Evaluating the Competition of Lignocellulose Raw Materials for their Use in Particleboard Production, Thermal Energy Recovery, and Pulp- and Papermaking

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There is increasing competition for raw materials between particleboard production, thermal energy recovery, and pulp- and papermaking. According to different scenarios, the consumption of lignocellulosic raw materials is increasing, which means that the competition is increasing. The primary production of lignocellulosic raw material in some regions may therefore reach the limit of sustainability; *i.e.,* the lignocellulosic raw material must be used more efficiently to reduce the risk of a shortage. The physical and chemical properties of the lignocellulosic raw material of selected species have therefore been surveyed, and the raw material properties that are important for each of the three competitors have been defined. The aim of the study is to characterise the lignocellulosic raw materials according to the three competing users and to show whether they are high or low in competition. As methods, a relative ranking of the species regarding their raw material properties and regarding the requirements of the competitors as well as cluster analysis were chosen. The results show that the most favourable raw materials are from coniferous species, while monocotyledon species show an opposite trend.

Keywords: Wood using industry; Properties of raw material; Requirements for raw materials; Expression of competition

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INTRODUCTION

The consumption of wood in Europe is increasing and might become, according to scenarios published in the Forest Sector Outlook Study, as large as Europe's combined forest growth increment (Jonsson *et al.* 2011). For industries using similar lignocellulosic raw materials such as the particleboard industry, the thermal energy recovery industry, and the pulp and paper industry, increasing consumption leads to increasing competition for raw materials. Promotion of wood as renewable energy and preservation of biological diversity, which will require forest land that could be used for timber production (United Nations 2011), might even tighten this effect.

Recently, attempts have been made to reduce the use of wood in particleboards by introducing other materials, such as polymers, starch-based granulates, and monocotyledons, which are sometimes available in the form of agricultural residues (Kharazipour *et al.* 2011; BASF 2013; ELKA 2013; Pfleiderer 2013). The Fraunhofer Institute, for example, tested agricultural plants and residues for particleboards with densities in the range of 200 to 550 kg/m^3 (WKI 2013), as monocotyledons not only can be a substitute for wood but also reduce the weight of the boards (Boquillon *et al.* 2004). Monocotyledon species are advantageous for low-density boards, as a basic requirement in particleboard production is a compaction rate of at least 1.3 of the raw material to achieve acceptable values for the modulus of rupture and the modulus of elasticity (Dias *et al.* 2005). These developments might lead towards specialised wood-based panels for certain applications and towards multi-component and multi-layered materials (Shalbafan *et al.* 2012). Nevertheless, not every raw material can be used for particleboard production, as there are technical restrictions related to the material properties. For particle and fibreboards as well as OSB (oriented strand board) there is a relationship between the properties of the raw material and the board with regard to density, stiffness, strength, dimensional stability, internal bond strength, surface strength, and appearance (Lundqvist and Gardiner 2011). Properties such as dimensional stability can be handled with water repellent treatments such as waxing during the production process (Xu *et al.* 2009) and avoiding raw materials with high swelling and shrinking rates. The product design and the size of particles can also influence the dimensional stability of the boards (Han *et al.* 1998). A problem for particleboards made of wood is that a decrease in density generally leads to a decrease in bending strength (Hacke *et al.* 2001) if no special design is chosen, as the stiffness and strength of the wood are directly correlated to the density. Dimensional stability, internal bond strength, surface strength, and colour depend not only on the lignocellulosic raw material itself, but on the combination of materials such as adhesives or additives used. A challenging feature is the contact area between particle and adhesive, as well as the impact of the environmental conditions on the final product.

For thermal energy recovery, important material properties are the moisture content, the calorific value, the proportions of fixed carbon and volatiles, the ash or residue content, and the alkali metal content. As moisture reduces the calorific value in proportion to the moisture content, herbaceous plant species with a low moisture content are favoured for thermal energy recovery (McKendry 2002). At a moisture content of 15%, the calorific values per mass (H_u) of straw and wood are about 3.5 and 4 MWh/Mg, respectively; *i.e.*, the difference is relatively small (Oechsner 2009). For the wood species common in Europe, the calorific value is in the range of 4 to 5 MWh/Mg (Biedermann and Obernberger 2005). The differences between straw and wood regarding ash content are greater, with 6% and 0.4% of the mass, and the ash softening points are 940 to 980 °C and 1220 to 1470 °C, respectively. All these characteristics have to be considered when choosing lignocellulosic raw materials for thermal energy recovery (Oechsner 2009).

