# Ash Content of Wood Pellets Made from Small Scots Pine (*Pinus sylvestris*) Trees with Bark

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**Abstract**

This article presents the influence of stem size of thinned trees on the amount of ash in wood pellets. If wood can be used with bark, material efficiency of pellet production increases. The article initiates discussion related to typical questions in the pellet industry, such as the applicability of pine with bark to produce wood pellets that meet European Union standards (EN 14961-2:2011 A1). The article shows that unbarked Finnish scots pine trees (*Pinus sylvestris* L.) over 11.16 m in length can be used as raw material without quality loss or ash content out of the range of the wood pellet standard. Three different diameter groups of pine were tested, and none exceeded the ash content limit (0.7%) set in the EN 14961-2:2011 standard.

Low ash content of wood material makes bark-free sawdust and shavings a superior raw material for high-quality wood pellets. Widening of the raw material base for wood pellets has required studies of roundwood as a raw material. Generally, the use of roundwood has increased the costs of pellet production dramatically (Van Loo and Koppejan 2008, Obernberger and Thek 2010), and debarking has been considered necessary to keep the ash content below the required 0.7 percent.

When the aim of boreal coniferous forest management is maximal economic profit, the forests require thinning (Kuuluvainen and Valsta 2009). In Finland, thinning most often means that the smallest and weakest trees are removed to provide more space for the trees that are left (Huuskonen 2008, Metsäntutkimuslaitos 2010). The wood harvested in a thinning operation is normally sold for raw material to the pulp and paper industry or to heating plants for fuel (as wood chips). A significant surplus of small pine in Finland presents an opportunity to use it as raw material for pellets. In addition, the availability and price of the traditional raw material for wood pellets is dependent on other manufacturing, such as sawdust from sawmills. As pointed out by many authors, an important fuel source should not be dependent on another industry (Gilbe et al. 2008a, 2008b; Lindström et al. 2010; Filbakk et al. 2011; Toscano et al. 2013; Paukkunen 2014).

Pelletizing woody raw material is understood quite well (Van Loo and Koppejan 2008, Obernberger and Thek 2010, Filbakk et al. 2011, Kallio 2011). Roundwood with bark may be a difficult raw material for acceptable wood pellets, however, because the amount of bark in the raw material affects the quality of wood fuel pellets (i.e., a higher ash content is associated with bark than with wood; Van Loo and Koppejan 2008, Lindström et al. 2010, Obernberger and Thek 2010). Also, contamination during logging and transportation may have a very important role when roundwood with bark is used as raw material for wood pellets (Gilbe et al. 2008b, Lindström et al. 2010, Miranda et al. 2012, Toscano et al. 2013). The European Standards for pelletized fuel (EN 14961-2:2011, European Committee for Standardization [CEN] 2011b) define the acceptable ash limits for each pellet grade. For example, the highest-grade pellet for nonindustrial use (Grade A1) requires that the ash content be equal to or less than 0.7 percent (dry weight basis) with an ash deformation temperature of greater than or equal to 1,200°C (EN ISO 17225-2:2014 [CEN 2014]). The EN ISO 17225-2:2014 standard has made the EN 14961-2:2011 standard outdated, but the quality demands

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for Grade A1 pellets have not changed from the earlier version. Data for the present study were collected and analyzed when EN 14961-2:2011 and other standards mentioned below were in effect. The high ash content of bark and the inorganic contaminates often embedded in the bark make undercutting the required ash content difficult to achieve (Lehtikangas 2001, Obernberger and Thek 2010, Filbakk et al. 2011, Örberg et al. 2014).

The average share of bark (dry weight basis) of pine trees, hereafter referred to as the bark share, is approximately 10.5 percent (Hakkila et al. 1995). Werkelin et al. (2005) have found that the normal amount of ash ranges from 0.2 to 0.3 percent for pine stemwood and from 1.9 to 2.6 percent for bark. Lindström et al. (2010) found that ash content of delimbed pine was 0.5 percent. Hakkila et al. (1995) developed an equation, using tree length as a dependent variable, to estimate the amount of bark based on the mass of the whole tree:

$$y = 4.57 + 63.16/x \quad (1)$$

where $y$ is the bark share (%, dry weight basis) of the whole tree and $x$ is the length of the tree (m). The coefficient of determination for Equation 1 was low ($R^2 = 0.44$).

The bark share in pine logs varies with the position in the tree from which the sample is taken. Pine has the thickest bark at the base of the stem and thinner bark at the top. Because the stem diameter is smaller at the top, the percentage of bark content increases toward the top (Hakkila 1989, Hakkila et al. 1995, Filbakk et al. 2011).

Debarking decreases the ash content of the raw material, but it also decreases material efficiency and economic sustainability. When stems are debarked, the amount of work required to prepare the raw material increases, but the quantity of raw material decreases due to wood fiber losses in the debarking process. Using a Thermo Rossi Eco-Therm1000 pellet stove, Sikanen and Vilppo (2012) found that the normal burning temperature was between 592°C and 810°C measured close to the combustion chamber. The melting point of pine bark ash is between 1,350°C and 1,450°C (Gilbe et al. 2008a), which means that uncontaminated bark could be a useful raw material for wood pellets. Studies also show that roundwood with bark is a useful raw material for Grade A1 pellets (see, e.g., Paukkunen 2014). The relative amount of bark from the dry weight of the whole wood is usually from 10 to 14 percent but is highly dependent on tree size. This represents a potential loss of raw material when roundwood is debarked. Smaller trees have relatively more bark than bigger trees (Hakkila et al. 1995), so an interesting question is: What size limits the use of pine wood as raw material for wood pellets? Also, can pine be used within some diameter limits for pellets without debarking, which would decrease the procurement costs of raw material and increase material efficiency in production?

The objectives of the present study were to determine (1) the possibility of making EN 14961-2:2011 Grade A1 pellets using young pine with bark as a raw material and (2) the influence of stem size when using young Scots pine (*Pinus sylvestris* L.) roundwood with bark as a raw material for wood pellets.

## Materials and Methods

Two plots were selected in May 2013 from forests owned by the University of Eastern Finland (UEF), Mekrijärvi Research Station. The forests are situated in eastern Finland at WGS84 coordinates 62°46.419′N, 30°58.173′E. In both forest plots, the major tree species were pine with a minor component of birch. Information about the plots, taken from the forest management plan valid for the years 2013 to 2024, is presented in Table 1.

