Biomass and Bioenergy 208 (2026) 108856

Contents lists available at ScienceDirect

Biomass and Bioenergy

journal homepage: www.elsevier.com/locate/biombioe

# Influence of forest management on chemical composition in 18-year-Old second-rotation poplar plantations

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ARTICLE INFO

*Keywords:*
Forest management
Fast-growing trees
Biomass chemical composition
Biomass
Thermochemical conversion

ABSTRACT

Efficient biomass production through management like thinning is crucial for increasing the supply of renewable and carbon neutral feedstock. However, change in growth rates may alter feedstock properties and affect subsequent bioenergy conversion, material and chemical production. This study evaluated the effects of thinning treatments and stem diameter on the fuel, elemental, and structural composition of stemwood and bark from second-rotation poplar plantation (original stand: 1100 stumps $ha^{-1}$). Two different thinning methods were applied: row thinning (removing all stems for every other row of plantation and reducing stump density to 550 stumps $ha^{-1}$) and stem thinning (retaining only the single largest stem per stump). The results showed that thinning method and stem diameter affect fuel and lignocellulosic composition. Single-stem trees at high stump density had the best fuel traits, with low ash and high volatile matter to fixed carbon (VM/FC) ratios, reflecting reduced growth competition. Smaller stems contained more ash and VM/FC in bark. Carbon, hydrogen, and nitrogen contents were not affected by treatments. Single-stem trees had higher hemicelluloses and lower lignin, indicating more complete cell wall development, while crowded, multi-stem conditions increased lignin. Highest extractives were found in bark from low-density single-stem trees. Both total biomass and structural components yields were highest for single-stem trees without row thinning. It highlights the benefits of stem thinning. This study suggests that both quality and quantity of biomass from second-rotation poplar plantation can be influenced by thinning treatments and stem diameter, with potential implications for bioenergy and bio-based chemicals or fuels.

## 1. Introduction

Bioenergy has been the largest renewable energy source, contributing to 55 % of the total renewable energy supply on average and more than 6 % of the global energy supply [1,2]. However, biomass needs to be sustainably produced to meet the demand without adversely affecting climate and biodiversity [3,4]. The European commission report [3] highlighted that afforestation of abandoned agricultural land contributes positively to both biodiversity and climate change in short term. One option of afforestation process is the usage of poplars, that is currently established on abandoned agricultural land [5–7] areas that are not used for food or feed production. The key advantages of this species include a shorter rotation period (15–30 years) and higher biomass productivity than conifer species, and the capacity for regeneration after harvest without replanting [8–10]. High biomass production of poplars and hybrid aspen can be achieved through thinning operations of varying intensity and by removing either whole-tree biomass or only logs. Variations in rotation duration, stem density, and spacing influence tree diameter and branching, which in turn lead to differences in wood properties and their suitability for different end uses [3,11,12]. Therefore, it is essential to account for the effects of forest management practices on biomass properties.

Important properties of biomass depend on the application areas. Generally, energy use from forest biomass is realized by thermochemical conversion technologies, which include mainly combustion, gasification, and pyrolysis based on the operating conditions and main products. Currently, combustion is mostly used for heat and power production using forest biomass as feedstock [13]. In addition, gasification and pyrolysis are emerging technologies mainly to produce biochar, bio-chemicals and biofuels [13–15]. The conversion efficiency is

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https://doi.org/10.1016/j.biombioe.2025.108856
Received 16 October 2025; Received in revised form 5 December 2025; Accepted 15 December 2025
Available online 19 December 2025

significantly influenced by the type of feedstock. Woody biomass is often the most preferred feedstock for thermochemical conversion processes due to its favorable characteristics, including low moisture content, low ash content, and relatively high lignin content [16,17]. It is typically classified into softwood and hardwood. Both exhibits distinct structural and compositional properties which influence thermochemical conversion processes in different ways [18–20]. Previous studies have examined the properties of various feedstocks and their impact on conversion processes [21–24]. However, the effect of forest management practices on feedstock properties remains insufficiently explored [12].

