Comparing Wood Chip Quality from Different Sources across the Southeastern United States

Dean L. Satterlee Patrick Hiesl Mathew Smidt Donald Hagan
Edd Watson Leah Gregory Brunella Rodrigues

Abstract

Global use of renewable energy has risen over the past few decades because of international energy policy changes, new legislation, and an effort to create a more sustainable energy source for a rapidly growing global population. One of these renewable energy sources is biofuels, specifically in the form of wood pellets created from wood chips. Wood pellet manufacturers in the southeastern United States must adhere to rigid quality-control standards of the European markets where their pellets are shipped and consumed. Thus, there is a need to improve our understanding of the factors that influence the quality of the source materials. Higher heating value (HHV), moisture content (MC), ash content, elemental composition, and size stratification are all important quality factors to consider when analyzing wood chips. Variations in these quality factors can cause longer drying times, blockages in feed systems, excess waste, and fluctuations in energy output. The objective of this study was to quantify these quality factors across multiple sources of wood chips. Softwood and hardwood in-woods chip samples as well as softwood mill residual chips were collected from thinnings and clear-cuts across the southeastern United States. Softwoods had a greater HHV and MC than hardwood chips, with 18,949 kJ/kg and 18,242 kJ/kg, respectively. Softwood thinnings had the highest HHV and lowest ash content. However, only 4 of the 60 samples analyzed were from softwood thinnings. This study provides an overview of the variation in wood chip quality across the southeastern United States.

In the past two centuries, the use of fossil fuels to power the world's growing energy demand has grown exponentially. Fossil fuel dependency is predicted to account for 83 percent of energy demand by 2030 (Shafiee and Topal 2008). In correlation, global electricity consumption is expected to more than double by 2060 (Kober et al. 2020). With energy demand being fulfilled primarily by nonrenewable resources such as fossil fuel, renewable energy resources such as biomass must be considered part of the long-term sustainable energy solution (International Energy Agency [IEA] 2021).

Biomass is any organic material from plants or animals that can produce energy or other products (US Energy Information Administration [EIA] 2020). Biomass from plants and animals only accounts for around 13 percent of global energy consumption and only 5 percent of US energy consumption (EIA 2020, Popp et al. 2021). Within the 13 percent of global bioenergy consumption, there are three main biomass sources: crops, crop residue, and woody biomass. In the global woody biomass sector, over 23 percent goes into energy production, making for a dependable renewable energy source (Popp et al. 2021). Woody biomass is often used in the form of wood chips that are processed for energy (EIA 2023).

In the southeastern United States, one of the main reasons for wood chip consumption is the production of wood pellets for use in the international market (Kittler et al. 2020). A recent European sustainable energy policy change has created a rising demand for wood pellets to fuel numerous retrofitted coal power plants (Goetzl 2015, Rietig 2021). Policy changes such as the Renewable Energy Directive; with goals of having European

---

The authors are, respectively, Graduate Research Assistant (deans@g.clemson.edu corresponding author]) and Assoc. Professor of Forest Operations (phiesl@clemson.edu), Dept. of Forestry and Environ. Conservation, Clemson Univ., Clemson, South Carolina; Research Forester/Engineer, USDA Forest Serv., Auburn, Alabama (Mathew.Smidt@usda.gov); Assoc. Professor of Forest Ecology, Dept. of Forestry and Environ. Conservation, Clemson Univ., Clemson, South Carolina (dhagan@clemson.edu); Forestry Technician, USDA Forest Serv., Auburn, Alabama (edd.watson@usda.gov); Lab. Manager, Baruch Institute of Coastal Ecology and Forest Sci., Georgetown, South Carolina (lgregor@clemson.edu); and Assistant Professor of Wood Utilization and Biomaterials, Dept. of Forestry and Environ. Conservation, Clemson Univ., Clemson, South Carolina (brunelr@clemson.edu). This paper was received for publication in February 2024. Article no. 24-00011.

Forest Prod. J. 74(2):178–184.
doi:10.13073/FPJ-D-24-00011

Union members achieve >40 percent of their energy deriving from renewables by 2030, have created a profitable market for companies to manufacture wood pellets from southeastern US feedstock and ship them overseas for use in the growing renewable energy market (Johnson et al 2012, Enviva 2020, Schipfer et al. 2020).

In wood-fired power plants, wood chips or pellets are used to produce energy, both of which must meet certain specifications. The pellets or chips are fed into combustion chambers to heat water and produce steam. The high pressure from the steam is then used to move a turbine and produce electricity by spinning a generator, similar to a coal-fired power plant (Ashizawa et al. 2022). The similarities between wood and coal combustion make it easy for coal-fired power plants to be converted to use woody biomass (Schwarzer et al. 2017). However, certain wood chip quality factors must be met to ensure optimal operation in wood-fired power plants. The quality of wood chips can be measured in several ways, but the most important factors to consider are wood chip size, moisture content (MC), ash content, and energy output (Forest Research 2023).

The International Organization for Standardization (ISO) sets the ideal specifications for wood chips used as biofuels in wood-fired power plants. The official ISO standard to abide by is ISO 17225-4:2021 (International Standardization Organization [ISO] 2021). Wood chip size needs to remain <8 inches in length and 2 inches in width, and MC needs to be <50 percent when wet to qualify for the Grade A classification (ISO 2021). Ash content must be ≤3 percent to qualify as a wood chip that meets the international standard (ISO 2021). Although not a quality standard, energy output in higher heating value (HHV) is important to consider as a wood chip quality factor because it correlates with how much energy the final wood chip may produce when combusted (Livestock and Poultry Environmental Learning Community Administration [LPELC Admin] 2019).