Trees for the present study were selected on May 14, 2013, and the main criterion for selection was the diameter measured at a height of 1.3 m. Three sample diameter groups were selected. Group 1 consisted of 50 trees from 4 to 8.9 cm in diameter at 1.3 m, Group 2 included 15 trees from 9 to 13.9 cm in diameter, and Group 3 contained eight trees from 14 to 20 cm in diameter. The selected trees within each group were of varying lengths. Table 2 presents the distribution of cut tree diameters from each group. Group 1 included four distribution classes, Group 2 had five distribution classes, and Group 3 contained six distribution classes.

Harvesting of the samples began on May 17, 2013, and was completed 5 days later. Each tree was cut and delimbed with a chainsaw, and disc specimens were cut from a sample of each diameter group as described below. The disc specimens were stored in a freezer the same day they were cut. The stems were transported to a separate area where they were chipped, dried, and pelletized. The first sample disc was cut 0.5 m from the felling cut, and the discs that followed were cut every 1 m from the previous cut. Sample discs were cut all the way to the top of the tree (Hakkila et al. 1995). An extra sample disc was cut from each sample tree to determine the age.

Harvested wood was transported to the chipping area using a car and trailer. Contamination from sand and dust was avoided at all times. The stems were chipped using a tractor-powered disc chipper emptying directly into the

*Table 1.—Information from sample plots.*

| Plot | Tree species | Avg. height (m) | Avg. diam. (cm) at height of 1.3 m | Avg. age (y) | Vol. ($m^3$/ha) | No. of stems/ha |
|---|---|---|---|---|---|---|
| 1 | Pine | 10 | 12.4 | 50 | 118 | 1,964 |
| | Birch | 11 | 12 | 45 | 3 | 19 |
| 2 | Pine | 13 | 12 | 50 | 233 | 5,336 |
| | Birch | 14 | 12 | 45 | 2 | 24 |

*Table 2.—Distribution of cut tree diameters of harvested trees.*

| Group | Diam. distribution (cm) | No. of stems |
|---|---|---|
| 1 | 4–5 | 14 |
| | 5.1–6 | 17 |
| | 6.1–7 | 17 |
| | 7.1–8.9 | 2 |
| 2 | 9–10 | 6 |
| | 10.1–11 | 3 |
| | 11.1–12 | 2 |
| | 12.1–13 | 1 |
| | 13.1–13.9 | 3 |
| 3 | 14–15 | 2 |
| | 15.1–16 | 2 |
| | 16.1–17 | 1 |
| | 17.1–18 | 2 |
| | 18.1–19 | 0 |
| | 19.1–20 | 1 |

dryer trailer. The chipped raw material was dried using a trailer-based batch dryer. The loaded trailer (volume, 3 $m^3$) was placed in a shipping container, and heated air (maximum temperature, 65°C) was blown through the wood chip batch. The heat was sourced from the district heating network through a heat exchanger to avoid contamination of the raw material during drying (Öhman et al. 2004). The dried raw material was milled to a suitable particle size using a Miller 20 hammer mill with a 6-mm sieve. The raw material was pelletized with a SPC PP300 pelletizer using a die with 50-mm-long press channels. No extra binding material, water, or steam was used during pelletizing. The raw materials from different diameter groups were pelletized separately.

The chemical and physical properties measured in the present study were as follows:

- From the raw material (bark): Moisture content (wet weight basis); ash content (dry weight basis); N (%; Kjeldahl); Al, B, Ca, Cu, Fe, K, Mg, Mn, Na, P, S, Si, and Zn (mg/kg); and gross calorific value (or higher heating value [HHV]), net calorific value (or lower heating value [LHV]), and LHV as received (MJ/kg).
- From the pellets: Moisture content (wet weight basis); ash content (dry weight basis); N (%; Kjeldahl); Al, B, Ca, Cu, Fe, K, Mg, Mn, Na, P, S, Si, and Zn (mg/kg); HHV, LHV, and LHV as received (MJ/kg); and mechanical durability (%).

The standards followed in the present study included the following:

- Chemical composition and ash content of pellets (EN 14961-2:2011)
- Mechanical durability of pellets and briquettes (EN 15210-1:2010 [CEN 2010f])
- Moisture content of raw material and pellets (EN 14774-1:2010, EN 14774-2:2010, and 14774-3:2010 [CEN 2010a, 2010b, 2010c])
- Sample preparation (EN 14778:2011 [CEN 2011a])
- Calorific values (EN 14918:2010 [CEN 2010e])
- Ash content (EN 14775:2010 [CEN 2010d])

It is important to know the bark share from the dry mass of the whole tree if the target is to meet the needs of the energy and lignocellulose industry (Hakkila et al. 1995). A subset of discs was selected from each diameter group to determine the bark share: 10 trees from Group 1, 5 trees from Group 2, and 3 trees from Group 3. The dry mass and bark share were determined from each sample tree (sample disc). The rest of the sample trees were used as the raw material for wood pellets; only sample discs were taken for this analysis. The dry mass and bark share were determined using the ovendrying method, and the drying was done at the UEF Mekrijärvi Research Station. The bark share was calculated as

$$y = x/(a + x) \tag{2}$$

where $y$ is the bark share (%, dry weight basis), $a$ is the weight of wood material (g, dry weight basis), and $x$ is the weight of bark (g, dry weight basis).

Fuel analysis was performed at the UEF and the Finnish Forest Research Institute. Chemical analysis was done at the UEF using inductive coupled plasma mass spectrometry (ICP). The durability of pellets was tested twice: The first test was performed on the day after the pellets were produced, and the second test was performed at least 86 days after the pellets were produced.

## Results and Discussion

The data compiled in the present study provide the basis for determining the suitability of unbarked tree stems as raw material for wood pellets. Results of the chemical and physical property analyses provide the information needed to determine if bark is a suitable raw material. The results of the bark share analysis provide the information needed to determine what size stems are acceptable.

### Chemical analysis of the bark

Results of the chemical analysis (ICP) are presented in Table 3. The Zn, P, S, K, and ash content measured in the bark were at the same levels as in previous studies (see, e.g.,

