers and wood acting as mechanical, inter-locking binders. In the RDF and plastic samples, the densification was still significant, however the hydrophobicity and elastic properties of the film plastics caused some spring-back and relaxation, hence the lower density than the biodegradables. A study by Krizan et al. (2011) was able to produce briquettes from mixed municipal waste with compact densities of up to 900 kg/m^3; the composition of the raw material was similar to the RDF used in this experiments, but with upwards of 38% woodchips added. There is no literature documenting achieved compact density for pellets made from MSW.

Certain experimental factors also played a role on the density of the pelletized product. For the RDF material, it was found that moisture content, pressure, and grind size had a significant influence on the density of the formed pellets. The 6.35 mm samples had noticeably greater density than the 3.18 mm samples.

For the biodegradable materials, increasing the temperature, pressure, and moisture content of the pellet die and plunger had a positive correlation on improving density. There was however, no significant effect of grind size of the material. While no literature is available for the effect of pelleting and material parameters on the compact density of MSW, a study on the pelleting of alfalfa found that screen size used for grinding, has less effect on the quality of a pellet than the geometric mean diameter which can vary greatly for the same grind size (Tabil and Sokhansanj 1996b).

The Design Expert software also determined that there are other multiple factor interactions between pelleting parameters that are significant in terms of compact density. Table 4 summarizes the analysis of variance (ANOVA) for all design interactions; values of “p-value” less than 0.05 indicate a significant interaction.

Table 3. The effect of pelleting parameters on compact density (kg/m3) of RDF and biodegradable material pellets

Grid Size (mm)	Moisture Content (% w.b.)	Applied Load (kN)					
		2		3		4	
		Die Temperature (°C)					
		50	90	50	90	50	90
Refuse Derived Fuel Fluff							
3.18	8	938 (34) [*]	885 (28)	887 (32)	887 (34)	918 (47)	926 (37)
	12	898 (40)	870 (33)	896 (20)	913 (17)	937 (24)	929 (19)
	16	905 (20)	923 (40)	915 (23)	938 (19)	926 (13)	930 (45)
6.35	8	950 (36)	972 (36)	993 (47)	1000 (41)	1010 (29)	1010 (48)
	12	988 (44)	979 (40)	989 (49)	998 (42)	1007 (58)	990 (35)
	16	982 (36)	1014 (40)	991 (39)	1018 (34)	993 (59)	1010 (28)
Biodegradable material							
3.18	8	1126 (15)	1134 (21)	1194 (27)	1218 (18)	1206 (28)	1237 (22)
	12	1179 (19)	1190 (19)	1199 (12)	1232 (24)	1235 (22)	1250 (34)
	16	1154 (15)	1175 (13)	1194 (29)	1217 (16)	1219 (17)	1254 (29)
6.35	8	1122 (15)	1155 (38)	1181 (27)	1199 (14)	1253 (25)	1285 (18)
	12	1135 (25)	1184 (33)	1189 (29)	1227 (19)	1233 (23)	1255 (14)
	16	1161 (30)	1182 (20)	1204 (36)	1217 (21)	1227 (18)	1242)

[*] Value in parentheses indicates the sample standard deviation where n=12.

Table 4. Significance of multiple factor interactions on compact density determined by ANOVA analysis in Design Expert

Interaction		p-Value	
Levels	Factors	RDF Material	Biodegradable Material
1FI [a]	Moisture Content	0.0036	<0.0001
	Temperature	0.1022	<0.0001
	Pressure	<0.0001	<0.0001
	Grind Size	<0.0001	0.5743
2FI	Moisture Content x Temperature	0.0093	0.4270
	Moisture Content x Pressure	0.1363	<0.0001
	Moisture Content x Grind Size	0.8520	0.0010
	Temperature x Pressure	0.1287	0.8247
	Temperature x Grind Size	0.1264	0.5890
	Pressure x Grind Size	0.1092	0.0023
3FI	Moisture Content x Temperature x Pressure	0.2788	0.1179
	Moisture Content x Temperature x Grind Size	0.4604	0.1170
	Moisture Content x Pressure x Grind Size	0.0149	0.0002
	Temperature x Pressure x Grind Size	0.0863	0.0244
4FI	Moisture Content x Temperature x Pressure x Grind Size	0.2201	0.8103

[a] 1FI means one-factor interaction, indicates the number of factors in the statistical analysis

Dimensional Stability Dimensions of the pellets were measured at Day 0 immediately after pelleting and on Day 14 after 2 weeks of relaxation to determine the dimensional stability of the pellets. For this experiment, the stability was represented as volumetric stability (equation 1).