Both the ash content and the ash melting point are strongly influenced by the chemical composition. The melting point, for example, decreases with increasing proportion of potassium and sodium, while increasing proportions of calcium, magnesium, and aluminium lead to an increase in melting point (Biedermann and Obernberger 2005; Oechsner 2009). Among the European wood species, the softwood species have higher calorific values and higher ash melting points, but also higher ash contents than the hardwood species (Schreiner 2009). This means that the chemical composition of the lignocellulose raw material is important, as melting points that are too low, slagging, deposit formation, and corrosion cause problems in firing systems. More economically than technically interesting is the calorific value *per* volume, as this value affects transaction costs. The calorific value per volume can vary between 2.1 MWh/m^3 for *Carpinus betulus* (hornbeam) to 0.14 MWh/m^3 for *Phalaris arundinacea* (reed canary grass), considering the bulk density of the grass (Biedermann and Obernberger 2005). In general, all economically favourable lignocellulosic raw materials are currently used for thermal energy recovery, but the density and moisture content have a strong impact on the transaction costs (Hamelinck *et al.* 2005; Altman *et al.* 2007; Möller and Nielsen 2007).

For the pulp and paper industry, the dimensions, slenderness ratio, flexibility coefficient, and Runkel ratio of the fibres are important (Ververis *et al.* 2004). In particular, when hardwood fibres are used for paper, the length-to-diameter ratio is important, as the fibres are generally shorter than softwood fibres (Horn 1978). The strong influence of fibre length and cell wall thickness on the mechanical properties of paper has been shown in many tests (Horn 1978; Horn and Setterholm 1990), with a direct proportional relationship between tensile strength and cellulose content (Madakadze *et al.* 1999). The coarseness of the fibres is estimated by the fibre width and wall thickness. For the stiffness, in addition to the width, wall thickness, and micro-fibril angle, the method of processing the fibres is important. Fibres for paper should generally be long (better fracture properties and wet strength of the paper), but not too long (negative influence on formation), thin-walled (better surface and optical properties), and flexible (positive for strength properties but negative for bulk) (Lundqvist and Gardiner 2011). Fibres with a long length, high slenderness ratio (> 33), and low Runkel ratio (< 1) are said to be the best for pulp- and papermaking (Xu *et al.* 2006). However, according to other sources, the slenderness ratio of the fibrous material should not be less than 70 for quality pulp and paper production (Shakhes *et al.* 2011), and the Runkel ratio should not exceed 1.25 (Antwi-Boasiako and Ayimasu 2012). The flexibility coefficient, which is an expression for the collapse of fibres resulting in surface contact and fibre-to-fibre bonding, is also important. Fibres with a flexibility coefficient greater than 75 collapse totally, leading to good surface contact and fibre-to-fibre bonding. When the flexibility coefficient is between 50 and 75, fibres collapse partly, forming elliptical cross-sections, which also lead to good surface contact and fibre-to-fibre bonding (Antwi-Boasiako and Ayimasu 2012).

The objective of this study is to show the competition for different species by estimating the suitability of different lignocellulosic raw materials for particleboard production, thermal energy recovery, and pulp- and papermaking, on the basis of their physical and chemical properties.

EXPERIMENTAL

Literature regarding the raw material properties of 21 species was compared. The species are either native species in Sweden or species which, due their high biomass production, might be interesting for cultivation in Sweden. These include five coniferous species, 12 broad-leaved species, and four monocotyledon species. The selected species and the literature data regarding their raw material properties are presented in Table 1. The motivation for selecting these raw material properties was as follows:

Particleboard production: For this study, it is suggested that the average density of the boards is in the range of 500 to 700 kg/m^3 and that water-based adhesives such as the conventional melamine urea formaldehyde (MUF) adhesives are used. This enables a ranking regarding the density of the species by taking an overall suggested average density for the boards of 600 kg/m^3 and a compression ratio of 1.3. The suggested density is comparable to the weighted mean density over all species included in this study. It is further suggested that the surface properties of the raw material can be combined under wettability by water. The pH value is also important, as it can have an impact on the curing of the adhesive. The amounts of fibres (tracheids) and the density are also important because they affect the mechanical properties of the raw material.

Thermal energy recovery: The calorific value *per* volume (MWh/m^3) is preferred to the value *per* mass (MWh/Mg), as the differences between species are larger and economic aspects such as logistic costs are indirectly included. This is valid also for the ash content and the ash melting point, which is affected by the chemical composition and has an impact on slagging, deposit formation, and corrosion.

Pulp- and papermaking: The slenderness, flexibility coefficient, and Runkel ratio of the fibres were calculated, as these are fundamental characteristics of the raw material for the pulp- and papermaking industry. The amount of fibres (tracheids) is included, as this value indirectly affects economic aspects such as the yield of fibres *per* volume or logistic costs.

Table 1. Literature Data Regarding the Raw Material Properties for the Different Species Used in This Study