*Table 3.—Average results from the chemical analyses of pellets and bark.*

| | Pellets | | | Bark | | |
|---|---|---|---|---|---|---|
| | Group 1 | Group 2 | Group 3 | Group 1 | Group 2 | Group 3 |
| Moisture content (%, wet wt basis) | 8.33 | 8.18 | 7.78 | 8.38 | 8.24 | 8.29 |
| Ash content (%, dry wt basis) | 0.493 | 0.356 | 0.396 | 1.613 | 1.528 | 1.528 |
| N (%, Kjeldahl) | 0.06953 | 0.06913 | 0.06771 | 0.35864 | 0.31802 | 0.31865 |
| Al (mg/kg) | 42.86 | 50.28 | 50.54 | 466.35 | 492.95 | 499.34 |
| B (mg/kg) | 1.59 | 1.60 | 1.53 | 6.36 | 6.32 | 5.74 |
| Ca (mg/kg) | 902.60 | 799.20 | 742.90 | 4,361.80 | 3,480.90 | 2595.70 |
| Cu (mg/kg) | 0.66 | 0.78 | 0.81 | 2.04 | 1.74 | 2.03 |
| Fe (mg/kg) | 18.86 | 23.96 | 16.87 | 28.54 | 21.36 | 25.56 |
| K (mg/kg) | 397.60 | 423.40 | 433.90 | 1,299.30 | 1,357.30 | 1,500.80 |
| Mg (mg/kg) | 204.10 | 194.50 | 176.70 | 723.90 | 622.80 | 565.50 |
| Mn (mg/kg) | 95.90 | 85.00 | 78.30 | 221.00 | 174.60 | 136.10 |
| Na (mg/kg) | 13.94 | 19.21 | 22.94 | 17.41 | 23.12 | 29.64 |
| P (mg/kg) | 78.47 | 77.71 | 86.68 | 460.23 | 420.88 | 482.96 |
| S (mg/kg) | 68.89 | 66.79 | 68.59 | 288.34 | 267.33 | 257.35 |
| Si (mg/kg) | 6.05 | 4.67 | 8.10 | 9.82 | 8.96 | 8.69 |
| Zn (mg/kg) | 10.43 | 9.73 | 10.98 | 34.89 | 25.50 | 25.68 |
| K:Si | 65.8 | 90.7 | 53.6 | 132.3 | 151.4 | 172.6 |
| Ca:Si | 149.3 | 171.3 | 91.8 | 444.2 | 388.4 | 298.6 |
| K:Ca | 0.440 | 0.530 | 0.584 | 0.298 | 0.390 | 0.578 |

Lehtikangas 2001, Hartmann 2007, Sippula et al. 2007, Aebiom 2008). The amount of Mg ranged from 566 to 724 mg/kg, which was approximately two times higher than what Sippula et al. (2007) found. The amount of Si ranged from 8.7 to 9.8 mg/kg, which was very much lower than reported by Gilbe et al. (2008a, 2008b) and Örberg et al. (2014).

## Chemical analysis of the pellets

The amounts of Ca, Mg, Fe, Zn, and Si measured in the pellets were similar to reports in the literature (Sippula et al. 2007, Okkonen et al. 2009, Paukkunen 2014). Differences, however, were found in the amounts of P and S, which were two times lower in the present study, and in the amount of K, which was approximately 0.5 times lower in the present study, compared with the values reported by others (Lehtikangas 2001, Hartmann 2007, Sippula et al. 2007, Aebiom 2008). The amount of Na ranged from 13.9 to 22.9 mg/kg, which was at the same level as that reported by Paukkunen (2014). According to the literature, the normal amount of Na would be approximately 20 to 80 mg/kg (Sippula et al. 2007, Okkonen et al. 2009). According to some previous studies, roundwood with bark can contain from 850 to 2,000 mg/kg Si, but these high values could be explained by sand contamination (Lindström et al. 2010, Örberg et al. 2014). The amount of Si in the pellets is important to know because it correlates to the melting temperature of the ash. If the Si content is high, the melting point of the ash will decrease (Obernberger and Thek 2010). A low melting point of the ash means the fuel pellet is less acceptable, especially for use in single-family houses. The Zn, Cu, N, S, and ash contents measured from pellets were lower than the limits in the EN 14961-2:2011 standard.

The limit on the amount of ash is 0.7 percent (EN 14961-2:2011) for Grade A1 pellets. The results of the present study show that the ash content of the pellets ranged from 0.36 to 0.49 percent, which falls below the acceptable ash limit (Table 3). These results (amounts of ash) are similar to those of earlier studies.

Fuel characteristics of pellets and bark are presented in Table 4. The energy values for bark were found to be similar to the values for the pellets. The range of HHV from 20.7 to 21.0 MJ/kg for the pellets compares favorably with the EN 14961-2:2011 standard.

*Table 4.—Characteristics of pellets and bark (analyzed by METLA).*[a]

| | HHV (MJ/kg) | LHV (MJ/kg) | LHV as received (MJ/kg) | MC (%) |
|---|---|---|---|---|
| Pellets | | | | |
| Group 1 | 20.73 | 19.34 | 17.75 | 7.33 |
| Group 2 | 20.70 | 19.31 | 17.79 | 6.97 |
| Group 3 | 21.01 | 19.62 | 18.35 | 5.77 |
| Bark | | | | |
| Group 1 | 21.30 | 20.02 | 18.15 | 8.29 |
| Group 2 | 20.81 | 19.52 | 17.69 | 8.30 |
| Group 3 | 21.08 | 19.80 | 17.88 | 8.61 |

[a] HHV = higher heating value (gross calorific value); LHV = lower heating value (net calorific value); MC = moisture content.

## Bark share

In the present study, the bark share of whole wood was determined from 18 trees. Tables 5, 6, and 7 present the measured and calculated bark share for each sample tree in Groups 1, 2, and 3, respectively. The lowest bark share (measured from a single tree) was 9.54 percent, the highest 15.7 percent, and the average 12.36 percent. Group 1, which had the smallest stems, had the highest average bark share (13.57%). The bark share of the trees varied with distance from the cutting point. The highest bark share bark was always in the top of the tree, the second highest in the bottom of the trunk, and the lowest in the middle section. In smaller trees (Group 1), the bark share was higher than in the larger trees (Groups 2 and 3). The average bark share was 13.57 percent for Group 1, 10.71 percent for Group 2,

*Table 5.—Measured and calculated bark share for sample trees in Group 1.*

| Tree | | | | Bark share (%) | | |
|---|---|---|---|---|---|---|
| No. | Diam. (m) | Height (m) | Age (y) | Measured | Hakkila et al. equation | Equation 3 |
| 20 | 6.5 | 8.6 | 39 | 11.06 | 11.91 | 12.90 |
| 34 | 6.5 | 10.5 | 40 | 14.19 | 10.59 | 12.09 |
| 36 | 4.5 | 6.7 | 33 | 15.68 | 14.00 | 13.72 |
| 15 | 6.0 | 7.3 | 49 | 11.67 | 13.22 | 13.46 |
| 5 | 4.0 | 5.1 | 39 | 14.50 | 16.95 | 14.41 |
| 30 | 5.5 | 8.5 | 53 | 13.66 | 12.00 | 12.95 |
| 40 | 4.0 | 6.7 | 36 | 15.05 | 14.00 | 13.72 |
| 45 | 4.0 | 8.1 | 29 | 13.58 | 12.37 | 13.12 |
| 24 | 6.5 | 9.2 | 41 | 12.42 | 11.44 | 12.65 |
| 10 | 7.5 | 7.7 | 55 | 13.89 | 12.77 | 13.29 |
| Avg. | 5.52 | 7.84 | 41.4 | 13.57 | 12.925 | 13.231 |

