INL/EXT-21-62176

Explore the Potential to Formulate Feedstock Blends from Diverse Biomass Inputs for Improved Processing Performance at Lower Costs

March 2021

For Task 3

Jaya Shankar Tumuluru

Changing the World's Energy Future

Idaho National Laboratory

INL is a U.S. Department of Energy National Laboratory operated by Battelle Energy Alliance, LLC

INL/EXT-21-62176

Explore the Potential to Formulate Feedstock Blends from Diverse Biomass Inputs for Improved Processing Performance at Lower Costs

For Task 3

Jaya Shankar Tumuluru

March 2021

Idaho National Laboratory
Idaho Falls, Idaho 83415

http://www.inl.gov

Prepared for the
U.S. Department of Energy
Under DOE Idaho Operations Office
Contract DE-AC07-05ID14517

ABSTRACT

This work aims to understand the pelleting characteristics of 2-in. top pine residue blended with switchgrass at high-moisture content. The process variables tested are blend moisture content, length-to-diameter (L/D) ratio in the pellet die, and the blend ratio. A flat die pellet mill was also used in this study. The pine and switchgrass blend ratios that were tested include: (1) 25% 2-in. top pine residue with 75% switchgrass; (2) 50% 2-in. top pine residue with 50% switchgrass; and (3) 75% 2-in. top pine residue with 25% switchgrass. The pelleting process conditions tested included the L/D ratio in the pellet die (i.e., 1.5 to 2.6) and the blend moisture content (i.e., 20 to 30%, w.b.). The analysis of the experimental data indicated that blending 25% switchgrass with 75% 2-in. top pine residue and 50% switchgrass with 50% 2-in. top pine residue resulted in pellets with a bulk density of >550 kg/m^3 and durability of >95. Optimization of the response-surface models developed for process conditions in terms of product properties indicated that a higher L/D ratio of 2.6 and a lower blend moisture content of 20% (w.b.) maximized bulk density and durability. Higher pine in the blends improved the pellet durability and reduced energy consumption. Tests were also conducted on blends of pine and switchgrass using a pilot-scale pellet mill by varying the blend moisture content and compression ratio of the pellet die. Pelleting tests on pure pine and switchgrass and their blends in a pilot-scale ring die pellet mill with a throughput of 1 ton/h has indicated pellets with durability >500 kg/m^3 and durability in the range of >90 and >95%. The demonstration of high-moisture pelleting of blends of 2- and 6-in. top pine residues and switchgrass blends indicated that good quality pellets with durability >90% and bulk density of >500 kg/m^3 can be produced.

Page intentionally left blank

CONTENTS

FIGURES

TABLES

Explore the Potential to Formulate Feedstock Blends from Diverse Biomass Inputs for Improved Processing Performance at Lower Costs

1. INTRODUCTION

Blending is a common method that mixes different types of biomass to improve their physical properties and chemical composition. In their studies on the pelleting of woody and herbaceous biomass blended feedstocks, Yancey et al. (2013) indicated that blending helps to reduce physical property and chemical composition variability in various biomass sources, while producing a consistent feedstock. For example, different grades of coals are blended to reduce their sulfur and nitrogen content. Various high-ash biomass sources are blended with low-ash biomass sources for biopower generation. In the agricultural industry, grains are blended to adjust their moisture content. In the feed industry, ingredients are blended to maintain the nutrient content of the feed (Tumuluru et al., 2011). Ray et al. (2017) suggested that biomass blending helps to overcome cost and quality limitations of biomass for biofuels production, while Edmunds et al. (2019) suggested that the blending of different biomass sources helps to improve feedstock specifications. For thermochemical conversion, attributes of interest include carbon content, total ash, and specific minerals, density, and moisture content.

According to Ray et al. (2017), Kenney et al. (2013), and Thompson et al. (2013), biomass blending helps to overcome challenges associated with feedstock quality, variability, supply, and cost. The major advantages of biomass blending are: (1) an increase in potential biomass supply for a given biorefinery area; (2) feedstock cost reduction; and (3) improvement in biomass flow and pelleting characteristics (Yancey et al., 2013; Crawford et al., 2015). Recently, the blending of different sources of lignocellulosic biomass to produce feedstocks for thermochemical conversion has gained importance. For example, Mahadevan et al. (2016) reported that blending switchgrass and southern pinewood resulted in bio-oils with low acidity and viscosity, but a higher water content. The major challenges of blending biomass from various sources are these variabilities in biomass physical properties in terms of particle size, moisture, and density. These feedstock variability parameters can result in issues related to feeding, handling, transport, and storage.

According to Tumuluru (2018), biomass pretreatment and preprocessing can help to overcome variability issues. Mechanical (e.g., size reduction, densification), chemical (e.g., ammonia fiber expansion, acid, alkali, ionic), and thermal (e.g., torrefaction, hydrothermal liquefaction) preprocessing and pretreatment help to address biomass variability in physical properties and chemical composition. In addition, Tumuluru and Yancey (2018) and Tumuluru et al. (2011) discovered that mechanical preprocessing and thermal pretreatment of biomass helps to improve biomass physical properties (such as particle size distribution and bulk density), chemical properties (such as proximate and ultimate composition), and energy property (such as calorific value).

1.1 Densification

The low bulk density of biomass, which is typically in the range of 150–200 kg/m^3 for woody biomass (Sahoo et al., 2018) and 80–100 kg/m^3 for herbaceous biomass (Tumuluru et al., 2011) limits its application at the commercial-scale. The low bulk densities of biomass make biomass material difficult to store, transport, and interface with biorefinery infeed systems (Sahoo et al., 2018). In general, high bulk, and low-energy-density biomass results in difficulty in feeding the biomass and reduces conversion efficiencies. Densification of biomass helps to overcome this limitation. According to Tumuluru et al. (2011), the densification process is critical for producing a feedstock material suitable as a commodity product. Densification helps to overcome the physical property variability issues, such as moisture, particle size distribution, and density. Densified biomass has improved handling and conveyance efficiencies throughout the supply system and biorefinery infeed, as well as improved feedstock uniformity and density. Common biomass densification systems have been adapted from other highly efficient processing industries like feed, food, and pharmacy, and include: (1) a pellet mill; (2) a cuber; (3) a briquette press; (4) a screw extruder; (5) a tabletizer; and (6) an agglomerator (Tumuluru et al., 2019; Pradhan et al., 2018).

1.2 Conventional Pelleting System

The major challenge in biomass pelleting using current industry standard processes is drying the biomass to about 10–12% (w.b.) moisture content with conventional costly drying systems, such as a rotary dryer (Tumuluru, 2014; 2015; and 2016). In their study on the validation of advanced feedstock supply systems, Searcy et al. (2015) indicated that one of the major limitations biorefineries face in using high-moisture woody and herbaceous biomass for biofuels production is the high drying costs. Various unit operations associated with the conventional pelleting process include a Stage 1 and Stage 2 grinder, a dryer, and a pellet mill, as shown in Figure 1.

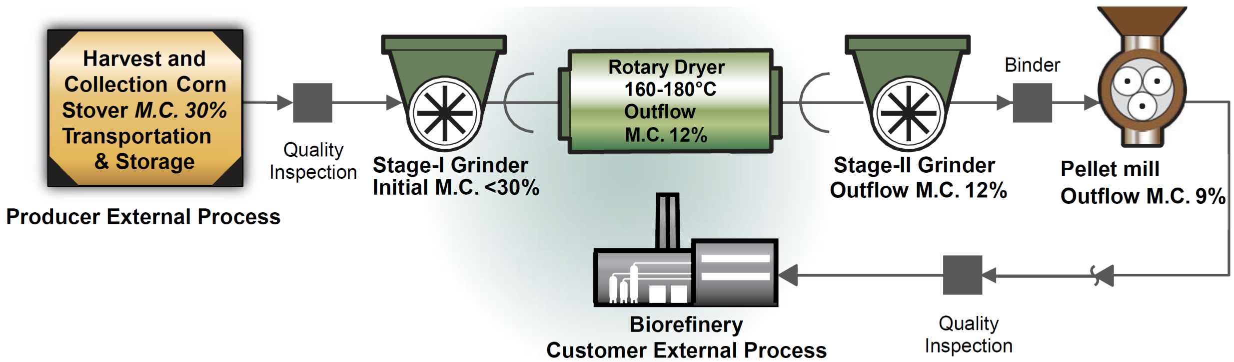

Figure 1. Various unit operations in the conventional pelleting process (Lamers et al., 2015).

Techno-economic analysis indicated efficient moisture management is critical for reducing the preprocessing costs of biomass (Tumuluru et al., 2014 and Lamers et al., 2015). According to Pirraglia et al. (2010), Sakkampang and Wongwuttanasatian (2014), and Yancey et al. (2013), the drying of biomass using rotary dryers is a significant energy-consuming unit operation in the pelleting process. According to Tumuluru (2015), drying biomass from 10–30% (w.b.) for pelleting takes about 65% energy, whereas pelleting itself only requires about 8–9%, as shown in Figure 2 (Tumuluru, 2015). Another major limitation with high-temperature biomass drying for biofuels production is the emission of volatile organic emissions.

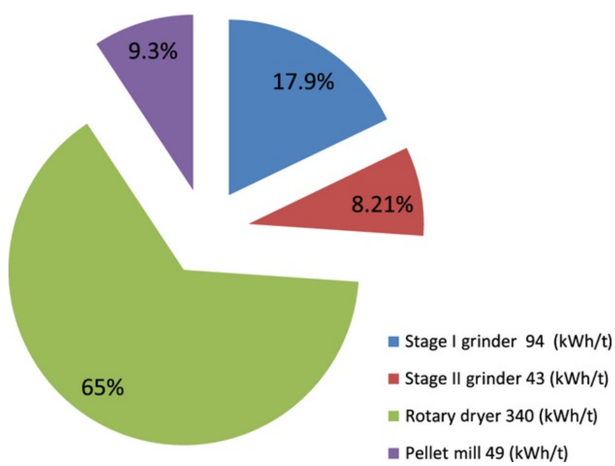

Figure 2. Energy consumption of various unit operations in woody biomass pelleting (Tumuluru 2015).

According to Granström (2005) and Johansson and Rasmuson (1998), woody biomass drying using a high-temperature rotary dryer results in the emission of volatiles and extractives that are suitable neither for human health nor the environment. When released into the environment, these emissions form photo-oxidants, which are dangerous if inhaled by humans and can also damage forests and the plant canopy.

1.3 High-Moisture Pelleting Process

In the conventional pelleting method, biomass is dried to about 10% before pelleting. In high-moisture biomass pelleting, the biomass is pelleted at >20% moisture content and the high-moisture pellets produced are further dried in low-temperature drying technologies, such as a grain or belt dryer. Pelleting biomass at high moisture content and then drying the produced pellets using low capital and low-temperature drying methods, such as with a grain or belt dryer, helps to reduce pelleting costs by about 50% (Lamers et al. 2015). High-moisture pelleting eliminates the energy-intensive rotary drying step at the front end with a grain dryer at the back-end of the pellet mill. Pelleting corn stover, ammonia fiber explosion pretreated corn stover, and municipal solid waste at high-moisture content of about >20% (w.b.) in a flat die and ring die pellet mill indicated that good quality pellets, in terms of density (>560 kg/m^3) and durability >95%, can be produced (Tumuluru, 2014 and 2015; Bonner et al., 2014). In the high-moisture pelleting process, as observed in Figure 3, the steam conditioning of biomass is replaced with a short preheating step. Also, Tumuluru (2014; 2015; and 2016) indicated that some of the moisture in the biomass is lost due to frictional heat developed in the die during compression and extrusion. When pelleting biomass with a moisture content greater than 20% prior to pellet milling, there is about a 5–10% moisture content loss in the biomass during the pelleting process. Further drying of the high-moisture pellets using a grain or belt dryer, which operates at <90°C, can significantly influence pelleting costs. Techno-economic analysis of this process compared with conventional methods indicated there is about a 50% reduction in pelleting costs for herbaceous biomass (Lamers et al., 2015). Tumuluru (2014; 2015; and 2016) and Tumuluru et al. (2016) have demonstrated this high-moisture pelleting process at moisture content >28% (w.b.) in a laboratory-scale flat die pellet mill. A recent study by Tumuluru involving scale-up of high-moisture pelleting in a ring die pellet mill with a throughput of 1 ton/hr has also indicated that this process is scalable. Furthermore, trends have matched with the data obtained with the laboratory-scale pellet mill.

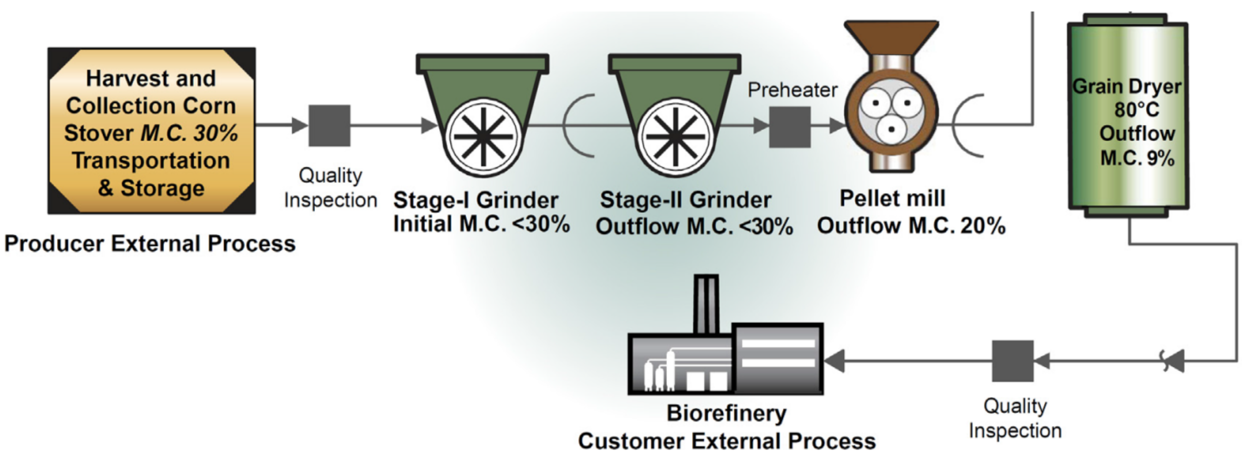

Figure 3. Energy consumption of various unit operations in woody biomass pelleting (Tumuluru 2015).

2. OBJECTIVES

The overall goal of the project is to develop and demonstrate a state-of-the-art biomass merchandising and processing depot to identify and reduce sources of variation along the supply chain of two high-impact biomass species (i.e., pine and switchgrass) and to develop practices that manage biomass variability to deliver a consistent feedstock optimized for performance in a specific conversion-technology platform (Rials, 2017). One way to manage the moisture and particle size variability is to densify the biomass. Many refineries are not ready to densify biomass, and the cost is a prohibitive factor. In this project, a new pelleting concept, such as high-moisture pelleting, were tested on woody and herbaceous biomass blends. The ability of this technology to efficiently manage the moisture in the blends was demonstrated. The data on pelleting the blends of woody and herbaceous biomass at high-moisture content (≥20%, w.b.) in a continuous flat die pellet mill and ring die pilot-scale mill are not available. Experimental data on how high-moisture content, the compression (L/D) ratio in the pellet die, and the blend ratio of pine and switchgrass impact pellet quality and energy consumption of the pelleting process are also not available.

The primary goal of this task was to develop the high-moisture pelleting process for forest residue and switchgrass blends. The specific objectives are to: (a) understand how the L/D ratio in the pellet die in a flat-die and ring die pellet mill and a blend moisture content in the range of 20–30% (w.b.) impacts the quality of the produced pellets using those blends; (b) develop response-surface models and surface plots to understand the interactive effect of process variables on pellet quality and the specific energy consumption (SEC) of the process; and (c) provide a pilot-scale demonstration of the forest residue and switchgrass blends at a higher moisture content.

3. MATERIALS AND METHODS

3.1 Feedstocks

Switchgrass and pine residue feedstocks were selected for this study based on their potential suitability for bioenergy feedstocks (Perlack and Stokes, 2011). The switchgrass, (*P. virgatum L.*) Alamo, was field-grown and harvested in Vonore, TN, and processed with a tub grinder by Genera Energy Inc. (Vonore, TN). The pine residue samples were harvested from forest stands in Auburn, AL, and consisted of composite samples of small diameter treetops, limbs, and needles from several Loblolly pine trees. Two batches were collected that differed by the diameter for the treetop (or stem), which was sectioned and included as the pine residue material. Residues harvested from 2-in. (50.8 mm) diameter tree tops and resides harvested from 6-in. (152.4 mm) diameter treetops were used in the studies. Pine residues were dried, and both pine residues and switchgrass were hammer-milled to pass through a 3/16-in. (4.76 mm) screen at Herty Advanced Biomaterials (Savannah, GA). Prior to the analytical analysis, samples were milled using a Wiley mill to pass through a 0.425 mm (40-mesh) screen. In FY-17, a flat die pellet mill was used to test the pelleting of switchgrass and pine residue blends at a higher moisture content.

In FY-18, the pilot-scale studies focused on the clean pine woodchip feedstocks provided by Auburn University. The pure wet pine wood chips provided by Auburn were transported to North Carolina State University for further drying to about 10% (w.b.) before shipping to Idaho National Laboratory (INL), as observed in Figure 4. The dried wood chips provided to INL were further ground in a hammer mill fitted with a 1/4-in. (6.35 mm) screen. The switchgrass that was also ground using a 1/4-in. screen in a hammer mill was provided by Genera Energy, Inc.

In FY-19, the pilot-scale demonstration of the high-moisture pelleting studies focused on 2- and 6-in. treetop pine residue, which was provided by Auburn. These pine wood chips, as observed in Figure 5, were then size-reduced at INL using a hammer mill fitted with a 1/4-in. screen. The switchgrass samples provided by Genera Energy, Inc., in FY-18 were also used for the FY-19 pelleting demonstration studies.

Figure 4. 3/16-in. milled 2- and 6-in. pine tops and switchgrass used for pelleting tests.

Figure 5. Pine wood chips used in the pelleting studies.

4. EXPERIMENTAL PLAN

4.1 Flat Die Pellet Mill Studies

Switchgrass with a 2-in. top pine residue blend ratio, blend moisture content, and pellet die compression (L/D) ratio were selected as the process variables for the high-moisture pelleting studies. Table 1 indicates the experimental conditions used for these tests, while Table 2 provides the experimental plan for the pelleting tests, which were conducted using 4.76 mm grind switchgrass and 2-in. top pine residue blends. Pelleting tests were conducted at each L/D ratio in the pellet die at three different blend moisture contents. The pelleting tests were conducted at 60 Hz rotational speed of the pellet die. The diameter of the pellet die used for the present study was 6 mm. The pellets produced were used to measure physical properties, such as pellet moisture content (%, w.b.), bulk density (kg/m^3), and durability (%). LabVIEW software was used to log the power data. These data are further used to calculate the SEC of the pelleting process. In the present study, an ECO-10 flat die pellet mill was used to perform the pelleting tests, as shown in Figure 6 (Tumuluru, 2015 and 2016). It has a hopper and screw feeder that feeds the pellet mill continuously. Flexible heating tape is also provided to the screw feeder and hopper, which can help to preheat the biomass before pelleting. A variable frequency drive is provided to the pellet mill to vary the rotational speed of the die. A horizontal pellet cooler is provided to cool the warm pellets coming out of the pellet die. Power-consumption during pelleting was measured using the power meter provided to the pellet mill.