Negative results indicate volumetric expansion, while positive values represent volumetric contraction during the relaxation period. Biodegradable pellets show very little change in volume, except for at moisture contents of 16% for the larger grind size; this could be a result of evaporation of the residual moisture from the pellets during relaxation, but may require further investigation. Mani et al. (2004) found that corn stover briquettes expand more with increased moisture content.

Table 5. Effect of pelleting parameters on dimensional (volumetric) stability (%) of refuse-derived fuel fluff and biodegradable pellets

Grind Size (mm)	Moisture Content (% w.b.)	Applied Load (kN)					
		2		3		4	
		Die Temperature (°C)					
		50	90	50	90	50	90
Refuse Derived Fuel Fluff							
3.18	8	-9.36 (4.16)*	0.28 (2.62)	-1.20 (4.66)	-6.63 (3.13)	-6.72 (3.03)	-1.41 (4.46)
	12	-9.85 (3.90)	-0.43 (2.74)	-2.61 (2.91)	-6.48 (6.36)	-7.05 (5.79)	-0.50 (2.66)
	16	-5.94 (1.76)	-2.81 (2.65)	-1.59 (1.89)	-6.86 (3.17)	-9.45 (3.79)	0.15 (3.30)
6.35	8	-5.68 (3.12)	-2.42 (3.12)	-2.10 (4.01)	-5.11 (4.16)	-8.38 (2.69)	-2.67 (4.09)
	12	-9.35 (3.48)	-2.16 (4.46)	-4.11 (3.79)	-10.70 (4.62)	-6.52 (4.90)	-1.82 (3.14)
	16	-3.24 (4.75)	5.31 (5.16)	1.07 (6.29)	0.83 (5.56)	-0.50 (4.78)	8.30 (3.10)
Biodegradable material							
3.18	8	-0.39 (1.59)	-0.55 (1.82)	1.42 (2.01)	-0.55 (1.82)	2.20 (3.41)	0.80 (1.65)
	12	-1.22 (1.55)	1.02 (2.06)	-0.48 (2.65)	1.02 (2.06)	0.95 (1.68)	0.73 (2.93)
	16	-0.56 (1.11)	0.56 (2.15)	1.52 (2.47)	0.56 (2.15)	0.57 (1.84)	1.91 (1.39)
6.35	8	-1.16 (3.59)	1.75 (1.43)	-0.77 (1.02)	1.75 (1.43)	-5.89 (1.74)	-4.23 (2.10)
	12	-0.99 (2.48)	1.40 (1.23)	-0.41 (1.95)	1.40 (1.23)	-1.65 (3.81)	1.34 (2.49)
	16	7.72 (3.04)	8.90 (2.06)	9.57 (1.56)	8.90 (2.06)	7.29 (1.85)	9.05 (1.71)

*Values in parentheses indicate the sample standard deviation where n=9.

In most of the experimental combinations, the RDF pellets experienced volumetric expansion after the 2-week relaxation period. This is primarily due to the hydrophobicity and elasticity of the plastic fraction in the sample.

Pellets produced from material prepared with a larger grind size, 6.35 mm, appeared to have a greater volumetric stability that those from a smaller grind size. This may be attributed to larger particles melting from the higher temperatures and sealing in the remaining material.

Similar biomass pelleting research produced by Shaw (2008) indicate slightly lower pellet densities after relaxation due to expansion for poplar and wheat straw, similar to expansions seen by the RDF pellets. The biodegradable material reacted similarly to pretreated material in the same experiment, wherein some contraction was seen opposed to expansion, indicating higher dimensional stability. It is possible that the broad range of physical and chemical origins, uses, and disposal methods of the various components of the MSW material act as pretreatment methods often required for densification of biomass.