MC is a quality factor to be considered when dealing with wood chips for energy production. Wood is hygroscopic, meaning its MC changes when the relative humidity in its surroundings changes (Loffer 2023). The hygroscopic properties of wood make MC an important factor in wood chips because wood chips with initial lower MC can soak up moisture from surrounding chips with higher MC. This can be a problem for wood chip processing mills as higher MC can result in longer and more intense drying times. Higher MCs also tend to require more efficient fuel mass flow rates to keep up with production, increasing costs and time consumption (Silva et al. 2021).

The size of wood chips can affect their overall quality and the energy production facilities in which they are used. Any mill that uses wood chips contains a transportation and hopper system, usually involving a variety of conveyor belts and feeding systems (KMEC Engineering 2018). Wood chips that are too long tend to block the bottom of silos and other openings, causing a buildup of wood chips that can result in costly downtime (Karjalainen and Bergström 2018). Wood chips that are too small can result in those particles filling the gaps between bigger chips, leading to poor air circulation and causing drying problems (Karjalainen and Bergström 2018).

Ash content is also of importance when considering wood chip quality. Ash content refers to the amount of ash remaining after a wood chip sample has been burned to its maximum gross heating value, usually represented as a percentage. Ash is composed of trace elements that do not combust under normal burning conditions (calcium, potassium, magnesium, etc.; Risse and Gaskin 2002). Ash content is essential when considering quality because it can lead to high ash deposition on heating surfaces and tail flues, two essential components in a combustion power plant (Sun et al. 2023). In general, a higher ash content decreases HHV, resulting in a loss of energy output (Lieskovský et al. 2017).

HHV, usually in kJ/kg, is an additional quality factor when analyzing wood chips that will go into the energy market. The HHV of wood chips is directly related to how efficient the wood chips are in the biofuels (Shehab et al. 2022). Wood chips with a higher HHV will produce more energy in a wood-fired power plant's combustion process, which will lead to better efficiency and production, making the HHV of wood chips important when considering wood chip quality factors (LPELC Admin 2019).

Mills may produce chips on site from timber or have manufacturing residues or in-woods, whole-tree chips delivered. Examples of mill residues are those derived from lumber mill processes where wood trimmings and extra shavings from general lumber production are used and contain only solid wood (Kittler et al. 2020). In-woods chips, or primary residuals, are wood chips sourced directly from a harvest site (Kittler et al. 2020). Sources of in-wood chips usually include in-woods chipping operations where whole trees are processed and chipped (Smith 1962). Additionally, subcategories of wood chip sources are important to consider, such as thinnings and clear-cuts, as these sources can differ in tree allometry, growth rates, growth conditions, and tree species composition.

The objectives of this study are to quantify potential differences in energy output, ash content, MC, and size stratification from softwood and hardwood chips originating in the southeastern United States from clear-cuts, thinnings, and mill residues.

Methods and Materials

Wood chip sample sources

Wood chip samples were collected from four different Enviva wood pellet manufacturing mills (Cottondale, Florida; Greenwood, South Carolina; Hamlet, North Carolina; Lucedale, Mississippi) across the southeastern United States (Fig. 1). At each mill, stratified samples were taken by filling a 19-liter bucket with wood chips from incoming wood chip trucks. Samples were collected with a shovel from the back of the truck, digging through the different layers. For some hardwood samples, the wood chips from the truck were dumped onto a concrete pad and a sample was taken from the resulting pile of wood chips.

After weighing, the wood chip samples were bagged, labeled, and taken back to the lab for testing. We also recorded the species group of each sample: hardwood or softwood. We also noted if the wood chips came from a local mill in the form of residue chips. For all chip samples, the procurement managers, or delegates, provided the global positioning system coordinates of the associated harvest site (Fig. 1).

Using ArcGIS Pro 3.1, two map layers were imported to compare before- and after-harvest site characteristics. The first layer was sourced from the European Space Agency's Sentinel-2 Level-2A satellite. This layer consists of 13 multispectral bands ranging from spatial resolution of 10, 20, and 60 m. The second layer referencing the after-harvest site