Table 1. Experimental conditions used for pelleting of pine and switchgrass blends.

Blend Feedstock	Process Variables	
	L/D Ratio of the Pellet Die (x1)	**Blend Moisture Content (%, w.b.) (x2)**
50% 2-in. top pine residue + 50% switchgrass	1.5, 2.0, 2.6	20, 25, 30
75% 2-in. top pine residue + 25% switchgrass	1.5, 2.0, 2.6	20, 25, 30
25% 2-in. top pine residue + 75% switchgrass	1.5, 2.0, 2.6	20, 25, 30

Note: Both the switchgrass and 2-in. top pine residue was ground in a hammer mill fitted with a 3/16-in. (4.8 mm) screen.

Table 2. Experimental plan for high-moisture pelleting in a pilot-scale pellet mill.

Experiment Number	Blend Moisture Content	L/D Ratio	Pellet Properties
1	20	5	• Pellet moisture content • Pellet bulk density • Pellet green and cured durability • SEC.
2	20	7	
3	20	9	
4	25	5	
5	25	7	
6	25	9	

Note: Blend ratio (e.g., switchgrass: southern pine): 25: 75; 50: 50; 75: 25; 100:0; and 0:100.

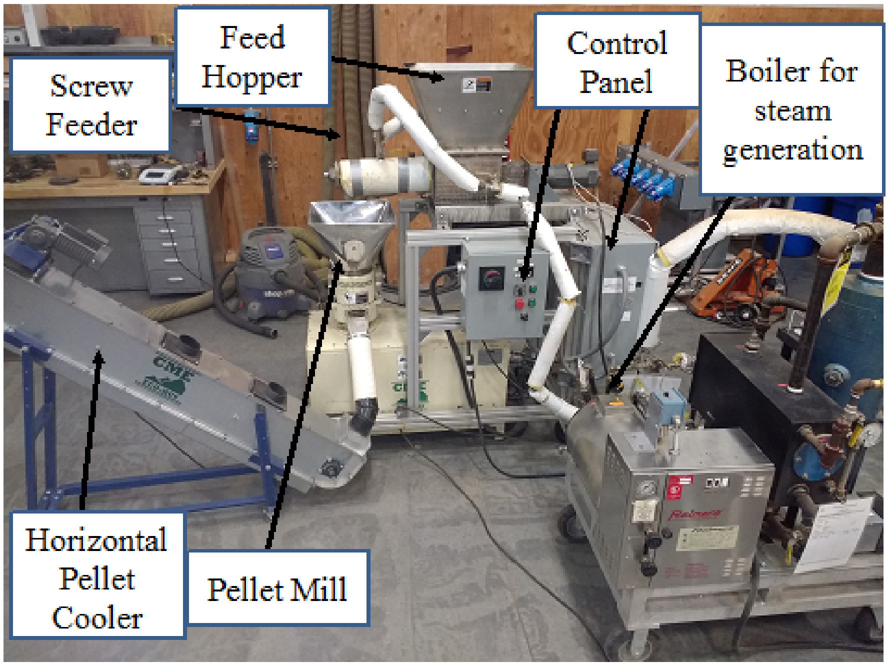

Figure 6. Flat die pellet mill at Idaho National Laboratory.

4.1.1 Pilot-Scale Pellet Mill

A pilot-scale pellet mill with a 1 ton/h throughput, as shown in Figure 7, was used in this study. The pellet mill is provided with a mixture where the moisture can be adjusted to the desired level. The pellet mill is provided with a steam conditioner to add moisture and heat during pelleting. The pellet is provided with different dies and compression ratios. In the present study, three L/D ratios (e.g., 5, 7, 9) were tested. The pellet mill is provided with a data logging system where the current and power-consumption during pelleting were recorded.

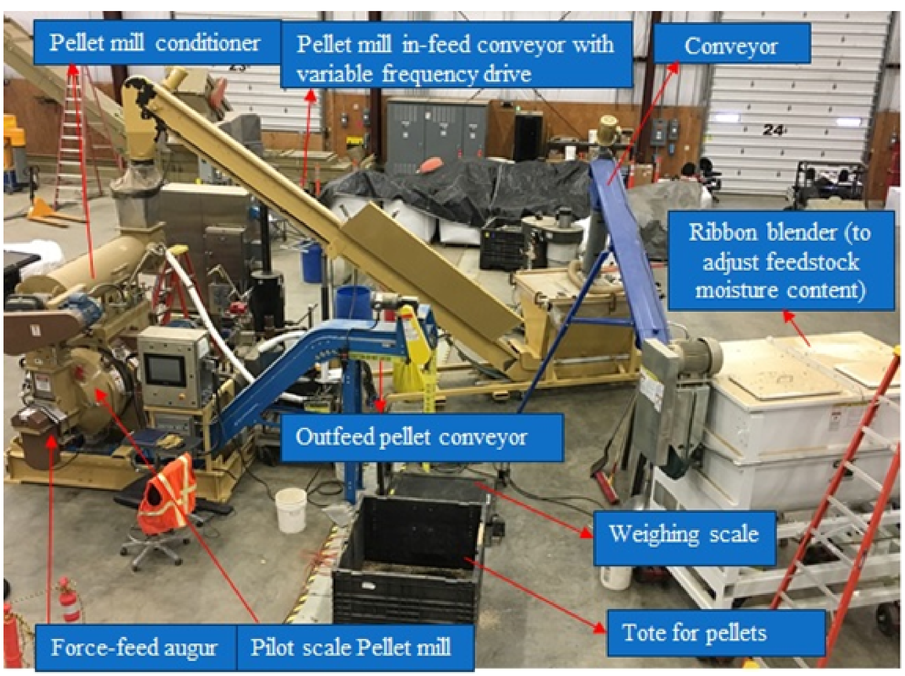

Figure 7. Pilot-scale pellet mill.

4.1.1.1 Objectives of the Pilot-Scale Demonstration Studies

The primary objectives of these studies were to demonstrate the high-moisture pelleting process using blends of 2- and 6-in. top pine residues and switchgrass blends at 20% (w.b.) moisture content and to collect the process and pellet quality data during pelleting using the NIR method developed in the project. At the conclusion of the project, the following was achieved:

- 2- and 6-in. pine wood chips provided by the Auburn University were ground in a hammer mill fitted with a 1/4-in. screen. The grinding energy and grind properties were collected.
- The pelleting of pine and switchgrass blends using a high-moisture pelleting process in a pilot-scale ring die pellet mill was demonstrated. The L/D ratio of the pellet die was 9, while the moisture content of the blend was 20% (w.b.).
- The University of Tennessee research team visited INL to collect the pellet quality data using the NIR method developed in this project during the pelleting of blends 2- and 6-in. pine and switchgrass blends.
- INL collected the process data during pelleting, including the pellet properties and energy consumption.
- The process data collected during pelleting was provided to the University of Tennessee for further analysis.
- The pellet samples were shipped to Auburn University for testing in their pilot-scale gasifier.

The experimental plan used for the pilot-scale studies is given in Table 3. The pilot-scale demonstration of high-moisture switchgrass and pine forest residue pelleting was carried out at a blend moisture content of 20% (w.b.) and a pellet die L/D ratio of 9. North Carolina State University provided two tons of 2-in. top pine and two tons of 6-in. top pine wood chips to INL. The chips were ground in a hammer mill fitted with a 1/4-in. screen at INL. The ground 2-in. and 6-in. top pines were further blended with the switchgrass and blended to about 20% (w.b.) moisture content. The pilot-scale Bliss pellet mill, available at INL's Biomass Feedstock National User Facility (BFNUF), was used to conduct the pelleting. The blended pellets were shipped to Auburn University for gasification studies. The pelleting data collected during this process will be used to calculate pelleting energy consumption. University of Tennessee visited INL during the pilot-scale demonstration to capture the compositional data using the near infrared system developed in the project.

Table 3. Experimental plan for pilot-scale demonstration.

Experiment Number	Blend Ratio	Pelleting Conditions	Pellet Properties
1	Blend and condition Pine 2-in. top/SWG – 50/50 mass ratio, about 1-ton and pelletize using pilot-scale pellet mill.	L/D ratio 9; blend moisture of 20%.	• Pellet density • Pellet durability • Pelleting energy consumption.
2	Blend and condition Pine 2-in. top/SWG – 60/40 mass ratio, about 1-ton and pelletize using pilot-scale pellet mill.		
3	Blend and condition Pine 6-in. top/SWG – 50/50 mass ratio, about 1-ton and pelletize using pilot-scale pellet mill.		
4	Blend and condition Pine 6-in. top/SWG – 60/40 mass ratio, about 1-ton and pelletize using pilot-scale pellet mill.		

4.2 Pellet Properties Measurement

Pellet moisture content was measured before and after drying, as well as the bulk density and durability, by using the American Society of Agricultural and Biological Engineers (ASABE) 2007 Standard S269.4 (2007). A complete description of these methods was given by Tumuluru (2014; 2015; 2016) and Tumuluru et al. (2016). In the case of moisture content, the biomass is dried in a mechanical oven at 105°C for 24 hours. In the case of bulk density, the dried pellets were poured in a cylindrical container, and the excess material was removed by striking a straight edge across the top of the container. The weight of the pellets in the container divided by the volume of the container gives the bulk density. Pellet durability was measured using the pellet durability tester, which has four compartments. Pellet samples were placed in each compartment and then rotated at 50 rpm for 10 min. The ratio of the mass of the pellets after tumbling to the mass of the pellets before tumbling is defined as pellet durability. All pellet properties are measured in triplicate. Power-consumption data during pelleting were logged using LabVIEW software (Tumuluru, 2015; 2015). An APT power-monitor meter connected to the pellet mill records the power in kilowatts. The no-load power at 60 Hz rotational speed was recorded by running the pellet mill empty. The SEC was calculated by subtracting the no-load kW from the full-load power using Equation (1).

(1)

5. RESULTS

5.1 Physical Properties of the Pine and Switchgrass Blends

Edmunds et al. (2018) discussed the physical properties of 2-in. top pine residue + switchgrass blends in detail. The average values of the individual and blend particle size information, bulk, particle and tap densities, compressibility, and Hausner ratio are given in Table 4. The bulk and tapped density of the blends of the 2-in. top pine residue + switchgrass indicated that d50 increased with an increase in pine percentage, whereas the span reduced with an increase in the pine percentage. The trends were similar for bulk, tap, and particle densities where higher pine percentage increased the density values.
Edmunds et al. (2018) reasoned that a higher span of switchgrass particles could be due to an elongated nature and a higher aspect ratio of the switchgrass grind. Also, the elongated nature of the switchgrass particles can result in entanglements of the particle, which increase void spaces and reduce density. The calculated flow properties, such as the Hausner ratio, were calculated using physical properties data. The Hausner ratio of the blends was in a range between 1.26 and 1.33 (2018).

Figure 8 shows the pellets made from 2-in. top pine residue + switchgrass blends at different blend moisture contents, and L/D ratio in the pellet die. The pelleting experiments were conducted based on the experimental design provided in Table 1. Some of the key results of blending 25% switchgrass + 75% 2-in. top pine residue and 50% switchgrass + 50% 2-in. top pine residue that helped to achieve the requisite bulk density and durability (>550 kg/m^3 and >95%) are provided in Figure 9 and Figure 10. The pelleting process conditions that resulted in bulk density >550 kg/m^3 and durability >95% were an L/D ratio of 2.6 and a blend moisture content of 20% (w.b.). More details about the flat die mill studies can be found in Tumuluru (2019). Response-surface models were also developed for the laboratory-scale pellet mill data.

Table 4. Physical characteristics of grinds from switchgrass and 2- and 6-in. top pine residue blends.

Sample	**Switchgrass**	**2-in. Pine**	**6-in. Pine**	**D50 (microns)**	**Span (d90-d10)/d50**	**Bulk Density (kg/m^3)**	**Particle Density (kg/m^3)**	**Tap Density (kg/m^3)**	**Compressibility**
Milled Switchgrass	100	0	0	534	2.12	166	1443.9	210.3	10.6
Milled Pine Top 2-in.	0	100	0	811	1.64	231.1	1439.7	301.7	11.9
Milled Pine Top 6-in.	0	0	100	697	1.84	229.5	1455.3	305.3	11.9
Blend 1 (SG-75%/ 6-in. pine-25%)	75	0	25	571	2.08	180.4	1418.4	235.3	11.9
Blend 2 (SG-50%/ 6-in. pine-50%)	50	0	50	674	2.01	192	1431.4	247.3	10.7
Blend 3 (SG-25%/ 6-in. pine-75%)	25	0	75	683	1.98	209.7	1441.5	256.7	8.6
Blend 4 (SG-75%/ 2-in. pine-25%)	75	25	0	674	2.07	180.4	1428.3	227.7	10.8
Blend 5 (SG-50%/ 2-in. pine-50%)	50	50	0	766	2.01	188.1	1427.6	240.3	10.6
Blend 6 (SG-25%/ 2-in. pine-75%)	25	75	0	801	1.97	207.6	1417.9	270	10.6
Blend 7 (2-in. pine 50%/ 6-in. pine-50%)	0	50	50	803	1.86	216.1	1431.4	298.3	9.94

Figure 8. Blend pellets made from 2-in. top pine + switchgrass blends at different moisture content values and L/D ratios of the pellet die.

Figure 9. Bulk density of the pellets produced using a blend of 2-in. top pine residue + switchgrass.

Figure 10. Durability of the pellets produced using a blend of 2-in. top pine residue + switchgrass.

Table 5 indicates the models developed for the blends of 2-in. top pine residue + switchgrass based on the experimental data obtained. Coefficient-to-determination values, which were in the range of 0.60 to 0.98, suggest that the models have described the pelleting process reasonably well with respect to the process variables tested. The statistical significance of the models developed for the different blends was evaluated based on the p value. For 50% 2-in. top pine residue +50% switchgrass the models developed pellet properties and SEC were found to be statistical non-significant whereas for durability it was found to be significant ($p<0.01$). In case of 75% 2-in. top pine residue + 25% switchgrass the models developed for pellet moisture content and durability were as found to be statistically not significant, whereas bulk density, and SEC were found to be statistically significant at $p<0.05$. In case of 25% 2-in. top pine residue + 75% switchgrass blend models, pellet moisture content, bulk density, durability were found to be statistically significant ($p<0.05$, $p<0.01$) whereas SEC model was found to statistically non-significant. Using these equations, response-surface plots were developed. The significance of response-surface plots is that they assist in understanding the interactive effect of the process variables (i.e., 2-in. top pine residue + switchgrass blend, blend moisture content, and compression ratio or L/D ratio) in the pellet die on product quality (i.e., blend pellet moisture content, bulk density, and durability) and the SEC of the pelleting process. More details about the pelleting pine and switchgrass blends in flat die pellet mill is given in our paper published in Energies Journal (Tumuluru, 2019).

Table 5. Response-surface models describing pellet properties and energy consumption of blends in respect to process conditions.

Physical Properties and Total Grinding Energy	Equation	(R2)
Blend Ratio: 50% 2-in. top pine residue +50% switchgrass		
Blend pellet moisture content (%, w.b.)		0.81
Bulk density (kg/m^3)		0.87
Durability (%)		0.97
SEC (kWh/ton)		0.73
Blend Ratio: 75% 2-in. top pine residue + 25% switchgrass		
Blend pellet moisture content (%, w.b.)		0.80
Bulk density (kg/m^3)		0.98
Durability (%)		0.60
SEC (kWh/ton)		0.88
Blend Ratio: 25% 2-in. top pine residue + 75% switchgrass		
Blend pellet moisture content (%, w.b.)		0.98
Bulk density (kg/m^3)		0.97
Durability (%)		0.88
SEC (kWh/ton)		0.66

Note: Both switchgrass and 2-in. top pine residue were ground in a hammer mill fitted with a 3/16-in. (4.8 mm) screen size; x1: L/D ratio of the pellet die; x2: Blend moisture content (%, w.b.).

5.2 Pilot-Scale Pellet Mill Results

Some of the experimental results from the pilot-scale results are given in Table 6, Table 7, Table 8, Table 9, and Table 10, respectively. In these tables, L/D represents the compression ratio of the die (e.g., length-to-diameter ratio), BD is the bulk density, D is the durability, and SD is the standard deviation.

Table 6. Pure southern yellow pine pellet properties.

Process Conditions		Pellet Properties							
L/D Ratio	Feedstock Moisture Content (%, w.b.)	Pellet Moisture Content (%, w.b.)	SD	BD (Kg/M^3)	SD	Before Drying		After Drying	
						D (%)	SD	D (%)	SD
7	18.40	13.53	0.69	569.70	3.00	93.46	0.90	92.95	0.28
9	19.46	12.95	0.24	535.83	5.00	95.34	0.28	94.76	0.29
7	17.17	11.21	0.20	607.15	6.00	96.44	0.20	95.82	0.11
7	24.66	16.22	0.46	473.44	2.00	89.56	0.65	90.59	0.35
9	24.45	17.42	0.51	493.72	5.00	93.57	0.70	93.39	0.44
SD: Standard deviation									

Table 7. Pure switchgrass pellet properties.

L/D Ratio	Feedstock Moisture Content (%, w.b.)	Pellet Moisture Content (%, w.b.)	SD	BD (Kg/M^3)	SD	Before Drying		After Drying	
						D (%)	SD	D (%)	SD
7	20.92	13.05	0.30	590.87	4.00	92.79	0.64	93.75	0.34
9	19.56	13.27	0.30	583.18	7.00	94.58	0.38	95.05	0.31
7	24.52	14.39	0.20	577.10	4.00	93.91	0.29	94.04	0.43
9	24.69	15.00	0.50	578.54	3.00	95.20	0.20	95.09	0.30
SD: Standard deviation									

Table 8. 75% southern yellow pine + 25% switchgrass pellet properties.

L/D Ratio	Feedstock Moisture Content (%, w.b.)	Pellet Moisture Content (%, w.b.)	SD	BD (Kg/M^3)	SD	Before Drying		After Drying	
						D (%)	SD	D (%)	SD
7	20.40	13.60	0.19	550.50	7.90	93.40	0.40	95.20	0.70
9	19.70	14.60	3.40	555.22	3.82	93.37	0.20	93.35	0.45
7	24.32	16.83	0.79	525.19	1.96	91.77	0.70	91.72	0.41
9	24.90	16.82	0.13	524.86	6.11	93.00	0.50	92.77	0.46
SD: Standard deviation									

Table 9. 50% southern yellow pine + 50% switchgrass pellet properties.

