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RESEARCH ARTICLE

Identifying key quality characteristics of woody biomass for bioenergy application: an international review

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Abstract

Biomass characteristics play an important role in product classification, economic values, and types of usage. This research was initiated by the IEA Bioenergy Technology Collaboration Programme, which aimed to review and identify the top biomass characteristics as they relate to commercially viable biomaterial and bioenergy processes. An online search (in English) was conducted using the following keywords: biomass, chips, quality, characteristics, moisture content, calorific values, contamination and ash content. The search was restricted to woody biomass and raw feedstock materials. Review results were classified based on regions including Africa, America, Asia, Europe and Oceania. Each case study was described based on the study background, type of biomass and biomass attributes that were measured. The key biomass characteristic was moisture content that was consistently measured in almost all reports. Ash content and calorific value were classified as second place in terms of frequency in the biomass studies. Lower frequency belonged to the attributes such as bulk density, contamination, particle shape and nutrient (elemental) content. Detailed information of different case studies is provided in this report. It is anticipated that this literature review will assist IEA Bioenergy and its industrial and scientific network to better understand the current knowledge gaps regarding woody biomass characterisation.

Keywords

Woody biomass, Quality characteristics, Moisture content, Calorific value, Contamination, Ash content

Introduction

Globally there is increased demand for sustainable energy solutions as well as an increasing range of bioproducts that are driving increased demand for biomass. As these markets grow and mature biomass producers will shift from primarily seeking out economically viable market options to seeking to access the highest value market their biomass resource is suitable for. The ability to match biomass quality and characteristics to market value and opportunities will require a shift from simple trading values based on volume, mass and moisture content to being able to identify and measure characteristics of the biomass that dictate its value in different energy and biomaterial production processes like calorific value, cellulosic content, ash content, fiber length/strength, etc. In addition to better positioning in high demand, multiple end-user markets, this basic knowledge of biomass quality will enable effective and economic access to areas with emerging biomass opportunities (Brown, 2022).

Biomass characteristics play an important role in product classification, economic values, and types of usage. One of the key characteristics is particle size distribution of wood chips. Handling and combustion of solid biofuel, ventilation properties and storage types can be impacted by particle size (Kristensen and Kofman, 2000). According to Kuptz et al. (2019) wood chip quality is a key factor to achieve low-emissions combustion of small boilers with capacity less than 100 kW.

There are two types of biomass lab analysis including proximate and ultimate analysis. Proximate analysis is a laboratory technique used to determine the major components or constituents of a sample. It provides information about the approximate composition of a substance based on its physical and chemical properties. The main components typically analysed in proximate analysis include moisture content, volatile matter, fixed carbon, and ash content. Ultimate analysis is a more comprehensive analytical technique that determines the elemental composition of a substance. It involves measuring the percentage of Carbon (C), Hydrogen (H), Nitrogen (N), Sulfur (S), and other elements present in the sample (Turn et al. 2005). Key quality characteristics of the woody biomass depend on the biomass conversion process and the related product. Kenney et al. (1992) mentioned that qualitative, physical, and chemical characteristics of biomass feedstocks are important when defining their suitability for different conversion systems. Different types of sugar such as hemicellylose and guaiacyl/syringyl ratio in the lignin are main qualitative traits. Moisture content and density are key factors for converting woody biomass into energy. According to Kenney et al. (1992) there are three main types of biomass process including direct combustion (heat process), thermochemical and biochemical. For the heat process the biomass feedstock requires low moisture content, high density, low cellulose/lignin ratio, high guaiacyl/syringyl ratio, high extractive content and low ash content. The thermochemical process would benefit from low moisture content, high density, low cellulose/lignin ratio, high guaiacyl/syringyl ratio and high extractive content. When the biomass feedstock has high cellulose/lignin ratio, low proportion of pentose sugars, low guaiacyl/syringyl ratio and minimum content of potentially toxic extractives or heavy metals then it may be ideal for biochemical processes.

This research was initiated by the International Energy Agency of Bioenergy Technology Collaboration Programme (IEA Bioenergy TCP) which aimed to review and identify the top 3 to 5 biomass characteristics as they relate to commercially viable biomaterial and bioenergy processes. The intention is to assist IEA Bioenergy and its industrial and scientific network to better understand the current knowledge gaps regarding woody biomass characterisation.

