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Article

Grinding and Pelleting Characteristics of Municipal Solid Waste Fractions

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Abstract: The efficient utilization of low-cost carbon feedstocks, such as municipal solid waste (MSW), in biorefineries has become increasingly important for reducing GHG emissions and meeting the growing demand for renewable energy sources. However, MSW as a feedstock presents several challenges, including high moisture content, compositional variability, particle size and shape, density, and ash content. To address these challenges, the potential of mechanical dewatering and high-moisture pelleting processes for densifying MSW fractions, such as paper, cardboard, thin plastic, and thick plastic, into low-cost carbon feedstocks with improved handling and conversion properties were investigated. The effect of these preprocessing technologies on the critical quality attributes (CQAs) of the resulting pellets, including bulk density, durability, and size uniformity, were evaluated. The results showed that with these preprocessing technologies, the paper and cardboard fractions could be pelleted at moisture contents over 40% (w.b.) while achieving >99% durability and >300 kg/m^3, while the high moisture plastic fractions were not suitable for pelleting. The thick plastic fraction processed in a screw press was shown to remove up to 30% of the moisture content in a single pass. These findings suggest that these mechanical preprocessing technologies can improve the physical properties of low-cost municipal solid waste fractions for biofuels production.

Keywords: MSW fractions; preprocessing; mechanical treatment; pellets; biomass; feedstock

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1. Introduction

Municipal solid waste is a significant source of low-cost carbon resources available for use as a potential energy feedstock. The United States (U.S.) Environmental Protection Agency (EPA) estimates that 292.4 million tons of municipal solid waste (MSW) is generated each year in the United States alone. Of this material, 50% is currently sent to landfills, while the rest is either recycled (23.6%), composted (8.5%), incinerated in waste to energy facilities (11.8%), or disposed of using other management pathways (6.1%) [1]. These MSW-derived low-cost carbon resources present an opportunity to decrease the reliance on woody and dedicated energy crops, which have drawn much attention as potential biofuel feedstock [2]. In addition, MSW-derived low-cost carbon resources are available at a nominal feedstock cost, which can have a significant impact on the biofuels production cost [3]. The utilization of these low-cost carbon resources for biofuels production will help reduce the dependence on fossil fuels for energy generation through conversion to synthetic fuels by gasification and pyrolysis and further refining using Fischer–Tropsch (FT) processes [4]. Bio-oil produced from the pyrolysis of various low-cost carbon resources can be further refined into high-value end products that can be used in the pharmaceutical, agricultural, and transportation industries [5]. The use of certain low-cost carbon resources contained within industrial solid wastes has been shown to improve the catalytic effects, thereby improving the pyrolysis products' quality and yield [6]. MSW is composed of various fractions of material consisting of paper, cardboard, and many types of plastics, among many other various fractions of material. Sprenger [7] reported that MSW consisted of 35% paper, 22% plastics, 14% textiles, and 6% organics, with the balance remaining as fines (23%), while a similar study reported MSW composition as 23.6% organics (food waste and yard trimmings), 28.5% paper, 10.6% plastics, and 20.2% construction and demolition waste [8]. MSW has been shown to be highly variable, as the composition shifts from city to city and with respect to time [9]. Inconsistencies in biomass composition and properties can present significant challenges in conversion processes [10].

One major challenge regarding the utilization of MSW as a biofuel feedstock is variability (particle size, shape, density, moisture content, time–temperature-dependent degradation, etc.), which poses handling/flowability and conveying issues [11], which densification has been shown to improve with respect to handling and conveying similar feedstocks [12,13]. High-moisture pelleting has been shown to have the potential to reduce costs and carbon emissions during the preprocessing of low-cost carbon resources by up to 40% as compared to a conventional pelleting process, where feedstock is first dried to 10% moisture and then pelleted [14]. High-moisture pelleting has been studied for agricultural residues and has been shown to produce quality pellets in terms of durability and bulk density at moisture contents as high as 25% [15]. Pradhan recently tested pelleting high moisture garden wastes at moistures as high as 35%, with quality pellets being produced at moisture contents above 20% [16]. A recent study conducted on high-moisture pelleting of MSW at 30% (w.b.) moisture content in collaboration between Fulcrum Bioenergy and Idaho National Laboratory (Idaho Falls, ID, USA) showed a 50% reduction in pellet cost and a 46% reduction in greenhouse gas emissions [17].

Another major challenge toward increased production and utilization of these low-cost carbon resources lies in the economics of the processes involved. The United States Government Accountability Office (GAO) released a study highlighting the progress toward the Grand Challenge goal of providing 3 billion gallons of SAF per year by 2030. Although production has increased significantly since 2016 (1.9 million gallons) to 2022 (15.8 million gallons), a significant production gap exists to reach the goals set. The current goal is to produce enough SAF to meet 100% of the aviation fuel demand in the US by 2050 [18], although current SAF production accounts for just 0.1% of the total jet fuel consumed within the United States. The GAO study cites the high price of SAF as a key factor inhibiting the increased production and utilization of SAF [19]. Optimizing the preprocessing of low-cost carbon feedstocks used to produce this particular fuel would help in the adoption and production capacity of biofuels.