Species	Runkel ratio -	Slenderness ratio -	Flexibility coefficient -	Amount of fibres (%)	Density (Kg/m^3)	Contact angle (Degree)	pH-value -	Calorific value (MWh/m^3)	Ash content (%)	Melting point (°C)
Picea abies	0.25	97	80	95	470	59	4.7	2.6	0.55	1260
Pinus sylvestris	0.28	110	78	90	490	69	5.1	2.9	0.35	1234
Abies alba	0.26	137	79	93	450	60	5.8	2.1	0.76	1229[b]
Larix spp.	0.26	97	80	91	590	66	4.8	2.9	0.25	1229[b]
Pseudotsuga menziesii	0.28	108	78	93	510	77	4.4	2.4	0.85	1229[b]
Betula spp.	0.41	54	71	65	650	66	4.8	3.3	0.35	1223[b]
Alnus glutinosa	0.29	85	77	58	550	70	4.7	3.2	0.53	1223[b]
Populus spp.	0.29	80	88	62	450	71	6.3	2.1	0.55	1162
Populus tremula	0.22	48	80	61	450	74	5.8	2.6	0.30	1223[b]
P. tremula x P. tremuloides	0.22	37	80	61	379	71	5.8	1.7	1.10	1215
Salix spp.	0.25	39	87	31	341	69[b]	5.0	1.7	0.45	1282
Fraxinus excelsior	0.32	67	80	62	720	68	5.8	3.3	0.52	1223[b]
Fagus sylvatica	0.82	67	47	51	680	67	5.5	1.9	0.75	1210
Quercus spp.	0.97	114	50	51	690	76	3.9	3.2	0.45	1223[b]
Tilia spp.	0.84	49	54	72	530	69[b]	4.9	1.1	1.00	1223[b]
Acer platanoides	0.22	45	82	72	490	69	5.1	2.3	0.37	1223[b]
Paulownia spp.	0.24	35	81	60	294	66	5.7	1.3	0.80	1161
Miscanthus spp.	1.39	70	42	46	240[a]	112	7.6	1.2	2.70	994
Phalaris arundinacea	0.78	56	56	45	191[a]	112[b]	7.6	0.9	6.80	1248
Triticum spp. (straw)	2.30	53	30	59	114[a]	112[b]	7.6	0.5	5.85	980
Brassica napus (straw)	0.85	52	54	61	145[a]	112[b]	7.6	0.6	5.50	977

The references for the different species are given in Table 2. Density is measured at a moisture content (based on dry weight) of 15%

[a] Bulk density

[b] Estimated values by means of comparable species because no literature data could be found

Table 2. References for the Data Given in Table 1

Picea abies	(Kramer *et al.* 1988; Hasler *et al.* 1994; Boehme and Hora 1996; Mantanis and Young 1997; Nurmi 1997; Bergh *et al.* 1999; Nussbaum 1999; de Meijer *et al.* 2000; Lässig and Močalov 2000; Balode *et al.* 2002; Schulze *et al.* 2002; Matthews and Mackie 2006; Rutz *et al.* 2006; Kaltschmitt *et al.* 2009; Sernek *et al.* 2010; Günther *et al.* 2012; Karl 2012; Navi and Sandberg 2012; EngineeringToolBox 2013)
Pinus sylvestris	(Bray 1963; Kramer *et al.* 1988; Hasler *et al.* 1994; Wilén *et al.* 1996; Nurmi 1997; Nussbaum 1999; Lässig and Močalov 2000; Schulze *et al.* 2002; Xiao *et al.* 2003; Mohammed-Ziegler *et al.* 2004; Kaltschmitt *et al.* 2009; Karl 2012; Navi and Sandberg 2012; Sedighi *et al.* 2012)
Abies alba	(Bray 1963; Kramer *et al.* 1988; Becker 1989; de Meijer *et al.* 2000; Lässig and Močalov 2000; Schulze *et al.* 2002; Macias *et al.* 2006; Matthews and Mackie 2006; Wagenführ 2007; Kaltschmitt *et al.* 2009; Karl 2012; Navi and Sandberg 2012)
Larix spp.	(Zavitkovski and Strong 1984; Kramer *et al.* 1988; Boehme and Hora 1996; Lässig and Močalov 2000; Peeters *et al.* 2004; Fior *et al.* 2005; Matthews and Mackie 2006; Wagenführ 2007; Bollschweiler *et al.* 2008; Lingua *et al.* 2008; Kaltschmitt *et al.* 2009; Luostarinen 2011; Karl 2012; EngineeringToolBox 2013)
Pseudotsuga menziesii	(Grier and Logan 1977; Boehme and Hora 1996; Mantanis and Young 1997; Zhang and Hebda 2004; Matthews and Mackie 2006; Kohnle 2007; Wagenführ 2007; Kaltschmitt *et al.* 2009; Sernek *et al.* 2010; Karl 2012; EngineeringToolBox 2013; Hermann and Lavender 2013)
Betula spp.	(Bray 1963; Kramer *et al.* 1988; Paavilainen and Torgilsson 1994; Syrjanen *et al.* 1994; Nurmi 1997; Lässig and Močalov 2000; Schulze *et al.* 2002; Stener and Hedenberg 2003; Matthews and Mackie 2006; Wagenführ 2007; Kaltschmitt *et al.* 2009; Sernek *et al.* 2010; Günther *et al.* 2012; Karl 2012; Viöl *et al.* 2012; EngineeringToolBox 2013; PaperonWeb 2013)
Alnus glutinosa	(Kramer *et al.* 1988; Nurmi 1997; Johansson 2000; Schulze *et al.* 2002; Mohammed-Ziegler *et al.* 2004; Wagenführ 2007; Kaltschmitt *et al.* 2009; Kiaei and Samariha 2011; Karl 2012)
Populus spp.	(Boehme and Hora 1996; Diamantidis and Koukios 2000; Barsoum 2001; Deiller *et al.* 2001; Benetka *et al.* 2002; Laureysens *et al.* 2003; Helle and Schleser 2004; Matthews and Mackie 2006; Rutz *et al.* 2006; Wagenführ 2007; Trnka *et al.* 2008; Kaltschmitt *et al.* 2009; Petrič *et al.* 2009; Sernek *et al.* 2010; Ráhel' *et al.* 2011; Karampinis *et al.* 2012; Karl 2012; Navi and Sandberg 2012; PaperonWeb 2013)
Populus tremula	(Syrjanen *et al.* 1994; Mantanis and Young 1997; Nurmi 1997; Johansson 1999; Liesebach *et al.* 1999; Diamantidis and Koukios 2000; Lässig and Močalov 2000; Schulze *et al.* 2002; Latva-Karjanmaa *et al.* 2003; Ellis and Coppins 2007; Wagenführ 2007; Enayati *et al.* 2009; Kaltschmitt *et al.* 2009; Karl 2012; Sansonetti *et al.* 2012 ; EngineeringToolBox 2013)