Methods

An online search (in English) was conducted using the following keywords: biomass, chips, quality, characteristics, moisture content, calorific value, contamination, ash content. Search engines such as Google Scholar, Scopus, Web of Science and Research Gate were used to find relevant articles via Google online search. The online search yielded 219,000 cases in total. The first 10 pages of online search were found to be relevant to the topic of the article. Out of 110 cases, 42 articles/reports published after 2000 and primarily over the last decade were chosen for this literature review which focused on woody biomass and its raw feedstock materials. The rest (68 cases) were excluded after checking their title and content as they were related to other types of biomass and feedstock. Review results were classified based on regions including America, Asia, Europe and Oceania. Each case study was described based on the study background, type of biomass and biomass attributes that were measured. Through a literature and technology review, current and near commercial technologies for the production of energy and materials from biomass were identified as well as what characteristic(s) of biomass was the key driver of the efficiency and effectiveness of the process. A list of the key characteristics was developed for each case study, and priorities based on how many bioenergy and bio material processes it has an important influence on (Brown, 2022).

AMERICA

Brazil

Generating energy from biomass is known as an opportunity in Brazil. Brazil has large Eucalypt plantations which cover about 6.9 million ha. Caraschi et al. (2019) reported that Eucalypt barks were one of the waste materials (including industrial waste and sweepings) that had low quality due to high ash content (up to 10%) and low calorific value. A combustion process was difficult due to the high moisture content of the barks. Rebeiro et al. (2021) evaluated the Eucalypt woodchip utilisation as a source of fuel in a thermal power plant. They sampled wood chips from 7 year old *Eucalyptus* hybrids *E. urophylla* x *E. grandis* that was harvested. Biomass characterisation was conducted by measuring attributes such as moisture content, bulk density, calorific value and ash content which are key factors to help reduce the costs and improve combustion performance to create sustainable thermal power generation.

Canada

Thiffault et al. (2019) investigated the properties of four types of residue feedstock including green wood chips, dry shavings, solid and engineered wood sawdust to optimize the quality of wood pellets. Tested properties included particle size distribution, moisture content, bulk density, ash content, calorific value, hemicelluloses, lignin, cellulose, extractives, ash major and minor elements, and carbon, nitrogen, and sulphur. Moisture content and biomass composition were the most impactful properties in terms of determining pellet quality. According to Canadian biomass producers moisture content is a key factor to predict the net calorific value of biomass materials (https://www.ontario.ca/page/biomass-burn-characteristics) while biomass composition, ash content, carbon, hydrogen, nitrogen, sulphur, chloride and soil contamination remain important factors to consider.

Mann (2012) compared yield and biomass characteristics of woody and herbaceous biomass in Southern Ontario including *Miscanthus*, switchgrass, willow, and poplar during the first and second years of growth. The characteristics tested included gross calorific value, ash level (%) and ash elemental analysis. The combustion characteristics of woody biomass were different to the grass biomass. A report published by FPInnovations provided a list of critical biomass attributes for various applications including direct combustion, gasification, pyrolysis, torrefaction, fermentation, and densification. Biomass format was one of the attributes including short and long logs, chunks, firewood, hog fuel, wood chips, construction and demolition waste, processing residue and sawdust. Other attributes included moisture content, calorific value, bulk density, foliage/bark content, ash, lignin, carbohydrate, extractive contents (Marinescu, 2013), extraneous material (stones, sand, and dirt) and contamination (such as glass, metal, plastics) (Natural Resources Canada https://www.nrcan.gc.ca). For the pyrolysis process, pre-treatment of the biomass feedstock can play a major role. Rezaei et al (2018) mentioned that these pre-treatments can change the biomass feedstock's size, shape, mineral content, composition, hygroscopic properties, homogeneity, grindability, stability and transportability.

