forests

Review

Production of Chips from Logging Residues and Their Quality for Energy: A Review of European Literature

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Abstract: Wood chips from logging residues are a renewable solid fuel that has become widely used in the energy sector. The current work presents a review of European papers on various aspects of wood chips production published in the years 2005–2018. The effects of the comminution method on the quality and energy parameters of the resulting wood chips were analysed. Most authors identified terrain and roadside chipping as the optimum technologies from the energy viewpoint. Furthermore, seasonal changes in the moisture content of wood chips have implications for their ash content and calorific value and determine the annual patterns of supplies to energy plants. In general, logging residues should be chipped approximately five to seven months after harvesting and delivered over economically feasible distances, which have increased in recent years due to the large dispersion of forest areas and energy plants. In a number of cases, logging residue chips did not meet the quality specifications contained in the relevant ISO standards, which may result in technological problems with their burning, especially in small to medium energy plants.

Keywords: biomass; bulk density; calorific value; chip quality standardization; chips size; forest chips; fraction distribution

1. Introduction

The use of biomass energy is thought to be a principal means of mitigating climate change and ensuring energy security both in Europe and around the world. According to the European Union Communication COM/2014/015 [1], the Member States should strive to generate 27% of their primary energy from renewable resources by 2030. One of such resources is forest biomass, which plays a significant role under the Renewable Energy Directive (RED), according to which it should contribute to 20% of renewable energy by 2020. Furthermore, this kind of biomass features prominently in ongoing discussions concerning the implementation of a resource-efficient and sustainable European energy system by 2030 [2]. The development of smart energy systems based on biomass as a source of primary energy can strengthen economic, environmental and social benefits [3]. Biomass resources, that is, forests, have scattered geographical distribution. This makes their harvesting, transport and storage challenging [4,5].

In the EU countries, wood consumption for energy generation is expected to grow from 346 million m^3 in 2010 (3.1 EJ) to 573 million m^3 (5 EJ) in 2020 and could reach as much as 752 million m^3 in 2030 (6.6 EJ) [6]. Bartoszewicz-Burczy and Soliński [7] estimated that by 2020 in Poland alone the market potential of forest biomass for energy purposes will increase to approx. 16 million m^3 of wood

(0.14 EJ), of which 8.1 million m^3 will be derived directly from forests and 7.9 million m^3 from the woodworking industry.

Of key importance in achieving these long-term goals are various forms of forest biomass, which are still underutilized due to their relatively low energy efficiency and high supply chain costs [8,9]. For that reason this kind of raw material is often used in small-scale applications. However, district heating systems and electricity-generating facilities have gained in importance in Europe in recent years [10]. Forest biomass consists of wood with no industrial uses, logging residues and industrial by-products. Depending on the biomass preparation process, different types of solid wood-based biofuel are available: firewood, wood chips, pellets, briquettes and charcoal. Compared to pellets and briquettes, wood chips and firewood are a minimally processed material, so their production chain has less impact on the environment than in case of other fuels [11,12]. Even if wood chips are a minimally processed fuel, they still have the advantage of being standardized in terms of size. In fact, wood chips have a defined particle size produced by mechanical treatment. They are sub-rectangular in shape, 5 to 50 mm long and their thickness is lower than the other dimensions. Although quality certification is not mandatory, it is a guarantee of the quality of biofuels. For this reason, it is strongly suggested to certify wood chips quality according to the standards in force and their final use in domestic or industrial appliances [13].

Logging residues are defined as the above-ground biomass that is left after harvesting of roundwood with a harvester or chainsaw [14–16], including branches, tops and small trees that end up on the ground during felling [17,18].

Within Europe, Finland and Sweden utilize the largest volumes of wood chips and it is expected that many other countries will follow suit. Nowadays, logging residues constitute the main source of wood chips in most countries but in the near future stumps and roundwood may play a more prominent role [19].