Populus deltoides	(Ilstedt and Gullberg 1993; Boehme and Hora 1996; Liesebach *et al.* 1999; Bungart *et al.* 2000; Diamantidis and Koukios 2000; Woods 2008; Kaltschmitt *et al.* 2009; Petrič *et al.* 2009; Christersson 2010; Pande and Dhiman 2010; Sannigrahi *et al.* 2010; Sernek *et al.* 2010; Ráhel' *et al.* 2011; Huda *et al.* 2012; Karl 2012)
Salix spp.	(Wilén *et al.* 1996; Labrecque *et al.* 1997; Bungart *et al.* 2000; Diamantidis and Koukios 2000; Lässig and Močalov 2000; Barsoum 2001; Deiller *et al.* 2001; Rutz *et al.* 2006; Wagenführ 2007; Wilkinson *et al.* 2007; Bridgeman *et al.* 2008; Woods 2008; Kaltschmitt *et al.* 2009; Kord and Kord 2011; Buček *et al.* 2012; Karampinis *et al.* 2012; Karl 2012; EngineeringToolBox 2013)
Fraxinus excelsior	(Bray 1963; Kramer *et al.* 1988; Neirynck *et al.* 2000; Deiller *et al.* 2001; Mohammed-Ziegler *et al.* 2004; Ritter *et al.* 2005; Matthews and Mackie 2006; Petritan *et al.* 2007; Wagenführ 2007; Kaltschmitt *et al.* 2009; Vitasse *et al.* 2009; Kiaei and Samariha 2011; Karl 2012)
Fagus sylvatica	(Bray 1963; Kramer *et al.* 1988; Hasler *et al.* 1994; Boehme and Hora 1996; Neirynck *et al.* 2000; Helle and Schleser 2004; Ritter *et al.* 2005; Petritan *et al.* 2007; Wagenführ 2007; Kaltschmitt *et al.* 2009; Vitasse *et al.* 2009; Karl 2012; Navi and Sandberg 2012; EngineeringToolBox 2013; PaperonWeb 2013)
Quercus spp.	(Kramer *et al.* 1988; Boehme and Hora 1996; Neirynck *et al.* 2000; Deiller *et al.* 2001; Helle and Schleser 2004; Mohammed-Ziegler *et al.* 2004; Ritter *et al.* 2005; Matthews and Mackie 2006; Wagenführ 2007; Kaltschmitt *et al.* 2009; Vitasse *et al.* 2009; Karl 2012; Navi and Sandberg 2012)
Tilia spp.	(Kirlum 1995; Mantanis and Young 1997; Neirynck *et al.* 2000; Wagenführ 2007; Kaltschmitt *et al.* 2009; Radoglou *et al.* 2009; Karl 2012; Kubrichtová and Kučerová 2012; EngineeringToolBox 2013)
Acer platanoides	(Kramer *et al.* 1988; Neirynck *et al.* 2000; Deiller *et al.* 2001; Mohammed-Ziegler *et al.* 2004; Petritan *et al.* 2007; Wagenführ 2007; Kaltschmitt *et al.* 2009; Vitasse *et al.* 2009; Günther *et al.* 2012; Karl 2012; EngineeringToolBox 2013)
Paulownia spp.	(Zhu *et al.* 1986; Cokesa *et al.* 2004; Woods 2008; Ashori and Nourbakhsh 2009; Kaltschmitt *et al.* 2009; Jaić *et al.* 2010; Rafat 2011; TGG 2011; Karampinis *et al.* 2012; López *et al.* 2012; Salari *et al.* 2012; Institute_LLC 2013)
Miscanthus spp.	(Hasler *et al.* 1994; Wilén *et al.* 1996; Diamantidis and Koukios 2000; Clifton-Brown *et al.* 2001; Han 2001; Jones and Walsh 2001; Visser and Pignatelli 2001; Wiśniewska *et al.* 2003; Clifton-Brown *et al.* 2004; Ververis *et al.* 2004; Liu *et al.* 2006; Heaton *et al.* 2008; McKervey *et al.* 2008; Kaltschmitt *et al.* 2009; Halvarsson *et al.* 2010; Hodgson *et al.* 2011; Nishiwaki *et al.* 2011; Karampinis *et al.* 2012; Karl 2012; Junjun and Chuanhui 2013)