USA

There have been several research projects conducted in the USA dealing with various types of biomass and species. In 2008 a study was carried out by CNH Industrial Group involving harvesting short rotation crops in Auburn using a Holland single pass harvester-chipper. The willow, poplar and Eucalypt stands were cut and chipped using the Holland harvester-chipper (Figure 1). The main biomass characteristics of willow stands were assessed which included moisture/energy content, size classification and ash content as selected elements (N, P, K, Ca, Cu, Mg, Na, S, and Zn) (Eisenbies et al. 2008).

Figure 1. Willow biomass chips for temporary storage in Upstate NY, USA (Eisenbies et al. 2008)

Eisenbies et al. (2016) studied the storage of willow stand chips collected by an unmodified New Holland FR9080 harvester, equipped with a New Holland 130FB coppice header near Groveland, New York. Changes on moisture content, ash content and calorific value were assessed during several months of storage. Chip quality change during the first two months of storage was minimal while it did not vary highly over a longer period. In a study by Turn et al. (2005) in plantations on the islands of Kauai and Hawaii wood chip samples (Figure 2) were collected from slab wood produced from sawmill operations. Several species including *Eucalyptus grandis,* ironwood, waiwi, tropical ash, and Moluccan albizia trees were chosen to sample randomly from the plantations.

Bulk density (dry and wet), particle size distribution, ash content, volatile matter content of bole wood samples and calorific value were assessed. The ultimate analysis evaluated the elements as Nitrogen, Carbon, Sulphur, and Chlorine.

Figure 2. Measuring wood chips bulk density in Hawaii, USA (Turn et al. 2005)

Ciolkosz (2010) indicated that calorific value, moisture content, chemical composition and size classification and density can impact the performance of biomass fuel (https://www.engineering.iastate.edu). A study in loblolly pine stands in central Georgia by Cutshall (2012) examined the impact of natural drying on the cost of whole tree chipping and transportation operations. Biomass characteristics such as calorific value, ash content, bark content and nutrient content of the produced wood chips were assessed. Drying reduced moisture content but did not significantly change the ash content. Transportation costs decreased due to reduced moisture content and increased payload (Cutshall, 2012).

Pradhan (2015) tested several physical treatments to reduce ash content and its impacts on pyrolysis products in Alabama based on sweetgum, residual pinewood, whole pinewood and dirty pinewood. To reduce soil contaminants from the wood chips (which could then reduce ash content) the following tools were tested: vibratory sieve shaker, hammer mill, and mixer. The vibratory force created by the vibratory sieve shaker, the rotary motion created by the mixer and the beating action by the hammer resulted in the separation of soil from wood chips.

Sharma et al. (2017) reported that ash content, calorific value, moisture content and density of the feedstock are the most critical attributes of biomass feedstocks. The research on pine and hardwood pellets in Louisiana suggested that these resources are suitable for gasification due to their high density and low moisture/ash content. Scholars in Georgia studied the biomass characteristics of two main species including Loblolly pine (*Pinus taeda*) and slash pine (*Pinus elliottii*) trees as main biomass resources in the Southeastern United States. Calorific value was claimed to be the most important variable for bioenergy production. The stands were thinned using feller-bunchers and grapple skidders. The whole trees were then chipped using a Morbark 30/36 drum-style chipper. Wood chips samples were collected which contained bark, needle, branch and wood. The samples were dried and screened by a 1 mm screener, then used for laboratory analysis. The research team applied near infrared reflectance (NIR) spectroscopy to measure gross/net calorific value, ash/moisture content, total carbon, total nitrogen/carbon/sulphur. The application of NIR provided accurate results with standard error less than twice of the laboratory method (Saha et al. 2017).

ASIA

India

Lenka (2016) published his thesis on "characterization of the properties of some biomass species and estimation of their power generation potentials" in India. He indicated that India has several energy resources and the energy demands of the country are high. Among the available energy resources, renewable energies sound attractive due to their low emissions. Power generation using biomass could be more environmentally friendly due to the large resource availability, low ash content and low pollutants element such as Cox, SOx and NOx. Two species including *Vachellia nilotica* and *Azadirachta indica* were tested. Their biomass samples contained leaf, branches, bark and root. Calorific value, fixed carbon content, moisture/ash content and bulk densities were measured. In the other trial Chakradhari and Patel (2016) sampled 53 trees in Chhattisgarh state. Various tree parts were sampled, and oven dried at 50°C for a period of one day. Then all samples were crushed and passed through a sieve of 0.25 mm. The characteristics such as bulk density, moisture/ash content and calorific value were assessed. Statistical results confirmed the larger bulk density increased calorific value based on a linear model function. Moisture content did not significantly change net calorific value. Following a linear model function higher ash content resulted in lower calorific value (Figure 3).