Objectives

Minimizing variability and improving handling within these low-cost MSW carbon resources is the focus of the work presented here through the manual sorting and characterization of the constituent components present within MSW. Densification using pellet mills helps to convert highly variable feedstocks into a consistent quality feedstock with definite size, shape, and density. Pellets have been shown to be a viable method for reducing greenhouse gas emissions economically by utilizing pellets as a replacement for fossil fuel-based energy [20].

The components of MSW that were of focus in this study were paper, cardboard, thin plastic, and thick plastic fractions of the whole MSW. Advanced preprocessing of these fractions was studied to characterize and understand how certain critical material attributes (CQAs), such as bulk density, moisture content, particle size, and pellet quality, were affected through various preprocessing steps. Conventional preprocessing of these residues is energy-intensive and makes it difficult to meet the desired CQAs in terms of physical properties. In this paper, advanced preprocessing technologies, such as mechanical dewatering, high-moisture pelleting, and low-temperature drying were studied to efficiently meet the critical CQAs, which have not previously been reported in the literature. Drying has been shown to be a significant point of research in the feedstock processing industry as costs and carbon emissions have become increasingly important [21]. Lower energy-intensive drying methods (grain drying, freeze drying, drum drying, and sun drying) do not have a correlation to pellet durability [22]. The primary goal of this study will be to assist in the conversion of low-cost and highly variable carbon resources into consistent, high-quality commodity-like products that can be handled efficiently, conveyed, stored, and transported. The specific objectives of this study are to develop energy-efficient preprocessing technologies to improve material quality attributes (e.g., moisture content, particle size distribution, ash content, and density) for low-cost carbon resources through novel high moisture preprocessing technologies. The technologies tested will address feedstock barriers such as quality, feedstock availability and cost, material handling, and transportation.

2. Materials and Methods

MSW samples were collected from bulk MSW collected from a material recovery facility (MRF) located in Salt Lake City, UT. Fractions of paper, cardboard, thin plastics, and thick plastics were manually sorted and initially processed in a Jordan Reduction Systems knife mill model #G1635 (Figure 1A) fitted with a 1.5-inch (38.1 mm) screen for initial size reduction. Alternatively, a shredder could be used for this initial size reduction. Each fraction was then size reduced further using a two-stage rotary shear crumbler fitted with a 4 mm head followed by a 2 mm head (Figure 1B), after which the material was screened with an orbital screen fitted with 2 screens designed to give geometric mean particle sizes of 2 mm. After size reduction, mechanical dewatering and high moisture densification were performed to understand how each fraction responded. As-received samples had a relatively low moisture content of less than 6% (w.b.), but depending on collection, storage, and transportation methods, the moisture content of the MSW could be highly variable. Additional processing steps could include washing for decontamination [23] or anaerobic digestion [24], which would leave a high moisture waste stream. To simulate these high moisture waste streams, the crumbled fractions were conditioned to 60% (w.b.) moisture content for the further processing steps.

Figure 1. (**A**) Forest Concepts rotary shear crumbler. (**B**) JRS knife mill. (**C**) Vincent Corporation screw press used for mechanical dewatering studies. (**D**) Low-temperature grain drier used for drying pellets.

The mechanical dewatering process was investigated to understand the MSW fraction's ability to expel water through compression. A small lab-scale Vincent Corporation screw press model #CP-4 with a capacity of 0.5–1.0 ton/day, as shown in Figure 1C, was used for the dewatering tests. The operation of the screw press included a screw auger inside a perforated tube with a pneumatic cylinder placed at the end of the tube that resisted the material conveying along the screw auger. This pneumatic cylinder's pressure was set to 100 psi (689.5 Kpa), which caused the material to be compressed within the perforated tube. The conveying force of the screw compresses the material until it causes the pneumatic cylinder to depress and force the material out of the end of the tube. As a result, surface moisture was expelled through the perforations in the tube and collected separately for waste disposal.

Densification processes were also studied to understand how each fraction reacted to high moisture pelleting. A series of tests were conducted on a 10 HP lab-scale flat die pellet mill (Colorado Mill Equipment, LLC. Model No: ECO-10, Serial No: 01011F10) fitted with a 6 mm die with a length-to-diameter (L/D) ratio of 2.6, and pellet properties were measured such as moisture content, density (bulk, tapped, unit, absolute), and durability before and after pelleting. Each of the pelleting experiments was conducted once, but pellet properties were measured in triplicates. After pelleting, the pellets still had a high moisture content and needed to be dried prior to storage to reduce degradation. A low temperature grain dryer (Figure 1D) was used to dry the pellets to a final storage moisture of less than 10% (w.b). Low-temperature driers have been shown to be effective at drying wood chips from 41.8% to 12.6% w.b. at temperatures of less than 100 °C while having negligible VOC emissions [25]. The drier heated ambient air to 40 °C, which was blown through the wet pellets for 30 min. Data are presented during each stage of the dewatering, pelleting, and drying process.

ASABE procedures [26] were followed for the data collection of pellet properties (moisture content, bulk and tapped density, and durability). Particle size distribution (PSD) analysis was performed using standards set forth in ASAE Standard S424 [27]. Screens used for PSD ranged from 7.92 mm to 0.15 mm. Proximate analysis measurements were determined using the ASTM D7582 [28] standard method developed initially for coal using a LECO 701 thermogravimetric analyzer. Ultimate analysis was determined using a LECO TruSpec CHN following the ASTM D3176-15 standard [29], while the calorific values were measured using a LECO AC600 isoperibolic system under the ASTM D5865/D5865M-19 [30] standard.