Phalaris arundinacea	(Paavilainen and Torgilsson 1994; Wilén *et al.* 1996; Pahkala and Pihala 2000; Han 2001; Finell 2003; Wiśniewska *et al.* 2003; Liu *et al.* 2006; Bridgeman *et al.* 2008; Komulainen *et al.* 2008; Casler *et al.* 2009; Halvarsson *et al.* 2010; Carlsson 2012; Greenhalf *et al.* 2012; Jansone *et al.* 2012; Strašil 2012; Junjun and Chuanhui 2013; USDA 2013)
Triticum spp. (straw)	(Hasler *et al.* 1994; Wilén *et al.* 1996; Porter and Gawith 1999; Diamantidis and Koukios 2000; Han 2001; Finell 2003; Wiśniewska *et al.* 2003; Kim and Dale 2004; Liu *et al.* 2006; Rutz *et al.* 2006; Tuck *et al.* 2006; Bridgeman *et al.* 2008; Lam *et al.* 2008; Enayati *et al.* 2009; Kaķītis *et al.* 2009; Kaltschmitt *et al.* 2009; Halvarsson *et al.* 2010; Greenhalf *et al.* 2012; Karl 2012; Junjun and Chuanhui 2013; Teagasc 2013)
Brassica napus (straw)	(Karaosmanoglu *et al.* 1999; Diamantidis and Koukios 2000; Han 2001; Wiśniewska *et al.* 2003; Liu *et al.* 2006; Tuck *et al.* 2006; Enayati *et al.* 2009; Kaltschmitt *et al.* 2009; Leticia *et al.* 2009; Halvarsson *et al.* 2010; Greenhalf *et al.* 2012; Chico-Santamarta *et al.* 2013; Junjun and Chuanhui 2013; Teagasc 2013)

The species are compared regarding their suitability for the three competitors based on their raw material properties, and the pressure of competition for the raw material of each species can then be deduced. For this purpose, the study is split into two parts: (1) The species are compared on the basis of literature data after they have been normalised to values between 0 and 1. This "relative method" (RM) includes selected limits or advantages regarding the raw material requirements of the competitors presented in Table 3. (2) A hierarchical cluster analysis (CA) in SPSS was carried out, also with normalised data in the range of 0 to 1. Ward's method with squared Euclidian distances as intervals was chosen for the CA. The monocotyledon species were excluded from the CA, as their raw material properties differed too much. The RM gives an expression for the suitability of the species for the three competitors, while the CA shows how much the different species differ from each other regarding their raw material properties. The CA is advantageous in two ways: Firstly, it can be seen as a type of validation as the species with similar raw materials should show also some agreement in the RM; secondly, large distances between the species create "groups", which can be illustrated as a dendrogram. Combination of the RM and the CA shows the pressure of competition on the different species from the three competitors.

Table 3. Criteria for the Raw Material Properties Showing Their Suitability for Particleboard Production, Thermal Energy Recovery, and Pulp- and Papermaking, Including the Limitations or Advantages Given in the Literature

	Criterion	**Unit**	**Explained by**	**Limitations/ Advantages**
Particleboard production	Density	g/m^3	$\frac{\text{Mass at MC=15\%}}{\text{Volume}}$	X ~ weighted average
	Wettability	°	Water drop contact angle	X < 70°
	pH-value	-	pH	X > average
	Amount of fibres	%	Percentage of fibres	X > average
Thermal energy recovery	Calorific value	MWh/m^3	$\frac{\text{Mass at MC=15\%}}{\text{Volume}}$	X < average
	Ash content	%	As a percentage of mass at MC=15%	X < average
	Ash melting point	°C	chemical composition (Ca+Mg : K+Na)	X < average
Pulp- and papermaking	Slenderness-ratio	-	$\frac{\text{Length of fibre}}{\text{Diameter of fibre}}$	X > 70
	Flexibility coefficient	-	$\frac{\text{Lumen diameter}}{\text{Diameter of fibre}}$	X > 70
	Runkel-ratio	-	$\frac{\text{2 * cell wall thickness}}{\text{Lumen diameter of fibre}}$	X < 1.25
	Amount of fibres	%	Percentage of fibres	X > average

MC, moisture content; X, wild-card for the individual value

RESULTS AND DISCUSSION

The species are compared regarding their suitability for the three competitors using the literature data normalised to values between 0 and 1. The results of this relative method (RM) are presented in Fig. 1 as a 3D graph, which is split into a 2D graph in Fig. 2, showing only the two competitors faced by particleboard production and making it easier to evaluate the competition for the different raw materials.