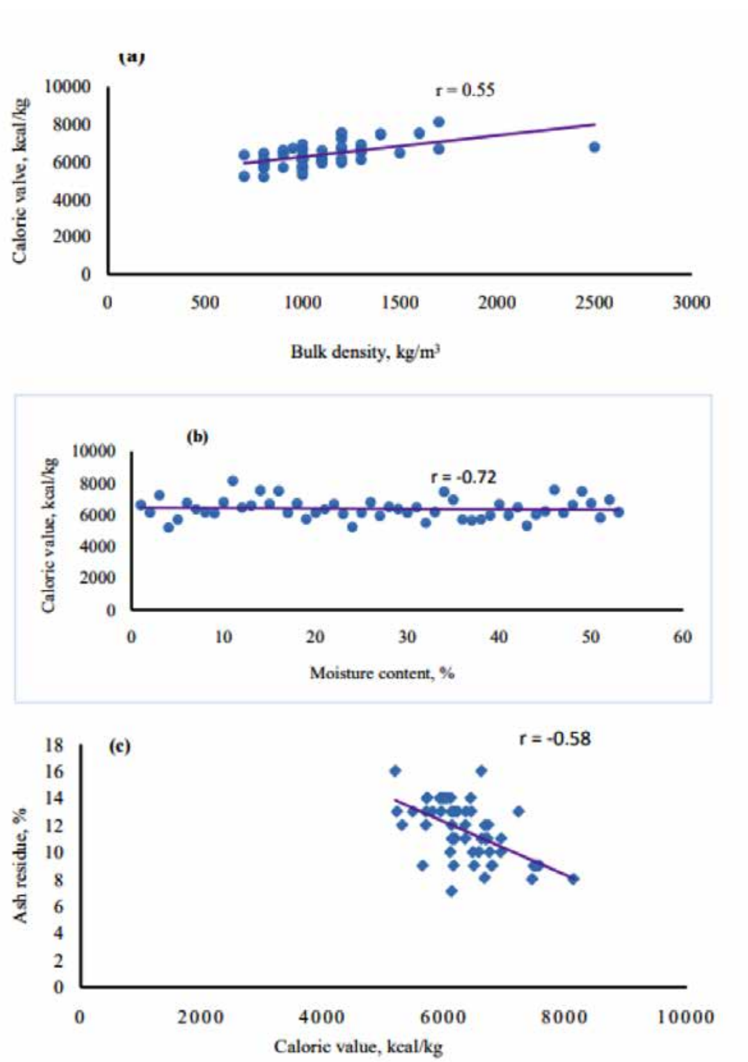

Figure 3. Correlation between bulk density, moisture content and calorific value (Chakradhari and Patel 2016)

Indonesia

One of the main forestry areas in Indonesia that can provide woody biomass for electric power generation purposes is the East Kalimantan Province. Yuliansyah et al. (2022) assessed the physical properties of fast-growing native species (medium tree with DBH of 6-8 cm) as bioelectricity feedstocks. The species in the trial included *Elaeocarpus ferrugineus (Jacq.) Steud., Ficus aurata (Miq.) Miq., Fordia splendidissima (Blume ex Miq.) Buijsen, Lindera lucida (Blume) Boerl., Mallotus paniculatus (Lam.) Mull. Arg. and Schima wallichii (DC)*. The research showed that processing solid wood into wood chips reduced the moisture content to achieve higher energy content. The wood chips from *F. splendidissima* provided the highest energy content (3.61 MWh/t) which indicated this species might be suitable to plant in large scale for bioenergy production in East Kalimantan.