3. Results

Initially, the manually sorted MSW fractions were size reduced using a knife mill fitted with a 1.5-inch (38.1 mm) screen to achieve a manageable particle size, after which a stage 2 size reduction to 2 mm in the rotary shear was performed (Figure 2). The plastic fractions did not have the ability to retain significant moisture and yielded an initial moisture content of less than 2% (w.b.), while the paper and cardboard fractions still had less than 6% (w.b.) moisture initially (Figure 3A). Through various collection, storage, and transportation methods, along with possible preprocessing techniques such as decontaminate washing or possible digestion technologies, the moisture content of the MSW fractions during further processing ended up being highly variable, with moisture contents reaching 60–70% (w.b.).

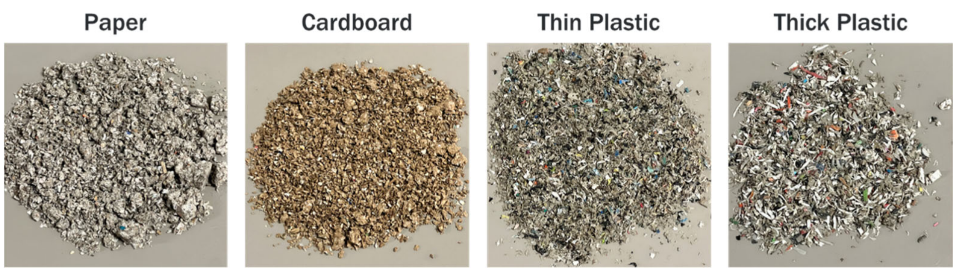

Figure 2. MSW fractions after crumbling to 2 mm.

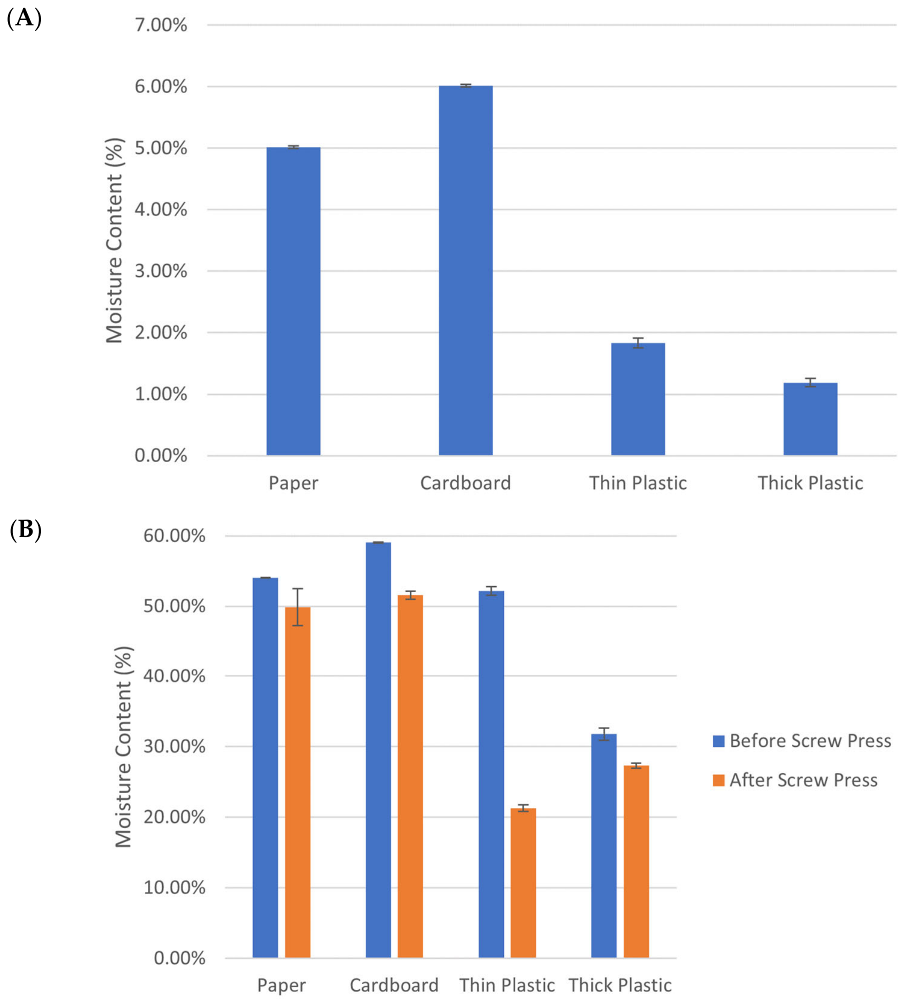

Figure 3. (**A**) Preconditioned moisture content of the manually sorted MSW fractions. (**B**) Moisture content of MSW fractions before and after dewatering using screw press.

3.1. Mechanical Dewatering

Mechanical dewatering was performed using the Vincent screw press as shown in Figure 1C. Each of the four fractions were conditioned to 60% (w.b.) to simulate a high moisture material caused by a previous washing or wet processing, and the fractions were then dewatered to understand the ability of mechanical forces to drive off moisture from these materials. The paper and cardboard fractions showed higher moisture reduction than the plastic fractions, which is thought to be on account of the way moisture is held within the particles. Moisture data for the fractions before and after screw pressing are shown in Figure 3B. The conditioned moisture content for the thick plastic was highly variable, and it could be because much of the moisture migrated to the bottom of the sample during sampling. Thick plastic could not hold enough moisture to reach an initial moisture content of 60% (w.b.).