Moisture Content The pelleting process and relaxation period both resulted in decreases in moisture content in the pellets. Pelleting resulted in a 1-10 % decrease in moisture content depending on the initial moisture content and the temperature of the pelleting die. Storage resulted in a further 1-3% decrease in moisture content of the pellets.

Tensile Strength Tensile strength of the pellets was derived from the maximum load at failure under diametral compression. The following table summarizes the average tensile strength for pellets produced under each treatment combination.

Table 6. Effect of experimental factors on the tensile strength (MPa) of refuse-derived fuel fluff and biodegradable material pellets

Grind Size (mm)	Moisture Content (% w.b.)	Applied Load (kN)					
		2		3		4	
		Die Temperature (°C)					
		50	90	50	90	50	90
Refuse Derived Fuel Fluff							
3.18	8	0.142 (0.067)*	0.166 (0.074)	0.165 (0.070)	0.112 (0.048)	0.102 (0.042)	0.206 (0.087)
	12	0.121 (0.102)	0.247 (0.089)	0.176 (0.075)	0.175 (0.094)	0.142 (0.061)	0.324 (0.098)
	16	0.255 (0.088)	0.323 (0.113)	0.285 (0.111)	0.284 (0.125)	0.258 (0.085)	0.361 (0.124)
6.35	8	0.271 (0.142)	0.460 (0.321)	0.334 (0.305)	0.337 (0.182)	0.310 (0.169)	0.275 (0.185)
	12	0.491 (0.319)	0.491 (0.245)	0.532 (0.345)	0.411 (0.298)	0.386 (0.243)	0.474 (0.244)
	16	0.450 (0.206)	0.667 (0.348)	0.630 (0.246)	0.430 (0.180)	0.420 (0.215)	0.533 (0.264)
Biodegradable material							
3.18	8	0.406 (0.128)	1.072 (0.333)	0.733 (0.197)	0.858 (0.272)	0.588 (0.157)	1.369 (0.284)
	12	0.772 (0.200)	1.264 (0.314)	0.715 (0.214)	0.988 (0.251)	0.838 (0.261)	1.360 (0.329)
	16	0.984 (0.240)	1.267 (0.252)	1.296 (0.532)	1.086 (0.223)	0.967 (0.259)	1.389 (0.312)
6.35	8	0.724 (0.302)	1.429 (0.441)	0.897 (0.290)	0.993 (0.361)	0.993 (0.353)	1.423 (0.454)
	12	0.853 (0.332)	1.473 (0.503)	1.227 (0.466)	1.477 (0.404)	1.004 (0.349)	1.823 (0.716)
	16	1.155 (0.246)	1.953 (0.562)	1.822 (0.675)	1.733 (0.482)	1.519 (0.515)	2.117 (0.651)

*Values in parentheses indicate the sample standard deviation where n=24.

In regards to the specific effects of the experimental factors on the tensile strength of the pellets produced, moisture content, pressure, and grind size all had positive correlations towards an increase in tensile strength for RDF pellets. There does not appear to be any significant effect of die temperature on the pellet strength however. The sample in which the material was conditioned to 16% w.b. and had a grind size of 6.35 mm showed the greatest tensile strength across all pelleting conditions (temperature and pressure combinations).

For the biodegradable pellets, all factors had a significant individual effect on the tensile strength. Once again, the strongest pellets were formed by material that was 16% w.b. moisture content and of a larger grind size, 6.35 mm. reaching over 2 MPa at highest pressure and temperature.

Untreated poplar and straw pellets produced by Shaw (2008) had mean tensile strengths between 0.5 and 1.3 MPa, while Tabil and Sokhansanj (1996) determined the tensile strength of alfalfa pellets to be between 0.2 and 2.2 MPa. Both the RDF and biodegradable material pellets showed very comparable tensile strengths with these values reported in literature for other biomass materials. Unlike these agricultural biomaterials however, increasing the moisture content of the MSW biomass helped to increase the tensile strength.

The Design Expert software determined the significant multiple factor interactions between pelleting parameters on tensile strength.

Table summarizes the analysis of variance (ANOVA) for all design interactions; values of “p-value” less than 0.05 indicate a significant interaction.