*Table 6.—Measured and calculated bark share for sample trees in Group 2.*

| Tree | | | | Bark share (%) | | |
|---|---|---|---|---|---|---|
| No. | Diam. (m) | Height (m) | Age (y) | Measured | Hakkila et al. equation | Equation 3 |
| 12 | 9.0 | 8.5 | 38 | 9.84 | 12.00 | 12.95 |
| 14 | 10.5 | 11.4 | 44 | 11.00 | 10.11 | 11.70 |
| 9 | 11.5 | 14.4 | 54 | 9.79 | 8.96 | 10.41 |
| 10 | 9.5 | 12.1 | 46 | 12.67 | 9.79 | 11.40 |
| 7 | 13.5 | 12.7 | 45 | 10.27 | 9.54 | 11.14 |
| Avg. | 10.8 | 11.82 | 45.4 | 10.714 | 10.08 | 11.52 |

*Table 7.—Measured and calculated bark share for sample trees in Group 3.*

| Tree | | | | Bark share (%) | | |
|---|---|---|---|---|---|---|
| No. | Diam. (m) | Height (m) | Age (y) | Measured | Hakkila et al. equation | Equation 3 |
| 5 | 20.0 | 13.4 | 45 | 10.58 | 9.28 | 10.84 |
| 4 | 16.0 | 13.9 | 40 | 13.17 | 9.11 | 10.62 |
| 2 | 15.0 | 12.7 | 45 | 9.54 | 9.54 | 11.14 |
| Avg. | 17.0 | 13.33 | 43.33 | 11.10 | 9.31 | 10.87 |

and 11.10 percent for Group 3. Table 8 presents the tree-specific equations where bark share is the dependent factor and measured bark share from the sample discs from different heights of the tree is the independent variable. Formulas were made using polynomial regression analysis.

Table 9 presents the calculated (using the tree-specific equations from Table 8) bark share at relative heights of the tree. There is an error between the measured bark share (whole tree, average) and the calculated bark share (average). The calculated values are closer to the top of the tree than the points where the original sample discs were taken, and because the bark share is greater closer to the top, the calculated average bark share is greater than the measured average bark share.

*Table 8.—Tree-specific equations using polynomial regression analysis.*[a]

| Group | Tree | Formula | $R^2$ |
|---|---|---|---|
| 3 | 5 | $Y = 0.3147x^2 - 3.1183x + 13.146$ | 0.9276 |
| | 4 | $Y = 0.4755x^2 - 5.1733x + 18.354$ | 0.9435 |
| | 2 | $Y = 0.3626x^2 - 3.3749x + 12.408$ | 0.9624 |
| 2 | 12 | $Y = 0.7045x^2 - 4.2484x + 11.865$ | 0.9794 |
| | 14 | $Y = 0.5137x^2 - 4.207x + 13.461$ | 0.9028 |
| | 9 | $Y = 0.1933x^2 - 1.595x + 8.3376$ | 0.9556 |
| | 10 | $Y = 0.479x^2 - 4.1989x + 14.909$ | 0.9201 |
| | 7 | $Y = 0.3892x^2 - 3.8198x + 14.546$ | 0.9307 |
| 1 | 20 | $Y = 0.6989x^2 - 4.7589x + 15.249$ | 0.9063 |
| | 34 | $Y = 0.6707x^2 - 5.5405x + 19.595$ | 0.8692 |
| | 36 | $Y = 1.3025x^2 - 6.495x + 19.641$ | 0.8595 |
| | 15 | $Y = 1.1275x^2 - 6.7988x + 17.139$ | 0.9903 |
| | 5 | $Y = 0.947x^2 - 3.4391x + 15.282$ | 0.8002 |
| | 30 | $Y = 0.731x^2 - 4.2575x + 15.161$ | 0.8943 |
| | 40 | $Y = 0.4411x^2 - 1.5185x + 14.347$ | 0.6980 |
| | 45 | $Y = 0.5855x^2 - 2.7933x + 13.847$ | 0.9104 |
| | 24 | $Y = 0.7399x^2 - 4.7041x + 13.668$ | 0.9186 |
| | 10 | $Y = 0.8456x^2 - 5.6372x + 19.879$ | 0.8233 |

[a] $Y$ = bark share (%); $x$ = height of the tree (m).

The relationship between tree length and amount of bark was tested using the linear regression model method. The resulting best-fit equation was

$$y = 16.601 - 0.430x \qquad (3)$$

where $y$ is the bark share (%, dry weight basis) and $x$ is the length of the tree (m). Although this model was statistically significant at $P = 0.01$, the $R^2$ value of 0.35 indicates that much of the variation remains unexplained. Similar results were reported by Hakkila et al. (1995).

The difference between the measured bark share and the estimated results using the model of Hakkila et al. or the regression model determined in the present study (Eq. 3) were analyzed by linear regression techniques to determine if the differences were dependent on tree length. No significant relationships were found. Based on a comparison of actual and calculated values, the regression equation defined in this study (Eq. 3) was a better predictor than the Hakkila et al. equation (Fig. 1). Figure 2 presents the discrepancy between the Hakkila et al. predicting model (Eq. 1) and the measured amount of bark. The discrepancy increases with tree height, indicating that Equation 1 is biased by tree height and therefore is less acceptable than Equation 3 for predictions.

Figure 3 presents the correlation between bark share ($y$ axis) and sample point of trees ($x$ axis; distance from cut [m]) by diameter group. The axial position in trees has strong correlation to the bark share. From the location of the cut, the bark share decreases toward the mid height of the tree. From the mid height of the tree, the bark share increases toward the top of the tree. A trend also was found between the diameter groups and the bark share, with the bark share being largest in Group 1 (the smallest-diameter trees).