During screw pressing of the paper and cardboard fractions, the material formed agglomerations or clumps as it was expelled from the screw press, which increased the average particle size (Figure 4B), while the plastic fractions did not agglomerate in the same manner and held a narrower particle size. The particle size distributions for the paper and cardboard were similar, with geometric mean particle sizes of nearly 4.3 mm, while the two plastic fractions followed similar size distributions centered around 2.0 mm. (Figure 4A) The fractions were all processed similarly, so differences in particle size distributions are related to material differences during size reduction and mechanical dewatering.

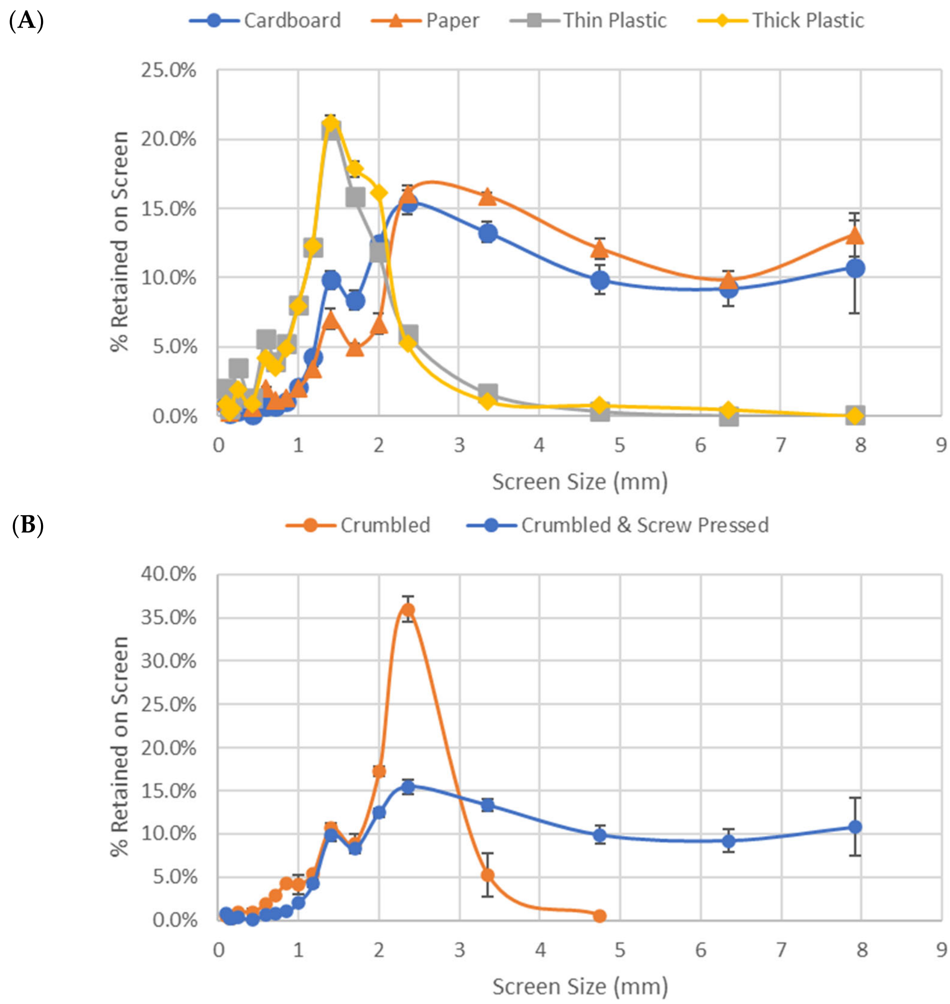

Figure 4. (**A**) Particle size distributions of the MSW fractions after the screw press. (**B**) Particle size distributions of cardboard both after crumbling and after crumbling then screw press.

Chemical compositional analysis was conducted for each of the fractions after mechanical dewatering to understand potential issues during further preconversion and conversion operations. Proximate, ultimate, and calorimetry measurements were derived for each of the samples, with a focus on the amount of ash present. Ash content is an important chemical component that can negatively impact the conversion characteristics for a specific feedstock (see Figure 5A). Thin plastic had the highest ash content of greater than 20%, while cardboard had just 5%. The samples tested were selected from raw MSW and were not washed, so particles had foreign dirt and other particles adhered to them, which was most evident in the thin plastic fraction. Thin plastic had increased levels of ash content compared to the other fractions tested, while additional work is needed to understand if contamination led to this outcome. The two plastic fractions showed higher heating values than the paper and cardboard fractions, which was expected, and these data are shown in Figure 5B. Bulk density and tapped density were also measured according to the ASTM D7481-18 [31] standard, and the data are shown below in Figure 5C. Again, the paper and cardboard fractions were similar, with bulk density values of roughly 125 kg/m^3, while the plastic fractions were quite different. Thick plastic had a bulk density of around 225 kg/m^3, while the thin plastic fraction had a bulk density of 75 kg/m^3. This is primarily because of the particle shape affecting the packing efficiency, since the density differences between the constituent plastics were quite similar. Thick plastics contained mostly different types of HDPE polyethylene bottles, ABS, and polycarbonate, among others, while the thin plastic fraction contained mostly LDPE plastic bags and polypropylene packaging, among others.