At the turn of the century, when biomass-derived solid fuels gained great popularity, the primary focus was on technology development, machinery selection and improved efficiency of the supply chain. Currently, research efforts are largely aimed at increasing work efficiency and product quality. Products parameters should meet the requirements of energy plants both in terms of their feed systems and characteristics of the combustion process [20,21]. It should be noted that forest biomass (logging residues, wood chips) may contain a large number of mineral contaminants, which adversely affect its energy properties [22,23].

Recent years have seen many publications concerning the utilization of forest biomass for energy purposes. Researchers have described possibilities of enhancing wood chips production efficiency [14], the effects of biomass characteristics on wood chipping productivity [24,25], storage-related problems [26], technological solutions facilitating forest energy procurement [27] and improving the quality of wood chips by reducing their moisture content [28]. Issues related to biomass storage, comminution, transport, as well as the economic impact of technology and work methods in the biomass supply chain have been addressed by Erber and Kühmaier [8,9].

Many papers have identified operator experience as a factor directly influencing wood chipping productivity and the end product quality. This is associated with individual work techniques, motor skills, as well as organization and decision-making abilities [24,29].

Wood chips quality is a major factor in energy production efficiency. According to Kuptz and Hartmann [13] and Nuutinen et al. [30], that quality depends on the type of comminuted biomass. In a study of wood chippers by Spinelli et al. [31], feedstock type had the strongest effect on chip quality. Indeed, chip size distribution was found to be directly affected by tree species and the kind of tree parts to be comminuted [28,29,32].

The quality requirements for wood biofuels are regulated by international standards, which set the limits for technical parameters that affect the quality of solid biomass as a fuel. In 2014, new standards were introduced. These are ISO 17225-1 (Solid biofuels–Fuel specifications and classes–Part 1: General requirements) [33] and ISO 17225-4 (Part 4: Graded wood chips) [34], which replaced EN 14691-1 [35] and EN 14691-4 [36], respectively. The main difference between the old and new standards is the definition of particle size distribution classes [37].

ISO 17225-1 describes the possible origins of forest biomass, as the origin influences the final quality of the biofuel [38,39]. Wood fuels are specified based on their origins and the source of their raw materials. They are classified in accordance with the woody biomass main class of raw material class 1 of Table 1 of the standard. Logging residues consist of tops and branches, which are cut from a stem and also un-merchantable small-sized stem wood (1.1.4) and are divided into five sub-classes:

1.1.4.1. Fresh/Green, Broad-leaf (including leaves);
1.1.4.2. Fresh/Green, Coniferous (including needles);
1.1.4.3. Stored, Broad-leaf;
1.1.4.4. Stored, Coniferous;
1.1.4.5. Blends and mixtures.

Furthermore, four quality classes are defined by the standard in force for non-industrial use: A1, A2, B1 and B2 [34]. Logging residue chips are graded as A1 or A2. The highest quality corresponds to A1 class, which is principally characterized by the lowest moisture content and lowest amount of ashes. The worst quality class is B2, where the only restrictions indicated by the standard concern the amount of ash (<3%), particle size distribution and elements content.

Wood fuel properties are divided into two categories: normative and informative [38]. In case of logging residue chips, the normative properties include: origin and source, traded form, particle size, moisture content and ash content, while informative ones include content of N, S and Cl, net calorific value, bulk density and ash fusibility [33].

When determining the quality of graded wood chips for non-industrial use, the following should be considered: normative properties (origin and source, particle size, moisture content, ash content, bulk density, mandatory only for B1 and B2 quality classes—content of N, S, Cl, As, Cd, Cr, Cu, Pb, Hg, Ni and Zn) and informative properties (net calorific value) [37,40–42].

This study aims to present the basic properties of logging residue chips on the basis of the European literature data, mainly from the period between 2005 and 2018. These properties are presented in relation to the valid standards for wood chips, namely ISO 17225-1 and ISO 17225-4.