It is clear that forest management influences tree growth and can have either positive or negative effects on biomass quality. Therefore, there is a need for comprehensive studies to assess the relationship between forest management strategies and biomass quality. This knowledge can contribute to the development of informed forest management pathways to produce trees with desirable traits for thermochemical conversion and the optimization of the whole value chain. Additionally, insights gained from this research can be applied to simulate and optimize process parameters for the efficient conversion of feedstocks into desired products. Feedstock properties can be classified as physical properties and compositional properties. Physical properties such as density, pore structure, cell wall thickness etc. affect the feedstock processability. Various types of chemical compositions such as lignocellulosic content, extractives, fuel composition (i.e. moisture, volatile matter, fixed carbon, and ash content), and elemental composition (both main elements (C, H, O, N) and ash-forming elements) can directly affect product yield and distribution, reaction kinetics, and conversion cost [25].

The fast-growing broad-leaved trees belong to the category of hardwood trees. They have different growth patterns, structure and wood chemistry compared to softwoods such as Spruce and Pine [18,26]. The major risk factors associated with spruce plantations are their vulnerability to wind, pests, and rot. Monoculture spruce plantations also reduce biodiversity and recreational value due to their dense and dark structure [27,28]. As an alternative, the establishment of fast-growing deciduous trees, such as poplar and hybrid aspen is proposed. These species offer economic viability, resilience to storm and pest attack, and are suitable for bioenergy production [28,29]. These tree species also allow for shorter harvest rotations, more efficient land use, and biodiversity conservation. Fast growing broadleaves such as hybrids of aspen and poplar are popular for use in short-rotation wood production and have been established in many parts of the world [5–7].

Previous studies investigated the effect of forest management on biomass productivity and wood properties in both conifers [6,30–34] and short-rotation poplar systems [35]. These studies focused on physical and mechanical properties of timber which includes wood density, fiber characteristics, cell wall thickness and tracheid properties. Several studies also investigated the influence of thinning on tree growth in terms of diameter, height and crown size [36–39]. Thinning is one commonly used management method to reduce competition between trees and increase growth of the remaining crop trees. A few studies investigated the effect of forest management, especially thinning, on wood chemistry. Singh et al. [40] reported that increased management intensity tends to alter nutrient cycling and wood production. Jyske et al. [41] found that long-term thinning in Norway spruce increased growth rate and reduced wood density although wood chemistry and tracheid properties remained unchanged. Grigoreva et al. [42] reported that different management techniques including thinning in pine trees, increased early- and late-wood width and cell wall thickness, and changed wood density. While the fuel characteristics of short-rotation (2–5 years) Populus systems have been extensively investigated [21,43] there is a notable lack of information concerning long-rotation regimes (15–30 years). This represents a significant knowledge gap, as long-rotation systems may exhibit different growth dynamics, bark-to-stemwood ratio, and wood chemical composition compared to short-rotation systems. It remains unclear whether the effect of forest management on structural and chemical composition of wood observed in conifers or short rotation populus can be directly extrapolated to these species.

The main objective of this study is to elucidate the impact of forest management on the biomass properties of poplar, which belongs to the category of fast-growing broad-leaved trees. Fuel composition, elemental composition, structural composition and extractive content were studied for second rotation poplar plantation (clone OP42) in Southern Sweden. At harvest the trees were 18 years and grown in different thinning treatments for 11 years [44]. The aim is to propose management pathways that enhance both the quality and quantity of long-rotation (15–30 years) poplar biomass for energy, chemicals or fuel applications.