The bulk density differences between the primary plastic types were not as great (HDPE ~961 kg/m^3 [32]; LDPE ~ 910 kg/m^3 [33]) as the differences between the thin and thick plastic fractions (225 kg/m^3 and 75 kg/m^3, respectively).

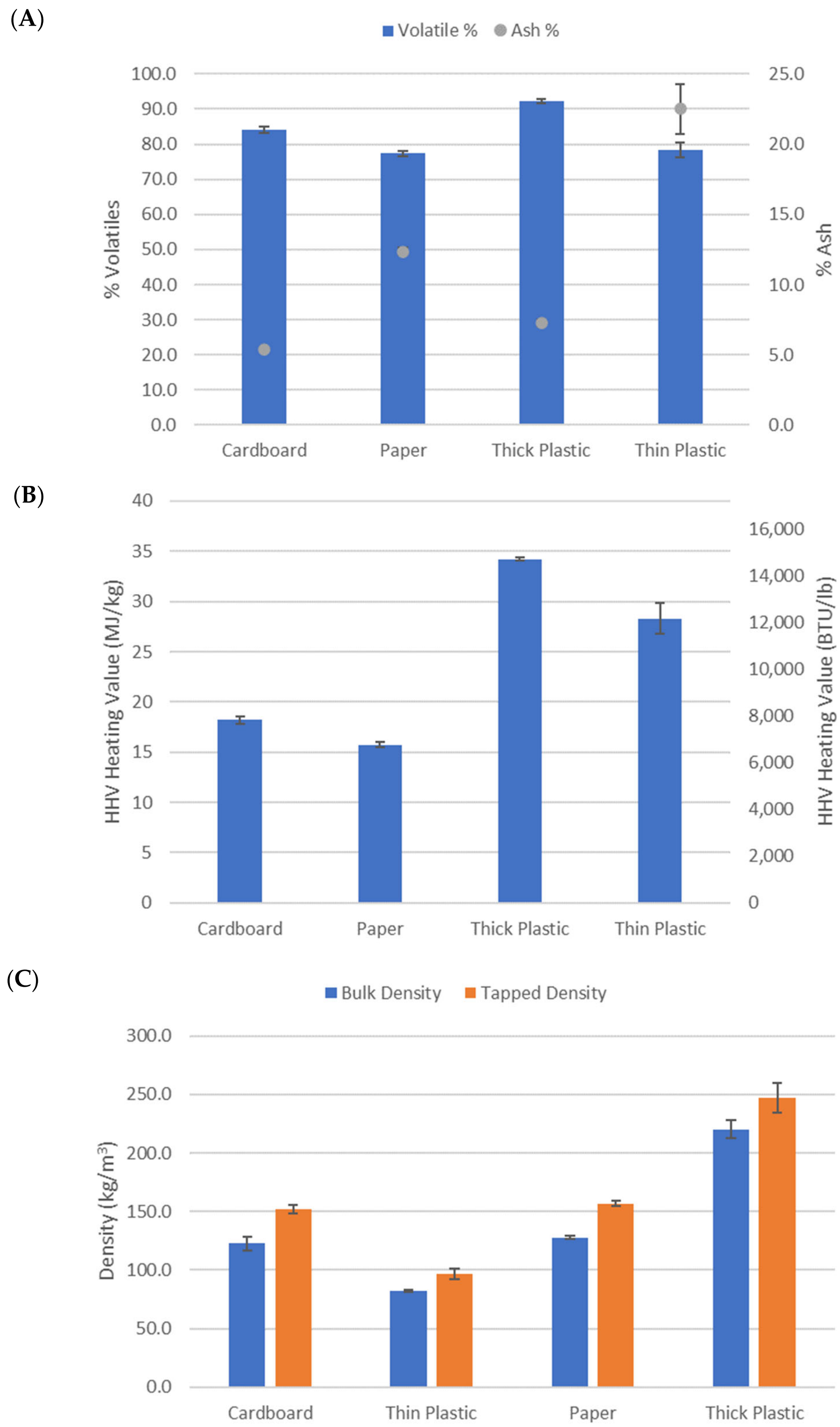

Figure 5. (**A**) Percent volatiles and ash of MSW fractions after screw press. (**B**) Higher heating value of the MSW fractions after screw press. (**C**) Bulk and tapped density of MSW fractions after screw press.

3.2. Pelleting

A flat die pellet mill was used to densify each fraction to characterize the pellet quality for each of the MSW fractions. The mass of pellets produced was collected to show the relative pelletability for each of the samples. Tests with a higher mass of pellets indicated a higher percentage of pellets relative to the fines produced when assuming a 2 kg initial feedstock mass (Figure 6A). The paper and cardboard had a high percentage of pellets, while the plastic blends had a very low percentage of pellets produced. The paper and cardboard fractions were able to make high quality pellets (>90% durability and >300 kg/m^3) despite having a higher initial moisture content (>40%). The paper fraction was able to form quality pellets with an initial moisture content of greater than 50% (w.b.) moisture content (Figure 6B), while the thick plastic fraction did not form any pellets at a 20% (w.b.) moisture content.