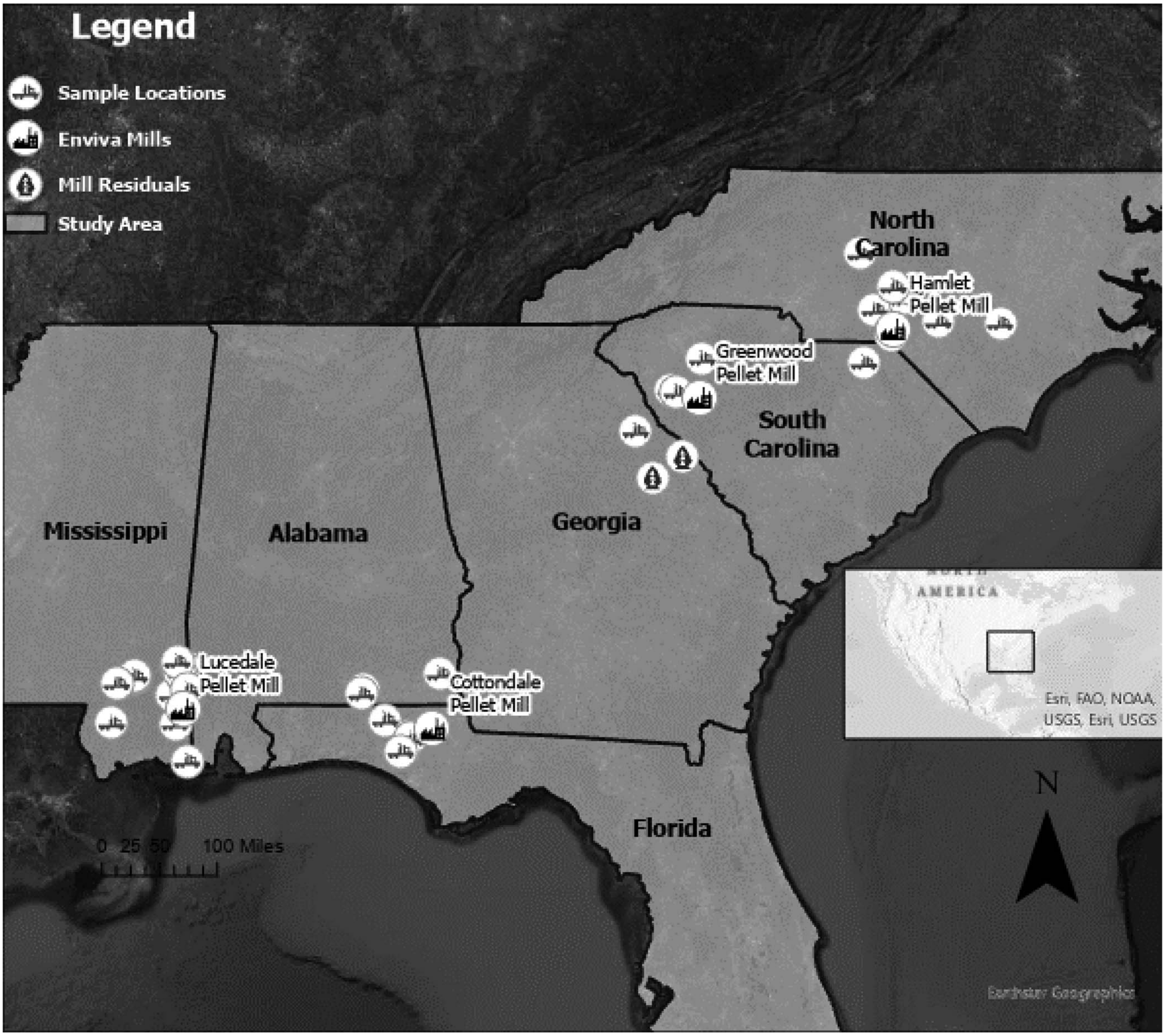

Figure 1.—All Envia mill locations and harvest tract locations from which samples were collected for the study.

characteristics originates from the US National Agricultural Imagery Program. It consists of recent high-resolution imagery at 1-m resolution or better, made available annually by the US Dept. of Agriculture Farm Services Agency during the growing season across the continental United States. The two layers were compared with the ArcGIS Pro world imagery base layer. This layer consists of satellite imagery taken in March 2021 before the harvest sites were harvested. Through these three-layer comparisons, the type of harvest was then classified as either a clear-cut or a thinning.

Lab analysis

MC was calculated by taking a subsample of 500 g from each sample. All samples were placed into an oven at 103°C and left to dry for 48 hours. Upon removing the samples, dry weights were recorded, and the MC was calculated by using the standard formula (Eq. 1) containing the variables of green weight (GW) and oven dry weight (ODW).

$$\mathrm{MC}\,(\%) = \frac{\mathrm{GW} - \mathrm{ODW}}{\mathrm{ODW}} \times 100 \tag{1}$$

Size stratification was calculated by taking a subsample of 6 to 8 liters and running it twice through a Chip Class$^{\mathrm{TM}}$ shaker machine with screen sizes ranging from 45 mm to 3 mm with an additional tray at the bottom for sample pieces $<$3 mm. The sizes of the trays in the shaker machine were 45-mm round, 10-mm bar, 7-mm bar, 5-mm bar, 3-mm bar, 3-mm round, and a collection tray. Sample size stratification was recorded by taking the weight of wood chips in each tray and dividing it by the total weight of wood chips sampled, multiplied by 100 to yield the percentage of the total sample accounted for each chip size class.

Ash content was calculated using an analytical laboratory procedure from the National Renewable Energy Laboratory (Sluiter et al. 2008). First, a crucible was weighed empty three times and an average weight was calculated. Then, 3 to 5 g of the raw wood chip sample was added into the crucible, and the weight was then recorded. Crucibles were then loosely fitted with a lid to allow airflow during the combustion process and placed into a Fisher Scientific muffle furnace. The muffle furnace was then programmed according to the standards set in the laboratory analytical procedure and run (Sluiter et al., 2008). After removal, the crucibles with the remaining ash in them were set aside for several hours in a desiccator to cool down and then their individual weights were recorded. Ash content was calculated by subtracting the weight of the empty crucible from the weight of the crucible with ash and then dividing the result by the ODW of the sample and multiplying the subsequent answer by 100 to get a percent (Eq. 2).

$$\text{Ash}\,\% = \frac{\text{Weight of crucible with ash} - \text{Weight of crucible}}{\text{ODW of sample}} \times 100 \tag{2}$$