EUROPE

Krajnc (2015) published a wood fuel handbook by the Food and Agriculture Organisation (FAO). She indicated that moisture content, gross and net calorific value, ash content and bulk density are the main characteristics for coniferous and broad-leaf woody species. Carbon (C), Oxygen (O) and Hydrogen (H) make up the main woody biomass chemical composition. After the combustion of woody biomass, harmful emissions elements include Sulphur (S), Nitrogen (N), Chlorine (C) and ash contents (Krajnc, 2015). Moskalik and Gendek (2019) conducted a review of European literatures on wood chip production and its quality from logging residues. They indicated that chipping logging residues in terrain or roadside are popular methods. Storage period from 5 to 7 months can be recommended to reduce moisture content by natural air drying in European climate conditions. Reducing moisture content improved calorific value and ash content. Moskalik and Gendek (2019) mentioned that there have been some cases that wood chips from logging residues did meet the required ISO standards due to technological problems occurring during combustion in small to medium energy plants.The Irish Department of Agriculture conducted a comprehensive review of standards of solid biofuels in 2016. Four wood fuels were considered including wood briquettes, wood pellets, wood chips/hogs and firewood. The physical and chemical properties included origin of wood, trade form, wood species, dimensions, moisture content, ash content, mechanical durability, bulk density, additives, net calorific value, Nitrogen/Sulphur/Chlorine content, Arsenic, Cadmium, Chromium, Copper, Lead, Mercury, Nickel, Zinc, ash melting behaviour and surface area (for briquettes) (Kofman, 2016). Vosic et al. (2021) considered moisture and ash contents, calorific value and particle size as main attributes in a Croatian case study on assessing the quality of wood chips of fir/spruce and beech energy roundwood under bark and debark treatments. Researcher from University of Strathclyde in UK developed a biomass installation feasibility tool that considered same biomass attributes (moisture/ash content, calorific value and particle size) (www.esru.strath.ac.uk; https://woodyfuel.co.uk/why-biomass-fuel-quality-is-important/).

Debarking reduced moisture and ash content. Wood species also made a significant impact on the gross calorific value and particle size distribution. Researchers in Lithuania measured moisture content, ash content and size distribution from wood chips of logging residues collected from a period of 3-years (Pedišius et al. 2021). Polish scholars considered quality attributes such as calorific value, moisture content, ash and Sulphur content to study various types of biomass resources including logging residues (Smaga et al. 2018; Smołka-Danielowska and Jabłońska 2021). Their research showed that the carbon content, H, O, N, S depends on wood species and length of drying period. Gavrilescu (2008) in Romania reported that solid woody waste generated in pulp and paper mills could be utilized as a source of energy. He considered calorific value, moisture/ash content and elemental analysis (C, H, S, N, O) as main biomass quality characteristics.

According to Slovakian researchers, bark has higher ash content compared with the branches and trunks. Large shares of bark during combustion may create further clinker in the furnace which will increase maintenance costs and cause more emissions. Nosek et al. (2016) collected bark samples from Norway spruce, birch, and European Beech. The main study finding pointed out that a 1% increase in bark content could increase the ash content from 0.033 to 0.044%. Another comprehensive research was reported by Dimitorva et al. (2017) in Bulgaria. These scholars studied important biomass characteristics such as bulk density, calorific value, cellulose, lignin, ash contents, carbon, hydrogen, nitrogen of stem wood of juvenile black locust trees and clones. The study sites were in Northern and Southeastern Bulgaria. The stands were young (2-6 years old) consisting of species such as hybrid black poplar (*Populus deltoides×P.nigra*) and *Paulownia sp.* The study confirmed that the age class of 2-6 years significantly impacted the bulk density. The wood density of poplar clones averaged at 300-400 kg/m^3 in this study. Black locusts reached the highest density of 450-650 kg/m^3. *Paulownia* trees had higher contents of cellulose, lignin and ash compared to other species. The highest calorific value was found in poplar stem wood. These findings confirmed that the studied species and clones could be considered as suitable biomass sources of generating energy (Dimitorva et al. 2017)

Pruning residues from five orchard species were collected and chipped using a prototype chipper model PC50 in Spain and Germany (Suardi et al. 2021). Parameters such as moisture content, apparent bulk density and particle size distribution were considered to assess the quality of the wood chips in this case study. Chipping knife type had an impact on the chip size. Continuous knife type yielded 97% higher material capacity than hoe shaped knives.