The results illustrate the difficult situation for the three competitors in two ways: (1) It seems that the same type of raw material is considered the best for all three competitors (Fig. 1), and (2) the differences between the raw materials, particularly the wood species, are quite small (Fig. 1 and Fig. 2). This can be supported by the dendrogram of the cluster analysis (CA) presented in Fig. 3 which shows three clusters, taking the greatest distances as borders between the groups. The softwood species and the hardwood species with medium to higher densities show the highest suitability, which can further been interpreted as higher competition. The wood species with the lowest suitability are lime (*Tilia* spp.), beech (*Fagus sylvatica*), and the fast-growing species, which also have a lower density. The lowest values, very different form the wood species, are associated with the monocotyledon species, which are not shown in Fig. 3, as they differ too much from the wood species.

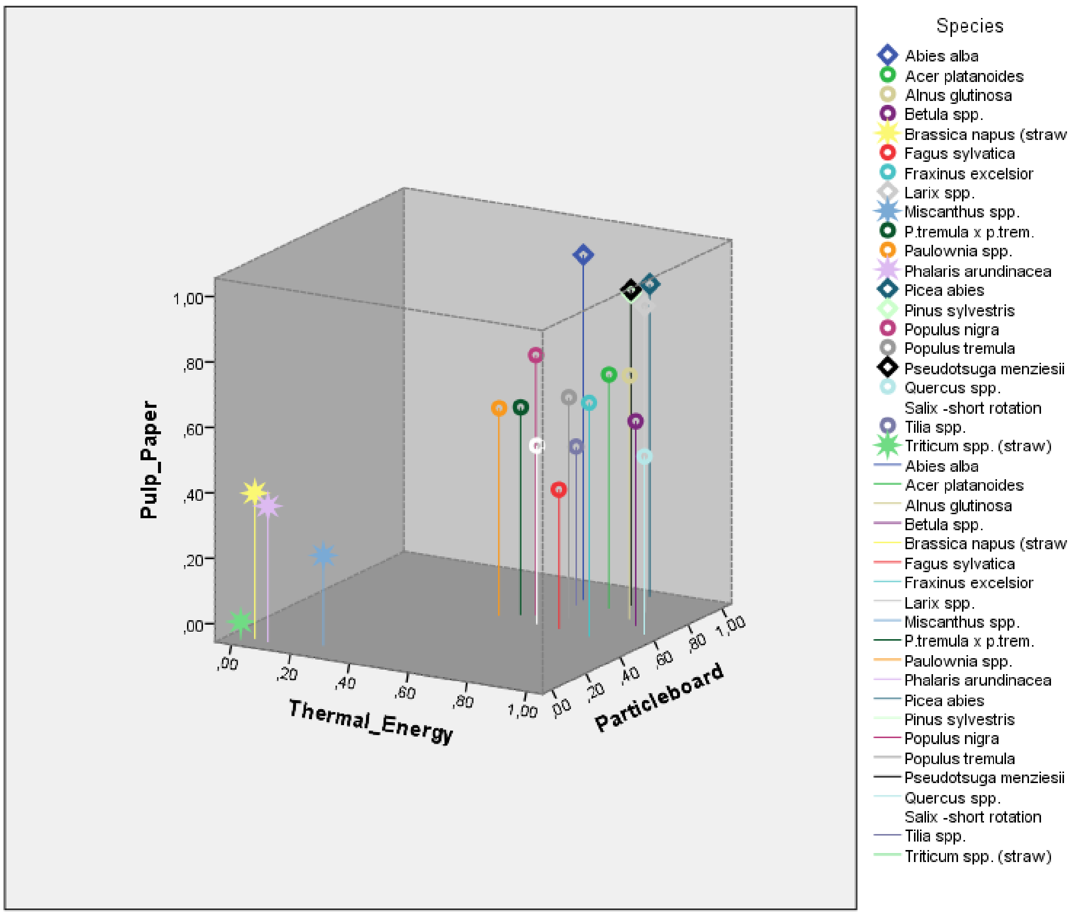

Fig. 1. Suitability of raw materials for particleboard production (Particleboard), thermal energy recovery (Thermal_Energy), and pulp- and papermaking (Pulp_Paper)

If the particleboard producing industry is considered as an industry seeking raw material with low competition, a 2-D figure can be drawn, showing the suitability for thermal energy recovery and pulp- and papermaking only (Fig. 2).