L/D Ratio	Feedstock Moisture Content (%, w.b.)	Pellet Moisture Content (%, w.b.)	SD	BD (Kg/M^3)	SD	Before Drying		After Drying	
						D (%)	SD	D (%)	SD
7	21.12	14.26	0.37	548.84	6.52	90.59	0.45	90.59	0.50
9	18.79	12.60	0.47	568.96	1.03	95.25	0.29	95.25	0.30
7	24.71	15.88	0.58	546.14	4.72	92.00	0.26	92.02	0.30
9	24.46	14.16	0.52	555.99	1.98	94.91	0.32	94.91	0.30
SD: Standard deviation									

Table 10. 25% southern yellow pine + 75% switchgrass pellet properties.

L/D Ratio	Feedstock Moisture Content (%, w.b.)	Pellet Moisture Content (%, w.b.)	SD	BD (Kg/M^3)	SD	Before Drying		After Drying	
						D (%)	SD	D (%)	SD
7	19.35	11.81	0.20	588.42	2.00	89.70	0.36	90.59	0.71
9	20.20	14.19	0.19	574.81	1.00	94.90	0.29	94.61	0.17
7	23.92	14.16	0.33	577.98	4.90	91.99	0.37	92.70	0.31
9	24.00	14.75	0.18	573.06	4.00	95.06	0.21	94.72	0.46

SD: Standard deviation

5.3 Observations

Pellet Moisture Content (%, w.b.)

- There is about 5-6% (w.b.) reduction of moisture during pelleting for all the conditions and for all the different blend ratios tested. This observation has corroborated with our earlier studies on high-moisture pelleting of corn stover.

Bulk Density

- At about 17-20% (w.b.) the bulk density of the pure southern yellow pine pellets were in the range of 536-607 kg/m^3 whereas increasing the feedstock moisture content to about 24.5% decreased the pellet bulk density to about 473-494 kg/m^3.
- The bulk density of pure switchgrass pellets at about 20% moisture content for 7 and 9 L/D ratio were in the range of 583-591 kg/m^3 whereas increasing the feedstock moisture content to 25% (w.b.) resulted in bulk density in the range of 577-578 kg/m^3.
- At 20% moisture content and L/D ratio of 7 and 9, 75% southern yellow pine + 25% switchgrass pellets had a bulk density in the range of 550-555 kg/m^3 whereas increasing the feedstock moisture content to about 25% resulted in a bulk density of around 525 kg/m^3.
- 50% southern yellow pine + 50% switchgrass pellets at 20% and 25% feedstock moisture content and L/D ratio of 7 and 9 resulted in bulk density values in the range of 546-569 kg/m^3.
- 25% southern yellow pine + 75% switchgrass pellets bulk density was in the range of 573-588 at L/D ratio of 7 and 9 and feedstock moisture content of 20% and 25% (w.b.).

Durability

- For pure southern yellow pine, the durability values for lower feedstock moisture content and higher L/D ratio resulted in durability values >95%.
- For switchgrass, the maximum durability of about 95% was observed for higher L/D ratio of 9 and feedstock moisture content of 20% and 25% (w.b.).
- For 75% southern yellow pine + 25% switchgrass, the highest durability value of 95% was observed at L/D ratio of 7 and feedstock moisture content of 20% (w.b.).
- Durability values of about 95% were observed at L/D ratio of 9 and feedstock moisture content of 20 and 25% for 50% southern yellow pine + 50% switchgrass.
- 25% southern yellow pine + 75% switchgrass resulted in maximum durability values of about 94-95% at L/D ratio of 9 and feedstock moisture content of 20% and25 % moisture content.

5.3.1 Models Development for Pilot-Scale Pellet Mill Data

The models that were developed for pure and blends of switchgrass and pine are given in Table 11. These models were further used to draw the surface plots to understand the interactive effect of feedstock moisture content and L/D ratio of the pellet die on pellet physical properties and pelleting energy consumption.

Table 11. Models to describe the pelleting of pure and blends of pine and switchgrass.

Physical Properties and Total Grinding Energy	Model	(R^2)
100% Pine		
Pellet moisture content (%, w.b.)		0.90
Bulk density (kg/m^3)		0.81
Green durability (%)		0.81
Cured durability		0.85
Pelleting energy (kWh/ton)		0.80
100% Switchgrass		
Pellet moisture content (%, w.b.)		0.63
Bulk density (kg/m^3)		0.70
Green durability (%)		0.98
Cured durability		0.94
Pelleting energy (kWh/ton)		0.73
Blend Ratio: 75% Pine and 25% Switchgrass		
Pellet moisture content (%, w.b.)		0.98
Bulk density (kg/m^3)		0.95
Green durability (%)		0.87
Cured durability		0.78
Pelleting energy (kWh/ton)		0.60
Blend Ratio: 50% Pine and 50% Switchgrass		
Pellet moisture content (%, w.b.)		0.70
Bulk density (kg/m^3)		0.94
Green durability (%)	6055	0.99
Cured durability		0.99
Pelleting energy (kWh/ton)		0.89
Blend Ratio: 25% Pine and 75% Switchgrass		
Pellet moisture content (%, w.b.)		0.58
Bulk density (kg/m^3)		0.68
Green durability (%)		0.97
Cured durability		0.92
Pelleting energy (kWh/ton)		0.30
Note: x1: L/D ratio of the pellet die; x2: Feedstock moisture content (w.b. %)		

5.3.2 Surface Plots

5.3.2.1 Surface Plots for 100% Pine

The surface plots indicate that increasing the moisture content and decreasing the L/D ratio reduced the quality of the pellets and increased the energy consumption of the process. The surface plots also indicate there is about 7-8% (w.b.) moisture loss in the pine when pelleted, as observed in Figure 11 and Figure 12. Pine pellets at 17% (w.b.) moisture content and an L/D ratio of 9 resulted in pellets with a moisture content of <11% (w.b.). At 17-22% (w.b.) moisture content and an L/D ratio of 9, the pellet properties in terms of bulk density and durability were >540 kg/m^3 and >95%, as shown in Figure 13, Figure 14, and Figure 15, respectively. The pelleting energy consumption was less than 100 kWh/ton when the moisture content was at about 17% (w.b.) and an L/D ratio of 5-9. Increasing the moisture increased the energy consumption of the pelleting process.

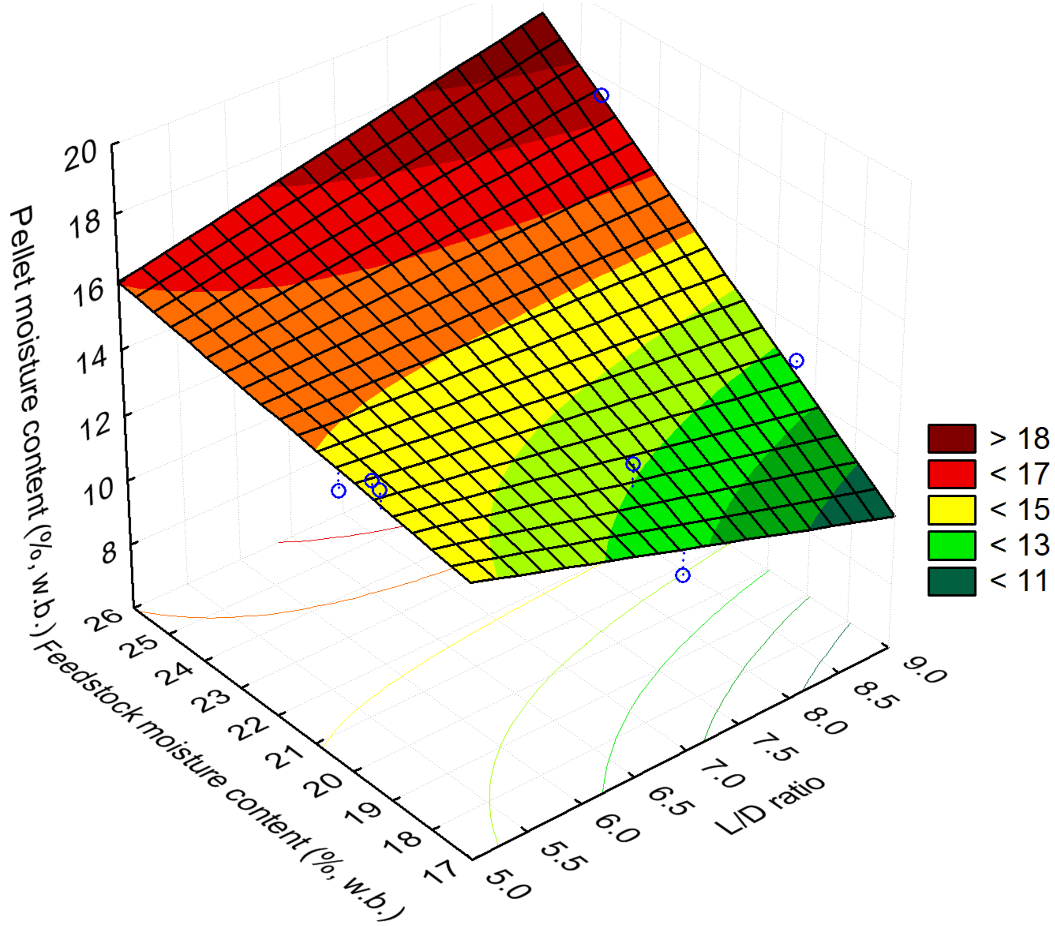

Figure 11. Effect of L/D ratio and feedstock moisture content on the pellet moisture content.

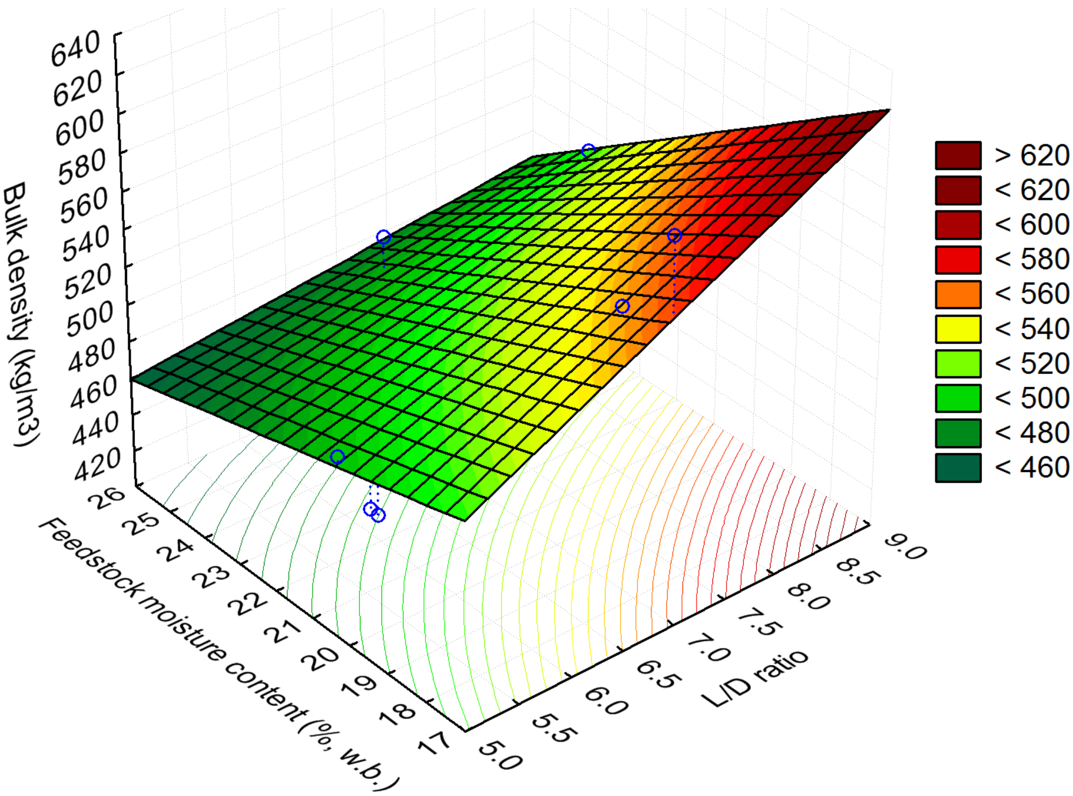

Figure 12. Effect of L/D ratio and feedstock moisture content on the pellet bulk density.

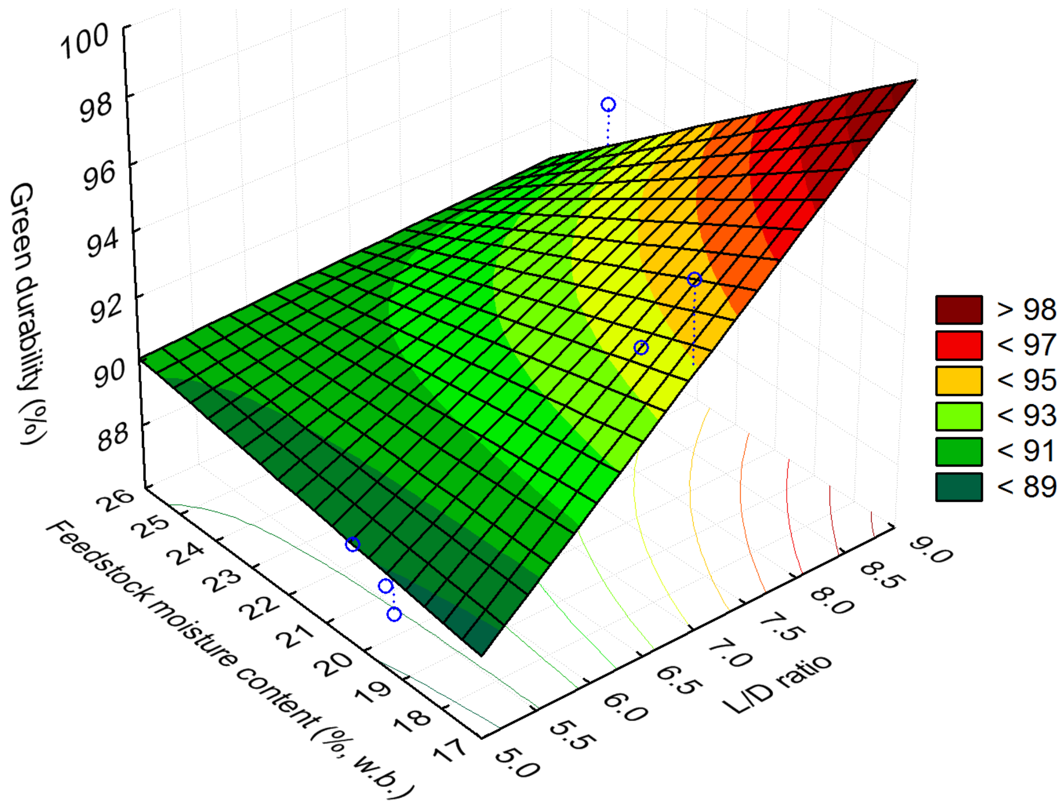

Figure 13. Effect of L/D ratio and feedstock moisture content on the pellet green durability.

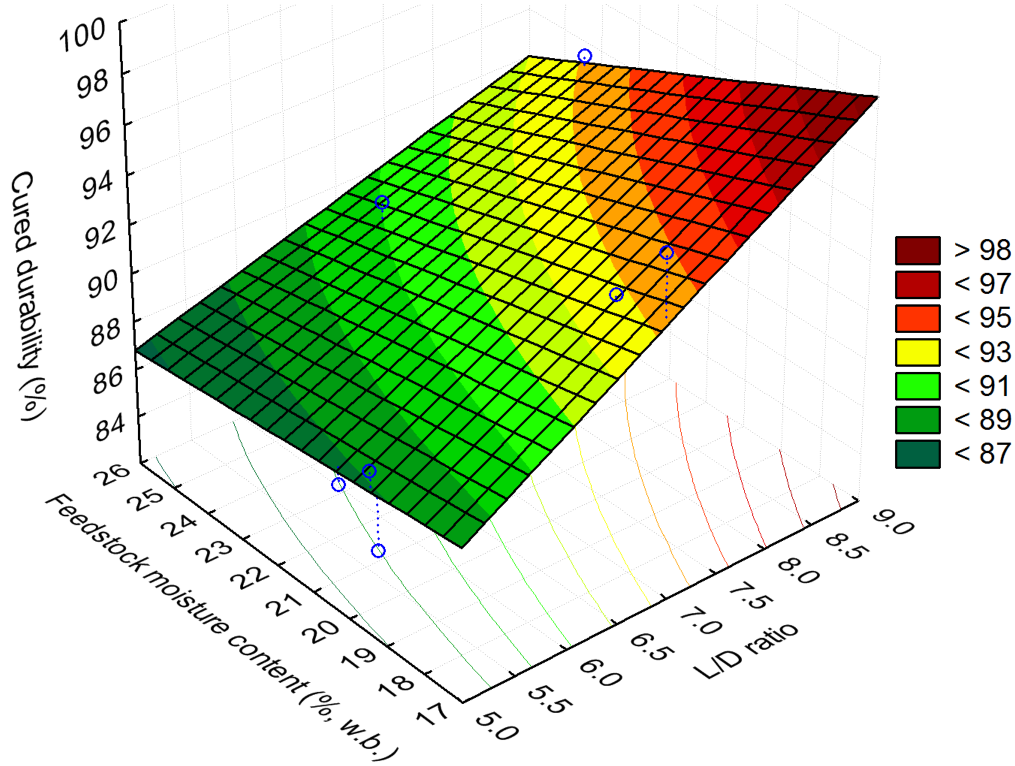

Figure 14. Effect of L/D ratio and feedstock moisture content on the pellet cured durability.