Germany

According to Kuptz and Hartmann (2014) parameters play a key role to determine physical and chemical characteristics of wood chips: moisture content, ash quality and content, calorific value, particle size and shape. When wood chips are used for small to medium size combustion units, they are transported from a bunker to the furnace using a hopper equipped with a horizontal agitator. Bulk density and moisture content of wood chips can impact this process. Rackl et al. (2019) compared two types of wood chip quality including high (without fine materials) and low (with fine materials). Their study indicated fine contents acted as solid lubricant between large particles. This resulted in higher flowability of a blend during feeding biomass to the combustion unit.

Sweden

There have been extensive research efforts on wood biomass characteristics in Sweden. Willow (Salix) is one of the fast-growing species dedicated to biomass production meant to feed small and large bioenergy plants. Willow stands can be harvested using intact stem removal systems with or without baling. Natural air drying is applied when moisture content reduction is desired. SP Technical Research Institute of Sweden (2015) have considered the following characteristics for willow wood chips including moisture content (that can change over the storage period of the willow bales/bundles), ash content and net calorific value. Kons (2015) reported that biomass terminals in Sweden play a key role in improving logistic efficiency and biomass quality. Kons' thesis showed that harvesting residues are mostly chipped at the terminals and their quality can be improved using screening that could reduce the share of fine material (<3.15mm) especially for logging residues created from tops and branches. Wästerlund et al. (2017) received wood chips from Latvia that were mostly produced from chipping logging residues and small stems (mainly spruce) (Figure 4). The impact of storage and natural air drying (for a period of 5.5 months) on wood chip properties was investigated. Moisture content, dry matter content and calorific value were the main biomass quality parameters in their trial.

Anerud et al. (2019) indicated that any degradation during the storage of the biomass material can result in increased environmental and economic risks/losses. Exposure to sun and air during the storage period could reduce dry mass losses due to microbial activities in the biomass materials. From an end-user perspective chipping to larger particle size can decrease the risk of surface exposure to the microbial activities. Coverage of residue/biomass piles can reduce the risk of re-wetting due to the rain and the recommended storage period is 3 to 4 months (Anerud et al. 2019). Anerud et al. (2020) reported another similar research that storage of wood chips could result in higher energy content and lower moisture. Stands consisted of a mix of pine (*Pinus spp.*), spruce (*Picea abies*), aspen (*Populus spp.*) and birch (*Betula spp.*) harvested during thinning. The coarse wood chips had lower moisture content than fine wood chips which resulted in 2-6% of the economic gain for large chip size production. Building on previous research Anerud et al. (2021) reported that biomass fuel quality can increase when wood chips are covered which depends on the type of cover material.

Considering the importance of forest fuel quality assessment, Fridh (2018) pointed out that accuracy and precision of measurements of moisture content and ash

Figure 4. Uncovered cross section of wood chips pile in Sweden (Wästerlund et al. 2017)

content is critical. He used several methods/tools such as electric capacitance (CAP), magnetic resonance (MR), near infrared spectroscopy (NIR), and X-ray technologies for moisture content measurement. MR was not impacted by fuel type and had highest accuracy while CAP resulted in the lowest accuracy in the trials. Ash content and particle size distribution could be measured using an X-ray tool. For particle size measurement the tool required calibration before usage to ensure high level of accuracy.

OCEANIA

Australia

Australia has mandatory standards for biofuel quality, but Boucher (2018) reported that biomass producers and users should ensure that moisture content (Figure 5) and contaminant levels are low. The main sources of wood biomass in Australia are harvesting residues from plantations such as Eucalypt (*Eucalyptus sp.*) and softwoods such as radiata pine (*Pinus radiata*) (Ghaffariyan and Dupuis, 2021). The utilisation of native forests is very much limited due to environmental issues in various states. In 2018, Victoria had 11 wood chips boilers - the large ones could accept wood chips with various particle size and moisture contents, however, the small boilers prefer to combust lower moisture content and more homogenous woodchip particle sizes (Boucher, 2018 and 2019). Other important criteria are calorific value (Ghaffariyan et al. 2013), particle size, rot/mold/contamination, amount of dirt, species (Boucher, 2018) and fraction of biomass components considered in Australian biomass recovery case studies (Ghaffariyan et al. 2014; Ghaffariyan et al. 2012; Ghaffariyan et al. 2011; Strandgard et al. 2020; Strandgard et al. 2022).