Wood chip sample elemental composition was calculated using a CHNS-O Flash 2000 elemental analyzer. A subsample of chips was processed in a Model 4 Thomas-Wiley Laboratory Mill$^{\text{TM}}$ and samples were then placed in a Fisher Scientific sieve with three trays: a number 40 on top (0.4191-mm-diameter holes), a number 60 in the middle (0.2490-mm-diameter holes), and a fine particle collection tray on the bottom. With all the samples placed on the top sieve tray, the sieve was closed and run for 15 minutes to sort out the different-sized particles. Upon completion, 10 to 15 g of the particles on the number 60 sieve were placed into a test tube for testing in the elemental analyzer. The elemental analyzer reported the percentages of C, H, and N in the samples. The HHV was then calculated from a predictive model in kJ/kg by using the elemental percentages (Friedl et al. 2005; Eq. 3).

$$\text{HHV} = 3.55\,\text{C}^2 - 232\,\text{C} - 2{,}230\,\text{H} + 51.2\,\text{C} \times \text{H} + 131\,\text{N} + 20{,}600 \tag{3}$$

Statistical analysis

Statistical analysis was done using Microsoft Excel® and JMP Pro version 16.2. For MC, ash content, HHV, and elemental makeup, we used a *t* test to compare hardwood and softwood species groups as well as hardwood clear-cuts with hardwood thinnings. Six one-way analyses of variance (ANOVAs) were conducted for the three quality factors and three elemental percentages between softwood clear-cuts, softwood thinnings, and softwood mill residuals. If a one-way ANOVA resulted in statistical significance, a Tukey honestly significant difference (HSD) post hoc test was performed using JMP Pro version 16.2 to find which groups had statistical significance between means. A Shapiro–Wilk test was used to test for normality in each individual source group using JMP Pro version 16.2.

Size stratification statistical tests were run by classifying the seven tray sizes into three chip class categories (<3 mm, 3 to 7 mm, and >7 mm). Although quality wood chips for fuel usage should be between 4 mm and 6 mm in width (Fuller 2004), we used a range of 3 to 7 mm on the basis of the available sieve sizes. The statistical analysis for size stratification was then conducted using the percentage of the total sample weight found in each category and conducting one-way ANOVAs, *t* tests, and Tukey HSD post hoc tests as described above between the different source categories.

Results

In total, we completed six ANOVAs, with two of the six tests showing significance, leading to two Tukey HSD tests. A total of 12 students' *t* tests was completed, with six showing significance at the 0.05 level, with *t* values from <0.0001 to 0.0427.

We collected a total of 60 wood chip samples across the southeastern United States (Table 1). MC was statistically different ($P < 0.001$) between softwood and hardwood chip samples, with an average of 53 percent for softwoods and 43 percent for hardwoods (Table 1). Within the softwood chip samples, we found statistical differences ($P = 0.035$) in chip samples from clear-cuts (54%) and mill residuals (47%). There was no significant difference in softwood MC between clear-cut and thinning chip samples ($P = 0.999$) or thinning and mill residual chips ($P = 0.166$). No statistically significant differences ($P = 0.638$) were found in hardwood MC between thinning and clear-cut chip samples. We found no significant differences ($P = 0.269$) in ash content among the samples (Table 1).

Results for the HHV of all samples showed a statistically significant difference ($P < 0.001$) between softwoods and hardwoods, with an average HHV of 18,949 kJ/kg and 18,242 kJ/kg, respectively (Table 1). We found that among the softwood samples, there were no significant differences between clear-cuts, thinnings, and mill residuals ($P = 0.569$; Table 1). However, there was a significant difference between

Table 1.—Moisture content, ash content, and higher heating value (HHV) summary statistics (mean, SD, minimum [min.], and maximum [max.]). Different letter superscripts after the mean indicate statistically significant differences ($P \leq 0.05$) within each category.

		Moisture content (%)				Ash content (%)				HHV (kJ/kg)			
Species group	*N*	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
Softwoods	36	53^{A}	6	37	63	5.91^{A}	4.90	0.23	14.80	$18{,}949^{A}$	262	18,227	19,500
Hardwoods	24	43^{B}	4	36	50	4.70^{A}	4.12	0.44	17.68	$18{,}242^{B}$	379	17,055	19,679
Softwoods													
Clear-cuts	26	54^{A}	6	37	62	7^{A}	5.09	0.26	14.77	$18{,}936^{A}$	279	18,227	19,500
Thinnings	4	54^{AB}	7	46	63	2.9^{A}	1.33	1.37	4.67	$19{,}083^{A}$	139	18,905	19,265
Mill Residuals	6	47^{B}	3	44	52	3.49^{A}	3.78	0.23	10.41	$18{,}914^{A}$	217	18,643	19,303
Hardwoods													
Clear-cuts	16	44^{A}	3	39	50	6.14^{A}	0.0482	0.0044	0.1768	$18{,}110^{A}$	328	17,055	18,557
Thinnings	8	41^{A}	3	36	46	3.45^{A}	0.0287	0.0074	0.1012	$18{,}359^{B}$	172	18,158	18,632

clear-cuts and thinnings within the hardwood category ($P = 0.029$), with an average HHV of 18,110 kJ/kg for clear-cuts and 18,359 kJ/kg for thinnings (Table 1).