## 2. Methods

### 2.1. Experimental design and thinning treatments

This study was conducted on second rotation poplar trees, clone OP42 *(Populus maximowiczii* A. Henry × *P. trichocarpa* Torr. and Gray*)* located near Skurup in southern Sweden. Initially, the poplar plantation were established by planting bare rooted plants with a spacing of 3 m (1100 stumps ha$^{-1}$) and harvested after 15 years and left for resprouting. Seven years after the first harvest, four thinning treatments were applied. These treatments combined two methods which are row thinning and stem thinning and differed in thinning intensity (i.e., the number of stems retained after thinning). In row thinning method (550 stumps ha$^{-1}$), the distance between stumps were increased by removing all the stems for every other row but the emerging muti stems groups were maintained resulting in 3000 stems ha-1. In stem thinning method (1100 stumps ha$^{-1}$ and 550 stumps ha$^{-1}$), the largest stem from each stump was kept and all other stems were removed, thus here single trees emerge from the stump. One plot was left untreated i.e. 1100 stumps with emerging muti stems groups were maintained resulting in 6000 stems ha$^{-1}$. For clarity, treatments were named according to thinning method (row thinning (550/1100 stumps ha$^{-1}$) and stem thinning: SS (single-stem growth) and MS (multi-stem growth). The resulting thinning treatments were named (Table 1) as: (1) 1100-MS, no thinning treatments were performed and (1100 stumps ha$^{-1}$, 6000 stems ha$^{-1}$), (2) 550-MS, light thinning through row thinning without stem thinning (550 stumps ha$^{-1}$, 3000 stems ha$^{-1}$), (3)1100-SS, medium thinning through stem thinning without row thinning (1100 stumps ha$^{-1}$, 1100 stems ha$^{-1}$), (4) 550-SS, heavy thinning through both row thinning and stem thinning (550 stumps ha$^{-1}$, 550 stems ha$^{-1}$). The number of stumps and stems are retained after thinning. This naming explicitly reflects the retained stump density and the number of stems per stump (MS = multiple stems present on each stump; SS = single-stem on each stump), the environmental conditions for the retained trees and competition between stems sharing the same root system. These codes correspond to names 'control,' 'row thinning,' 1100 and, 550 in Reference [44], with the modified naming adopted here solely for convenience and to provide clearer interpretation of thinning type and spatial arrangement.

The thinning treatments were performed on 12 plots, and four plots were left untreated or unthinned plots (Figs. 1 and 2a, 2b). There are four plots per treatment that are distributed randomly. The plot size was 24 × 24 m with a buffer zone of 6 m between the treatments. The

**Table 1**
Thinning treatments.

| Number of stumps ha$^{-1}$ | Number of stems/stump | |
|---|---|---|
| | Single stem | Multistem |
| 1100 | 1100-SS | 1100-MS |
| 550 | 550-SS | 550-MS |

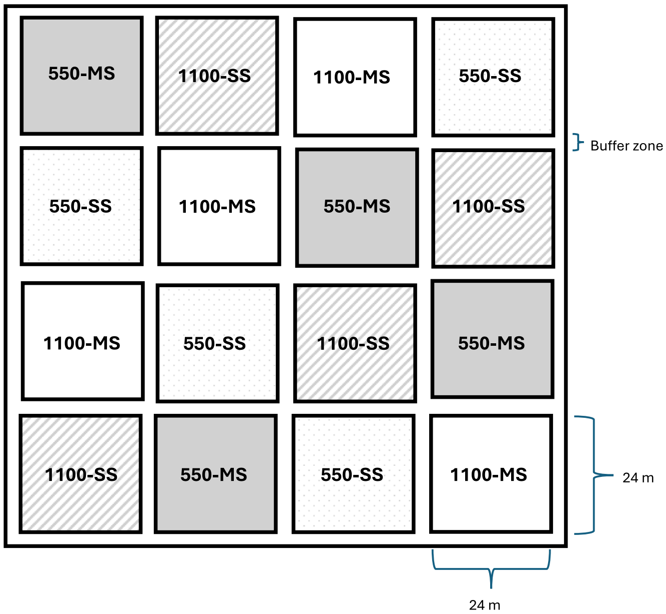


**Fig. 1.** Experimental design of the plots with thinning treatments.

thinning treatments influenced the stem diameter distribution in these plots as shown in Table 2, adopted from Ref. [44].

### 2.2. Sample collection and preparation

Eleven years post-thinning (stand age of 18 years) trees were collected from all 16 plots, i.e. four plots per thinning treatment (1100-Ms, 550-MS, 1100-SS and, 550-SS). From 1100-MS plots, trees were randomly collected for three diameter ranges (8–10 cm, 15–17 cm, and 19–24 cm). From 550-MS and 1100-SS plots, trees within the 19–24 cm diameter range were collected, while from 550-SS plots, trees in the 28–32 cm diameter range were collected. For each diameter class within each thinning treatment, two trees were sampled per plot, giving a total of eight trees per diameter class and treatment (2 trees × 4 plots). The trees were collected as wood discs of 3–5 cm thickness from every 2 m height from breast height (i.e. 1.3 m above the ground) of the tree. All the discs were air dried, and bark was removed from the stemwood to prepare individual samples of bark (BM) and stemwood (SM). Each collected wood disc was chipped using a woodchipper (Lumag Flismaskin Rambo HC15E) and milled (SM300 with 2 mm sieve, from Retsch) separately first and then mixed at a ratio proportional to the cross-section area of each disc to generate the representative sample of the whole tree. Finally, samples from all eight trees with the same thinning conditions and diameter ranges were mixed to reduce the uncertainty due to individual tree variations. More detailed description of the sample collection and preparation methods are described in the supplementary material (Table A.1).