The cardboard pellets (Figure 6C) produced the highest quality pellets in terms of bulk density at 356.5 $\pm$ 7.34 kg/m^3, as well as the highest durability of 99.2% $\pm$ 0.05% when tested according to the ASAE 269.4 standard [26]. The cardboard fraction had an initial moisture content of 43.6% $\pm$ 0.64% prior to pelleting. Thick plastic did not form any pellets, and the material that came out of the pellet mill did not change significantly from the initial material, while the thin plastic fraction formed low quality pellets (Figure 6E).

After pelleting, the moisture content of the pellets was greater than 10% (w.b.) (paper pellets were 50% (w.b.)), which is too high for storage and handling. The pellets were then dried using a grain dryer (Figure 1D) for stable storage and handling. Each fraction was dried using the same airflow, temperature, and time settings on the grain dryer. Each fraction was dried for 30 min at 40° C with the air door setting at 100%. The final moisture content of each fraction is shown below in Figure 7A. For the thick plastic fraction, there were not any pellets produced, so there is no moisture data for this material. After pelleting, the paper fraction had the highest moisture at 52.5% (w.b.), but after drying for 30 min, the pellet moisture decreased to 20% (w.b.). The bulk density target in the pellet mill to form transportable pellets is 300 kg/m^3, which the paper and cardboard pellets achieved. The density values for each of the tests are shown below in Figure 7B. The pellet diameter is also shown in relation to the density values for each of the pelleting tests performed. Pellet durability was measured for each of the samples to determine the amount of fines produced after simulated handling and transportation of pellets according to ASABE standards. The durability measurements were taken after pellets were grain-dried (Figure 7C). The 100% cardboard pellets had the highest durability at around 99%, while thin plastic had the lowest durability of roughly 90%. All pellet samples were dried using the same drying time of 30 min without respect to the pre-dried moisture content, so final moisture contents were found to be variable. To produce a stable pellet, the final moisture content would need to be less than 10%, so the grain drying parameters would need to be altered to achieve this.