Results for the elemental composition between softwoods and hardwoods showed no statistical significance for N ($P = 0.061$), statistical significance for C ($P < 0.001$), and statistical significance for H ($P = 0.015$; Table 2). Between softwoods and hardwoods, the average C was 47.81 and 46.05 percent, respectively, and the average H was 5.83 and 5.73 percent, respectively (Table 2). In the softwoods category, we found no significant differences in N between clear-cuts and thinnings ($P = 0.227$) or between thinnings and mill residuals ($P = 0.497$; Table 2). However, we did find a significant difference in N between clear-cuts and mill residuals ($P = 0.003$), with the average N being 0.43 and 0.29 percent, respectively (Table 2). There were no differences in the softwood category for C ($P = 0.457$) or H ($P = 0.397$; Table 2). In the hardwoods category, we found no statistical significance between clear-cuts and thinnings for N ($P = 0.594$) or H ($P = 0.560$; Table 2). However, there was a difference between hardwood clear-cuts and hardwood thinnings for C ($P = 0.021$; Table 2).

For size stratification we found a statistical significance between softwoods and hardwoods for chips passing through 3-mm bar ($P = 0.001$), the 3-to-7-mm size class ($P = 0.005$), and chips thicker than 7 mm ($P < 0.001$; Fig. 2). In the softwoods category, no significant differences were found between clear-cuts and thinnings ($P = 0.837$) in the <3-mm size class. However, statistical significances were found in softwoods <3-mm between clear-cuts and mill residuals ($P < 0.001$), and thinnings and mill residuals ($P < 0.001$; Figure 2). In the softwoods category, there were no differences found between clear-cuts and thinnings ($P = 0.568$) or thinnings and mill residuals ($P = 0.819$) in the 3-to-7-mm size class (Fig. 2). However, we did find significant differences in the softwoods 3 to 7 mm between clear-cuts and mill residuals ($P = 0.013$) with a weight distribution of 85 and 69 percent respectively (Fig. 2). Additionally, in the softwoods category, there were no differences found between clear-cuts and thinnings ($P = 0.817$) or thinnings and mill residuals ($P = 0.137$) in the >7-mm size class (Fig. 2). However, we did find significance in the softwoods >7 mm between clear-cuts and mill residuals ($P < 0.001$), with a weight distribution of 7 and 31 percent respectively (Fig. 2). In the hardwoods category, statistical significance was found in the <3-mm size class between clear-cuts and thinnings ($P = 0.029$), with a weight distribution of 2 and 7 percent respectively (Fig. 2). In contrast, no differences were found between clear-cuts and thinnings in hardwoods in the 3-to-7-mm size class ($P = 0.977$) or the >7-mm size class ($P = 0.994$; Fig. 2).

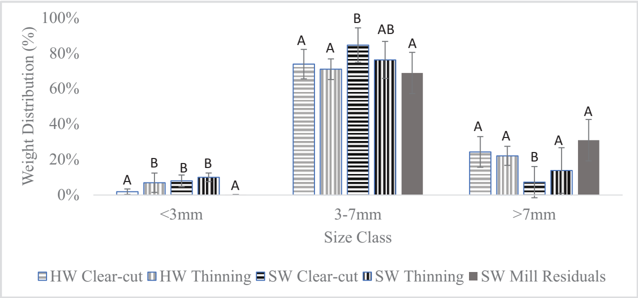

Figure 2.—Size stratification with standard deviation error bars for three size classes and five chip source types. The letters above the error bars show significant differences within each individual size class.

Discussion

The MC of wood chip samples is important from the mill standpoint, as it can affect drying times and energy costs depending on the product being made (Price 2011). It is well documented that the average MC of GW differs between softwood and hardwood, with softwood MC being slightly higher. The differences found in softwoods may be explained by softwood clear-cut samples coming from GW, whereas softwood mill residuals came from lumber mill scraps after lumber production. Once the wood is cut, it immediately begins to lose moisture and head toward its fiber saturation point, the point at which only cell walls are completely saturated, with no water in cell lumina (Forest Products Laboratory—USDA 2010, Meier 2015). Once wood reaches the fiber saturation point, it will continue to lose moisture in the form of bound water, water trapped within the cell, as well as fluctuate with humidity, rainfall, and storage conditions (Meier 2015).

Ash content is an important quality factor to consider when analyzing wood as a biofuel because higher ash contents can cause severe ash deposition and corrosion on heating surfaces in the power-plant setting (Sun et al. 2023). Hardwoods generally have a higher ash content than softwoods (Risse and Gaskin 2002). However, no differences were found in ash content when comparing softwoods with hardwoods. This could be explained by the varying amounts of bark and leaves contained in each sample, as it has been shown that an increase in bark and leaf content generally results in higher ash content (Risse and Gaskin 2002). The lack of differences found in the

Table 2.—Elemental composition summary statistics for N, C, and H (mean, SD, minimum [min.], and maximum [max.]). Different letter superscripts after the mean indicate statistically significant differences ($P \leq 0.05$) within each category.