### 2.3. Analysis methods

The effect of thinning was checked using two-way ANOVA. Factor 1: Stems per stump (reflects whether stem had to compete with other stems sharing the same stump), Levels: single stem per stump (stem thinning occurred) and multi-stem per stump (no stem thinning). Factor 2: Stump density (reflects the difference in available land for each root system), Levels: 1100 stumps $ha^{-1}$(no row thinning), 550 stumps $ha^{-1}$(row thinning applied). The effect of diameter was studied only in 1100-MS (unthinned stand) and checked using one-way ANOVA (factor: stem diameter, Levels: 9–11 cm, 12–15 cm and 22–25 cm). The effect was considered significant with the confidence interval of 95 % (i.e., P-value $<0.05$).

#### 2.3.1. Proximate and ultimate analyses

The representative samples of particle size 1–2 mm was used for proximate analysis. The ash content was determined according to SS-EN-ISO 18122:2015 by heating the samples in an open crucible to 250 °C (4.5 °C/min), followed by 550 °C (10 °C/min) using an electric muffle furnace (LE 1/11, Nabertherm) and kept until achieving constant mass. To determine the content of volatile matter (VM), the samples in a crucible with a lid were placed in the muffle furnace at 900 °C for 7 min according to SS-EN-ISO 18123:2015. Both measurement data was corrected to dry basis with the moisture content measured by moisture analyzer (MJ33 moisture analyzer, Mettler Toledo). The fixed carbon (FC) content was calculated by difference from the ash content and volatile matter content. For each analysis, three replicates were performed.

Finely ground samples were used for ultimate analysis to determine the total content of carbon, hydrogen and nitrogen. The analysis was carried out according to SS-EN-ISO 16948:2015 using an elemental analyzer (EA3000, Eurovector). For each sample, three replicates were made.

#### 2.3.2. Structural composition analysis

Another way to determine the composition of biomass is based on its structural composition. Forest biomass, or more broadly, lignocellulosic biomass mainly consists of cellulose, hemicellulose, lignin, extractives, and ash-forming matter. The ash content was determined by the method described in section *2.3.1*. All the other fractions were determined by following the laboratory analytical protocol from the National Renewable Energy Laboratory (NREL).

The extractives were determined according to the NREL LAP-010 protocol [45], in a Soxhlet extraction system using absolute ethanol (purity ≥99.8 %) as solvent, under reflux for 20 h (six Soxhlet cycles per hour). 3.000 ± 0.005 g of samples with 1–2 mm of sieve size were used for extraction. After the extraction, the solvent was evaporated using a rotary evaporator at the temperature of 40 °C for the determination of mass. The solid residue was dried in an oven at the temperature of 40 °C for 24 h. The amount of extractives was determined by the mass ratio of the extracted sample to the original biomass, and the result was reported as a percentage of the original sample. For each sample, two replicates were performed. The mass closure was calculated, and the difference between the measured components (percentage of extractives and percentage of solid residue) and the percentage of total solid content in the original biomass was found to be less than 5 %.

Determination of structural carbohydrates, as well as acid-soluble and insoluble lignin, were performed according to the National Renewable Energy Laboratory protocols [46,47]. Sulphuric acid (72 %, 3.00 ± 0.01 ml) was added to 300 ± 10 mg of the extracted sample (1–2 mm) in a pressure tube and placed in a water bath at 30 °C for 1 h with constant stirring at every 5–10 min. Next, it was diluted to 4 % concentration by adding 84 ± 0.04 ml of deionized water. The samples were then autoclaved for 1 h at a temperature of 121 °C to complete the hydrolysis. After the hydrolysis, the samples were filtered, and the acid-insoluble lignin was determined as the mass of the solid residue after drying at 105 °C. The acid-soluble lignin was determined in the filtrate by measuring the absorbance at 240 nm using a UV/VIS spectrophotometer (UV-1280-UV-VIS Spectrophotometer, Shimadzu). The remaining acid solution was neutralized and used for sugar analysis. The composition of polysaccharides was evaluated by determining the content of monosaccharides (rhamnose, arabinose, xylose, galactose, mannose and glucose) in the hydrolysate. The measurement was conducted using high-performance anion exchange chromatography (HPAEC) (Thermo Scientific, Waltham, MA, USA) using a CarboPac PA-20 column (3 × 150 mm; Dionex™, Thermo Scientific) with a pulsed amperometric detector equipped with a gold electrode. The analysis was performed for 60 min at 30 °C with a flow rate of 0.4 ml/min. The mobile phase consisted of Eluent A (deionized water), Eluent B (200 mM NaOH), and Eluent C (100 mM NaOAc in 100 mM NaOH). The eluent