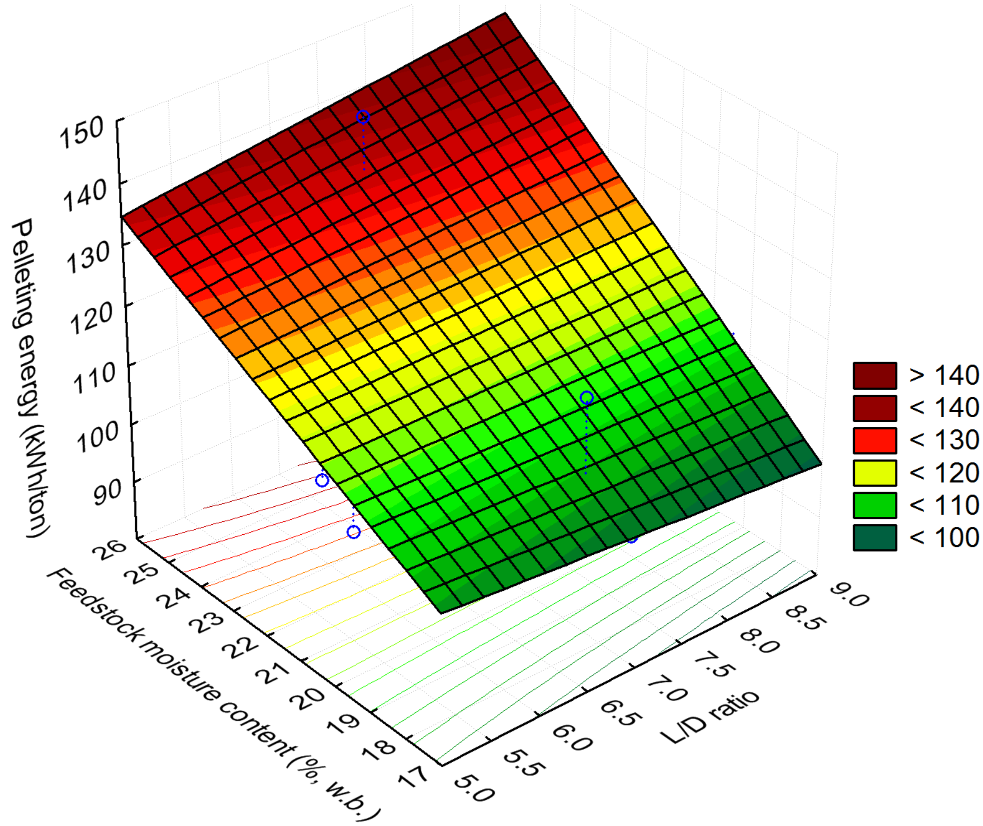

Figure 15. Effect of L/D ratio and feedstock moisture content on the pelleting energy.

5.3.2.2 Surface Plots for 100% Switchgrass

The results indicated that there is about 5-10% moisture loss during pelleting of switchgrass, as observed in Figure 16. When pelleted at 17% (w.b.), switchgrass lost about 5% (w.b.) moisture content, whereas at 25% (w.b.) moisture content and an L/D ratio of 5-9, there is about 10% (w.b.) moisture loss in switchgrass. The lowest bulk density was observed at a lower L/D ratio of 5. At 17% moisture content and a L/D ratio of 5, the observed bulk density was about 530 kg/m^3, whereas when the L/D ratio was increased to 9 for the same moisture content, the bulk density values increased to >590 kg/m^3 , as shown in Figure 17. In the case of green and cured durability, a higher moisture content of 25% (w.b.) and a higher L/D ratio resulted in higher values of >94%, whereas a lower L/D ratio of 5 reduced the durability values to <87%, as can be seen in Figure 18 and Figure 19, respectively. A lower moisture content of about 17% (w.b.) and an LD ratio of 5-9 resulted in a lower pelleting energy (<120 kWh/ton), whereas increasing the moisture content to 25% at either a lower or higher L/D ratio resulted in a higher pelleting energy of >180 kWh/ton, as observed in Figure 20.

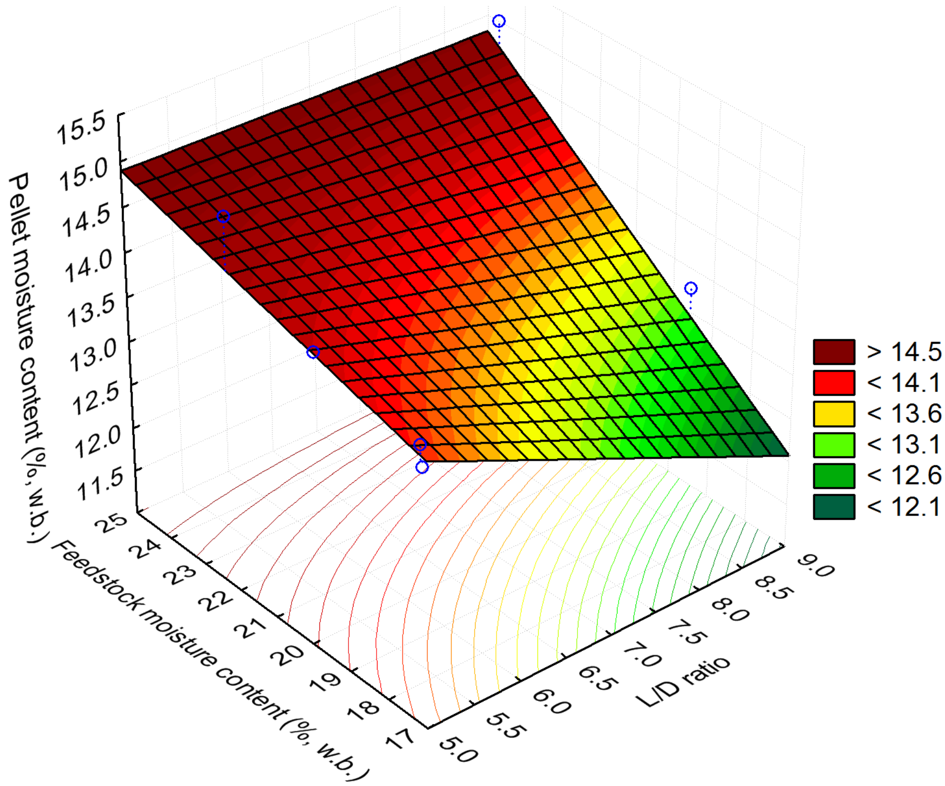

Figure 16. Effect of L/D ratio and feedstock moisture content on the pellet moisture content.

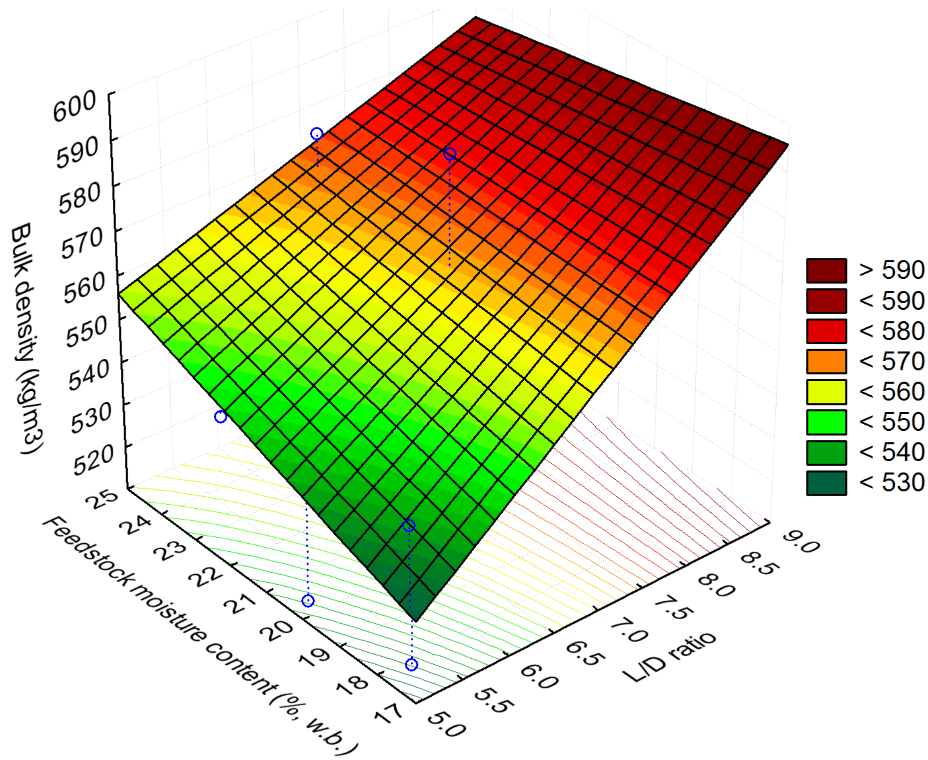

Figure 17. Effect of L/D ratio and feedstock moisture content on the pellet bulk density.

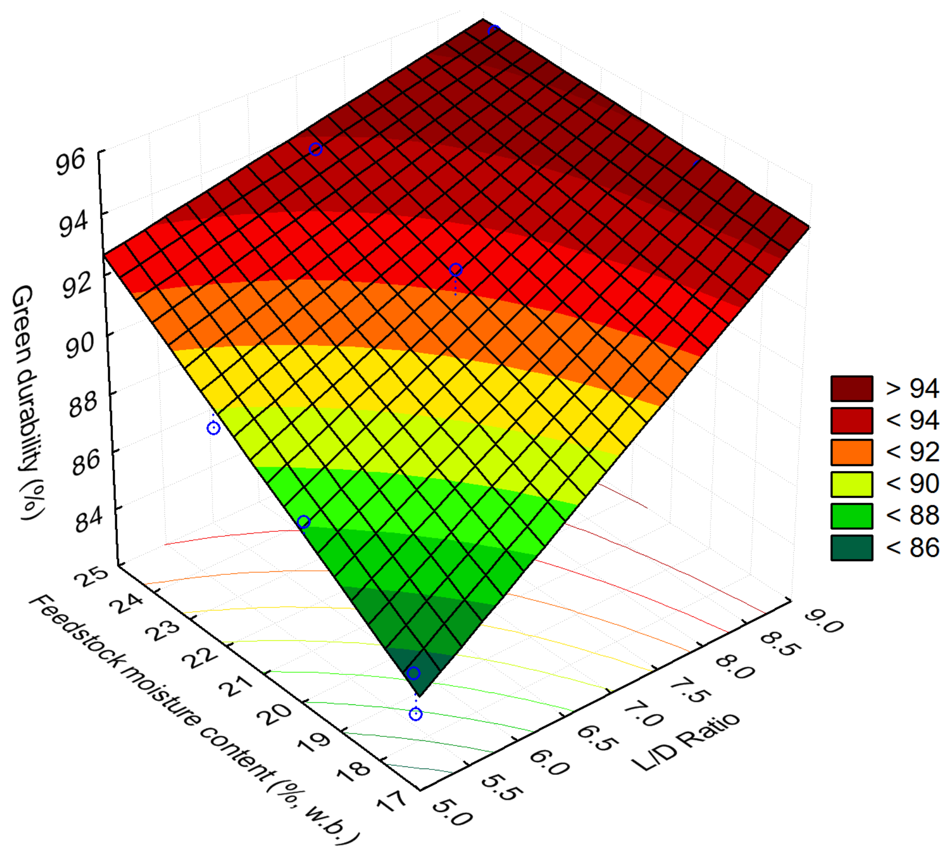

Figure 18. Effect of L/D ratio and feedstock moisture content on the pellet green durability.

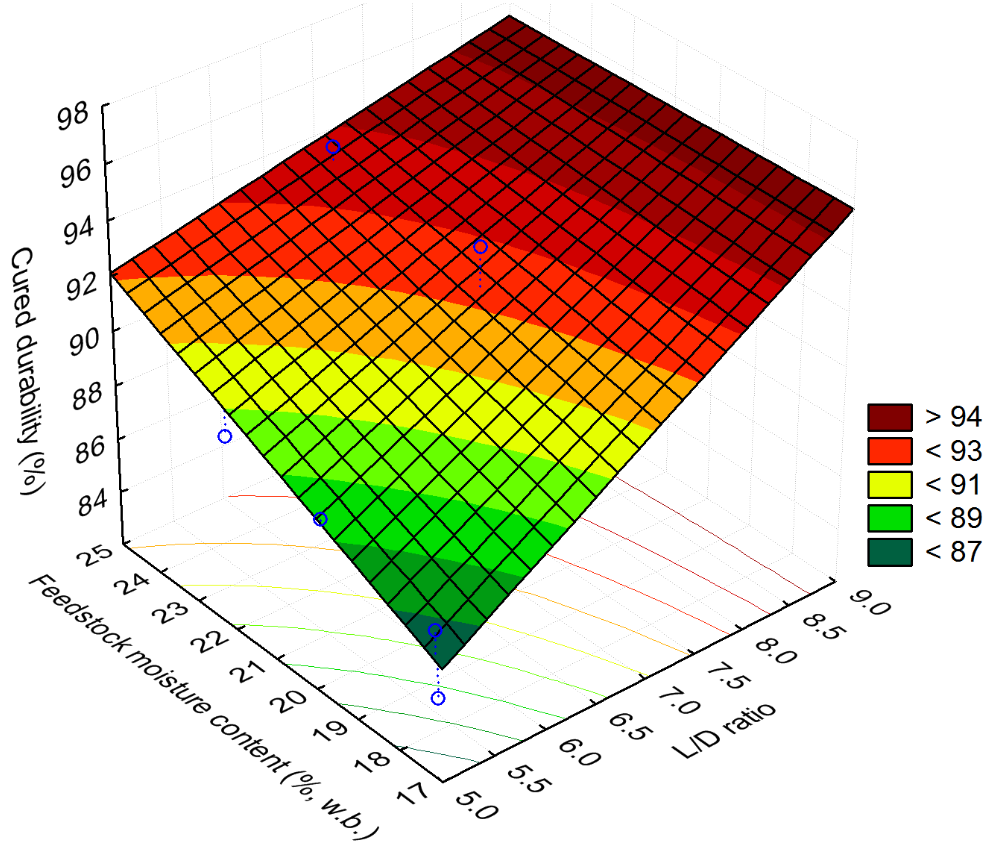

Figure 19. Effect of L/D ratio and feedstock moisture content on the pellet cured durability.

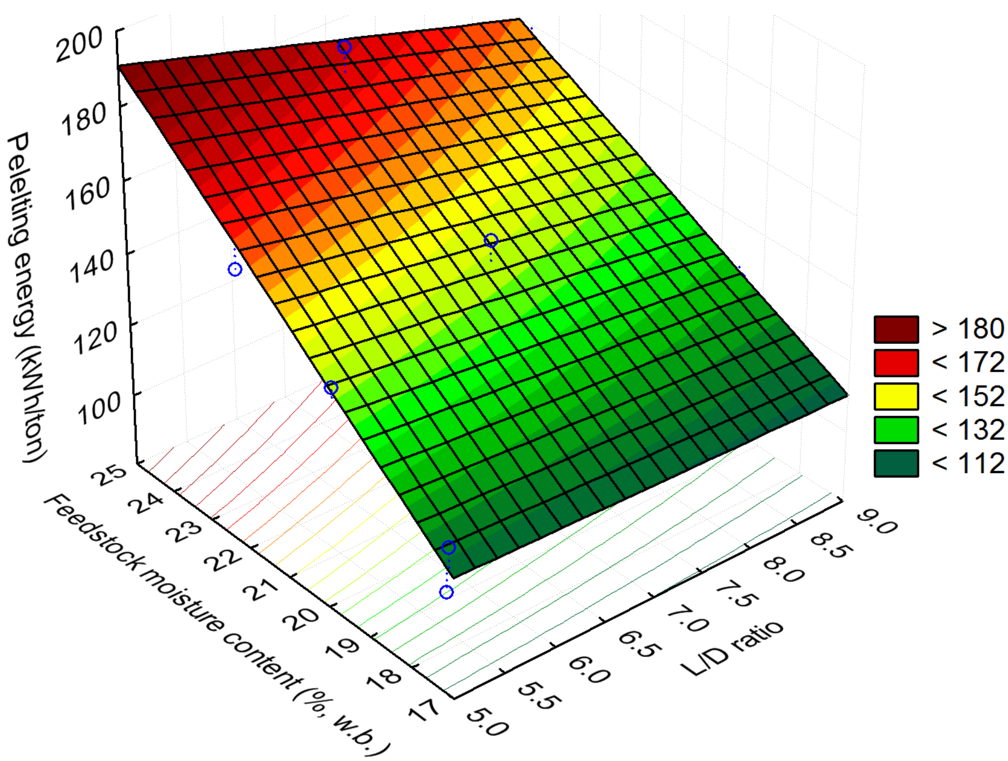

Figure 20. Effect of L/D ratio and feedstock moisture content on the pelleting energy.

5.3.2.3 Surface Plots for 75% Pine and 25% Switchgrass

At 19% (w.b.) moisture content and an L/D ratio of 9, the pellet moisture content was <12.5% (w.b.), whereas at 25% (w.b.) moisture content, the pellet moisture content was about 17% (w.b.). There was about 7-9% moisture loss during pelleting 75% pine and 25 % switchgrass blends, as can be seen in Figure 21. The maximum bulk density observed at an L/D ratio of 9 and a feedstock moisture content of 19% (w.b.) was about >580 kg/m^3, whereas lowering the L/D ratio to 5 at the same moisture content reduced the bulk density values to <464 kg/m^3, as shown in Figure 22. The green and cured durability values increased with an increase in the L/D ratio and a decrease in the feedstock moisture content. At an L/D ratio of 9 and a feedstock moisture content of 19% (w.b.), the observed green and cured durability values were >94%, whereas increasing the moisture content to 25% (w.b.) and reducing the L/D ratio to 5 reduced the green and cured durability values to <85%, as observed in Figure 23 and Figure 24, respectively. In the case of pelleting energy consumption at a higher moisture content of 25% (w.b.) and a higher L/D ratio of 9 resulted in pelleting energy values of >140 kWh/ton, whereas increasing the L/D ratio to 9 and lowering the feedstock moisture content to 19% resulted in the lowest pelleting energy consumption (<102 kWh/ton), as can be seen in Figure 25.

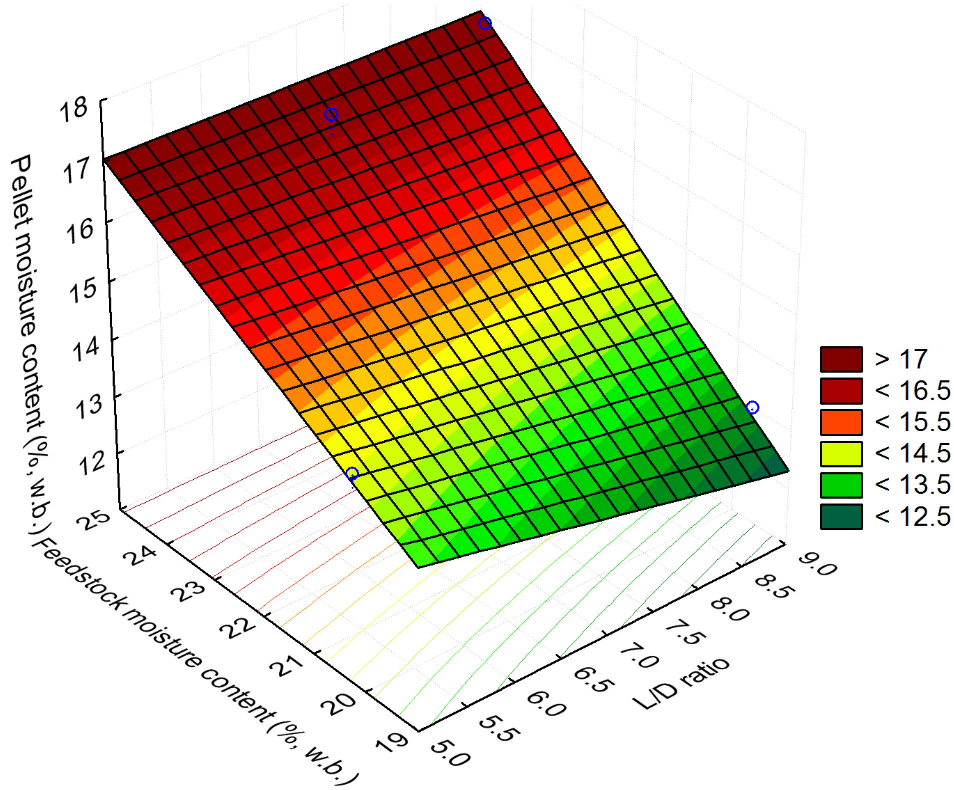

Figure 21. Effect of L/D ratio and feedstock moisture content on the pellet moisture content.