		Nitrogen (%)				Carbon (%)				Hydrogen (%)			
Species group	N	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.	Mean	SD	Min.	Max.
Softwoods	36	0.39^{A}	0.10	0.26	0.62	47.81^{A}	0.63	46.07	49.16	5.83^{A}	0.12	5.56	6.04
Hardwoods	24	0.44^{A}	0.08	0.30	0.60	46.05^{B}	0.91	42.93	49.17	5.73^{B}	0.20	5.20	6.35
Softwoods													
Clear-cuts	26	0.43^{A}	0.09	0.29	0.62	47.77^{A}	0.68	46.07	49.16	5.83^{A}	0.12	5.56	6.04
Thinnings	4	0.35^{AB}	0.05	0.30	0.41	48.20^{A}	0.27	47.84	48.52	5.77^{A}	0.12	5.63	5.94
Mill residuals	6	0.29^{B}	0.03	0.26	0.35	47.74^{A}	0.48	47.11	48.58	5.87^{A}	0.10	5.71	6.01
Hardwoods (HW)													
Clear-cuts	16	0.43^{A}	0.08	0.31	0.60	45.72^{A}	0.86	42.93	46.91	5.71^{A}	0.17	5.29	6.02
Thinnings	8	0.45^{A}	0.07	0.30	0.52	46.39^{B}	0.40	45.87	47.03	5.66^{A}	0.18	5.20	5.81

softwoods and hardwoods could also be explained by the data being skewed because of trees being dragged on the logging site. Trees being dragged on the ground will pick up more soil, which could have skewed the ash content results with dirty chips. No differences being found between wood chip sources in both softwoods and hardwoods could also be explained by similarities in species and geographic location. Most softwoods collected were likely pines such as loblolly pine (*Pinus taeda*), whereas most hardwoods collected were likely oaks (*Quercus* spp.) or undesired/unmerchantable hardwoods. However, we did not identify species within the chip samples and also did not measure the bark or leaf content within our samples. Given that all samples were collected in the same geographic region, the similarities in growth factors, which are known to affect ash content, and the similarities in species could explain why no differences were found between the wood sources in both softwoods and hardwoods (Demeyer et al. 2001).

It is known from various studies that the HHV in softwoods tends to be slightly higher than in hardwoods (White 1987). Previous studies have also shown that C in hardwood samples ranges from 46.3 to 50.0 percent, whereas softwood samples range slightly higher, from 47.2 to 55.2 percent (Lamlom and Savidge 2003). An increase in both C and H correlates with an increase in HHV because they are the main elements responsible for the energy content in biofuels (Miranda et al. 2015). The differences found in the percentage of C and H between the softwoods and hardwoods were similar to those in previous studies (Lamlom and Savidge 2003; Rowell et al. 2012), with both C and H higher in softwoods. The lack of differences found when comparing the HHV of wood chip sources within the softwood species could also be explained by the elemental composition of the samples. Although there was a difference between the N percentages, there was no difference between the C and H percentages, the two key elements to consider with energy content (Miranda et al. 2015). Study limitations may also play a factor in no differences being found for HHV in softwoods, as the subsamples used in the elemental analyzer may have contained fluctuations in bark content, which is known to change the HHV of wood samples (Nosek et al. 2016, Neumann and Lawes 2021).

Since wood chip samples sourced from thinning operations tend to be whole trees, they may have a varying bark content compared with wood chips sourced from unmerchantable treetops in clear-cut operations (Hammond et al. 2015, Neumann and Lawes 2021). The addition of bark content by 5 to 10 percent has been shown to decrease the combustion heat values of wood samples, possibly explaining the lower HHV found in the hardwood clear-cuts (Nosek et al. 2016). The findings in higher C and H elemental compositions, along with differences in bark content, could explain the significant difference in HHV found when comparing thinnings and clear-cuts in the hardwood species.

Hardwoods are generally denser and stronger than softwoods (Claisse 2016). Additionally, the strength and density of these hardwoods combined with possible whole trees being chipped during clear-cut operations could cause difficulty in standard chippers used in in-woods chipping operations. It is also known that different wood chip storage times and initial log lengths can affect wood chip size distribution (Silveira et al. 2023). Different wood chipper types and the quality of maintenance can also play a role in wood chip size stratification (Gard Timmerfors et al. 2020, Walls 2021). This could lead to a lower percentage of wood chips in the <3-mm size class when compared with other wood sources. However, we cannot be certain about these assumptions because the mechanical condition and type of chipper used in these operations are unknown and data were not collected. The difference found when comparing softwood clear-cuts with softwood mill residuals may be attributed to the mill residuals production process, where the byproduct manufacturers most likely favor a larger size when marketing to wood chip purchasers (Krigstin et al. 2012). No differences were found between the softwood clear-cuts and softwood thinning harvest types, which could be explained by the similar species compositions. However, ISO standards indicate that the standard for Grade A wood chips lies between 2 and 8 mm in thickness (ISO 2021). Given the screen sizes used in this study of 3 to 7 mm, it is possible that the size distribution in wood chips sampled had a slightly higher percentage in the ISO standard for Grade A wood chips because of the inaccuracies in available screen sizes for the study (Krigstin et al. 2012).

Conclusion

When considering all wood chip sources studied, wood chips that originate from a softwood thinning are the most favorable from a bioenergy standards perspective. Although the only downside may be higher MC slightly above the ISO standard of 50 percent, the ash content, size stratification, and HHV quality factors combined appear to be better than any other studied wood chip source. The only source studied that met the ISO standard of being ≤ 3 percent ash content was softwood thinnings, which could serve as a significant benefit to wood-fired power plants by saving on downtime for cleaning combustion chambers and preventing economic loss via less production time. Most of the wood chips sourced from softwood thinnings also lay well within the ideal 3- to 7-mm category for thickness, upward of 70 percent of its weight distribution. Most important, the softwood thinning harvest type was found to have the greatest HHV compared with all other studied wood sources, making it the ideal option for wood pellet suppliers whose end customer pays them on the basis of energy output. The results for each of these quality factors would provide pellet mills with reduced drying times, less residual waste, more uniform wood chip size, and higher HHV. However, only four samples of softwood thinnings were collected, meaning that to further solidify these conclusions more data need to be collected, with an emphasis on softwood thinnings.