Figure 4 presents the basis of the linear regression analysis (Eq. 3). Variation of the bark share between trees

*Table 9.—Calculated bark share using tree-specific equations.*

| Group | Tree | Measured bark share[a] | Calculated bark share (%) at relative heights (% from tree height) of: 0.1 | 0.2 | 0.3 | 0.4 | 0.5 | 0.6 | 0.7 | 0.8 | 0.9 | 1 | Avg. (% of whole tree) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | 5 | 10.58 | 9.53 | 7.05 | 5.70 | 5.47 | 6.38 | 8.42 | 11.59 | 15.88 | 21.31 | 27.87 | 11.92 |
| | 4 | 13.17 | 12.08 | 7.65 | 5.05 | 4.29 | 5.37 | 8.28 | 13.03 | 19.62 | 28.05 | 38.32 | 14.17 |
| | 2 | 9.54 | 8.71 | 6.17 | 4.80 | 4.61 | 5.57 | 7.71 | 11.01 | 15.49 | 21.13 | 27.93 | 11.31 |
| 2 | 12 | 9.84 | 8.76 | 6.68 | 5.61 | 5.56 | 6.53 | 8.52 | 11.53 | 15.55 | 20.59 | 26.65 | 11.60 |
| | 14 | 11.00 | 9.33 | 6.54 | 5.08 | 4.95 | 6.16 | 8.70 | 12.58 | 17.79 | 24.34 | 32.22 | 12.77 |
| | 9 | 9.79 | 6.44 | 5.35 | 5.05 | 5.56 | 6.87 | 8.99 | 11.90 | 15.62 | 20.13 | 25.45 | 11.14 |
| | 10 | 12.67 | 10.53 | 7.55 | 5.98 | 5.81 | 7.04 | 9.68 | 13.72 | 19.16 | 26.00 | 34.25 | 13.97 |
| | 7 | 10.27 | 10.32 | 7.36 | 5.65 | 5.19 | 5.99 | 8.04 | 11.36 | 15.92 | 21.74 | 28.82 | 12.04 |
| 1 | 20 | 11.06 | 11.67 | 9.13 | 7.62 | 7.15 | 7.70 | 9.30 | 11.92 | 15.58 | 20.28 | 26.01 | 12.64 |
| | 34 | 14.19 | 14.52 | 10.92 | 8.80 | 8.16 | 8.99 | 11.31 | 15.11 | 20.38 | 27.13 | 35.36 | 16.07 |
| | 36 | 15.68 | 15.87 | 13.28 | 11.85 | 11.59 | 12.50 | 14.58 | 17.83 | 22.25 | 27.84 | 34.59 | 18.22 |
| | 15 | 11.67 | 12.78 | 9.62 | 7.66 | 6.90 | 7.34 | 8.99 | 11.84 | 15.89 | 21.14 | 27.59 | 12.97 |
| | 5 | 14.50 | 13.77 | 12.76 | 12.24 | 12.21 | 12.67 | 13.63 | 15.07 | 17.01 | 19.45 | 22.37 | 15.12 |
| | 30 | 13.66 | 12.07 | 10.04 | 9.06 | 9.14 | 10.27 | 12.46 | 15.71 | 20.01 | 25.37 | 31.79 | 15.59 |
| | 40 | 15.05 | 13.53 | 13.10 | 13.08 | 13.45 | 14.21 | 15.37 | 16.93 | 18.88 | 21.23 | 23.97 | 16.37 |
| | 45 | 13.58 | 11.97 | 10.86 | 10.52 | 10.94 | 12.14 | 14.10 | 16.83 | 20.33 | 24.60 | 29.64 | 16.19 |
| | 24 | 12.42 | 9.97 | 7.52 | 6.32 | 6.38 | 7.69 | 10.25 | 14.06 | 19.13 | 25.44 | 33.02 | 13.98 |
| | 10 | 13.89 | 16.04 | 13.20 | 11.37 | 10.54 | 10.71 | 11.88 | 14.06 | 17.24 | 21.42 | 26.61 | 15.31 |

[a] Percentage of whole tree on a dry weight basis.

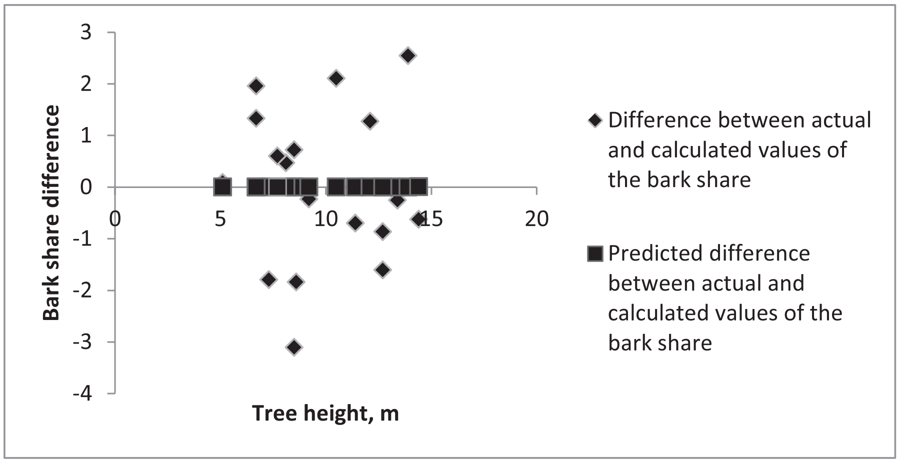


*Figure 1.—Difference between the measured bark share and the bark share calculated using Equation 3.*

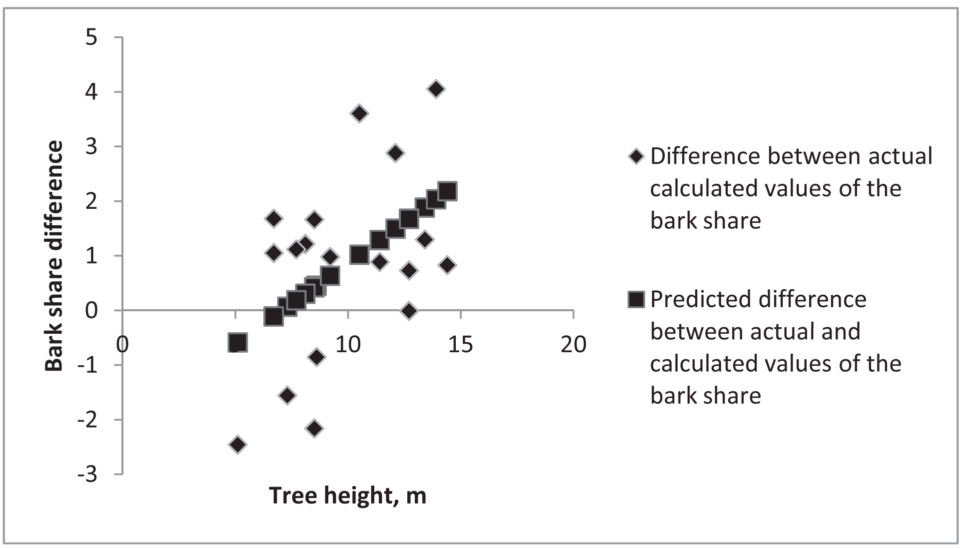


*Figure 2.—Difference between the measured bark share and the bark share calculated using the equation of Hakkila et al. (1995).*

can be seen from the figure. The horizontal line across the figure presents the limit of the maximal bark share (15.4%) when the target is under the EN standard ash limit (0.7%). The area of the square box presents the 95 percent confidence interval of the linear regression. Two values (square points) are calculated using Equation 3. The round spot on the horizontal line is the minimum length of the tree that is useful for raw material for EN standard Grade A1 pellets.