2. Materials and Methods

Publications concerning utilization of forest biomass for energy purposes and its quality characteristics from the years 2005–2018 were identified by querying the databases Google Scholar, Scopus and Web of Science with key words such as "forest chips," "wood chips," "energy wood chips," "logging residues," "wood chips quality," "wood chips transportation," "fraction distribution," "calorific value" and "ash content." Within the specified time range, the databases returned the following number of publications: 145 to 61,882 (WoS), 755 to 78,736 (Scopus) and 24,700 to 1,710,000 (Scholar). Next, logical operators and combining of two or three keywords into thematic groups were applied in order to reduce the number of records. The logical operators OR and AND were used to ensure that at least one of the terms was found in the title or abstract of each paper. Only publications from European countries were included in further analysis. Altogether, we identified references to more than 180 papers but only a part of them met the criteria for inclusion.

The papers were classified into several thematic groups, including wood chips production (machines involved, chipping process location), wood chips quality (size, fraction distribution, moisture content), energy parameters (gross calorific value, net calorific value, ash content), transport (distance) and quality improvement (increasing calorific value by moisture content reduction and screening).

3. Results and Discussion

3.1. Technologies of Logging Residues Chipping

One of the greatest challenges to increased utilization of forest biomass is the availability and proper use of suitable harvesting technologies to meet the growing demand for this raw material [25].

Energy plants typically use forest biomass in the form of wood chips, whose quality may be improved by the right selection and fine-tuning of machinery [43,44], wood chips screening [45,46], as well as appropriate biomass preparation and storage before and after comminution [26]. Wood chips screening should minimize the content of fine particles [47] in order to enhance the parameters of the combustion process.

Chips vary in size and shape, depending on the comminution technology used. Crushers (shredders) hammer pieces of wood apart and produce a material which is coarse and inhomogeneous in size, while chippers cut the wood with knives and produce more uniform pieces that are slick and easy to convey [48,49]. Chippers might be classified according to technology (disk and drum chippers are primarily used) or performance. There are mobile and stationary chippers. The former can move to chipping sites in the forest, whereas stationary chippers are located at larger bioenergy conversion plants or industrial sites but also at terminals [50,51]. Stationary chippers have generally higher capacities, thereby making chipping more efficient.

The Table 1 shows the classification of technical systems for logging residues harvesting. Depending on the technology applied, chipping can be affected directly at the stand or at the forest road, the terminal or the power plant [52].

Table 1. Classification of technical systems for logging residue harvesting [52].

Number	Place of Comminution or Compacting			
	Forest Site	Forest Road	Terminal	Plant
1	Chipping			
2		Chipping		
3			Chipping	
4				Chipping
5	Bundling [a]	Bundling [b]	Chipping	
6	Bundling [a]	Bundling [b]		Chipping
7	Bundling [a]			Chipping

[a] Bundling at the terrain (Nordic method). [b] Bundling at the forest road after cable yarding (Central European method).

One method involves terrain comminution with chips fed directly into the container of a self-propelled wood chipper; subsequently, on the skid road, chips are transferred onto the container or semi-trailer of a truck. Between felling and chipping, the material can be left in the stand for drying [22,53].

The most common supply chain in Scandinavia and Central Europe is based on roadside comminution of logging residues [14,19,54]. That system involves harvesters and conventional forwarders designed for roundwood forwarding [55,56]. At the roadside, logging residues are chipped with either a truck-mounted or tractor-based chipper and loaded directly onto a chip truck [57]. Chipping of logging residues directly at the forest road is reported in many studies in Northern Europe [58,59], as well as Central and Southern Europe [14,22,60–63].

If the terminal is the point of comminution, the assortments for transport are loose material (logging residues, small roundwood and low-quality roundwood) or bundles [52,64]. Typically, stationary chippers are used at terminals, as compared to mobile ones they offer higher productivity, shorter set-up times and higher chip quality [65]. In case of transporting loose fuel wood, transport volumes are very high due to its low bulk density, which is the main disadvantage of this system [14]. Similar strengths and weaknesses characterize chipping at the bioenergy conversion plant [59,66].