Table 7. Significance of multiple factor interactions on tensile strength determined by ANOVA analysis in Design Expert

Interaction		p-Value	
Levels	Factors	RDF Material	Biodegradable Material
1FI [a]	Moisture Content	0.0036	<0.0001
	Temperature	0.1022	<0.0001
	Pressure	<0.0001	<0.0001
	Grind Size	<0.0001	<0.0001
2FI	Moisture Content x Temperature	0.0093	0.3111
	Moisture Content x Pressure	0.1363	0.0073
	Moisture Content x Grind Size	0.8520	<0.0001
	Temperature x Pressure	0.1287	0.1183
	Temperature x Grind Size	0.1264	0.0922
	Pressure x Grind Size	0.1092	0.0814
3FI	Moisture Content x Temperature x Pressure	0.2788	0.0427
	Moisture Content x Temperature x Grind Size	0.4604	0.0364
	Moisture Content x Pressure x Grind Size	0.0149	0.0004
	Temperature x Pressure x Grind Size	0.0863	0.1504
4FI	Moisture Content x Temperature x Pressure x Grind Size	0.2201	0.4039

[a] 1FI means one-factor interaction, indicates the number of factors in the statistical analysis

Factors Resulting in High Quality Pellets

Single pelleting trials are used to determine the factors that are significant in pelletization of biomaterials, as well as to determine the levels of each factor which produce higher quality pellets. These narrowed parameters were then tested further in pilot-scale pelleting to emulate industry-scale pelleting processes and to further evaluate the quality of pellets produced in a larger quantity.

The Design Expert software determined that moisture content and pressure are significant for both the RDF and the biodegradable materials. A grind size of 6.35 mm resulted in the highest compact density and tensile strength for both materials. As expected, a larger pressure, resulting from an applied load of 4 kN, resulted in higher compact pellet density in all cases. There is less differentiation of the effect of pelleting pressure on tensile strength across each moisture content and temperature combination. Further, the load applied in a full-scale pellet mill is dependent on the material, and is estimated to be higher than loads tested in the SPU trials; therefore, the pressure achieved in subsequent pellet trials will be uncontrolled.

A die temperature of 90°C results in the highest average compact density and tensile strength. Due to the desirability of reducing the energy required to produce pellets, pilot-scale pelleting will further evaluate the effect of temperature on the production of quality pellets by completing runs with and without preheating.

In all of the diametral compression tests, pellets produced from material with 16% w.b. initial moisture content had the highest tensile strength. The effect of moisture content on compact density was less consistent; however, quality pellets were produced at all levels. Therefore, since high moisture contents are common in the raw MSW RDF-fluff material, a moisture content of 16% w.b. would be used for further trials.

Physical Characteristics of Pilot-Scale Produced Pellets Physical characterization of the pellets produced using the CPM-CL5 pellet mill was completed following a storage period of one week. Table 8Table summarizes the measured characteristics, including unit and bulk densities, durability, moisture content, and ash content for each sample.

Table 8. Physical properties and ash content of pilot-scale produced pellets

Sample	Durability (kg/m^3)	Density		Moisture Content (% w.b.)	Ash Content (%)
		Unit (kg/m^3)	Bulk (kg/m^3)		
RDF: 16 % m.c No preheating 0% AK-2	93.2 (0.2) [a]	1187 (96) [b]	633 (7) [a]	11.6	39.4 (1.5) [c]
RDF: 16 % m.c No preheating 0.15% AK-2	95.5 (0.6)	1137 (59)	570 (12)	11.2	19.1 (1.3)
RDF: 16 % m.c Preheating at 50°C 0% AK-2	94.7 (0.5)	1122 (128)	531 (13)	6.7	28.2 (1.2)
RDF: 16 % m.c Preheating at 50°C 0.15% AK-2	97.6 (0.4)	1167 (73)	619 (5)	2.6	26.5 (1.1)
Biodegradables: 16 % m.c Preheating at 50°C 0% AK-2	91.7 (1.5)	1135 (60)	663(7)	3.5	19.7 (3.1)
Biodegradables: 16 % m.c Preheating at 50°C 0.15% AK-2	88.2 (1.4)	1164 (63)	660 (10)	3.2	22.9 (0.2)

[a] Value in parenthesis is standard deviation; n=3.

[b] Value in in parenthesis is standard deviation; n=20.

[c] Value in parenthesis is standard deviation; n=2.