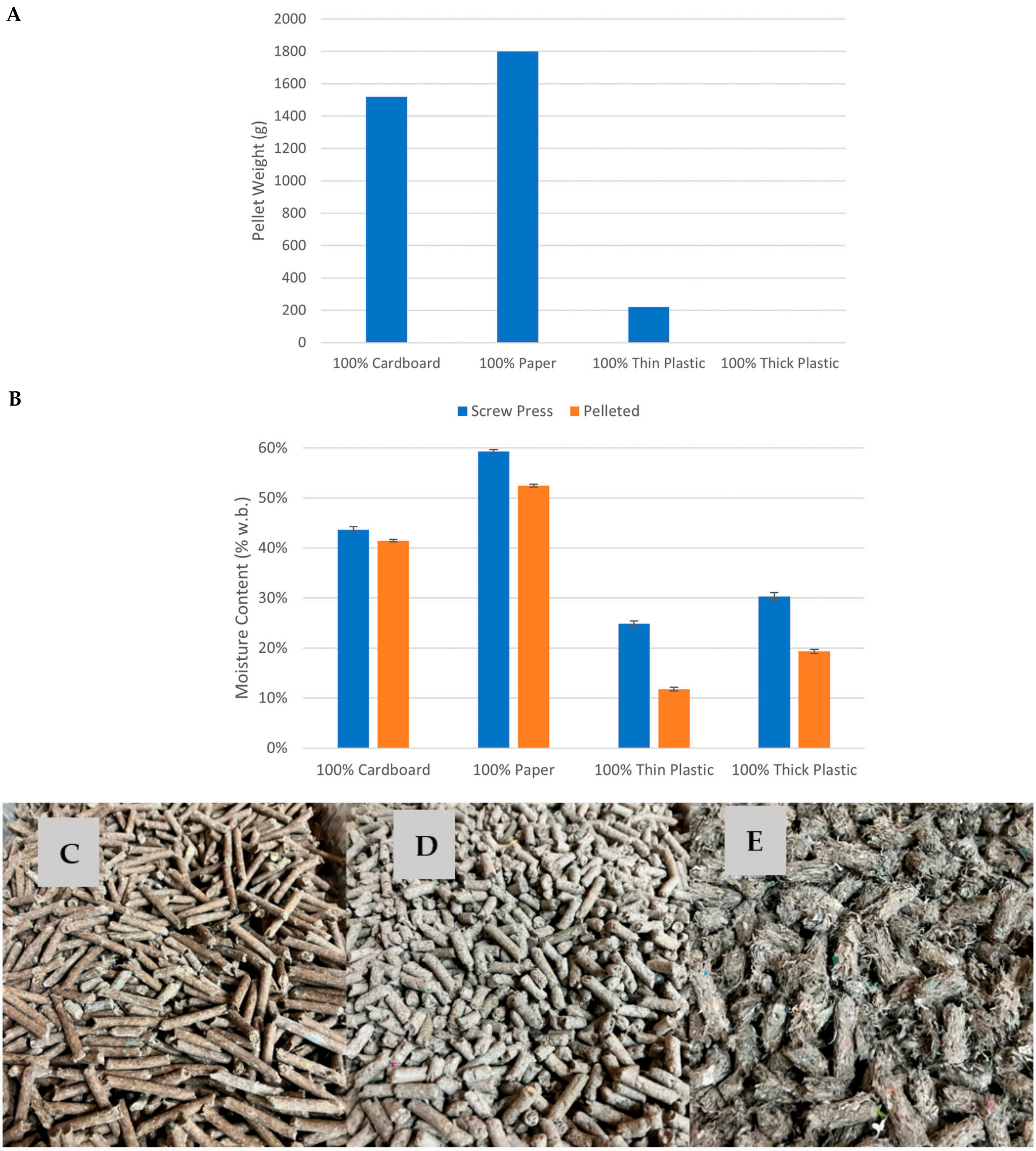

Figure 6. (**A**) Weight of pellets after sieving fines for each MSW fraction. (**B**) Moisture content of the pelleted MSW fractions before and after pelleting. (Thick plastic did not form pellets). (**C**) Cardboard pellets. (**D**) Paper pellets. (**E**) Thin plastic pellets.

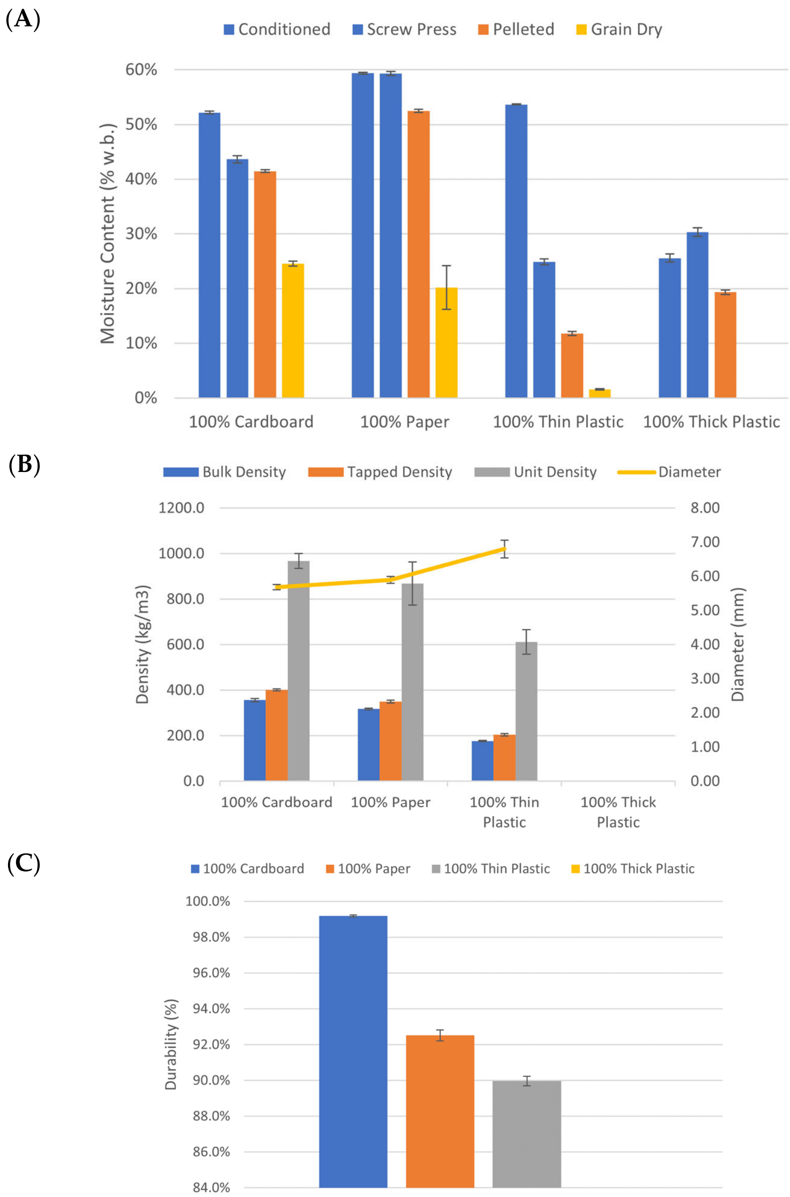

Figure 7. (**A**) Moisture content of MSW fractions during processing operations. (**B**) MSW fraction pellet density and diameter. (**C**) Durability measurements for dried pellet samples.

4. Discussion

MSW, which consists of many various components, typically has low density and an irregular size and shape, thus making feeding and handling difficult. MSW composition has been shown to be highly variable with respect to regional differences, as well as variable over time as shifts in consumer preferences change [34]. In Kenya, the composition of MSW has been shown to include 58.2% organic material, 17.3% paper/cardboard, 11.8% plastics, 2.3% glass, 2.6% metal, and 7.8% textiles [35]. The USEPA reported that the United States MSW composition to be 12.7% organics, 31% paper/cardboard, 12.0% plastic, 4.9% glass, 8.4% metal, and 31% textiles as of 2007 [36]. Each fraction regarding MSW has an optimum use case and recycling pathway, and, as such, understanding the differences in pelleting each fraction was studied.