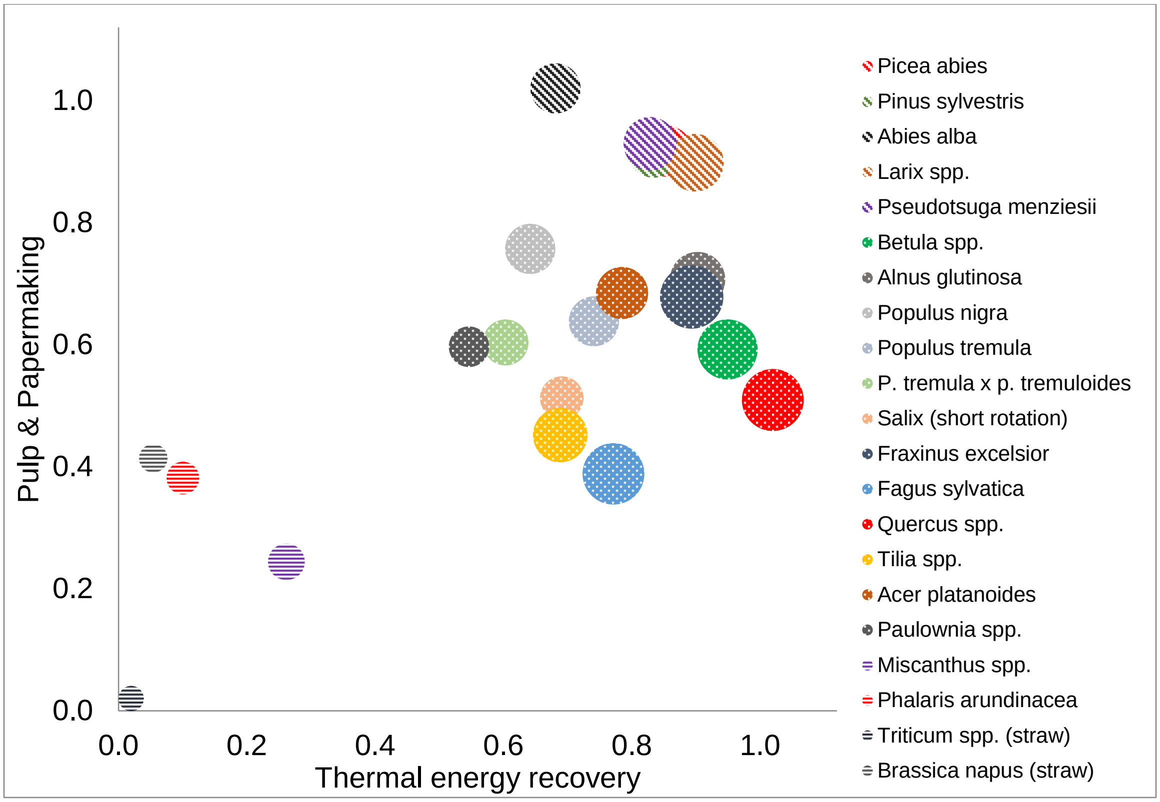

Fig. 2. Suitability of raw material for thermal energy recovery (Thermal energy recovery) and pulp- and papermaking (Pulp & Papermaking). The size of the discs indicates the density of the raw material

The results presented in Fig. 2 illustrate the difficult situation for the particleboard producing industry. The softwood species and the hardwood species with medium and higher densities show a high suitability, which means greater competition. The wooden species with the lowest suitability for thermal energy recovery and for pulp- and papermaking are the fast-growing species with low densities, such as paulownia (*Paulownia* spp.), willow (*Salix* spp.), and hybrid aspen (*Populus tremula x P. tremuloides*). The lowest suitability for thermal energy recovery and pulp- and papermaking, far from the wood species, is associated with the monocotyledon species, which would make them a source with low competition for particleboard production. Unfortunately, the group associated with the monocotyledon species also shows the lowest suitability for particleboard production (Fig. 1).