[d] AK-2: Fuel additive used to increase fusion point of inorganic elements.

While the unit densities of samples appear to be very similar, the bulk densities of the biodegradable pellets (660 - 663 kg/m^3) are slightly greater than that of the RDF samples (531 - 633 kg/m^3). This may be a result of the poorer durability of the biodegradable pellets (88.2 - 91.7%), and therefore a greater number of fines to fill the pore spaces. The two RDF samples with the AK-2 added displayed the greatest durability (95.5 - 97.6%), although the AK-2 at such low quantities likely is not the attributing factor; however, it can be noted that it does not play an adverse role on the quality of the pellets produced. Commercially produced alfalfa pellets subjected to the durability test resulted in values of 96.1-98.6% (Larsen et al. 1996). Briquette durability for barley, canola, oat, and wheat straws were recorded as 42-95% by Song et al. (2010).

In terms of moisture content of the pellets, it can be noted that the samples that were not pre-heated by the conditioning chamber of the pellet mill prior to pelleting had a higher moisture content (11.2 - 11.6%) in pellet form than the samples that were preheated (2.6 - 6.7%). The additional travel time through the conditioning chamber with the added heat would have dried the material that was conditioned. While in the single pelleting trials it was noted that a higher moisture content material at higher temperature pelleting was beneficial for both RDF and the biodegradable fraction materials, the ‘dried’ material during preheating produced comparable pellets to the unheated “moist’ samples.

Preheating does appear to be a decent way to reduce the moisture content of the final product; as this is a challenge faced by the industry collaborator at the Edmonton Waste Management Centre.

Ash content of all pellets (19.1 - 39.4% d.b.) is greater than the 1% by mass required for first quality fuel pellet; this is likely due to the 'dustiness' of the material and consistent with past examination of RDF pellets. There appears to be a positive effect of adding AK-2 on reducing the ash content in the RDF pellets; further investigation would be necessary to evaluate the extent to which the ash content could be influenced.

A study in Greece found the local MSW stream to have an average ash content of 5.31% (Gidarakos et al. 2005), while a Nigerian study determined the ash content of its MSW to be 36-46 % (Daura et al. 2014). When compared to traditional biomass, woody materials typically have ash contents less than 1%, whereas herbaceous, fast-growing biomass such as straw and hay can contain 5-20% ash (Stahl et al. 2004). Therefore, since MSW is so variable, the ash content to can be very different depending on the source and composition. The "dusty" material used in this experiment however, is at the highest end of ash contents reported for biomass in literature, and remains a concern for efficiency when discussed in terms of waste-to-energy. After sorting, an additional step of sieving fine particles could be implemented prior to particle size reduction; however, this may also increase the cost of operation.

Techno-Economic Analysis for Scaling-Up the Process of Pelletizing MSW The required throughput capacity of a full-scale pelletization operation for the EWMC, based on 140 000 Mg/yr contracted to Enerkem, would be 16.7 Mg/h assuming 350 days per year of continuous operation.

The study revealed that size reduction to 6.35 mm, as would be required for a 6.35 mm pellet die, was an unreasonable goal based on the desired throughput capacity and existing technologies. Many machines (>15) running in parallel would be required to achieve the minimum throughput and aggressive wear on the machine from the RDF would result in frequent and costly maintenance. A total cost estimate to achieve the desired throughput of 6.35 mm MSW RDF-fluff was $27.83/Mg.

Several manufacturers were able to provide information in regards to producing 6.35 mm diameter pellets, consistent with the initial pelleting trials; however, due to the unfeasibility of size reduction to facilitate this size of pellet, other options were also explored and reported. Two companies familiar with densification of RDF for other applications indicated that a densified product that is more uniform and easier to handle than the raw material could be produced from 25.4 mm or 50.8 mm material using a die with a diameter of 18-25 mm. Cost estimates for this process were provided as a feasible alternative, although further investigation into suitability of this densified product for the EWMC application would need to be evaluated. This iterative analysis is not within the scope of this research project, but is recommended for further study.

The average cost to produce 6.35 mm pellets was $10/Mg. When added to the cost for size reduction, the total cost to shred and densify the RDF material would be approximately $38/Mg. In comparison, the average cost to produce crumb pellets (150 – 300 kg/m^3), soft pellets (250 – 400 kg/m^3), and hard pellets (>400 kg/m^3) were $5.64/Mg, $8.96/Mg, and $16.20/Mg respectively. A complete summary of costs for each operation is found in Table 9.