## Estimating pellet ash and bark share

Using the equations and relationships derived in the present study and those of other researchers, it is possible to estimate the pellet ash content expected from different bark/wood feedstock combinations. Two examples follow.

First, estimates of the contribution of bark content to the total ash content in wood pellets vary in the literature. Filbakk et al. (2011) found that the ash content of wood pellets would be 0.55 percent when the bark content is 10 percent of the raw material. Using this relationship, it is possible to calculate the bark share that would produce a given pellet ash content for a given mass ($M$):

$$M_{\text{pellet ash}} = 0.0055 \times M_{\text{pellet}} \qquad \text{(Filbakk et al. 2011)}$$

$$M_{\text{bark}} = 0.10 \times M_{\text{pellet}} = 0.10 \times M_{\text{bark}} + M_{\text{wood}} \qquad \text{(Filbakk et al. 2011)}$$

$$M_{\text{pellet ash}} = (0.0055/0.10) \times M_{\text{bark}}$$

Thus,

$$M_{\text{bark}} = M_{\text{pellet ash}}/0.055$$

If this were a linear relationship, then the above equation could be used to determine the weight of pellet ash from any quantity of bark. For example, the calculation of the amount of bark that would yield the allowable limit of 0.7 percent ash content for Grade A1 pellet (as defined by EN 14961-2) is

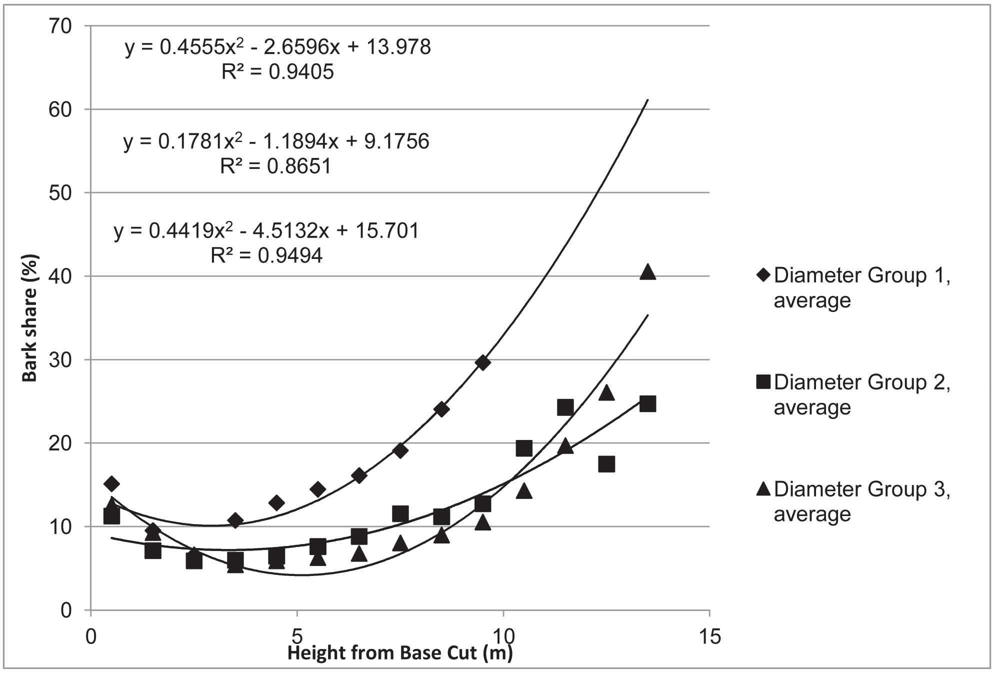


*Figure 3.—Average bark share as a function of the axial position in trees by diameter group.*

$$M_{\text{bark}} = M_{\text{pellet ash}}/0.055 = (0.007 \times M_{\text{pellet}})/0.055 = 0.127 \times M_{\text{pellet}}$$

In other words, using the relationship of Filbakk et al. of bark content greater than 12.7 percent of the total weight of wood will produce pellets with an ash content greater than the allowable 0.7 percent.

Second, deriving a similar relationship from the data collected in the present study:

$$M_{\text{pellet ash}} = M_{\text{stemwood ash}} + M_{\text{bark ash}}$$

$$M_{\text{bark ash}} = 0.018 \times M_{\text{bark}} \qquad \text{(present study)}$$

$$M_{\text{stemwood ash}} = 0.005 \times M_{\text{stemwood ash}} \qquad \text{(Hakkila et al. 1995)}$$

Then,

$$M_{\text{pellet ash}} = 0.005 \times M_{\text{stemwood}} + 0.018 \times M_{\text{bark}}$$

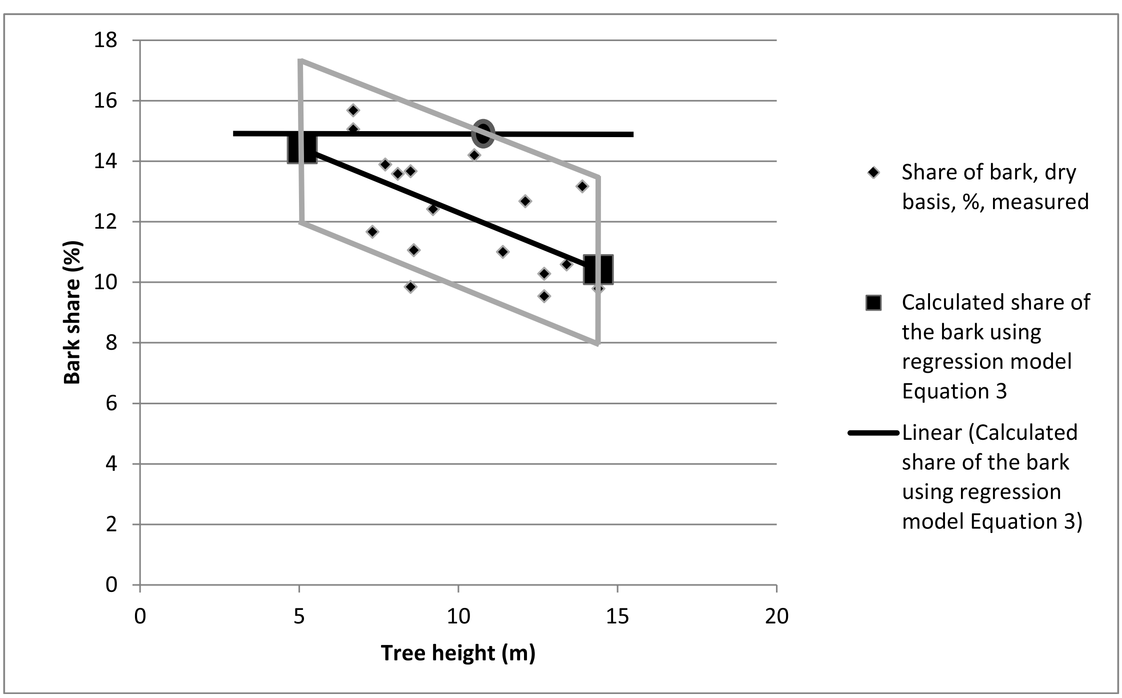


*Figure 4.—Relationship between the bark share prediction model (Eq. 3) and the measured bark share.*