Bundles of forest residues can be used for a supply chain where chipping is done at the power plant or terminal [22,67–70]. Chipping at the customer's site is cheaper but powerful chippers are required to chip bundles [71].

The economic aspects of wood chipping were analysed by Röser et al. [72], who claimed that the process may be made cost-efficient by applying the technologies successfully used in other countries and adjusting them to local conditions. The economic feasibility of wood chips production and transport is affected by considerable fragmentation of forest areas, long distances to major consumers of energy biomass, as well as low bulk density and calorific value of wood chips. These factors impede the utilization of forest biomass on a large scale, make land transport expensive and adversely impact the economic and environmental efficiency of the process.

3.2. Moisture Content, Calorific Value, Ash Content

The moisture content of wood chips is a critical parameter influencing their calorific value and thus quality. The methodology for determining this parameter is provided in the standards ISO 18134-1 [73] and ISO 18134-2 [74]. Furthermore, ISO 17225-1 [33] defines eleven classes of moisture content for wood chips, from M 10 (≤10%) to M 55+ (>55%). For chips for non-industrial use (according to ISO 17225-4 [34]), there are two moisture ranges, M 10 (≤10%) and M 25 (≤25%), in the A1 class and just one range, M 35 (≤25%), in the A2 class.

Analysis of data on wood chips supplies to an energy facility revealed that the moisture content (and the related calorific value) of wood chips was closely associated with atmospheric conditions and month of the year [21]. The lowest average moisture content (27.7%) and the highest net calorific value (12.9 MJ·kg^{-1}) were found in September, while the least favourable energy parameters were recorded in February (moisture content: 47.1%, net calorific value: 8.7 MJ·kg^{-1}). This relation was explained by seasonal changes in temperature and precipitation. These results were corroborated in another study encompassing measurements on 485 days [28], in which the highest moisture content of wood chips (42%–46%) was recorded for the winter months, with the lowest (28%) was observed in September (the average annual moisture content amounted to approx. 41%). Similar results were reported in studies by Laitila et al. [75] and Badal et al. [76], where the average moisture content of wood chips from different raw materials ranged from 40% to 50%. Furthermore, wood chips which were stored in piles in the summertime (when demand from energy plants was low) had a tendency to remoisten, with an average moisture content of 39%.

Another study reported a relatively high moisture content (>43%) of wood chips made from logging residues of various tree species [23]. This was largely attributable to a substantial content (approx. 30%) of foliage (needles, leaves), bark and other contaminants with a moisture content of more than 70%. To improve the quality of wood chips and reduce moisture, logging residues may be seasoned in the clear-cut area for several months [20,29,77]. After 5–7 months of seasoning the average moisture content of logging residues decreased to approximately 28%. Similar results were obtained by Kuptz et al. [13] and Afzal et al. [78]. The average moisture content of wood chips produced from recently cut wood was 48.9%. Drying of the unchipped material for one summer reduced this parameter to 30.6%. The drying performance of logging residue brush piles depends on numerous factors, such as air humidity, temperature, soil humidity and temperature, precipitation, solar radiation and airflow velocity [79]. Utilization facilities generally prefer a material of lower moisture, as this raises the heat value of the fuel. They usually encourage producers to use procedures, such as transpirational drying, that minimize moisture content prior to delivery [80]. The moisture content of logging residues may also be reduced by covering them with for example, impregnated paper, which may be subsequently comminuted together with biomass [54,61]. Liaqat [81] observed in his study that piles of logging residues placed in a slope and under the shade of trees showed higher moisture and ash content than those located in a plain site. Increment in ash content could be explained by higher amount of contamination and led to lower calorific value.

As demonstrated by the aforementioned results, the moisture content of logging residue chips often exceeded specifications for the quality classes A1 and A2 of ISO 17225-4 (≤15% and ≤35%, respectively). It means that small energy plants may face some technological problems when burning such a material.