Table 9. Summary of unit operations costs from techno-economic feasibility study (Agnew and Harrison 2017)

Manufacturer (Model)	No. of Units	Throughput per unit (tonnes/h)	Daily Run Time (h/day)	Capital Cost		Operating Cost			Total Cost ($/tonne)
				Total ($)	Cost/tonne ($/tonne)	Electricity ($/tonne)	Maintenance ($/tonne)	Labour ($/tonne)	
Size Reduction to 6.35 mm									
Vecoplan (Granulator)	15	2.2	12	5,000,000	1.59	unavailable	12.32	13.92	27.83
Pelletization (6.35 mm diameter pellets)									
CPM (7936-12)	4	5	20	2,619,000	0.83	3.00	2.67	3.09	9.59
Bliss Industries (B200B-175)	2	17	12	796,000	0.25	1.42	7.55	0.93	10.15
Pelletization using 50.8 mm fluff									
Kahl (Crumb)	2	15	13.3	1,455,000	0.46	2.00	2.00	1.03	5.49
	1	20	20	728,000	0.23	2.00	2.00	1.55	5.78
Kahl (Soft Pellets)	3	8	16.7	2,183,000	0.69	3.20	3.33	2.58	9.81
	2	14	14.3	1,455,000	0.46	3.20	3.33	1.11	8.10
Kahl (Hard Pellets)	5	4	20	3,636,000	1.15	6.40	6.67	3.09	17.32
	2	10	20	1,455,000	0.46	6.40	6.67	1.55	15.08
Lundell Enterprises	10	2.7	15	3,812,000	1.19	4.10	3.93	4.64	13.66

A techno-economic study by Shahrukh et al. (2016) reports that the cost of producing pellets from other biomaterials such as straw, forest residue, and switchgrass is \$101/Mg, \$96/Mg, and \$97/Mg respectively. These values incorporate the full life-cycle costs of production, including transportation to the processing facility. Since MSW is a waste product, those costs not associated with size reduction and densification are recouped by the tipping fee charged by the city for disposing of the garbage and are therefore negligible. Thus, the cost to produce a quality densified MSW-RDF material is much lower than similar materials that have been investigated or biofuels application. Since the EWMC does not recoup any of the costs from sale of a converted product, they are likely interested in the least expensive option that successfully improves the consistency and handling of the RDF product that is supplied to Enerkem.

The market futures price of ethanol at end of day on May 18, 2017 was \$0.526/L (Nasdaq 2017). The production rate of ethanol from RDF is reported by Enerkem as 38 million L/year from 140 000 Mg of feedstock (Enerkem 2017), resulting in a conversion estimate of 271 L/Mg. This translates to an approximate market value of \$143/Mg of RDF. Therefore, depending on the cost of conversion to ethanol there may be potential for densification of RDF-fluff into a 6.35 mm product to be feasible.

CONCLUSION The following conclusions can be drawn on the pelletization trials that were successfully conducted for the Edmonton Waste Management Centre:

1. The RDF-fluff supplied by the City of Edmonton consists of mostly paper, plastics, and textiles. The sample that was provided was very dry, 5.5% wet basis, and contained a large quantity of fines. The RDF-fluff was segregated into biodegradable (41% by weight) and plastic fractions (22% by weight) for pelletization trials to determine the potential for higher quality feedstocks.
2. From single pelleting trials, quality RDF and biodegradable material pellets were both formed at a grind size of 6.35 mm at 16% moisture under pelleting conditions of 90°C and 4000 N applied load.
3. From pilot-scale pelleting, it was determined that all of the samples produced durable pellets (88-94%), however, the ash content was around 20% for all samples which is expected for municipal solid waste, but does not meet requirements for high grade fuel pellets.

4. Pellets with 6.35 m diameter could be produced for an average cost of $38/Mg, although the aggressive process of the size reduction required indicates that it may not be a technically feasible option. Alternative densification operations were proposed as more feasible options, but they require further investigation to determine consistency with single pelleting trial parameter results and criteria.

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