Acknowledgments

We would like to acknowledge the USFS Southern Research Station in Auburn, AL for their funding of this research project and help in collecting and processing samples in their laboratory. We would also like to acknowledge the Baruch Institute of Coastal Ecology and Forest Sciences, specifically Mrs. Leah Gregory, for helping process samples. Finally, we would like to thank Enviva® for access to their mills to collect our samples, and their network of procurement foresters for providing timber harvest site information.

Literature Cited

Ashizawa, M., M. Otaka, H. Yamamoto, and A. Akisawa. 2022. CO2 Emissions and economy of co-firing carbonized wood pellets at coal-fired power plants: The case of overseas production of pellets and use in Japan. *Energies* 15(5):1770. https://doi.org/10.3390/en15051770

Claisse, P. A. 2016. Timber. *In:* Civil Engineering Materials. Elsevier, Oxford, UK. pp. 369–386. https://doi.org/10.1016/B978-0-08-100275-9.00033-4

Demeyer, A., J. C. Voundi Nkana, and M. G. Verloo. 2001. Characteristics of wood ash and influence on soil properties and nutrient uptake: An overview. *Bioresour. Technol*. 77(3):287–295. https://doi.org/10.1016/S0960-8524(00)00043-2

Enviva. 2020. At a glance. Enviva. https://www.envivabiomass.com/at-a-glance/ Accessed November 13, 2023.

Forest Research. (2023). *Types of Wood Fuel*.

Friedl, A., E. Padouvas, H. Rotter, and K. Varmuza. 2005. Prediction of heating values of biomass fuel from elemental composition. *Anal. Chim. Acta* 544(1–2):192–198. https://doi.org/10.1016/j.aca.2005.01.041

Fuller, W. S. 2004. Pulping|chip preparation. *In:* Encyclopedia of Forest Sciences, J. Burley (Ed.). Elsevier, Oxford, UK. pp. 883–899. https://doi.org/10.1016/B0-12-145160-7/00126-5

Gard Timmerfors, J., T. Sjölund, and L. J. Jönsson 2020. New drum-chipping technology for a more uniform size distribution of wood chips. *Holzforschung* 74(2):116–122. https://doi.org/10.1515/hf-2018-0279

Goetzl, A. 2015. Developments in the global trade of wood pellets. Office of Industries, US International Trade Commission, Washington, D.C.

Hammond, D. H., J. M. Varner, J. S. Kush, and Z. Fan. 2015. Contrasting sapling bark allocation of five southeastern USA hardwood tree species in a fire prone ecosystem. *Ecosphere* 6(7):1–13. https://doi.org/10.1890/ES15-00065.1

International Energy Agency (IEA). 2021. Share of world total final consumption by source, 2019—Charts—Data & Statistics. IEA, Paris.

International Standardization Organization (ISO). 2021. Solid biofuels. Fuel specifications and classes. Part 4: Graded wood chips. ISO 17225-4:2021.

Johnson, F. X., H. Pacini, and E. Smeets. 2012. Transformations in EU biofuels markets under the Renewable Energy Directive and the implications for land use, trade and forests. Center for International Forestry Research, Jawa Barat, Indonesia. https://doi.org/10.17528/cifor/003775

Karjalainen, M. and D. Bergström. 2018. Particle size analysis of wood chips. *BioHub*. https://biofuelregion.se/wp-content/uploads/2018/12/Infosheet-No-37-Particle-Size-Analysis-of-Wood-Chips.pdf#:~:text=Wood%20chips%20used%20in%20heat%20and%20power%20production,small%20diameter%20roundwood%20produced%20with%20a%20mobile%20chipper. Accessed March 15, 2023.

Kittler, B., I. Stupak, and C. T. Smith. 2020. Assessing the wood sourcing practices of the U.S. industrial wood pellet industry supplying European energy demand. *Energy Sustain. Soc*. 10(23). https://doi.org/10.1186/s13705-020-00255-4

KMEC Engineering. (2018). Working principle of pellet mill and pellet plant. KMEC Engineering. http://www.biomasspelletplant.com/news/Working-Principle-Pellet-Plant.html. Accessed November 13, 2023.

Kober, T., H. W. Schiffer, M. Densing, and E. Panos. 2020. Global energy perspectives to 2060—WEC's world energy scenarios 2019. *Energy Strat. Rev*. 31:100523. https://doi.org/10.1016/j.esr.2020.100523

Krigstin, S., K. Hayashi, J. Tchórzewski, and S. Wetzel. 2012. Current inventory and modelling of sawmill residues in Eastern Canada. *Forestry Chron*. 88(5):626–635. https://doi.org/10.5558/tfc2012-116

Lamlom, S. H. and R. A. Savidge. 2003. A reassessment of carbon content in wood: Variation within and between 41 North American species. *Biomass Bioenergy* 25(4)381–388. https://doi.org/10.1016/S0961-9534(03)00033-3

Lieskovský, M., M. Jankovský, M. Trenčiansky, J. Merganič, and J. Dvořák. 2017. Ash content vs. the economics of using wood chips for energy: Model based on data from Central Europe. *BioResources* 12(1):1579–1592. https://doi.org/10.15376/biores.12.1.1579-1592

Livestock and Poultry Environmental Learning Community (LPELC Administration) 2019. What is the difference between the "higher heating value" (HHV) and "lower heating value" (LHV) of a biomass fuel, and why is the difference important? Livestock and Poultry Environmental Learning Community. https://lpelc.org/

Loffer, L. 2023. Acceptable moisture levels in wood—Knowing the moisture content. WagnerMeters, Rogue River, Oregon.