The preprocessing technologies investigated such as mechanical dewatering, high-moisture pelleting, and low-temperature drying are of importance because of the effect that these physical properties have on conversion into bioenergy. Lower ash content has been shown to improve the yield of bio-oil during pyrolysis, and decreased moisture content has been shown to improve the quality of the bio-oil [5]. Moisture content relates to the energy efficiency of a thermochemical conversion process, since moisture retained in the feedstock must first be vaporized prior to the devolatilization of the material, thereby reducing the efficiency of the process. During the gasification of MSW, increased moisture content has been shown to decrease the quality of the syngas produced, and a reduction in energy conversion efficiency was observed [37]. Drying of the feedstock prior to densification is also highly energy-intensive and is typically a large contributor of carbon emissions [38] within a thermochemical conversion process, since natural gas rotary drum kiln dryers are the standard method for industrial drying [39].

Rather than improving these existing drying methods, this study looks at achieving incremental drying though high-moisture processing and low-energy dewatering methods. This study focused on two approaches to reducing the moisture content of the fractions through mechanical dewatering via screw press and high moisture densification. A screw press was shown to be one option toward reducing the role of a rotary kiln dryer in the preprocessing of the material and, therefore, reducing energy consumption and carbon emissions during the preprocessing of this material [40]. Cardboard and paper fractions only exhibited minimal moisture losses of less than 10%, as shown in Figure 3B. The two plastic fractions (rigid and thin) were not capable of being conditioned to the target moisture content of 60% (w.b.), although they were conditioned to a moisture content of approximately 50% (w.b.) for the thin plastic and only roughly 30% (w.b.) for the rigid plastic fraction. The moisture retained in the plastic fractions was more easily dewatered using the screw press. The paper and cardboard fractions were thought to absorb more secondary bound water, which proved more difficult to remove mechanically. It has been previously reported that water chemistry within biomass can take the form of primary bound water, secondary bound water, and free water. Primary bound moisture relates to water's interaction with carbohydrates via hydrogen bonds, while secondary bound water is water held within the porous hydrophilic cellular structure and is also referred to as thin-film water. Free moisture refers to the moisture held within biomass fibers through capillary forces and exhibits high mobility within the material [41]. The thin plastic was able to remove ~30% (w.b.) of its total moisture during mechanical dewatering compared to the other fractions. This is thought to be because the moisture measured in the plastic samples showed that they were overwhelmingly free of moisture.

Variability has long been another significant hurdle that is necessary to address for low-cost carbon resources to become more widely utilized and preprocessed into high-quality feedstock [42]. This variability stems from inherent material differences, varying drying rates and absorption rates for the various materials, upstream processes used for washing treatments, or environmental conditions that the material had previously been exposed to [20,21]. Fractionation has been shown as a possible way to address the variability of a mixed waste stream and to allow for further processing [10]. MSW fractionation was used to isolate these material differences regarding high-moisture processing.

High-moisture pelleting was also investigated to understand the relative ability of each fraction to form pellets under high-moisture conditions. High-moisture pelleting has been shown to reduce the moisture content of the material during each stage of processing, thereby reducing the drying required during a dedicated drying process [14,17]. The results from this study have shown that high-moisture plastic fractions formed little or no quality pellets, while high-moisture paper and cardboard fractions made quality pellets at moisture contents of up to 50% (w.b.). The drawbacks of high-moisture processing include increased energy consumption of the pellet mill, potential handling/conveying issues within upstream handling, and conveying prior to the pellet mill. The high-moisture pellets still had moisture contents that were too high for storage (>10%), but in the densified state, they were able to be dried using energy-efficient low-temperature grain driers to remove a significant portion of the remaining moisture, although an in-depth study on drying performance from these pellets was not undertaken as part of this study.

5. Conclusions

MSW is a low-cost carbon resource that has been shown to be a potential feedstock for biofuel production through necessary preprocessing steps. Redirecting the material bound for a landfill and producing a usable product or energy feedstock can help to reduce the carbon intensity of many different thermochemical and manufacturing processes. Compositional, moisture content, and particle size inconsistencies present a major challenge toward the utilization of MSW as a feedstock. Understanding preprocessing technologies and the effects on these inconsistencies was the major focus of this research study. The results in the study indicate that the proposed high-moisture preprocessing technologies can potentially address critical quality attributes (low density, high ash content, poor pellet quality, and variable moisture retention).

Based on the present study, the following conclusions are drawn:

1. Mechanical dewatering using a screw press was shown to be less effective at moisture removal from paper and cardboard fractions, while it showed to be effective at moisture removal from plastic fractions.
2. High-moisture pelleting resulted in highly durable (>99%) and dense (>300 kg/m^3) pellets that were formed from paper and cardboard fractions at initial moisture contents nearing 50%.
3. High-moisture processing is a feasible option for reducing processing energy requirements and costs by eliminating rotary dryers from the processing flowchart.
4. Plastic fractions did not produce quality pellets at high moisture levels.
5. The high-moisture MSW pellets were able to be dried using a grain-type low-temperature dryer to produce a moisture content that was suitable for storage (<10%).

This study enhances the understanding of moisture management and high-moisture densification in the context of bioenergy feedstocks derived from MSW. Future research may focus on investigating fractionation and reblending techniques to mitigate the inherent variability in MSW feedstock, thereby presenting potential solutions to this challenge.

Author Contributions: Z.S. and B.I. wrote the original draft of the manuscript; Z.S. conducted the experiments; J.S.T. developed the concept and methodology; N.Y. managed the project. All the authors thoroughly reviewed and edited the manuscript. All authors have read and agreed to the published version of the manuscript.

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