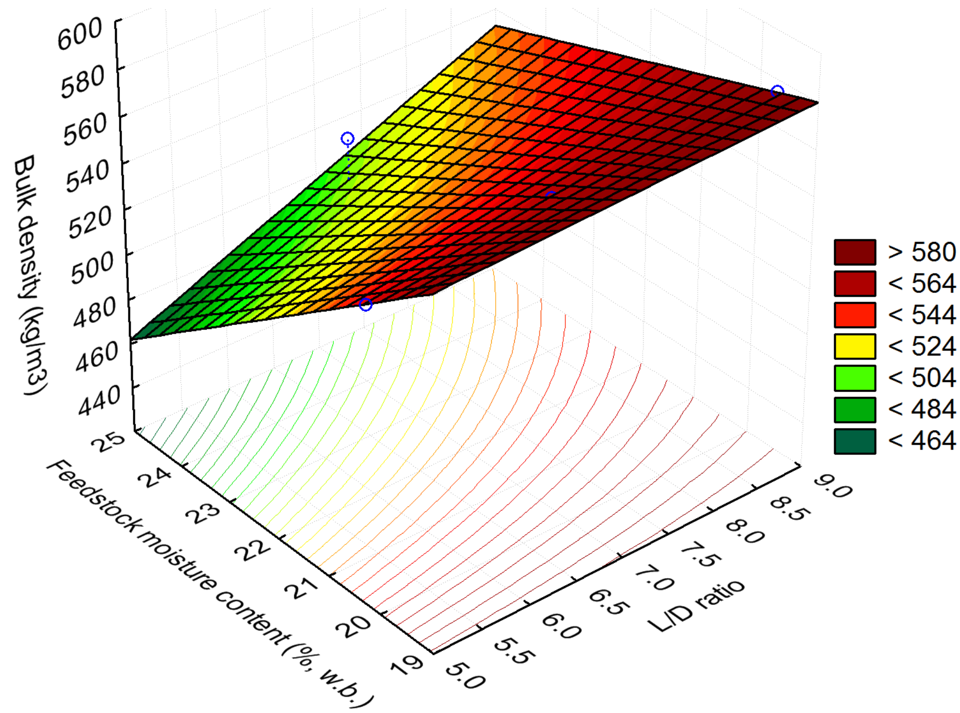

Figure 22. Effect of L/D ratio and feedstock moisture content on the pellet bulk density.

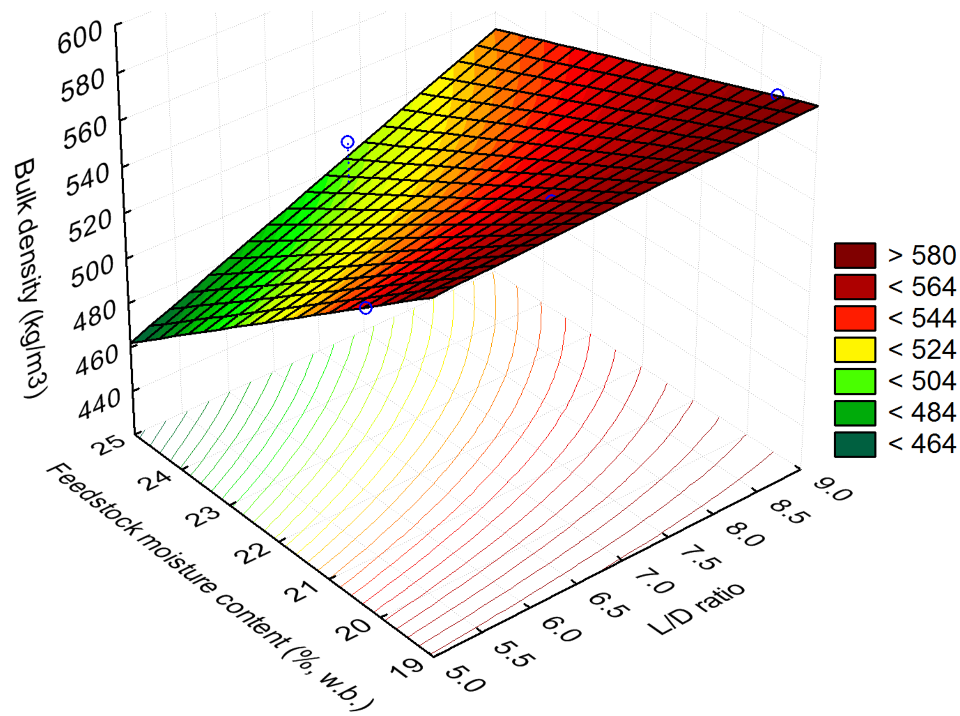

Figure 23. Effect of L/D ratio and feedstock moisture content on the pellet green durability.

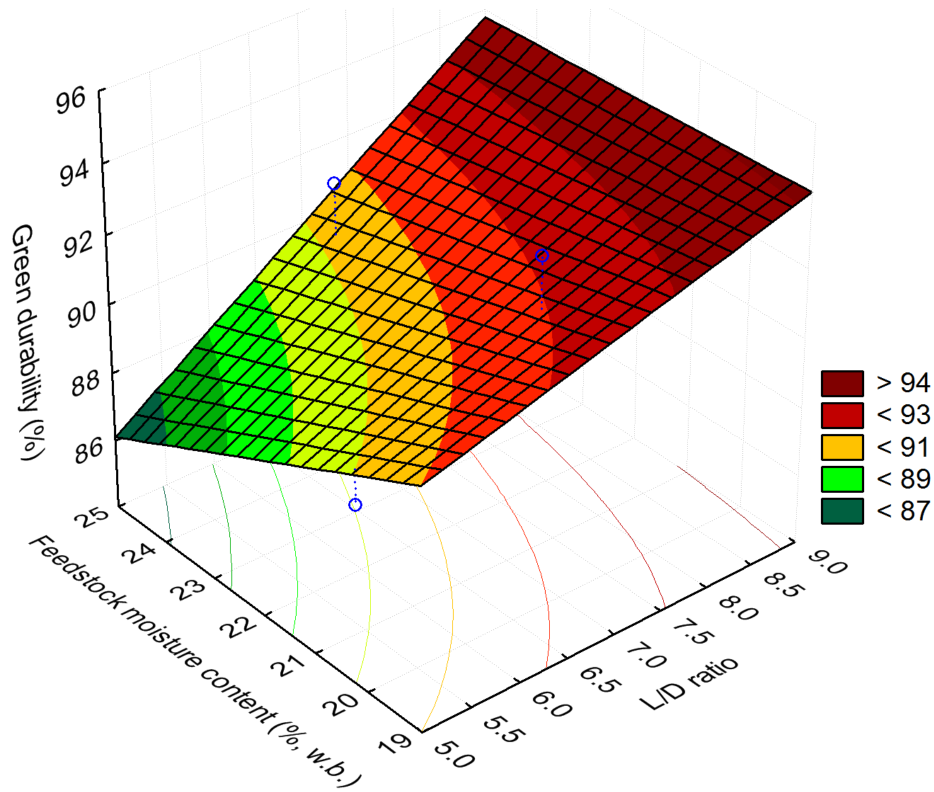

Figure 24. Effect of L/D ratio and feedstock moisture content on the pellet cured durability.

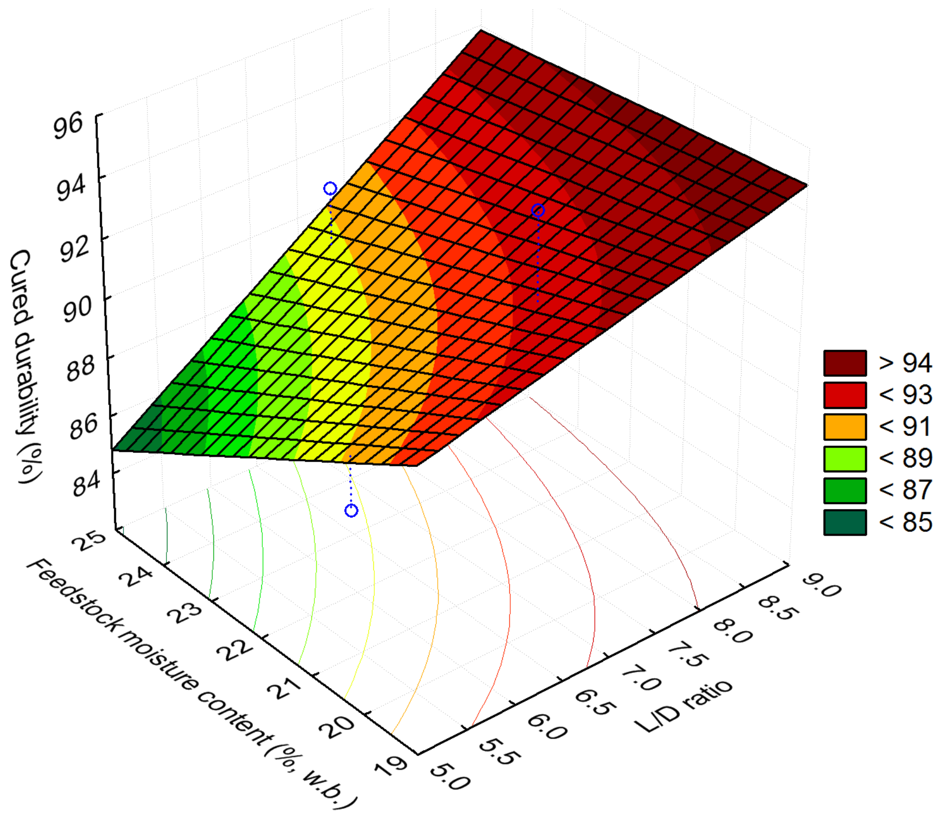

Figure 25. Effect of L/D ratio and feedstock moisture content on the pellet energy.

5.3.2.4 Surface Plots for 50% Pine and 50% Switchgrass

A lower feedstock moisture content of 18% (w.b.) and a higher L/D ratio of 9 resulted in the lowest moisture content (<12.75%, w.b.) observed in the 50% pine and 50% switchgrass pellets. In addition, the surface plot indicated that at a higher moisture content of 25% (w.b.) and a L/D ratio of 9, the final moisture content of the pellets was about 14% (w.b.), which means there is about 12% (w.b.) moisture loss during pelleting, as observed in Figure 26. In the case of bulk density, a lower moisture content of 18 and an L/D ratio of 9 resulted in bulk density values of >560 kg/m^3, as can be seen in Figure 27. Increasing the feedstock moisture content to 25% (w.b.) resulted in a slight decrease in bulk density values (546-556 kg/m^3). The lowest bulk density of <526 kg/m^3 was observed at an L/D ratio of 5 and a feedstock moisture content of 18% (w.b.). In the case of green and cured durability, a maximum value of >94% was observed at an L/D ratio of 9 and a feedstock moisture content of 18% (w.b.). At the same L/D ratio and increasing the feedstock moisture content to 25% (w.b.) resulted in lower green and cured durability values (<86 and <84 %), as shown in Figure 28 and Figure 29, respectively. The pelleting energy of 50% pine and 50% switchgrass was maximized at a lower L/D ratio of 5 and a higher moisture content of 25% (w.b.), whereas a lower moisture content of 18% (w.b.) resulted in lower pelleting energies (<122 kWh/ton) at the different L/D ratios tested (5-9), as observed in Figure 30.

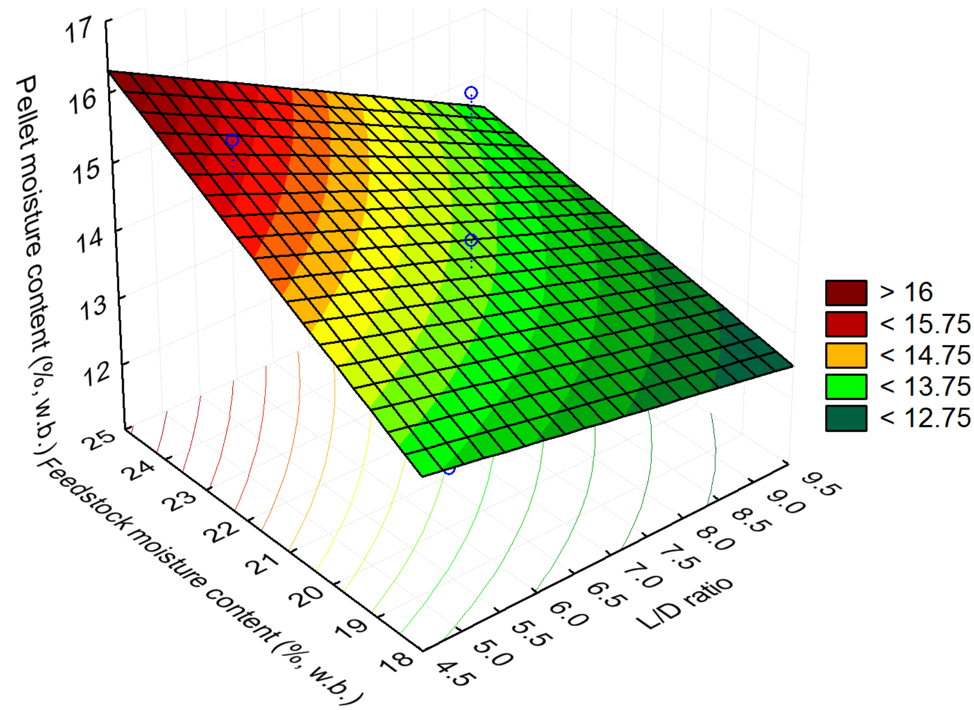

Figure 26. Effect of L/D ratio and feedstock moisture content on the pellet moisture content.

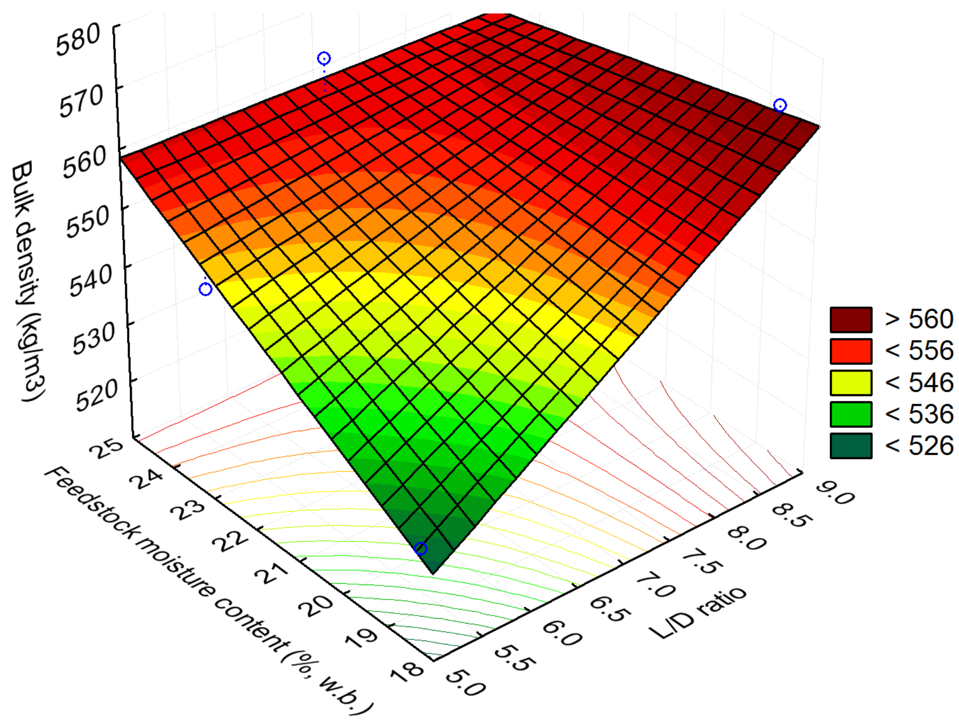

Figure 27. Effect of L/D ratio and feedstock moisture content on the pellet bulk density.

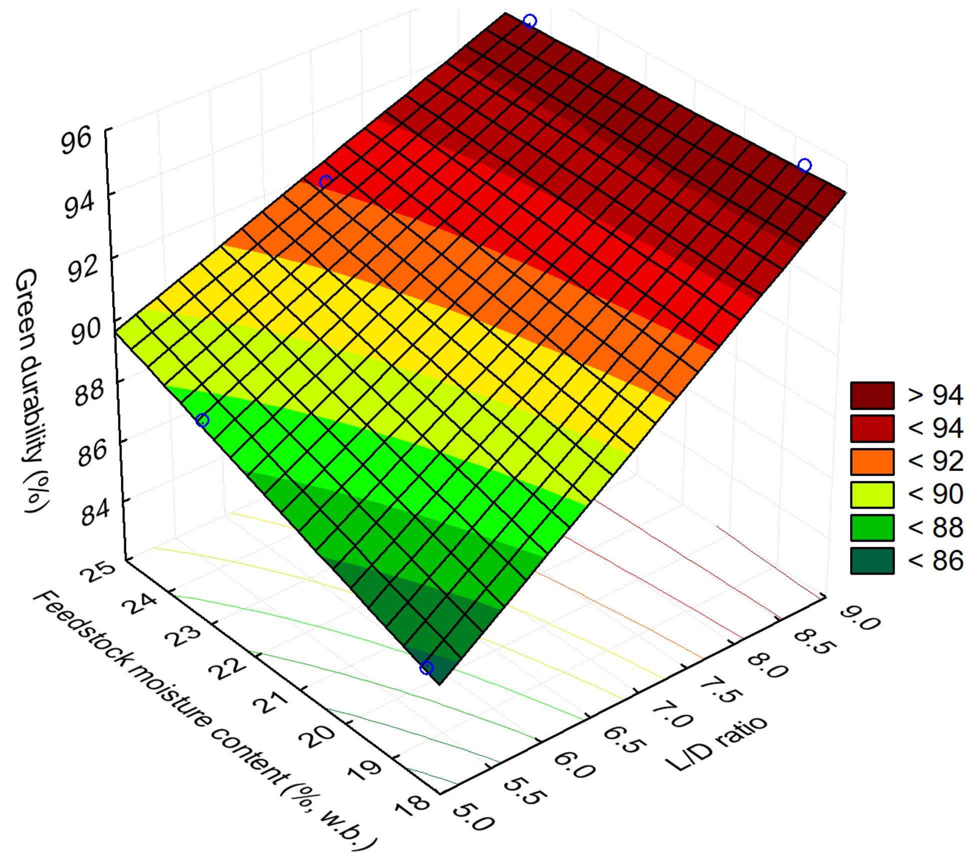

Figure 28. Effect of L/D ratio and feedstock moisture content on the pellet green durability.