Moisture content significantly influences net calorific value [82]. With an increase in moisture, the latter is reduced proportionally. Vaporizing water requires energy from the burning process (2.6 MJ per kilogram of water), thus reducing the net heating value of the fuel [83]. Net calorific value is determined according to ISO 18125 [84]. For a fresh material with moisture content of 43%–62%, this parameter ranges from 5.6 to 9.6 MJ·kg^{-1} [38,82,85]. From the power generation perspective, it is naturally more beneficial to burn a material which is as dry as possible. The gross heating value of wood does not vary considerably between tree species (18.7–21.9 MJ·kg^{-1}), though it is slightly higher in coniferous species than in broadleaved or deciduous ones [86].

Another factor affecting the quality and calorific value of wood chips from logging residues is ash content. This parameter is determined according to ISO 18122 [87]. Ash is one of by-products generated during biomass burning. Biomass ash consists of various proportions of silicon, aluminium, iron, calcium, magnesium, sodium, potassium, titanium and manganese, with heavy metals as impurities [88].

Ash content of forest residues may be higher compared to that of energy roundwood (ISO 17225-1) [33] and often exceeds the requirements of ISO 17225-4 (max. 1.5% in the A2 class) [37]. The average ash content of wood chips from logging residues is 3%–4% [21], which is approximately 1% and 1%–2% higher than that reported for chips from branches [89] and whole trees [90], respectively. Chipped forest residues usually include bark, needles or leaf and are sometimes contaminated with sand. Their composition significantly affects ash content [52,91].

As for moisture content, also here changes are seasonal. From June to September, when biomass is the driest, ash content is the highest (approximately 5% or more). Ash affects the combustion efficiency and may cause problems with slag in furnaces, surface contamination of heat exchangers and corrosion of combustion systems [92–94]. It is also the most important discrimination parameter in wood quality classes, which are related to the maximum ash content [95]. As demonstrated in a study by Huber et al. [46], wood chips quality improvement by reducing ash content may be achieved with screening, which removes over-sized particles.

One study compared various comminuted types of forest biomass, including sawmill waste, logging residues from several tree species obtained using various technologies as well as bundled Norway spruce residues [22]. The highest net calorific value and the lowest ash content were reported for wood chips from sawmill waste. Conversely, bundling of logging residues was found to be the least favourable method, resulting in the lowest calorific value and the highest ash content. From an energy viewpoint, the optimum technologies involve comminution of logging residues either directly in the clear-cut area or after piling them at the roadside. Those technologies lead to wood chips with net calorific value of approx. 18 MJ·kg^{-1} and ash content of approximately 3.2%.

Another important aspect was the experience of chipper and forwarder operators. It was found that most contaminants in wood chips were attributable to sinking of the grabber in the soil while picking up branches, which resulted in transfer of mineral particles to the chipping or bundling machinery [22].

3.3. Wood Chips Size and Fraction Distribution

The size and fraction distribution of wood chips are important quality indicators for energy plants, as these parameters substantially affect fuel feeding systems and the combustion process [96]. Both official standards and internal documents of energy plants specify acceptable proportions of various particle sizes [97]. ISO 17225-1 defines ten classes of wood chips of different particle sizes, from P16S to P300, depending on the main fraction (at least 60%; 3.5 to 300 mm), coarse fraction (e.g., <6% and >31.5 mm for P16S), maximum length for over-sized particles (<45 mm for P16S) and cross sectional area (<2 cm^2 for P16S). EN 14691-4 [36] used to be the reference standard for wood chips for non-industrial use but in 2014 it was replaced by ISO 17225-4 [34]. The main difference between the two standards is related to the particle size distribution of wood chips. The percentage required in the ISO standard is lower than under the EN standard and the percentage of fine particles ($\leq$3.15 mm) associated with the main fraction is higher. Another difference is in the allowable percentage and size of overlengths. Furthermore, in the ISO 17225-4 standard there are only three particle size classes (P16S, P31S and P45S) instead of four in the older standard. The quality of wood chips with reference to the aforementioned standards was compared by Zanetti et al. [37], who concluded that, compared to EN, the ISO classification increased the number of wood chips samples belonging to quality classes A1, A2 and B1 and decreased the number of not classified (NC) samples. Consequently, the introduction of the ISO classification favours the demand for quality by end users in terms of particle size distribution classification offered by wood chips producers. [37]. According to Spinelli et al. [97], the size distribution of wood particles is affected by moisture content: the higher it is, the greater the share of finer fractions. It should be noted that the moisture content of wood chips is significantly influenced by the presence of foliage contaminants, which contain up to twice as much moisture as wood [23].