Meier, E. 2015. Wood! Identifying and using hundreds of woods worldwide. The Wood Database. https://www.wood-database.com/ Accessed 23 Jul. 2023.

Miranda, T., I. Montero, F. J. Sepúlveda, J. I. Arranz, C. V. Rojas, and S. Nogales. 2015. A review of pellets from different sources. *Materials* 8(4):1413–1427. https://doi.org/10.3390/ma8041413

Neumann, M. and M. J. Lawes. 2021. Quantifying carbon in tree bark: The importance of bark morphology and tree size. *Methods Ecol. Evol*. 12(4):646–654. https://doi.org/10.1111/2041-210X.13546

Nosek, R., M. Holubcik, and J. Jandacka. 2016. The impact of bark content of wood biomass on biofuel properties. BioResources 11(1):44–53. https://doi.org/10.15376/biores.11.1.44-53

Popp, J., S. Kovács, J. Oláh, Z. Divéki, and E. Balázs. 2021. Bioeconomy: Biomass and biomass-based energy supply and demand. *New Biotechnol*., 60:76–84. https://doi.org/10.1016/j.nbt.2020.10.004

Price, M. 2011. Woodchip drying. *In*: Centre for Forest Resources & Management: Project report (FCPR045) (Issue April).

Rietig, K. 2021. Multilevel reinforcing dynamics: Global climate governance and European renewable energy policy. *Publ. Admin*. 99(1):55–71. https://doi.org/10.1111/padm.12674

Risse, M. and J. Gaskin. 2002. Best management practices for wood ash as agricultural soil amendment. UGA Cooperative Extension Bulletin, 1142 (November).

Rowell, R., R. Pettersen, and M. Tshabalala. 2012. Cell wall chemistry. *In:* Handbook of Wood Chemistry and Wood Composites. 2nd ed. R. Rowell (Ed.). CRC Press, Boca Raton, Florida. pp. 33–74.

Schipfer, F., L. Kranzl, O. Olsson, and P. Lamers. 2020. The European wood pellets for heating market—Price developments, trade and market efficiency. *Energy* 212:118636. https://doi.org/10.1016/j.energy.2020.118636

Schwarzer, L., P. A. Jensen, P. Glarborg, J. K. Holm, and K. Dam-Johansen. 2017. Understanding biomass ignition in power plant mills. Presented at the 25th European Biomass Conference and Exhibition Proceedings, June 12–15, Stockholm, Sweden.

Shafiee, S. and E. Topal. 2008. An econometrics view of worldwide fossil fuel consumption and the role of US. *Energy Policy* 36(2):775–786. https://doi.org/10.1016/j.enpol.2007.11.002

Shehab, M., Stratulat, C., Ozcan, K., Boztepe, A., Isleyen, A., Zondervan, E., & Moshammer, K. (2022). A Comprehensive Analysis of the Risks Associated with the Determination of Biofuels' Calorific Value by Bomb Calorimetry. *Energies*, 15(8). https://doi.org/10.3390/en15082771

Silva, J., A. C. Ferreira, S. Teixeira, L. Martins, E. Ferreira, and J. C. Teixeira. 2021. Sawdust drying process in a large-scale pellets facility: An energy and exergy analysis. *Clean. Environ. Syst*. 2:100037. https://doi.org/10.1016/j.cesys.2021.100037

Silveira, D. J., A. Durigan, T. Monteiro, I. M. Sgarbiero, and D. A. Silva. 2023. Influence of storage time and log length on the distribution of wood chip size. *BioResources* 18(3):4510–4518. https://doi.org/10.15376/biores.18.3.4510-4518

Sluiter, A., B. Hames, R. Ruiz, C. Scarlata, J. Sluiter, and D. Templeton. 2008. Determination of ash in biomass. NREL Laboratory Analytical Procedure (LAP). *In*: National Renewable Energy Laboratory Technical Report NREL/TP-510-42622. US Department of Energy, Washington, D.C.

Smith, D. 1962. The Practice of Silviculture. 7th ed. John Wiley & Sons, Hoboken, New Jersey. 578 pp.

Sun, P., C. Wang, M. Zhang, L. Cui, and Y. Dong. 2023. Ash problems and prevention measures in power plants burning high alkali fuel: Brief review and future perspectives. *Sci. Total Environ*. 901:165985. https://doi.org/10.1016/j.scitotenv.2023.165985

US Department of Agriculture (USDA) Forest Products Laboratory. 2010. Wood handbook: Wood as an engineering material. *In:* USDA General Technical Report FPL-GTR-190. Madison, Wisconsin.

US Energy Information Administration (EIA). 2020. Biomass explained. Independent statistics and analysis. EIA, Washington, D.C. https://www.eia.gov/energyexplained/biomass/ Accessed July 12, 2023.

US Energy Information Administration (EIA). 2023. Wood and wood waste. EIA, Washington, D.C. https://www.eia.gov/energyexplained/biomass/wood-and-wood-waste.php Accessed August 18, 2023.

Walls, C. 2021. Kraft pulp mill wood chips. Industrial Equipment Manufacturing Ltd., Surrey, British Columbia, Canada.

White, R. H. 1987. Effect of lignin content and extractives on the higher heating value of wood. *Wood Fiber Sci*. 19(4):446–452.