Because

$$M_{\text{total}} = M_{\text{stemwood}} + M_{\text{bark}}$$

then

$$M_{\text{pellet ash}} = 0.005 \times (M_{\text{total}} - M_{\text{bark}}) + (0.018 \times M_{\text{bark}})$$

Simplifying,

$$\text{Ash}_{\text{share of total}\,M} = 0.005 + 0.013 \times \text{Bark}_{\text{share of total}\,M}$$

Using the above equation, the bark share for a pellet ash content of 0.7 percent is

$$(M_{\text{bark}}/M_{\text{total}}) = (0.007 - 0.005)/0.013 = 0.154$$

or 15.4 percent.

Using the relationship derived from Filbakk et al. (2011) and the regression equation developed by Hakkila et al. (1995), the minimum tree length would be approximately 7.8 m. Applying the Hakkila et al. regression to the bark share of 15.4 percent determined in the present study results in a minimum tree length of approximately 5.8 m. Using the 15.4 percent bark share and Equation 3 derived in the present study, the estimated minimum tree length is approximately 3.8 m. As a comparison, using the more rigorous equation developed for Group 1 trees, the minimum tree length is 6.8 m.

This exercise illustrates how the rough estimates calculated using simple linear regression techniques vary greatly from the more rigorous approach of using a best-fit model to determine the relationship between bark share and tree length.

The reason for the poor adjusted $R^2$ of the model (Eq. 3) is the normal variation of the bark share in nature. The standard error (SE) of the estimate was 1.577425, and the $F$ value was 10.0, which means a Student's critical $t$ value of 2.28. Using the bark share of 15.4 percent for a pellet ash content of 0.7 percent, the minimum length of the tree can be calculated from Equation 3 (provided above). Then, with 2.28 as the term of the normal distribution and 1.577425 as the SE of the estimate,

$$16.601 - (0.430x) + 2.28(1.577425) = 15.4$$

where $x = 11.1570$ m. So the minimum length of the tree when using the 95 percent confidence interval is 11.16 m when the maximal amount of ash is the EN standard 14961-2:2011 limit of 0.7 percent.

Significance of bark share and tree diameter (between Groups 1, 2, and 3) was tested using one-way analysis of variance. Tree diameter was significant to bark share ($P = 0.005$). The average bark share was 13.57 percent for Group 1, 10.71 percent for Group 2, and 11.10 percent for Group 3.

## Pellet durability

The durability of the pellets produced from each diameter group differed depending on when the pellets were tested (Table 10). When pellets were tested the day after they were produced, the durability failed to meet the minimum standard for the highest-quality pellets (Grade A1) defined by the European Standard EN 14961-2 A1. Testing the pellets again after 86 days changed the results to all pellets meeting the standard. This suggests that the bonding of wood particles increases with age (curing). It was not a goal of the present study to determine the optimal manufacturing parameters for producing Grade A1 pellets, but it is well known that durability can be improved by using the optimum settings.

*Table 10.—Mechanical durability of the pellets.*

| | Mechanical durability (% wet basis) | | | |
|---|---|---|---|---|
| | | Our test results | | |
| Test condition | EN 14961-2:2011[a] | Group 1 | Group 2 | Group 3 |
| At production | 97.5 | 97.5 | 97.1 | 95.4 |
| Aged for 86 d | 97.5 | 98.0 | 99.5 | 98.8 |

[a] Standard for Grade A1 pellets (European Committee for Standardization 2011b).

Many factors influence the durability of pellets (e.g., particle size of raw material, amount of bark, moisture of raw material, pelletizing technology and settings used, and time between harvesting and drying; Lehtikangas 2001, Obernberger and Thek 2010, Paukkunen et al. 2010, Filbakk et al. 2011). Durability demands of CEN 14961-2 A1 could be met when using a longer press tunnel (e.g., 55 or 60 mm) and longer aging (longer storage) of the raw material. Using hot steam as a pretreatment method just before pelletizing also might increase the durability of pellets (Obernberger and Thek 2010, Filbakk et al. 2011).

## Conclusions

The results of the present study reveal that small-diameter pine with bark could be used as a raw material for Grade A1 (EN 14961-2:2011) pellets in terms of chemical composition and ash amount of pellets. In this study, pellets did not reach the durability demands of the Grade A1 pellets when tested the day after pressing, but all pellets did reach the durability demands when testing was done 86 days after pressing. Further study is needed to find the optimum production settings needed to produce consistent and acceptable durability. Quite a large deviation in the amount of bark is found between trees, but the length of trees is a statistically relevant, independent factor to explain the amount of bark. The sample size of the present study was limited (two forest plots, 73 trees), but it seems that the amount of bark will not be the limiting factor when pine roundwood with bark is used as raw material for EN 14961-2:2011 Grade A1 wood pellets. The present results show that the 0.7 percent limit of ash content will be exceeded if pine trees shorter than 11.16 m are used as raw material for wood pellets. A modeling approach for pellet ash content can most probably be used for other wood species if adequate bark/wood models are developed.

The present study also confirms that contamination of pellet raw material with soil and sand should be avoided in every way. Previous studies have shown much higher amounts of Si than the present one, during which great care was taken to avoid contamination of the raw material.

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## Literature Cited

Aebiom. 2008. Wood fuels handbook. http://www.aebiom.org/IMG/pdf/WOOD_FUELS_HANDBOOK_BTC_EN.pdf. Accessed May 27, 2014.