According to Kons et al. [47], wood chips with a low proportion of fine particles ensure optimum combustion conditions. Roundwood gives wood chips of better quality, as they are more homogeneous and have high wood content; hence, they are recommended for energy plants with high quality requirements. Conversely, a German study by Kuptz and Hartmann [13] has reported that wood chips from logging residues, due to their variation in size and composition, are more suitable for medium-sized and large energy plants that do not require chips of very high quality. The factors significantly influencing the size distribution of wood chips include tree species and tree parts from which they are made [32,98,99]. The studies by Nati et al. [32], Spinelli and Magagnotti [100] and Krajnc and Dolšak [101] indicate that the average size of pine chips is smaller than that of poplar and beech ones. According to the authors, this is associated with wood hardness and structure. This fraction distribution is beneficial for energy plants as it leads to a higher proportion of finer fractions and lower ash content [102].

Spinelli et al. [97] observed a Pezzolato PTH 900/660M wood chipper which was used to comminute fresh and dry beech and larch residues and found that moisture content significantly affected particle size distribution (they obtained a 90% proportion of acceptable particle sizes).

In addition to tree species and tree parts, the particle size and fraction distribution of wood chips depend also on the chipper parameters. Of particular importance is the sharpness of chipper knives [49,75]. In a study involving a Bruks 805CT chipper operating in various tree stands, sharp knives led to approx. 20%–30% larger wood chips as compared to blunt knives (69%–79% vs. 76%–96% shares of the <32 mm fraction). The average particle size and fraction distribution also depend on the type of feedstock (branches, bundles, roundwood), wood chips composition, as well as chipper type (mobile or electric stationary) [23]. Larger wood chips are obtained by comminuting logging residues with a mobile chipper in the forest site (72% of the <32 mm fraction), while the smallest wood chips are produced by comminuting bundles with an electric chipper (91% of the <32 mm fraction). Finally, of note is a large proportion of contaminants and uncomminuted pieces (approx. 30%), especially in wood chips from spruce residues.

Especially smaller furnaces (<1 MW) require fuel of specific physical properties, such as low moisture content, low ash content and homogeneous particle shape. High shares of fine material (<3.15 mm) may lead to clogged screw conveyors, uneven combustion performance within boilers or problems during storage space filling, such as dust emission or dust explosion [103].

3.4. Transport of Wood Chips and Their Bulk Density

Wood chips and bundles are usually transported from forest sites by truck. Typical logging trucks are used for bundles [70], while wood chips are usually carried in semi-trailers or trucks with containers [72]. At the beginning of the 21st century it was thought that wood chips could be transported only over short distances to local consumers. However, given the growing demand for that fuel from power plants equipped with biomass-fired boilers, both the number of destinations and transport distances increased considerably.

In most European countries, energy wood and wood chips are predominantly transported by truck [52] but in Finland [104,105] and Austria [91] they are increasingly transported by rail or water over medium to long distances. Truck transport for biomass is generally used over relatively short distances (<100 km), when flexibility is required to access small production sites or when train and ship infrastructure is absent [106]. Economical transport distances have been reported to be up to 50–100 km for wood chips from logging residues [107–109], 150 km for roundwood chips [110] and 100–200 km for wood chips from energy tree crops [111]. Rail transport is recommended for more distant destinations (over 145 km) [52,106]. At the same time, ship transport has the highest time dependent costs and, therefore, using the waterway is only economic over long distances, exceeding 800 km [112].