Major findings from international literature review are summarised in Table 1. This table provides an overview of location, biomass feedstock type and studied biomass quality characteristics by various scholars around the world.

Figure 5. Measuring moisture content of wood chips in Australia (Boucher, 2019)

Table 1. Summary of biomass characteristics studies for different regions and woody biomass feedstocks

Region/ country	Biomass feedstock	Species	Most important biomass attributes	Reference
America Brazil	barks	*Eucalypt* sp.	moisture/ash content, calorific value	Caraschi et al. 2019
Brazil	wood chips	*Eucalyptus hybrids E. urophylla* x E. *grandis*	moisture/ash content, bulk density, calorific value	Rebeiro et al. 2021
Canada	logs, chunks, firewood, hog fuel, green wood chips, dry shavings, solid and engineered wood, sawdust, construction and demolition waste, processing residue	N/A	moisture content/calorific value, biomass compositions, soil contamination, bulk density, foliage/bark content, ash, lignin, carbohydrate, extractive contents	Thiffualt et al. (2019) https://www.ontario.ca Marinescu (2013)
Canada	yield samples from biomass crop	*Miscanthus*, switchgrass, willow, and poplar (Species unknown)	gross calorific value, ash (%), ash elemental analysis	Mann (2012)
USA	wood chips from whole tree chipping	Willow (Species unknown)	moisture/energy content, size classification and ash content	Eisenbies et al. 2008 Eisenbies et al. 2016
USA	wood chips from slab wood from sawmills	*Eucalyptus grandis*	bulk density, particle size distribution, ash/volatile matter content, calorific value	Turn et al. 2005
USA	wood chips from whole tree chipping	Loblolly Pine	calorific value, moisture content, ash/bark/nutrient content	Cutshall (2012)

USA	wood chips	Sweetgum and pine (Species unknown)	ash content and particle size	Pradhan (2015)
USA	pellets	Pine and hardwood (species N/A)	density, ash/moisture content, calorific value	Sharma et al. (2017)
USA	wood chips	*Pinus taeda, Pinus elliottii*	calorific value, ash/moisture contents, carbon/nitrogen/ sulphur content	Saha et al. (2017)
Asia India	various parts including leaf, branches, bark and root	*Vachellia nilotica, Azadirachta indica,* other speciece	calorific value, fixed carbon content, moisture/ash content, bulk density	Lenka (2016) Chakradhari and Patel (2016)
Indone-sia	various parts of trees grinded	*Fordia splendidissima* and others fast-growing species	moisture content, calorific value, wood density	Yuliansyah et al. (2022)
Europe	wood chips from logging residues	N/A	moisture/ash content, calorific value	Moskalik and Gendek (2019)
Croatia	wood chips	*Abies alba, Picea abies, Fagus sylvatica*	moisture/ash content, calorific value, particle size	Vosic et al. (2021)
Ger-many	wood chips from logging residues	N/A	moisture content, ash quality and content, calorific value, particle size and shape.	Kuptz and Hartmann (2019)
Ger-many	wood chips from logging residues	N/A	bulk density and moisture content	Rackl et al. (2019)
Roma-nia	woody waste in pulp and paper mills	N/A	calorific value, moisture/ash content and elemental analysis (c, h, s, n, o)	Gavrilescu (2008)
Slova-kia	wood chunk and wood chips	*Picea abies, Betula pendula, Fagus Silvatica*	ash content and moisture content	Nosek et al. (2016)
Sweden	wood chips	Willow ((Species unknown)	moisture/ash content, net calorific value	SP Technical Research Institute of Sweden (2015)
Sweden	wood chips	*Picea abies*	moisture/dry matter content, calorific value	Wästerlund et al. 2017
Sweden	wood chips	*Pinus* spp., *Picea abies, Populus spp. Betula* spp	moisture/ash content, net calorific value, particle size	Anerud et al. 2020
Oce-ania Aus-tralia	wood chips, slash bundles	*Eucalypt* sp., *Pinus* sp.	moisture content, calorific value, particle size, rot/mold/ contamination, amount of dirt, species, biomass fraction	Boucher, 2018; Ghaffariyan et al. 2012; Ghaffariyan et al. 2011

Conclusions

Overall understating from international studies (Table 1) is that the key biomass characteristic which was consistently measured in almost all research projects is moisture content of the biomass. Ash content and calorific value are classified as second place in terms of frequency in the biomass studies. Attributes such as bulk density, contamination, particle shape and nutrient (elemental) content had a lower rate of mention in the literature.