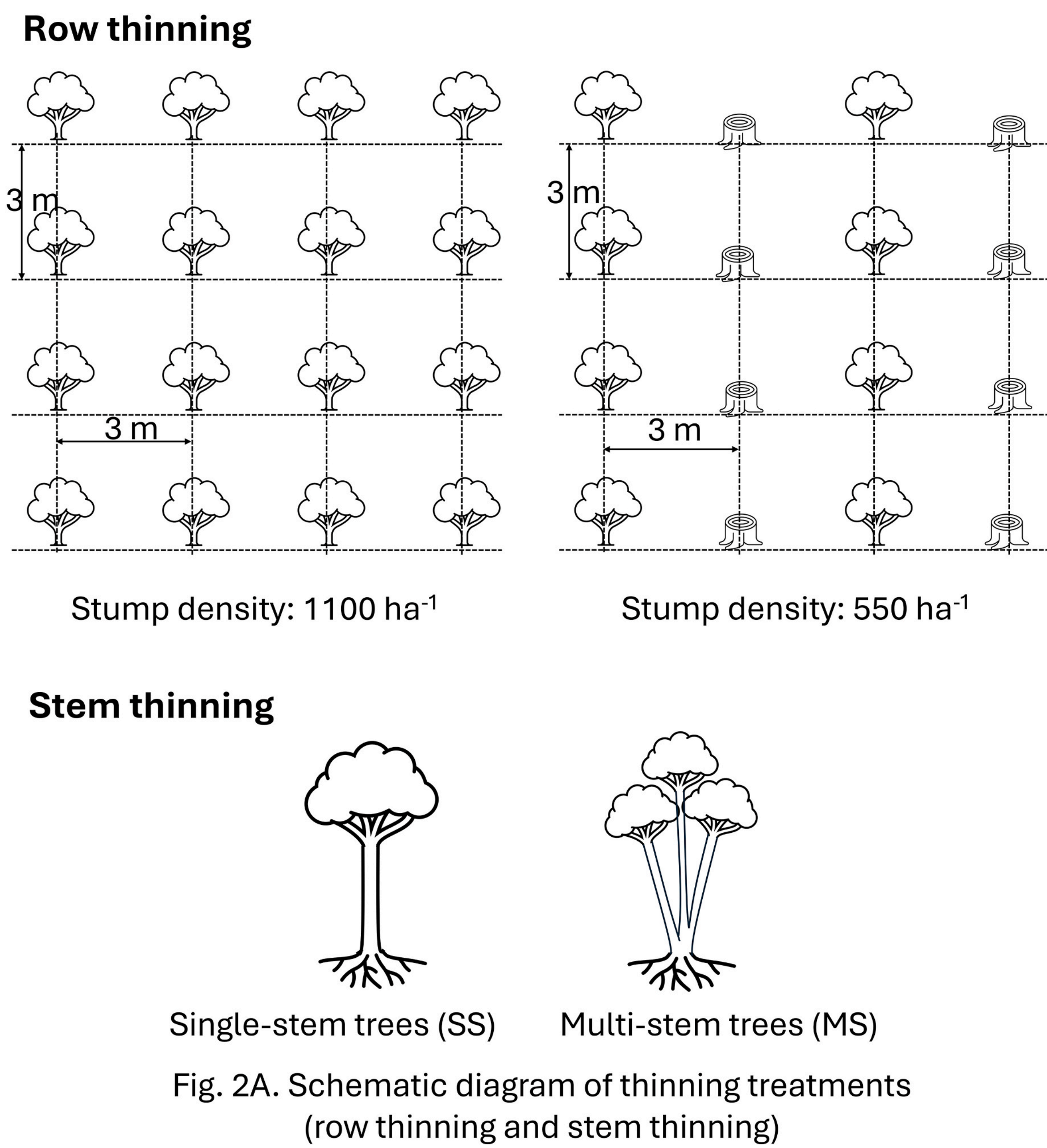


**Fig. 2a.** Schematic diagram of thinning treatments (stem thinning and row thinning).

composition was varied according to the following profile: 0–18min, isocratic step (98.8 % A and1.2 % B); 18–20 min, increase of B from 1.2 to 50 % in A; 20–30min, 50 % A and 50 % B; 30.1–46 min, 100 % C; 46.1–50 min, 100 % B; and 50.1–60 min, 98.8 % A and 1.2 % B.