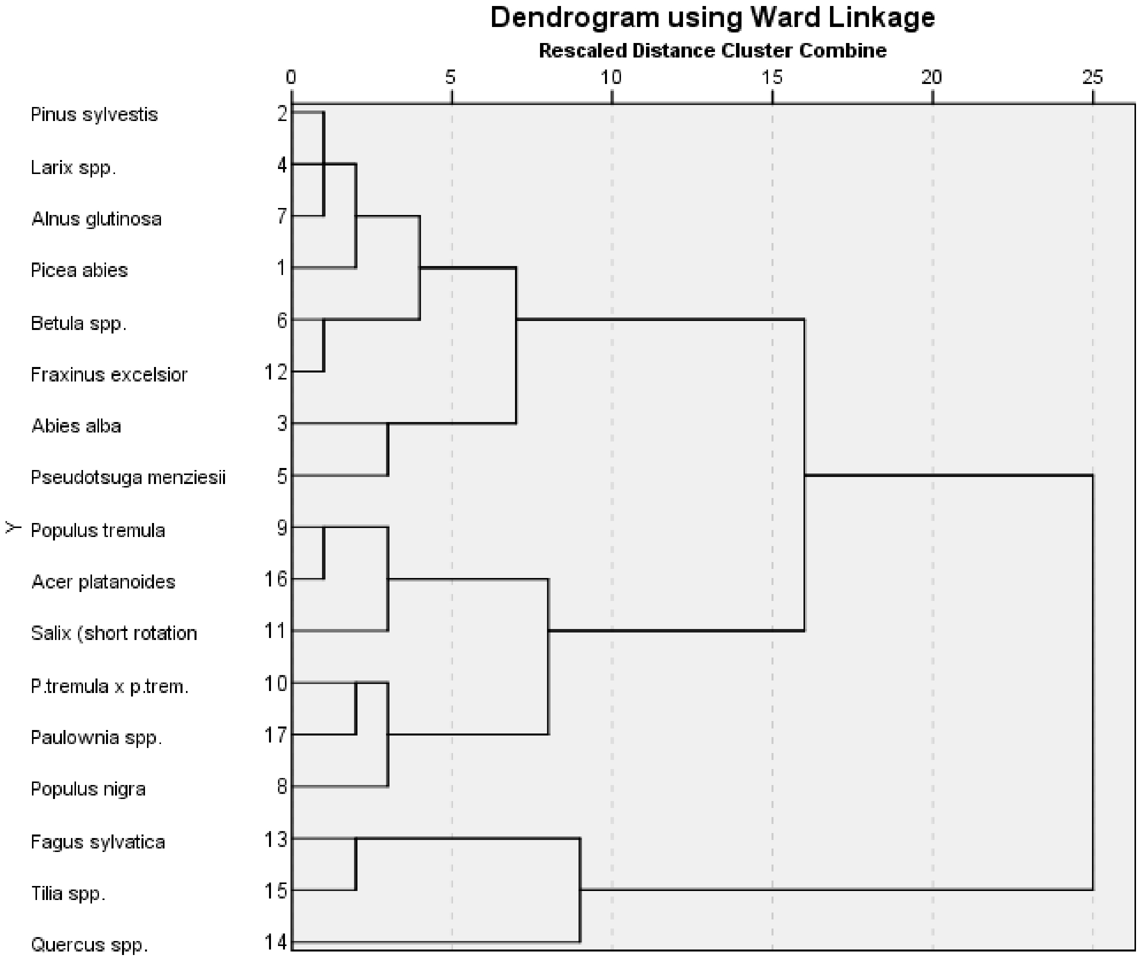

Fig. 3. Dendrogram of cluster analysis of the wooden species regarding the wood properties presented in Table 1 using the Ward linkage method. The species were analysed regarding their raw material properties such as fibre properties, density, and calorific value. Species which show a low distance from each other can be grouped together. This dendrogram shows three main clusters.

The dendrogram of the CA (Fig. 3) provides information about the similarity of the different wood species. If the three main clusters of Fig. 3 are compared with the RM (Fig. 1), it can be suggested that the first group from Scots pine (*Pinus sylvestris*) to Douglas fir (*Pseudotsuga menziesii*) has the greatest suitability, which can be interpreted as a proxy for greatest competition. This group includes all the coniferous species considered in this study and also alder (*Alnus glutinosa*), birch (*Betula spp.*), and ash (*Fraxinus excelsior*). The group from aspen (*Populus tremula*) to poplar (*Populus nigra*) in Fig. 3 show less favourable raw material properties for all three competitors. The group of beech (*Fagus sylvatica*), lime (*Tilia* spp.), and oak (*Quercus* spp.) are at the greatest distance and are the species with the raw material properties which are least favourable for pulp- and papermaking.

This ranking is relative, in the sense that the results depend on the species or data taken into account. In addition, the thermal energy recovery was defined by raw material properties like the other two competitors, but in general all the species listed can be used for energy production. Fast-growing species from plantations with short rotation times, for example, are nowadays used for energy, *i.e.*, the species which, according to this study, show a lower competition and less suitability for thermal energy recovery.

The species high up in the dendrogram have the highest competition, while the species lower down face less competition from the three competitors. The greatest difference in raw material properties may explain why the particleboard production is trying to use monocotyledon species as raw material. Besides the effect of lighter boards, it seems also be an advantage to use a raw material of lower competition. The combination of the two methods can be interpreted as follows:

Highest competition: species that show values of at least 90% for one competitor and at least 70% for the other competitor in the "relative" method (RM). In the dendrogram of the cluster analysis (CA), these are the species from *Pinus sylvestris* to *Pseudotsuga menziesii*.

Medium competition: species that show values between 50% and 80% in the RM. In the dendrogram of the CA, these are the species from *Populus tremula* to *Populus nigra*.

Low competition: species that show at least one value lower than 50% but more than 30% for all values in the RM. In the dendrogram of the CA, these are the species from *Fagus sylvatica* to *Quercus* spp.

Lowest competition: species which show values lower than 30% for at least one competitor in the RM. These are the monocotyledon species, which were not included in the cluster analysis as their raw material properties differ too much from those of the wood species.

CONCLUSIONS

1. It was possible to use the raw material properties of different species in combination with the requirements of the industries as a basis for the calculation of relative suitability for different potential applications.
2. The combination of the relative method and the cluster analysis makes it possible to express the competition between particleboard production, thermal energy recovery, and pulp and paper-making for their raw material.
3. Coniferous species show the highest competition, being the most suitable for all three areas of application. Deciduous species with lower densities, such as poplar, aspen, and paulownia, seem to have much less competition and seem to be to the same extent suitable for both particleboard production and thermal energy recovery, while the monocotyledons were generally excluded, as their raw material properties differ too much from those of wood species.

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