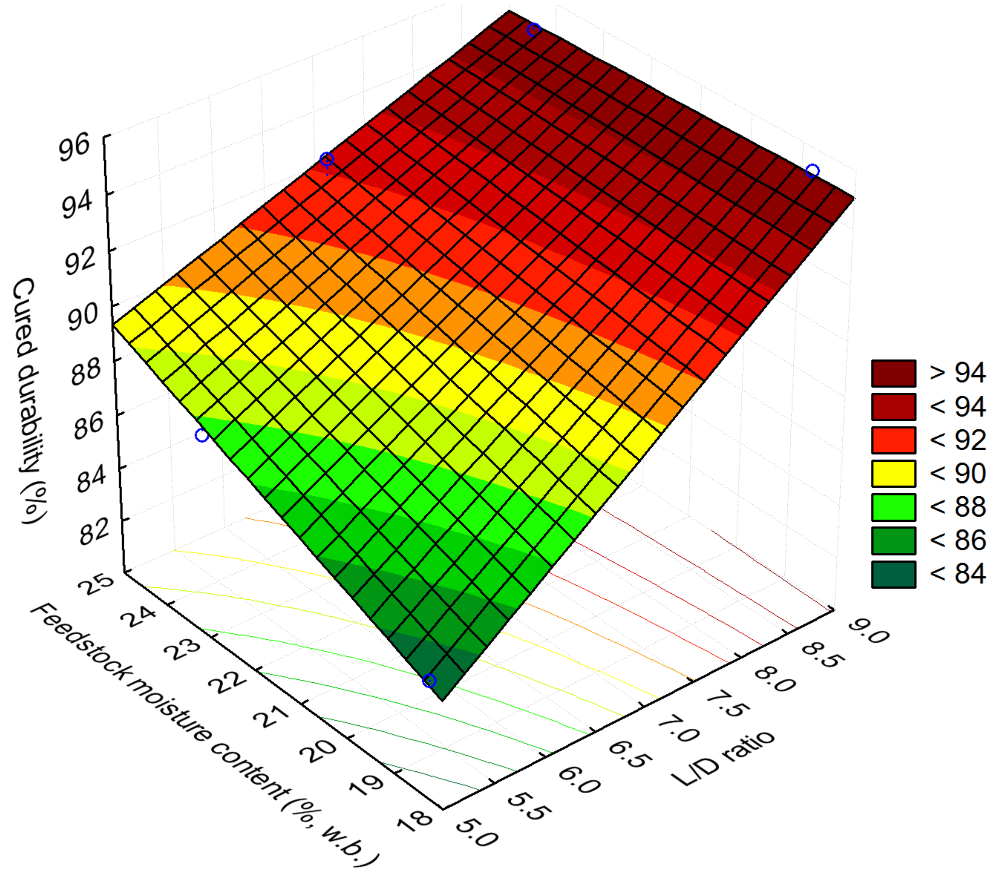

Figure 29. Effect of L/D ratio and feedstock moisture content on the pellet cured durability.

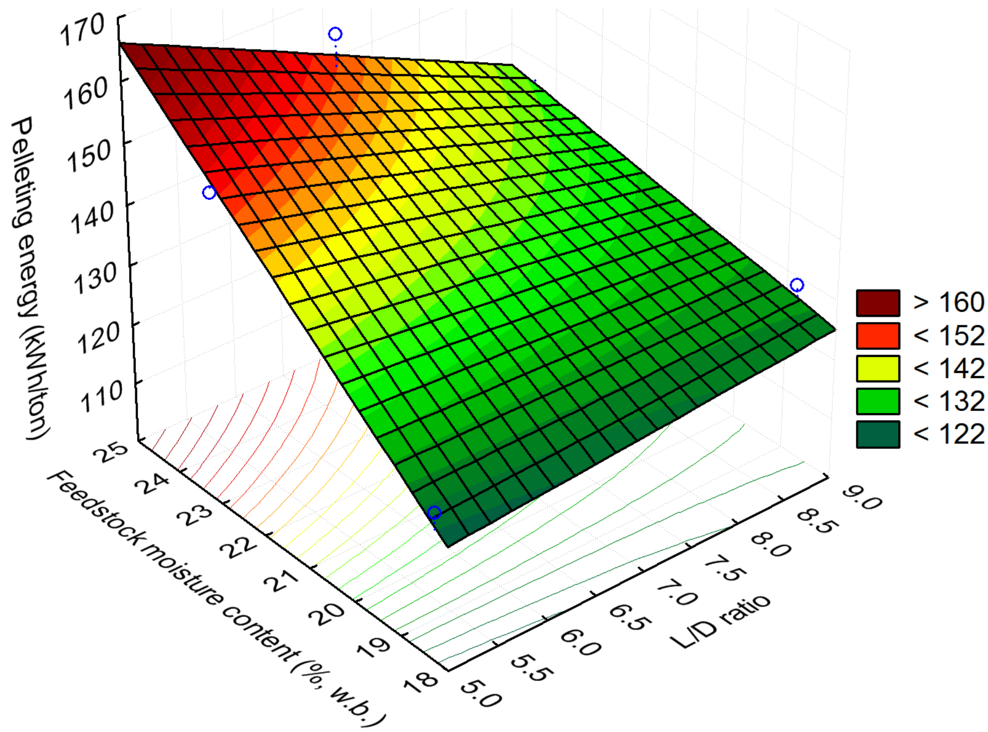

Figure 30. Effect of L/D ratio and feedstock moisture content on the pelleting energy.

5.3.2.5 Surface Plots for 25% Pine and 75% Switchgrass

The pellet moisture content surface plot indicated that the L/D ratio did not have a major effect on the final moisture content, but the initial moisture content of the blend had a significant effect on moisture loss in the feedstock during pelleting. When the feedstock was pelleted at 25% (w.b.) moisture content, a moisture loss of 10% (w.b.) was observed, as can be seen in Figure 31. The final pelleted product had a moisture content of about 15% (w.b.). Pellet bulk density at an L/D ratio of 9 was in the range of 560-580 kg/m^3, whereas increasing the moisture content and lowering the L/D ratio resulted in lower bulk density values of <480 kg/m^3, as observed in Figure 32. The green and cured durability values were at their highest (94%) when the blend was pelleted at an L/D ratio of 9 at several moisture content values tested (18-25%, w.b.), whereas lowering the L/D ratio to 5 and increasing the moisture content to 25% resulted in green and cured durability values of <80% , as shown in Figure 33 and Figure 34, respectively. In the case of pelleting energy, an L/D ratio of 9 and a higher moisture content of 25% (w.b.) resulted in the highest pelleting values of >160 kWh/ton, as shown in Figure 35. At lower moisture content values, the L/D ratio did not have a significant effect on pelleting energy values. The lowest pelleting energy value of <132 kWh/ton was observed at an L/D ratio of 5 and a feedstock moisture content of 19% (w.b.).

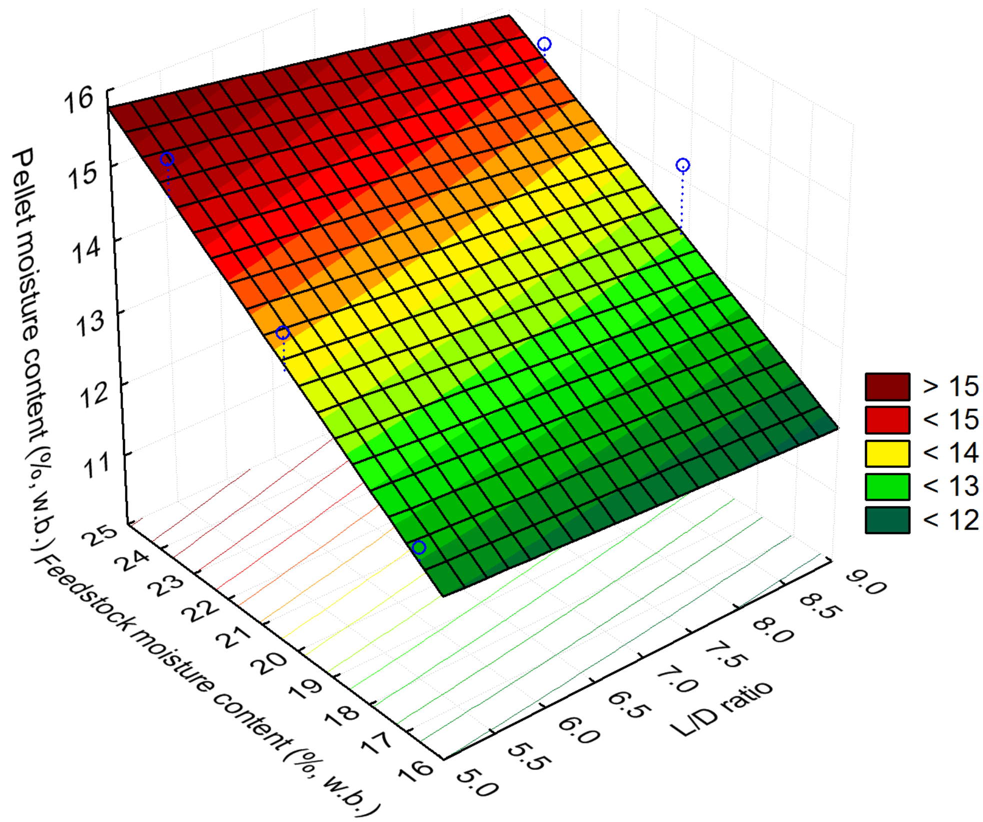

Figure 31. Effect of L/D ratio and feedstock moisture content on the pellet moisture content.

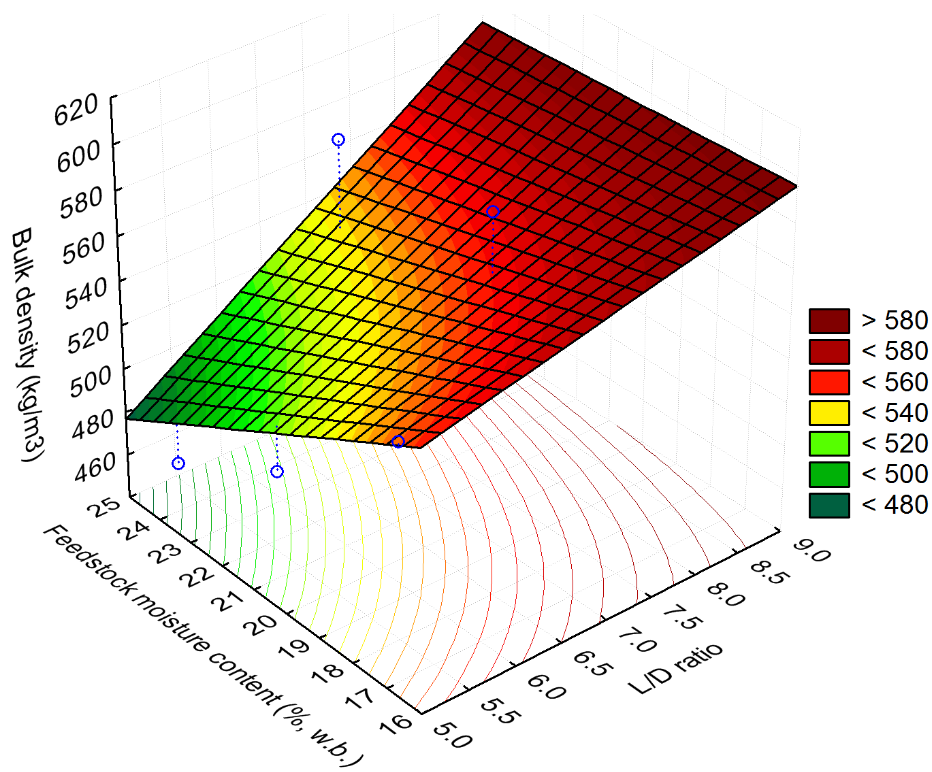

Figure 32. Effect of L/D ratio and feedstock moisture content on the pellet bulk density.

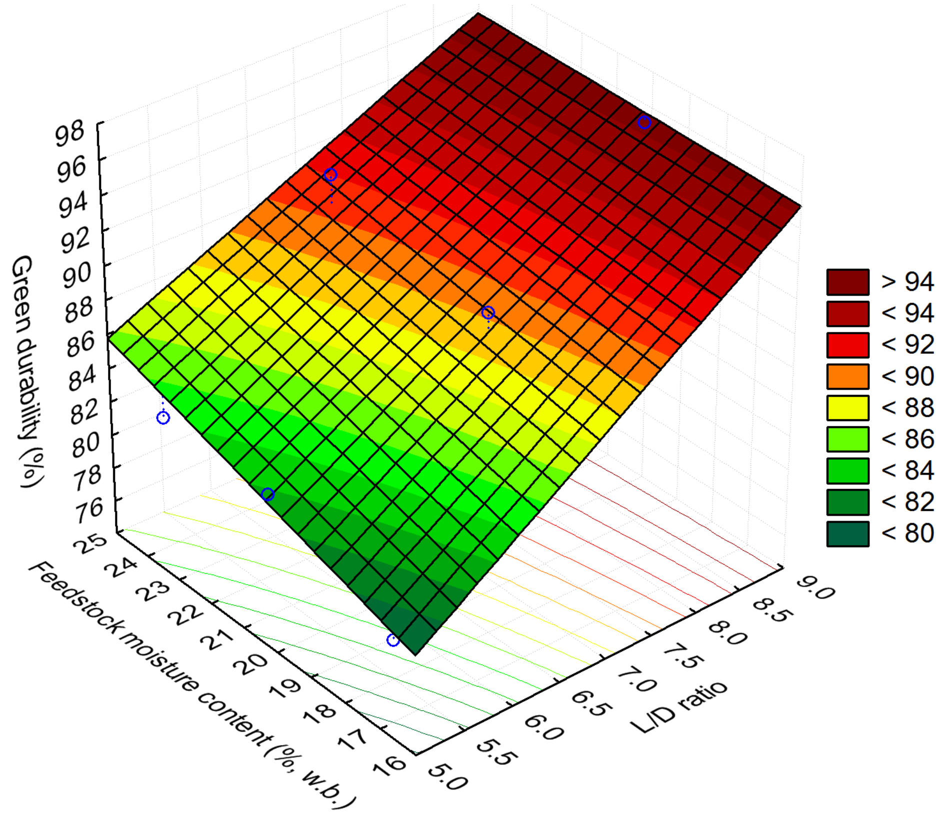

Figure 33. Effect of L/D ratio and feedstock moisture content on the pellet green durability.

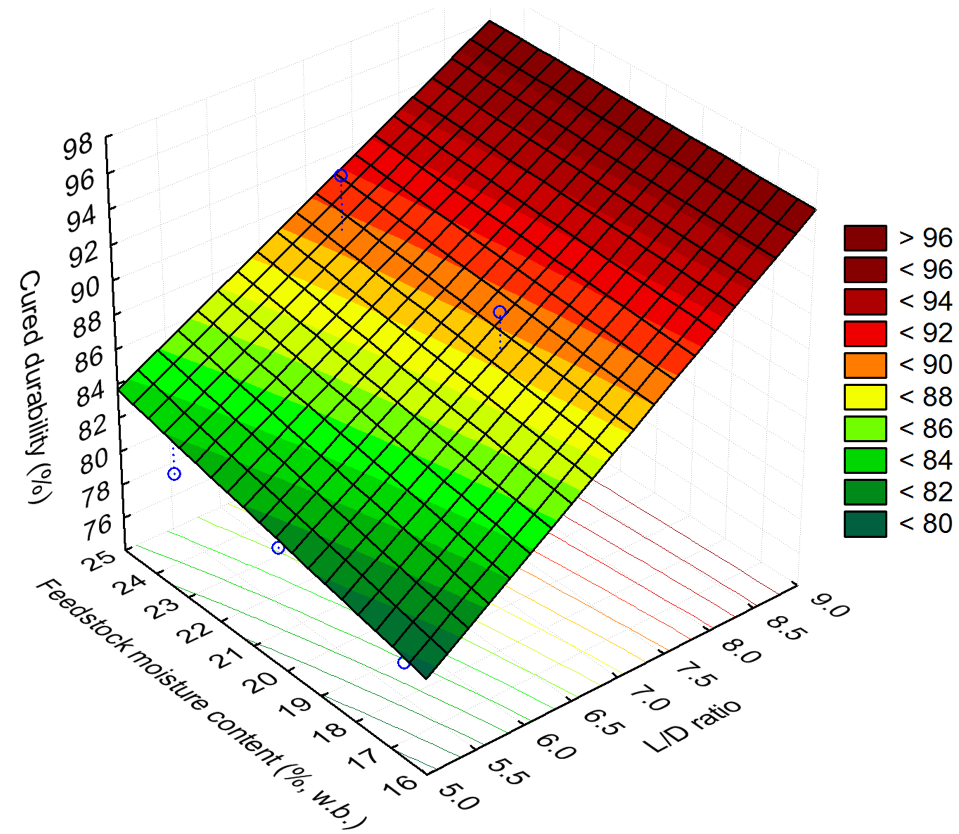

Figure 34. Effect of L/D ratio and feedstock moisture content on the pellet cured durability.

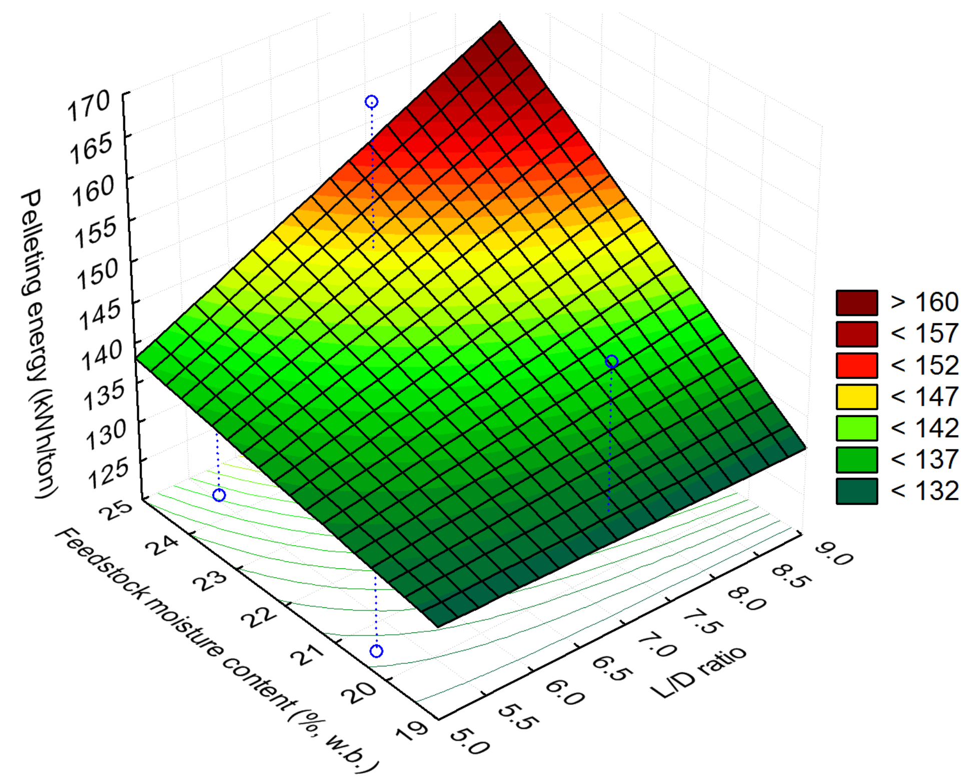

Figure 35. Effect of L/D ratio and feedstock moisture content on the pelleting energy.