### *2.4. Estimation of expected yield of structural components from the stand*

Total stemwood biomass production (Mg DM $ha^{-1}$) was adopted from Ref. [44], which reported stand level production of stemwood with bark. In our study, compositional analysis was conducted separately for stemwood and bark from trees representing the mean diameter class of each stand. The relative proportions of bark and stemwood within the total biomass were estimated using data from sampled trees, where cross-sectional discs of 5 cm thickness were obtained at every 2-m interval along the stem. The dry weights of bark and stemwood were measured separately for each disc, and the resulting ratios were used to calculate the total wood biomass into bark and stemwood components.

The structural composition data for bark and stemwood (section 3.3), obtained on a dry basis, were used to calculate the expected yields of cellulose, hemicellulose, lignin and, extractives from total stemwood and bark. In this study, we analyzed only living biomass. Although the original yield data included total biomass (living, thinning removals, and dead biomass), the diameters of trees at the time of sample collection differed from those at the time of thinning (11 years earlier). To avoid inaccuracies arising from the changes in stem diameter, thinning removals were not included. In addition, dead biomass in the stand reflects tree mortality accumulated over many years, with different stages of decomposition including fungal decay. Because of this variability, its chemical composition is not comparable to those of living stems. Dead biomass was excluded from this study to avoid inducing additional uncertainties in the results.


**Fig. 2b.** Representative stand photographs corresponding to each thinning treatments. 1100-MS: no thinning, 550-MS: row thinning without stem thinning, 1100-SS: stem thinning without row thinning, 550-SS: stem thinning and row thinning. (photographs taken in February and the white colouration on the ground is snow).

**Table 2**
Number of stumps, number of stems, stem diameter distribution and mean stem diameter in each treatment.

| Thinning treatment | Number of stumps ha$^{-1}$ | Number of stems ha$^{-1}$ | Stem diameter distribution (cm) | Mean stem diameter (cm) |
|---|---|---|---|---|
| 1100-MS | 1100 | 6000 | 10–30 | 19 |
| 550-MS | 550 | 3000 | 10–30 | 20 |
| 1100-SS | 1100 | 1100 | 20–30 | 22 |
| 550-SS | 550 | 550 | 20–40 | 28 |

## 3. Results and discussion

### 3.1. Fuel composition

The proximate analysis results (Tables 3 and 4) showed similar values with the existing literature values for poplar [48–50]. Across all samples, bark consistently exhibited higher ash content and lower volatile matter to fixed carbon (VM/FC) ratios than stemwood, which aligns with general trends in biomass composition.

#### 3.1.1. Effects of thinning treatment on fuel composition

Samples from different thinning treatments showed a distinct trend influenced by both stump density (1100 vs. 550 stumps per hectare) and stem type (single stem vs. multi-stems per stump). The two-way ANOVA showed that both stump density and stem type had a significant effect on ash content in stemwood (*Stump density:* $P = 0.0002$*; Stem type:* $P = 0.0002$) and bark (*Stump density:* $P = 2.40E\text{-}06$*; Stem type:* $P = 1.0355E\text{-}07$). Similarly, both factors significantly influenced the VM/FC ratio in stemwood (*Stump density:* $P = 6.576E\text{-}09$*; Stem type:* $P = 3.912E\text{-}09$) and bark (*Stump density,* $P = 1.6483E\text{-}05$*; Stem type:* $P = 1.32E\text{-}08$). Additionally, a significant interaction effect between stump density and stem type was observed for the VM/FC ratio in both stemwood ($P = 6.62E\text{-}06$) *and bark* ($P = 1.9818E\text{-}07$), indicating that the effect of one factor on VM/FC ratio depends on the level of the other.