European Committee for Standardization (CEN). 2010a. Solid biofuels. Determination of moisture content. Oven dry method. Part 1. Total moisture. Reference method. EN 14774-1:2010. CEN, Brussels.
European Committee for Standardization (CEN). 2010b. Solid biofuels. Determination of moisture content. Oven dry method. Part 2. Total moisture. Simplified method. EN 14774-2:2010. CEN, Brussels.
European Committee for Standardization (CEN). 2010c. Solid biofuels. Determination of moisture content. Oven dry method. Part 3. Moisture in general analysis sample. EN 14774-3:2010. CEN, Brussels.
European Committee for Standardization (CEN). 2010d. Solid biofuels. Determination of ash content. EN 14775. CEN, Brussels.
European Committee for Standardization (CEN). 2010e. Solid biofuels. Determination of calorific value. EN 14918:2010. CEN, Brussels.
European Committee for Standardization (CEN). 2010f. Solid biofuels. Determination of mechanical durability of pellets and briquettes. Part 1: Pellets. EN 15210-1:2010. CEN, Brussels.
European Committee for Standardization (CEN). 2011a. Solid biofuels—Sampling. EN 14778:2011. CEN, Brussels.
European Committee for Standardization (CEN). 2011b. Solid biofuels. Fuel specifications and classes. Part 2: Wood pellets for non-industrial use. EN 14961-2:2011. CEN, Brussels.
European Committee for Standardization (CEN). 2014. Solid biofuels. Fuel specifications and classes. Part 2: Graded wood pellets. EN ISO 17225-2:2014. CEN, Brussels.
Filbakk, T., R. Jirjis, J. Nurmi, and O. Hib. 2011. The effect of bark content on quality parameters of Scots pine (*Pinus sylvestris* L.) pellets. *Biomass Bioenergy* 35:3342–3349.
Gilbe, G., E. Lindström, R. Backman, R. Samuelson, J. Burvall, and M. Öhman. 2008a. Predicting slagging tendencies for biomass pellets fired in residential appliances: A comparison of different prediction methods. *Energy Fuels* 22:3680–3686.
Gilbe, G., M. Öhman, E. Lindström, D. Boström, R. Backman, R. Samuelson, and J. Burvall. 2008b. Slagging characteristics during residential combustion of biomass pellets. *Energy Fuels* 22:3536–3543.
Hakkila, P. 1989. Utilization of Residual Forest Biomass. Springer, New York. 568 pp.
Hakkila, P., H. Kalaja, and P. ja Saranpää. 1995. Etelä-Suomen ensiharvennusmänniköt kuitu- ja energialähteenä [Southern Finland located pine dominated young forests as a fiber and energy source]. Metsäntutkimuslaitoksen tiedonantoja 582. 100 pp.
Hartmann, H. 2007. Handbuch Bioenergie-Kleinanlagen. 3. überarbeitete Auflage 2013 [Bioenergy manual—Small scale plants]. http://mediathek.fnr.de/media/downloadable/files/samples/h/a/handbuchkleinanlagen2013-web_1.pdf. Accessed May 27, 2014.
Huuskonen, S. 2008. The development of young Scots pine stands—Precommercial and first commercial thinning. Dissertationes Forestales 62. http://www.metla.fi/dissertationes/df62.htm. Accessed May 25, 2014. (In Finnish with English summary.)
Kallio, M. 2011. Critical review on the pelletizing technology. IEE/09/758/SI2.558286 - MixBioPells. https://www.dbfz.de/fileadmin/MixBioPells/publications/D31_Critical_Review_about_pelletising_and_combustion_technology_FINAL.pdf. Accessed May 23, 2014.
Kuuluvainen, J. and L. Valsta. 2009. Metsäekonomian perusteet [Basics of Forest Economics]. Gaudeamus. 332 pp.
Lehtikangas, P. 2001. Quality of pelletized sawdust, logging residues and bark. *Biomass Bioenergy* 20:351–360.
Lindström, E., S. H. Larsson, D. Boström, and M. Öhman. 2010. Slagging characteristics during combustion of woody biomass pellets made from a range of different forestry assortments. *Energy Fuels* 24:3456–3461.
Metsäntutkimuslaitos. 2010. Finnish Statistical Yearbook of Forestry. Vammalan kirjapaino Oy, Sastamala, Finland. 470 pp.
Miranda, I., J. Gominho, I. Mirra, and H. Pereira. 2012. Chemical characterization of barks from *Picea abies* and *Pinus sylvestris* after fractioning into different particle sizes. *Ind. Crops Prod*. 36:395–400.
Obernberger, I. and G. Thek. 2010. The Pellet Handbook: The Production and Thermal Utilisation of Biomass Pellets. Earthscan, London. 549 pp.
Öhman M., A. Nordin H. Hedman, and R. Jiris. 2004. Reasons for slagging during stemwood pellet combustion and measures for prevention. *Biomass Bionergy* 27:597–605.
Okkonen, L., S. Paukkunen, H. Lamberg, O. Sippula, J. Tissari, and J. Jokiniemi. 2009. PELLETime investigates alternative raw materials of pellet production. *In:* Bioenergy 2009: Book of Proceedings, Part II, Sustainable Bioenergy Business, 4th International Bioenergy Conference, M. Savolainen (Ed.), August 31–September 4, 2009, Jyväskylä, Finland; Finbio. pp. 755–759.
Örberg, H., S. Jansson, G. Kalèn, M. Thyrel, and S. Xiong. 2014. Combustion and slagging behavior of biomass pellets using a burner cup developed for ash-rich fuels. *Energy Fuels* 28:1103–1110.
Paukkunen, S. 2014. Opportunities to use thinning wood as raw material for wood pellets. *Croat*. *J. Forest Eng*. 35(1):23–33.
Paukkunen, S., L. Sikanen., T. Vilppo, and H. Lamberg. 2010. Energy pellets in the future—Markets and raw materials. *In:* Forest Bioenergy 2010: Book of Proceedings, September 4–6, 2010, Tampere, Finland; Finbio. pp. 305–313.
Sikanen, L. and T. Vilppo. 2012. Small scale pilot combustion experiments with wood pellets—The effect of pellet length. *Open Renew*. *Energy J*. 5:1–6.
Sippula, O., K. Hytönen, J. Tissari, T. Raunemaa, and J. Jokiniemi. 2007. Effect of wood fuel on the emissions from a top-feed pellet stove. *Energy Fuels* 21:1151–1160.
Toscano, G., G. Riva, E. Foppa Pedretti, F. Corinaldesi, C. Mengarelli, and D. Duca. 2013. Investigation on wood pellet quality and relationship between ash content and most important chemical elements. *Biomass Bioenergy* 56:317–322.
Van Loo, S. and J. Koppejan. 2008. The Handbook of Biomass Combustion & Co-firing. Earthscan, London. 442 pp.
Werkelin, J., B.-J. Skrifvars, and M. Hupa. 2005. Ash-forming elements in four Scandinavian wood species. *Biomass Bioenergy* 29:451–466.