5.3.2.6 Optimization of the Response-Surface Models

The hybrid genetic algorithm, shown in Figure 36, was used to optimize the developed response-surface models, as observed previously in Table 11. These models were optimized to find the optimized process conditions that can result in a minimum of pellet moisture content and pelleting energy, as well as a maximum of green durability, cured durability, and bulk density. Table 12 and Table 13, respectively, show the individual optimum process conditions and common optimum process conditions that can result in a maximum of bulk density and cured durability. In the case of individual optimum process conditions, the regression models developed for each pellet property and pelleting energy (see Table 12) was used to optimize the process.

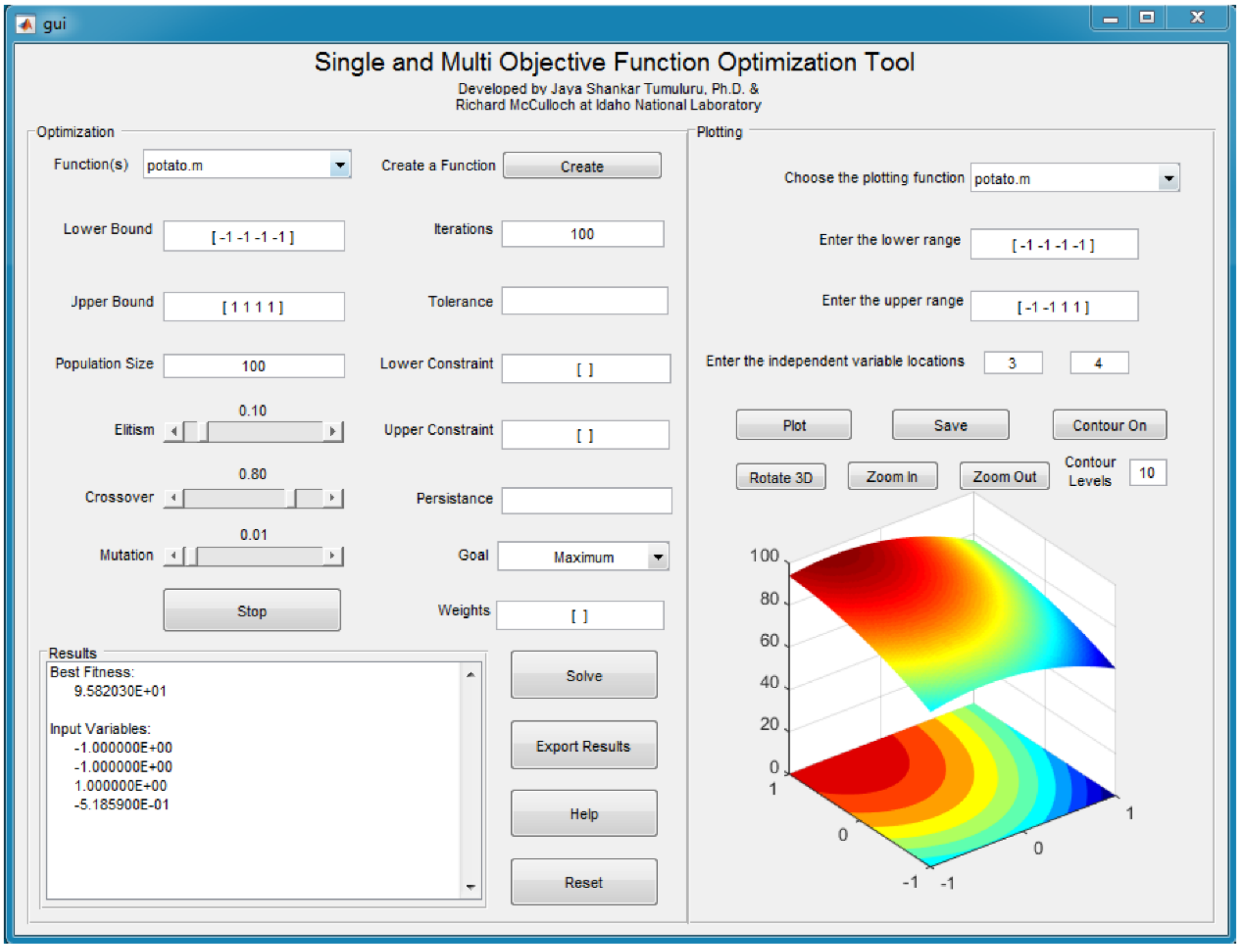

Figure 36. Optimization software used in the present study.

Table 12. Individual and common optimum process conditions for maximizing pellet properties and minimizing the energy consumption for 50% 2-in. milled pine and 50% milled switchgrass blends.

Pellet Properties	Maximum	Minimum	Individual and Common Optimum Process Conditions	
			L/D Ratio	Feedstock Moisture Content (%, w.b.)
100% Switchgrass				
Pellet moisture content (%, w.b.)		13.22	8.967	17.03
Bulk density (kg/m^3)	591.41		8.977	17.03
Green durability (%)	95.37		8.954	24.96
Cured durability (%)	95.62		8.994	17.23
Pelleting energy (kWh/ton)		86.32	5.019	17.19
75% Pine + 25% Switchgrass				
Pellet moisture content (%, w.b.)		12.33	8.917	19.00
Bulk density (kg/m^3)	578.94		8.975	19.13
Green durability (%)	94.01		8.861	19.02
Cured durability (%)	94.7		8.865	19.11
Pelleting energy (kWh/ton)		100.78	8.932	19.04
50% Pine + 50% Switchgrass				
Pellet moisture content (%, w.b.)	12.66		8.879	18.15
Bulk density (kg/m^3)	569.04		8.984	18.03
Green durability (%)	94.82		8.875	18.24
Cured durability (%)	94.97		8.9576	18.22
Pelleting energy (kWh/ton)	120.82		5.211	18.00
25% Pine + 75% Switchgrass				
Pellet moisture content (%, w.b.)		11.92	8.993	16.07
Bulk density (kg/m^3)	594.89		8.926	16.20
Green durability (%)	95.43		8.859	24.82
Cured durability (%)	96.01		8.995	24.89
Pelleting energy (kWh/ton)		116.42	8.99	16.06
100% Pine				
Pellet moisture content (%, w.b.)		10.41	8.736	17.04
Bulk density (kg/m^3)	616.18		8.919	17.14
Green durability (%)	99.35		8.967	17.13
Cured durability (%)	98.24		8.968	17.20
SEC (kWh/ton)		99.38	8.958	17.20

In the case of common optimum pelleting process conditions that can maximize bulk density and durability, the individual regressions developed for bulk density and cured durability (see Table 13) are used. Both these regressions are combined together to find the pelleting process conditions (e.g., L/D ratio and feedstock moisture content), which can maximize the bulk density and cured durability values. Table 12 and Table 13 are the individual and common optimum process conditions identified for pellet properties for pure and blends of pine and switchgrass.

Table 13. Individual and common optimum process conditions for maximizing pellet properties density and durability.

Pellet Properties	Maximum	Minimum	Individual and Common Optimum Process Conditions	
			L/D Ratio	Feedstock Moisture Content (%, w.b.)
100% Switchgrass				
Bulk density (kg/m^3)	594.81		8.94	17.03
Durability (%, w.b.)	95.50			
75% Pine + 25% Switchgrass				
Bulk density (kg/m^3)	579.48		8.92	19.05
Durability (%, w.b.)	94.76			
50% Pine + 50% Switchgrass				
Bulk density (kg/m^3)	568.299		8.92	18.05
Durability (%, w.b.)	94.87			
25% Pine + 75% Switchgrass				
Bulk density (kg/m^3)	585.72		8.89	24.82
Durability (%, w.b.)	95.69			
100% Pine				
Bulk density (kg/m^3)	617.22		8.8842	17.01
Durability (%, w.b.)	98.16			

The results of the optimization indicated that the process conditions that can help to reach the bulk density target value of >480 kg/m^3, whereas in the case of durability, the blend ratio of 25% pine and 75% switchgrass and pure pine and switchgrass helped to meet the desired durability values of >95%. In the case of other blend ratios (e.g., 50% pine + 50% switchgrass and 75% pine + 25% switchgrass), the predicted durability values are >94.75% (e.g., close to 95%). It can be concluded that the blend ratios and pure feedstocks of switchgrass and pine had met the desired physical quality attributes in terms of density and durability when pelleted at high-moisture content values.

5.3.3 Pilot-Scale Demonstration of Pelleting of Pine and Switchgrass Blends

5.3.3.1 Grinding Data Results

The 1/4-in. hammer mill grind switchgrass samples and 2-in. and 6-in. top pine residues provided by our project partner, Genera, were used in the pilot-scale demonstration studies. These two samples were ground in the five ton/h Bliss hammer mill at INL. The grind properties are given in Table 14 and Figure 37 gives the grinding energy for 2- and 6-in. top pine residues. Pelleting tests were conducted based on the experimental plan given in Table 3 and Table 15 gives the pellet properties and energy consumption of the pelleting process, as well as the amount of material pelleted for each run. The pellets produced using 50% 2-in. top pine + 50% switchgrass and 50% 6-in. top pine + 50% switchgrass was the best in terms of unit, bulk, and tapped density. The measured durability values were 92-93%. The energy consumption was lower when the pine content in the blend was increased to 60% in the blend. The pellets that are produced at different blend ratios were provided to the Auburn University for the gasification tests and the pellet process data to the University of Tennessee. In addition, the demonstration team from University of Tennessee visited INL to record the grind and pelleting properties using the NIR developed in this project, as observed in Figure 38 and Figure 39.

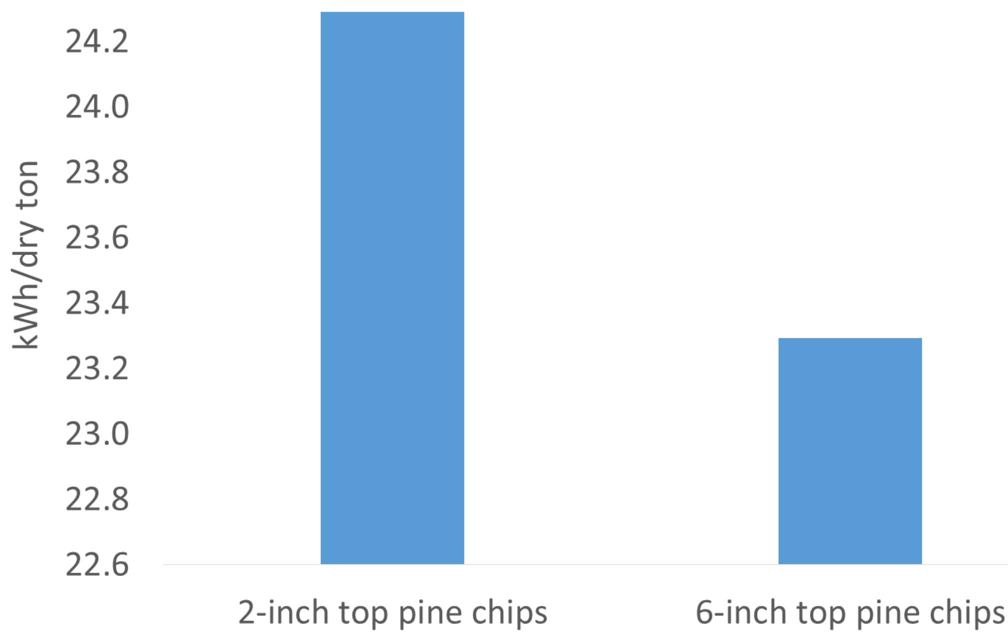

Figure 37. Grinding energy consumption for 2 and 6-in. pine tops (kWh/ton).

Table 14. Physical properties of 2- and 6-in. top pine 1/4-in. grinds.

Particle Dimensions	2-In. Top Pine	6-In. Top Pine
Geometric mean particle length (mm)	1.217	1.302
d10 (mm)	0.286	0.342
d50 (mm)	0.999	1.056
d90 (mm)	2.494	2.497

Table 15. Pellet properties 2- and 6-in. top pine residue and switchgrass blends.

Pellet Properties				
	50% 6-In. Top Pine+50% Switchgrass	**60% 6-In. Top Pine+40% Switchgrass**	**60% 2-In. Top Pine+40% Switchgrass**	**50% 2-In. Top Pine+50% Switchgrass**
Unit Density (kg/m^3)	943.8	1016	954.4	1082.7
Bulk Density (kg/m^3)	560.6	556.8	473.7	586.2
Tapped Density (kg/m^3)	603.5	599.2	510.3	628.7
Durability (%)	93.0	92.0	80.2	91.1
SEC (kWh/ton)	98.0	89.0	87.0	95.0
Final Pellet Weight (lb)	1710.0	417.0	1687.0	412.0

Figure 38. Pilot-scale demonstration of pelleting of blends of 2- and 6-in. pine and switchgrass blends.

Figure 39. UT-team measuring the properties using the NIR system developed in this project for blends of 2- and 6-in. pine and switchgrass blends of raw and pellets.

6. DISCUSSION

Moisture loss was observed when 2-in. top pine+switchgrass blends that were pelleted at high mositure contents. The loss of moisture varied for the blend ratios tested and for the pelleting process variables, such as the L/D ratio and blend moisture content. There was about 6–10% (w.b.) moisture loss during pelleting, and the loss was largely dependent on the initial moisture content of the blend, and less on the L/D ratio of the pellet die. This observation corroborates with earlier work on corn stover and lodgepole and the loss of moisture was dependent on the initial moisture content of the feedstock. Tumuluru (2016) has reasoned that the loss of moisture during pelleting can be attributed both to frictional heat developed in the die and to further cooling, which can dry most of the pellet surface moisture, resulting in partially dried pellets. Tumuluru (2018) indicated that high-moisture pelleting process not only densifies the biomass but helps to drive some of the moisture from the feedstock. Also, high-moisture pelleting makes drying optional. If, for example, the pellets do not have to be stored for long periods of time and do not require transportation over longer distances, the partially dried pellets can be used as such without any further drying for the biochemical conversion process. This is generally true in biochemical conversion where biomass is rewetted during pretreatment and conversion. Also, in this process, the moisture in the biomass is more efficiently managed, which reduces the cost of preprocessing significantly. Lamers et al. (2015) indicated a 40% reduction in pellet production costs mainly due to moisture loss during pelleting and drying the high-moisture pellets using low-temperature dryers, such as grain or belt dryers, provide cost-savings that are 10 times lower and can operate using low-quality heat.

In general, low bulk density is another major limitation of herbaceous biomass and results in issues related to storage, handling, and transportation (Sahoo and Mani, 2016, Sahoo and Mani, 2017) These limitations pose a serious challenge for biomass applications on a commercial scale. The present pelleting study indicates that bulk density increases by almost by 3–5 times over the raw material, and the increase in the density is dependent on the process conditions selected. In their studies on biomass blending and densification impacts on the feedstock supply chain and biochemical conversion, Ray et al. (2017) concluded that low-density biomass requires more resources for transportation and shipping. In their review on biomass densification systems, Tumuluru et al. (2011) suggested that pellet mills, briquette presses, cubers, agglomerators, and tablet presses all help to improve bulk density and produce a consistent product in terms of physical properties (e.g., size, shape, bulk density). Densification of biomass also helps to improve handling and conveyance efficiencies in biomass supply systems and infeed. A big challenge for using biomass blends in biorefineries is feeding and handling. Due to variations in bulk density and particle size distribution, the blends will segregate during storage, handling, and feeding, and can influence feed-handling and conversion process efficiencies. According to Ray et al. (2017), the use of blended and densified feedstocks in conversion pathways instead of conventionally ground biomass from a single source addresses several challenges in the current biomass supply chain, such as transportation, storage, cost, quality, and supply variability. Edmunds et al. (2018), Tumuluru et al. (2015) and Sahoo and Mani (2017) reported that herbaceous biomass, such as switchgrass, has a bulk density in the range of 150–160 kg/m3. Based on the present study, pelleting blends of switchgrass + 2-in. top pine residue increased bulk density values to about 540–580 kg/m3. Also, because the moisture content of the pellets is <10% (w.b.), they are more aerobically stable during storage.

The present research indicated that both the L/D ratio of the pellet die or compression pressure and blend moisture content influenced the bulk density and durability of the produced pellets. A higher L/D ratio and lower moisture content increased the bulk density for all the blend ratios tested. Studies conducted by Said et al. (2015) on rice straw in a flat die pellet mill showed that the durability of the pellets is strongly dependent on the effectiveness of the interparticle bonds created during pelleting. Their studies indicated that higher moisture content (10–17%, w.b.) increased durability, but decreased bulk density values. A similar observation was observed by Serrano et al. (2011) on barley straw, where an increase in moisture content increased the length of the pellet and its durability but decreased durability values. Studies conducted by Rhén et al. (2005) on the pelleting of woody biomass (Norway spruce) at different preheating temperatures and pressure indicated that both preheating temperature and moisture content had a significant effect on the bulk density of the pellets produced. Studies conducted by Jackson et al. (2016) and Sarkar et al. (2014) also indicated that pelleting corn stover and switchgrass at a higher moisture content of about 20–26 % (w.b.) resulted in pellets with a bulk density in the range of 500-600 kg/m3. The research conducted by the earlier researcher and the observations from the present study also seems to corroborate that increasing the moisture content decreases the bulk densified of the pellets produced.