The highest ash content was found in multi-stem trees with low stump density (550-MS), followed by multi-stem trees with high stump density (1100-MS), single stem trees with low stump density (550-SS), and single-stem trees with high stump density (1100-SS). The trend was consistent for both stemwood and bark. These results suggest that thinning by retaining only the largest stems and increasing stump density reduces ash content. The high ash content observed in multi-stem trees is likely attributable to their increased nutrient demand required to support the growth of multiple shoots, resulting in enhanced mineral uptake. However, nutrient uptake is not solely demand-driven; it is also influenced by mineral concentration in the surrounding environment [51]. Lower stump number density per unit area may enhance nutrient uptake by increasing the soil volume accessible to individual stumps. These findings indicate that plants adjust nutrient uptake and allocation strategies based on both internal growth demand and external resource availability.

**Table 3**
Effects of thinning treatment on fuel composition.

| Sample | Treatment | Ash content % (Dry basis) | Volatile matter (VM)% (Dry basis) | Fixed carbon (FC) % (Dry basis) | VM/FC ratio % (Dry basis) |
|---|---|---|---|---|---|
| Stemwood | 1100-MS | 0.65 ± 0.01 | 80.45 ± 0.07 | 11.62 ± 0.06 | 6.92 ± 0.05 |
| | 550-MS | 0.76 ± 0.02 | 79.77 ± 0.06 | 12.82 ± 0.08 | 6.22 ± 0.04 |
| | 1100-SS | 0.54 ± 0.05 | 81.72 ± 0.07 | 11.29 ± 0.02 | 7.24 ± 0.02 |
| | 550-SS | 0.64 ± 0.02 | 80.39 ± 0.01 | 11.57 ± 0.02 | 6.95 ± 0.01 |
| Bark | 1100-MS | 6.69 ± 0.12 | 69.91 ± 0.10 | 16.69 ± 0.06 | 4.19 ± 0.02 |
| | 550-MS | 7.11 ± 0.02 | 68.42 ± 0.08 | 16.98 ± 0.07 | 4.03 ± 0.02 |
| | 1100-SS | 6 ± 0.03 | 70.54 ± 0.17 | 16.27 ± 0.19 | 4.34 ± 0.06 |
| | 550-SS | 6.46 ± 0.02 | 71.48 ± 0.10 | 14.56 ± 0.10 | 4.91 ± 0.04 |

**Table 4**
Effects of stem diameters on fuel composition in unthinned stand (1100-MS).

| Sample | Stem diameters (cm) | Ash content % (Dry basis) | Volatile matter (VM)% (Dry basis) | Fixed carbon (FC) % (Dry basis) | Volatile matter/Fixed carbon ratio % (Dry basis) |
|---|---|---|---|---|---|
| Stemwood | 8–10 | 0.91 ± 0.10 | 80.05 ± 0.04 | 11.75 ± 0.07 | 6.81 ± 0.04 |
| | 15–17 | 0.74 ± 0.03 | 81.19 ± 0.08 | 10.8 ± 0.10 | 7.47 ± 0.08 |
| | 19–24 | 0.64 ± 0.01 | 80.45 ± 0.07 | 11.62 ± 0.06 | 6.92 ± 0.05 |
| Bark | 8–10 | 7.15 ± 0.03 | 70.04 ± 0.07 | 15.43 ± 0.05 | 4.54 ± 0.02 |
| | 15–17 | 7.21 ± 0.03 | 69.40 ± 0.20 | 15.99 ± 0.21 | 4.35 ± 0.07 |
| | 19–24 | 6.69 ± 0.12 | 69.91 ± 0.10 | 16.69 ± 0.06 | 4.19 ± 0.02 |

The differences in ash content affect the absolute values of both volatile matter (VM) and fixed carbon (FC). Therefore, the VM/FC ratios were used to examine the change in the composition of combustible fraction without the influence of ash content changes. In stemwood, the highest VM/FC ratio was recorded in 1100-SS, followed by 550-SS, 1100-MS, and 550-MS. This suggests that trees subjected to heavier thinning and maintaining a single stem allocate more resources toward rapid growth, leading to increased accumulation of metabolically active compounds that contribute to volatile matter. This supports the resource allocation hypothesis, where faster-growing trees prioritize resource investment into growth-related compounds, resulting in a higher VM/FC ratio [51,52]. Whereas, in bark, 550-SS contained the highest VM/FC ratio instead of 1100-SS among the single stem treatment. This could be due to the increased bark thickness in 550-SS resulting from larger stem diameter, where the thicker bark may be enriched with more extractives that contribute to higher volatile matter [53–56]. This suggests that in managed stands with high growth rates, stemwood primarily allocates resources toward growth, while bark prioritizes defense.