Thiffault et al. (2019) concluded that woody residues (especially sawdust) have high levels of contaminant and aluminium can have negative impacts on the quality of wood pellets as products. They suggested considering higher quality control practices to ensure the woody residues meet the required specifications of the end users. From wood chip size perspective, research finding showed that increased target chip size can increase the competitiveness of forest biomass through decreased production costs and reduced storage costs. It can also ensure higher and more consistent fuel quality (Anerud et al. 2020).

From application perspective, German scholars such as Kuptz and Hartmann (2014) suggested that wood chip quality is a function of their usage type. For small furnace systems (<1 MW) the quality of wood chips is critical, however, for application in large furnace systems (>1 MW) the quality is less important and a secondary issue. Increased wood chips quality for large furnace systems only adds unnecessary costs that should be avoided.

Natural Resources Canada pointed out that reducing moisture content and fine materials in biomass wood chips can help to minimise some risks including microbiological activities, composting and self-ignition. Thus, covering the low moisture wood chips piles is suggested where possible (Natural Resources Canada https://www.nrcan.gc.ca). Increasing chip size during chipping operation can reduce production and storage costs; that can result in enhanced competitiveness of forest biomass (Anerud et al. 2020). Coverage of wood chips can generally increase the annual utilisation of trucks and chippers which can reduce operating costs (Anerud et al. 2021).

Biomass characteristics can change over the life of trees. Thus Mann (2012) suggested monitoring the changes of fuel characteristics over the life of the plantation to understand which species are the most suitable for bioenergy production.

Different measurement methods yield different levels of accuracy. In addition to current laboratory methods to measure biomass characteristics (calorific value, moisture/ash content etc.) Saha et al. (2017) and Fridh (2017) suggested using NIR spectroscopy, X-ray and electric capacitance and magnetic resonance which provide low error of measurement with quicker and easier application.

Future research projects can fill the knowledge gap by studying the biomass quality characteristics from biomass feedstocks and species that have not been yet investigated. In Oceania, the biomass quality of some commercial species (in different types of biomass feedstocks) could be further investigated. The suggested species include *Corymbia maculate*, *Pinus radiata, Pinus elliottii, Pinus caribaea, Pinus taeda, Araucaria cunninghamii, Eucalyptus globolus, Eucalyptus nitens, Eucalyptus dunnii* and *Eucalyp-*

tus cloeziana. In Asia, there is a gap of knowledge on quality characteristics of main species (in various types of biomass feedstocks) such as Chinese fir (*Cunninghamia lanceolata*) [in China], sugi (*Cryptomeria japonica*), hinoki (*Chamaecyparis obtusa*), pines (*Pinus spp.*) and Japanese larch (*Larix leptolepis*) [in Japan], Rubber (*Hevea brasiliensis*), teak (*Tectona spp.*), pines and *Acacia mangium* [in Indonesia and Thailand]. There is also a knowledge gap in Africa in the exploration of a variety of biomass types and commercial woody species including pine, eucalyptus and wattle (*Acacia spp*.). European forest biomass quality studies have been mainly published in Sweden and Germany. Future research could be carried out in some Central and Eastern countries to meet with the current demands of bioenergy. South America is another region that could benefit from further research projects on forest biomass quality assessment with various commercial species including pines (*Pinus spp.*), acacia (*Acacia spp*.) and teak (*Tectona spp*.) under various biomass feedstocks (wood chips, bundles etc.). Most of the current knowledge covers the application of woody biomass for bioenergy generation such as heat/power. Future studies around the world could evaluate the quality of biomass for other applications such as biofuels and bioproducts.

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