Currently, the major challenge to use pelleted biomass in biorefining operations is the cost. In this study, the high-moisture pelleting process that was tested helps to significantly reduce pelleting costs. Also, this process helps to produce pellets with different bulk density and durability values. According to Tumuluru (2016), if pellets are transported by a truck, which is a weight-limited system, very high bulk densities are not needed to fill the truck. Based on maximum weight and volume of the truck, densified products with a bulk density in the range of 350–400 kg/m3 can fill the truck to capacity. Also if the pellets are transported to shorter distances they do not neet to meet the durability standards set for long-distance transportation. Tumuluru (2016) suggested that the cost of pellet production using conventional method cannot be completely offset by saving in the transportation costs especially if the transportation distances are less than 200–300 miles. One way to make pelleting an economically viable technology for the biorefineries is by reducing the cost. The high-moisture pelleting tested in this study can make pelleting more cost-effective. Also, the cost-savings achieved in terms of storage, handling, and feeding due to the use of pellets are not quantified throughly, it they are quantified it can make pelleting a more favorable operation for biorefineries. Another major advantage of blending woody with herbaceous biomass is that it improves the chemical composition. Woody biomass has a higher carbon content and is lower in ash, while the herbaceous biomass is lower in carbon content and higher in ash. Blending woody with herbaceous biomass can help to overcome herbaceous biomass feedstock specification limitations and make them meet specifications required for thermochemical conversion in terms of calorific value, volatiles, oxygen, hydrogen, nitrogen, chlorine, sulfur, nitrogen, and ash content (Edmunds et al., 2018).

In general, the lignin in the biomass is considered a natural binding agent and plays an important role in the densification process. In the present study, increasing the pine content in the blend to 75% increased durability values and reduced the SEC. In his studies on the pelleting of woody and herbaceous biomass at high-moisture content, Tumuluru (2018) indicated that higher lignin content in woody biomass increased the bulk and durability values of the pellets. In addition, the same study also indicated that energy sorghum resulted in low-quality pellets in terms of their density and durability. According to Tumuluru et al. (2012), grasses with lower lignin content are difficult to pelletize and consume higher pelleting energy, in addition to producing low-quality pellets in terms of their density and durability. However, the same authors indicated that blending straws and grasses with woody biomass, which has higher lignin and lower ash content, could help to improve pellet properties and reduce pelleting energy consumption. Harun and Afzal (20150) in their studies on chemical and mechanical propeties of agricultural and woody biomass indicated that higher percentages of woody biomass in the blend of pine and switchgrass increased the pellet strenght and the durability values. This present research corroborates this observation and proves that blending pine with switchgrass does indeed help to produce a good pellet quality in terms of pellet durability.

Edmunds et al. (2018) indicated that switchgrass has about 21% lignin content, while 2-in. top pine residue has about 37.5% on an as-received dry-weight basis. The previous research published on pelleting of grasses indicated that grasses take more energy to pellet as well as they do not make a good pellet due to its low lignin content and needle-shaped particles. Pine and switchgrass blending studies conducted by Edmunds et al. (2018) indicated that significant improvement in terms of lignin content and particle size distribution could be achieved. These improvements in terms of physical properties and biochemical composition, especially lignin, can help to produce good quality pellets at lower energy consumption. The blending of these types of biomass not only helps to modify their chemical composition but often improve their pelleting characteristics as well, due to better interlocking ability and flowability of the biomass in the pellet die. This observation was corroborated by the present study, where increasing the pine percentage to 75% in the blend improved the durability of the pellets. Also, the energy consumption of the pelleting process was lower when the pine percentage was higher in the blends tested. The improvements in bulk density and durability and lower energy consumption for the pine and switchgrass blend pellets tested can be due to improved chemical composition and particle size distribution, which might have resulted in better flow characteristics in the pellet die.

Many researchers have indicated that particle size distribution has a significant impact on the quality of the produced pellets (Tumuluru et al., 2011; MacBain, 1996; and Payne, 1978). It is critical to manage the particle size to produce the right quality of densified products at a lower SEC. The blending of woody and herbaceous biomass helps to alter particle size distribution and can make feedstock suitable for different densification systems. In general, a pellet mill requires smaller particles as the contact area between the particles plays a major role in creating necessary bonding between the particles. The common bonding mechanism during pelleting are: (1) particle bonding due to interfacial forces and capillary pressures; and (2) solid bridges which are formed due to chemical reactions, sintering, solidification, hardening of the binder, hardening of the melted substances, or crystallization of the dissolved materials results in agglomeration of biomass particles (Tumuluru et al., 2011). In addition, according to MacBain (1996) and Payne (1978), finely ground materials are suitable for pelleting because they have higher surface area to absorb steam during conditioning and can result in higher-starch gelatinization and increased particle binding. The same authors have also suggested that a certain ratio of fines—medium and coarse particles—are necessary to improve pellet quality and reduce pelleting energy consumption. Based on the present study, blending of pine and switchgrass at different ratios might have influenced particle size distributions, positively impacted pellet quality (i.e., bulk density and durability), and reduced the overall SEC of the pelleting process. The future work on pelleting of blends of woody and herbaceous biomass should be focused on testing the process in ring die pellet mill at pilot and commercial scale, understand how the chemical composition and energy properties changes with respect to moisture content and pelleting process variables such as L/D ratio and understand the effect of grind size on the quality of the pellets and energy consumption of the process.

7. CONCLUSIONS

Based on the findings in the present research, the following conclusions were drawn:

- Both laboratory- and pilot-scale studies has indicated that pellet properties improved with increasing the L/D ratio of the pellet die and decreasing the blend moisture content.
- Different blend ratios resulted in pellets with bulk density in the range of 500-600 kg/m^3.
- Moisture loss during pelleting was higher at high blend moisture content, which corroborates with earlier studies on pelleting corn stover using a laboratory-scale felt die and a pilot-scale ring die pellet mill. There is about 6-10% (w.b.) moisture loss during pelleting of blends of 2-in. top pines residues and switchgrass blends.
- Both blend moisture content and L/D ratio of the pellet die had a significant effect on the pellet properties and the SEC for the three blend ratios tested.
- Higher switchgrass percentage increased the SEC of the pelleting process. At a higher 2-in. pine residue percentage, the SEC reduced to about 90 kWh/ton, whereas increasing the moisture content of the blend ratio increased the SEC.
- Higher durability values were observed when L/D ratio, and pine content are higher and moisture content is lower.
- Blending pine with switchgrass has helped to improve the physical, chemical and energy properties.

8. REFERENCES

American Society of Agricultural and Biological Engineers (ASABE), Standards, S269.4. Cubes, Pellets, and Crumbles – Definitions and Methods for Determining Density, Durability, and Moisture Content. ASABE, St. Joseph, MI, USA, 2007.

Bonner, I.J.; Thompson, D.N.; Plummer, M.; Dee, M.; Tumuluru, J.S.; Pace, D.; Teymouri, F.; Campbell, T.; Bals, B. Impact of ammonia fiber expansion (AFEX) pretreatment on energy consumption during drying, grinding, and pelletization of corn stover. Drying Technol. January 08, 2016 (published online). Available online: https://doi.org/10.1080/07373937.2015.1112809 (accessed on 30 January 2019).

Crawford, N.C.; Ray, A.E.; Yancey, N.A.; Nagle, N. Evaluating the pelletization of "pure" and blended lignocellulosic biomass feedstocks. Fuel Process. Technol. 2015, 140, 46–56. Available online: https://doi.org/10.1016/j.fuproc.2015.08.023 (accessed on 30 January 2019).

Edmunds, C.W.; Reyes Molina, E.A.; André, N.; Hamilton, C.; Park, S.; Fasina, O.; Adhikari, S.; Kelley, S.S.; Tumuluru, J.S.; Rials, T.G.; Labbé, N. Blended feedstocks for thermochemical conversion: Biomass characterization and bio-oil production from switchgrass-pine residues blends. Front. Energy Res. 2018, 6, 79. Available online: https://doi.org/10.3389/fenrg.2018.00079 (accessed on 30 January 2019).

Granström, K. Emissions of volatile organic compounds from wood. Ph.D. thesis. Department of Environmental and Energy Systems, Karlstad University, 2005.

Harun, N. Y. and Afzal, M. T. 2015. Chemical and mechanical properties of pellets made from agricultural and woody biomass blends. Transactions of the ASABE, 58(4), 921-930.

Hoover A.N.; Tumuluru, J.S.; Teymouri, F.; Moore, M.; Gresham, G. Effect of pelleting process variables on physical properties and sugar yields of ammonia fiber expansion (AFEX) pretreated corn stover. Bioresource Technol. 2014, 164, 128–135. Available online: https://doi.org/10.1016/j.biortech.2014.02.005 (accessed on 30 January 2019).

Johansson, A.; Rasmuson, A. The release of monoterpenes during convective drying of wood chips. Drying Technol. 1998, 16(7), 1395-1428. Available online: https://doi.org/10.1080/07373939808917467 (accessed on 30 January 2019).

Kenney, K.L.; Smith, W.A.; Gresham, G.L.; Westover, T.L. Understanding biomass feedstock variability. Biofuels 2013, 4, 111–127. Available online: https://doi.org/10.4155/bfs.12.83 (accessed on 30 January 2019).

Lamers, P.; Roni, M.S.; Tumuluru, J.S.; Jacobson, J.J.; Cafferty, K.G.; Hansen, J.K.; Kenney, K.; Teymouri, F.; Bals, B. Techno-economic analysis of decentralized biomass processing depots. Bioresource Technol. 2015, 194, 205–213. Available online: https://doi.org/10.1016/j.biortech.2015.07.009 (accessed on 30 January 2019).

MacBain, R. Pelleting animal feed. American Feed Manufacturers Association, Arlington, VA, USA, 1966.

Mahadevan, R.; Adhikari, S.; Shakya, R.; Wang, K.; Dayton, D.; Lehrich, M.; Taylor, S.E. Effect of alkali and alkaline earth metals on in-situ catalytic fast pyrolysis of lignocellulosic biomass: A Microreactor Study. Energy Fuels 2016, 30, 3045–3056. Available online: https://doi.org/10.1021/acs.energyfuels.5b02984 (accessed on 30 January 2019).

Payne, J.D. Improving quality of pellet feeds. Milling Feed and Fertiliser 1978, 161, 34–41.

Perlack, R.D.; Wright, L.L.; Turhollow, A.; Graham, R.L.; Stokes, B.J.; Erbach, D.C. Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply. U.S. Department of Energy, Oak Ridge National Laboratory, Oak Ridge, TN, USA, 2005. Available online: https://www1.eere.energy.gov/bioenergy/pdfs/final_billionton_vision_report2.pdf (accessed 30 January 2019).

Pirraglia, A.; Gonzalez, R.; Saloni, D. Techno-economical analysis of wood pellets production from U.S. manufacturers. BioRes. 2010, 5, 2374–2390. Available online: https://bioresources.cnr.ncsu.edu/BioRes_05/BioRes_05_4_2374_Pirraglia_GS_Techno_Econ_Anal_Wood_Pellets_US_Prodn_1108.pdf (accessed on 30 January 2019).

Pradhan, P.; Arora, A.; Mahajani, S.M. Pilot scale evaluation of fuel pellets production from garden waste biomass. Energy Sustain. Dev. 2018, 43, 1–14. Available online: https://doi.org/10.1016/j.esd.2017.11.005 (accessed 30 January 2019).

Ray, A.E.; Li, C.; Thompson, V.S.; Daubaras, D.L.; Nagle, N.J.; Hartley, D.S. Biomass blending and densification: Impacts on feedstock supply and biochemical conversion performance. In Biomass Volume Estimation and Valorization for Energy; Tumuluru, J.S., Ed; IntechOpen, 2017. Available online: https://doi.org/10.1089/ind.2011.7.384 (accessed on 30 January 2019).

Rhén, C.; Gref, R.; Sjöström, M.; Wästerlund, I. Effects of raw material moisture content: Densification pressure and temperature on some properties of Norway spruce pellets. Fuel Process Technol. 2005, 87(1), 11–16. Available online: https://doi.org/10.1016/j.fuproc.2005.03.003 (accessed 30 January 2019).

Rials, T.G. Next Generation Logistics Systems for Delivering Optimal Biomass Feedstocks to Biorefining Industries in the Southeastern U.S.: Logistics for Enhanced Attributes Feedstock (LEAF) DOE-funded Project Peer Review, March 8, 2017. Available online: https://www.energy.gov/sites/prod/files/2017/05/f34/fsl_rials_123107.pdf (accessed on 30 January 2019).

Sahoo, K.; Bilek, E.M.; Bergman, R.D.; Kizha, A.R.; Mani, S. Economic analysis of forest residues supply chain options to produce enhanced quality feedstocks. Biofuels, Bioproducts & Biorefining 2018, 12.

Sahoo, K.; Mani, S. Engineering Economics of Cotton Stalk Supply Logistics Systems for Bioenergy Applications. Transactions of the ASABE 2016, 59, doi:10.13031/trans.59.11533.

Sahoo, K.; Mani, S. Techno-economic assessment of biomass bales storage systems for a large-scale biorefinery. Biofuels, Bioproducts and Biorefining 2017, 11, 417-429, doi:10.1002/bbb.1751.

Said, N.; Abdel Daiem, M.M.; Garcia-Maraver, A.; Zamorano, M. Influence of densification parameters on quality properties of rice straw pellets. Fuel Process. Technol. 2015, 138, 56–64. Available online: https://doi.org/10.1016/j.fuproc.2015.05.011 (accessed 30 January 2019).

Sakkampang, C.; Wongwuttanasatian, T. Study of ratio of energy consumption and gained energy during briquetting process for glycerin – biomass briquette fuel. Fuel 2014, 115, 186–189. Available online: https://doi.org/10.1016/j.fuel.2013.07.023 (accessed on 30 January 2019).

Sarkar, M.; Kumar, A.: Tumuluru, J.S.; Patil, K.N.; Bellmer, D.D. Gasification performance of switchgrass pretreated with torrefaction and densification. Applied Energy 2014, 127, 194-201. Available online: https://doi.org/10.1016/j.apenergy.2014.04.027 (accessed 30 January 2019).

Searcy, E.; Lamers, P.; Hansen, J.; Jacobson, J.; Hess, R.; Webb, E. Advanced Feedstock Supply System Validation Workshop - Summary Report. Report INL/EXT-10-18930; U.S. Department of Energy (DOE) Bioenergy Technologies Office (BETO), Idaho National Laboratory (INL), Oak Ridge National Laboratory (ORNL), Golden, CO, USA, 2015. Available online: https://bioenergykdf.net/system/files/1/15-50315-R3_Summary_Report_Only_ONLINE.PDF (accessed 30 January 2019).

Serrano, C.; Monedero, E.; Lapuerta, M.; Portero, H. Effect of moisture content, particle size, and pine addition on quality parameters of barley straw pellets. Fuel Process. Technol. 2011, 92, 699–706. Available online: https://doi.org/10.1016/j.fuproc.2010.11.031 (accessed 30 January 2019).

Thompson, D.N.; Campbell, T.; Bals, B.; Runge, T.; Teymouri, F.; Ovard, L.P. Chemical preconversion: Application of low-severity pretreatment chemistries for commoditization of lignocellulosic feedstock. Biofuels 2013, 4, 323–340. Available online: https://doi.org/10.4155/bfs.13.15 (accessed on 30 January 2019).

Tumuluru, J.S. Effect of pellet die diameter on density and durability of pellets made from high-moisture woody and herbaceous biomass. Carbon Res. Conv. 2018, 1(1), 44–54. Available online: https://doi.org/10.1016/j.crcon.2018.06.002 (accessed 30 January 2019).

Tumuluru, J.S. Effect of process variables on the density and durability of the pellets made from high moisture corn stover. Biosyst. Eng. 2014, 119, 44–57. Available online: https://doi.org/10.1016/j.biosystemseng.2013.11.012 (accessed on 30 January 2019).

Tumuluru, J.S. High moisture corn stover pelleting in a flat die pellet mill fitted with a 6 mm die: Physical properties and specific energy consumption. Energy Sci. Eng. 2015, 3, 327–341. Available online: https://doi.org/10.1002/ese3.74 (accessed on 30 January 2019).

Tumuluru, J.S. Specific energy consumption and quality of wood pellets produced using high-moisture lodgepole pine grind in a flat die pellet mill. Chem. Eng. Res. Des. 2016, 110, 82–97. Available online: https://doi.org/10.1016/j.cherd.2016.04.007 (accessed on 30 January 2019).

Tumuluru, J.S. Thermal pretreatment of biomass to make it suitable for biopower application. In Biomass Preprocessing and Pretreatments for Production of Biofuels; Tumuluru, J.S., Ed.; CRC Press: Boca Raton, FL, USA, 2018.

Tumuluru, J.S. Why biomass preprocessing and pretreatments? In Biomass Preprocessing and Pretreatments for Production of Biofuels; Tumuluru, J.S., Ed.; CRC Press: Boca Raton, FL, USA, 2018.

Tumuluru, J.S.; Cafferty, K.G.; Kenney, K.L. Techno-economic analysis of conventional, high-moisture pelletization, and briquetting process. American Society of Agricultural and Biological Engineer Annual Meeting, Paper No. 141911360, Montreal, Quebec, Canada, July 13–16, 2014. Available online: https://doi.org/10.13031/aim.20141911360 (accessed on 30 January 2019).

Tumuluru, J.S.; Conner, C.C.; Hoover, A.N. Method to produce durable pellets at lower energy consumption using high-moisture corn stover and a corn starch binder in a flat die pellet mill. J. Vis. Exp. 2016, 112, e54092. Available online: https://doi.org/10.3791/54092 (accessed on 30 January 2019).

Tumuluru, J.S.; Lim, C.J.; Bi, X.T.; Kuang, X.; Melin, S.; Yazdanpanah, F.; Sokhansanj, S. Analysis on storage off-gas emissions from woody, herbaceous, and torrefied biomass. Energies 2015, 8(3), 1745–1759. Available online: https://doi.org/10.3390/en8031745 (accessed 30 January 2019).

Tumuluru, J.S.; Sokhansanj, S.; Hess, J.R.; Wright, C.T.; Boardman, R.D. A review on biomass torrefaction process and product properties for energy applications. Ind. Biotechnol. 2011, 7, 384–401 Available online: https://doi.org/10.1089/ind.2011.7.384 (accessed on 30 January 2019).

Tumuluru, J.S.; Wright, C.T.; Hess, J.R.; Kenney, K.L. A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application. Biofuel Bioprod. Biorefin. 2011, 5, 683–707. Available online: https://doi.org/10.5772/67207 (accessed on 30 January 2019).

Tumuluru, J.S.; Yancey, N. Conventional and advanced mechanical preprocessing methods for biomass: Performance quality attributes and cost analysis. In Biomass Preprocessing and Pretreatments for Production of Biofuels; Tumuluru, J.S., Ed.; CRC Press: Boca Raton, FL, USA, 2018.

Tumuluru, T.S.; Hess, J.R.; Boardman, R.D.; Wright, C.T.; Westover, T.L. Formulation, pretreatment, and densification options to improve biomass specifications for co-firing high percentages with coal. Ind. Biotechnol. 2012, 8(3), 113–132. Available online: https://doi.org/10.1089/ind.2012.0004 (accessed on 30 January 2019).

Yancey, N.A.; Tumuluru, J.S.; Wright, C.T. Drying, grinding, and pelletization studies on raw and formulated biomass feedstocks for bioenergy applications. J. Biobased Mater. Bioenergy 2013, 7, 549–558. Available online: https://doi.org/10.1166/jbmb.2013.1390 (accessed on 30 January 2019).