The amount of energy per unit of payload delivered to the end customer depends on bulk density. Bulk density is determined according to ISO 17828 [113] for material as received. ISO 17225-1 defines seven different grades with respect to bulk density, from BD150 ($\geq$150 kg$\cdot$m^{-3}) to BD450+ (>450 kg$\cdot$m^{-3}). For chips for non-industrial use (ISO 17225-4), the three first grades are permitted in A1 class and the four first grades are permitted in A2 class.

While conventional forest products generally exceed the maximum allowable load volumes [114], fuel wood in an unprocessed form may have bulk density of only 120 to 150 kg$\cdot$m^{-3} [80]. The bulk density of green chips varies with species. It generally ranges from 150–230 kg$\cdot$m^{-3} for dry wood chips [115–117] to 111–340 kg$\cdot$m^{-3} for chips with moisture content of 10%–53% [116,118–121]. A semi-trailer of capacity of 91 m^3 can carry approx. 23 Mg of wood chips with moisture content of 41% [28,122].

Goltsev et al. [107] calculated the economically feasible transport distance in Russia and Finland for wood chips with moisture content of approx. 50% and relatively low density. According to the authors, the cost of transporting wood chips over a distance of approx. 80 km in trucks with trailers of combined capacity of 100 m^3 amounts to 3.4–4.7 € m^{-3} (approx. 3.7 € m^{-3} in Russia and 5 € m^{-3} in Finland). Furthermore, according to Kühmaier et al. [123], one can achieve transport costs of 0.32–0.49 € m^{-3} only if the moisture content of wood chips is equal to or less than 35%. Gołos and Kaliszewski [85] argue after Piszczalka et al. [124] that due to cost-efficiency and environmental considerations, it would be economically feasible to transport unprocessed biomass over distances of up to 30 km. In addition, given the seasonal changes in demand for wood chips (associated with ambient temperature) and seasonal variations in their moisture content, one can use logistics planning to successfully manage the stock levels and energy parameters of wood chips in storage areas [91].

Based on wood chip transport data for Poland, Gendek et al. [28] calculated the profit that could be derived by suppliers from reducing the moisture content of payload during transport (thus improving its quality). Given the initial 45% moisture content of wood chips, a decrease by 1%–7% would lead to earnings of €4.7–30 per 24 Mg, which could translate into thousands of euros annually for suppliers conducting continuous operations throughout most of the year.

4. Conclusions

The most common supply chain of forest biomass for energy production in European countries is based on comminuting the raw material at the roadside. The applied technology affects the quality of energy wood chips, especially their calorific value and ash content, which are critical to the combustion process. To obtain the optimum energy parameters, logging residues should be chipped directly in the clear-cut area or at the roadside after prior stacking. Bundling and comminuting at the customer's facility is the least favourable, as it leads to substantial contamination with mineral matter. This entails lower calorific value and high ash content, compromising the value of wood chips as a fuel.

The energy efficiency of wood chips combustion is significantly affected by their quality parameters, that is size fraction distribution, as well as ash and moisture content. In general, wood chips should be characterized by a low proportion of fine particles. Typical ash content ranges from 3% to 4%, which is acceptable in most cases.

The moisture content of logging residue chips largely depends on how much foliage they contain and on the prevailing weather conditions. In order to naturally reduce moisture content (to approx. 30%) and increase calorific value, logging residues should be comminuted after approx. 5–7 months of seasoning on a forest site. The lowest moisture content can be achieved in September.

Quality of logging residue chips needs to be assessed according to the standards in force (ISO 17225-1 and ISO 17225-4) and their intended use: domestic or industrial. At times, excessive moisture or high mineral content (contributing to slag formation) may result in problems with chip combustion, especially in small energy plants.

With a view to improving the quality of energy biomass, it is necessary to conduct further studies concerning wood chips from logging residues, which to date have been the subject of few publications. Basic research should be carried out concerning their moisture content, elements composition and calorific value in order to enhance the energy efficiency of the combustion process and reduce the emission of harmful substances.

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