#### 3.1.2. Effects of stem diameters on fuel composition

Table 4 shows the effects of stem diameter on fuel composition. The one-way ANOVA showed that stem diameter (8–10 cm, 15–17 cm, and 19–24 cm in unthinned stand) had a significant effect on ash content in both stemwood ($P = 0.004$) and bark ($P = 0.0002$).

In stemwood, ash content has increased as the diameter decreased. This suggests that smaller diameter trees accumulate minerals (ash-forming elements) at a higher concentration per unit mass of stemwood than bigger trees. One possible explanation for the higher ash content in smaller or slower-growing trees is that, as growth rate decreases, the smaller mass of stemwood is exposed to the same amount of mineral-containing water recirculation, leading to a relatively greater accumulation of minerals [51]. Previous studies have also suggested that slowly growing trees may allocate more resources to defense and storage rather than growth, which could contribute to higher concentrations of ash-forming elements [52,53]. However, it is not yet clear whether these differences are due to changes in cell structure or other physiological mechanisms. However, in bark, there was no clear trend in the effect of stem diameter. Medium diameter trees (15–17 cm) showed the highest ash content, followed by the smallest (8–10 cm), and the largest diameter (19–24 cm) trees. This could be because the relative bark diameters (hence, relative mass) decrease with the increase of stem diameter, which counteracts against the trend found in the stemwood [57–59].

Similarly, stem diameter significantly influenced the VM/FC ratio in stemwood ($P = 2.043E\text{-}05$) and bark ($P = 0.0002$). The stemwood VM/FC was highest in medium-diameter trees, followed by large-diameter trees and small-diameter trees. Conversely, in bark, the trend was reversed, with small trees showing the highest VM/FC, followed by medium trees, and bigger trees. This inverse relationship between stemwood and bark suggests that growth rate differentially influences their composition across different tissues. Compared to trees with diameters of 19–24 cm, those in the 8–10 cm range exhibit slower growth. According to the growth rate hypothesis by Ref. [53], plants experiencing limited growth tend to allocate more resources toward defense rather than biomass production. In trees, extractives play central roles in defense strategies and are present in high amounts in bark. The higher VM/FC ratio observed in the bark of smaller trees may be attributed to their elevated extractive content, as many of these compounds are highly volatile [52,54–56]. In contrast, in stemwood, larger trees tend to have a greater proportion of stem tissue, which may contribute to a higher VM/FC ratio compared to smaller trees. The results indicate that in unmanaged stands, trees tend to prioritize defense over growth in both stemwood and bark.

### 3.2. Effects of thinning treatments and stem diameters on elemental composition

Carbon, hydrogen, and nitrogen composition displayed no significant differences across thinning treatments and stem diameters (Tables 5 and 6). Nitrogen content was higher in the bark compared to the stemwood. Meanwhile, carbon and hydrogen levels showed a slight increase in the stemwood relative to the bark. These values are consistent with those previously reported for poplar biomass [17,48,49].

### 3.3. Structural composition (cellulose, hemicelluloses, lignin, and extractives)

The structural carbohydrates analyzed include cellulose, hemicelluloses (comprising arabinose, galactose, xylose, mannose, and uronic acid), lignin (both acid-soluble and acid-insoluble forms), and extractives. The results indicate that cellulose and hemicelluloses content were consistently higher in stemwood than in bark, whereas bark exhibited higher lignin and extractive content across all samples. Within the hemicelluloses fraction, stemwood contained a higher proportion of xylose and mannose, while bark was enriched in arabinose, galactose, and uronic acid. The detailed composition of hemicelluloses and lignin components given in supplementary material (Tables A.2-A.5). This distribution aligns with the general trend reported in poplar biomass composition [22–24,34]. However, some additional variations were observed because of thinning treatments and diameter.

The biomass compositional values are reported on a received basis (Tables 7 and 9). However, to accurately compare cellulose, hemicelluloses, and lignin contents, values are presented on an extractive-free basis (Tables 8 and 10). It should be noted that total mass closure calculations are based on the received basis.

#### 3.3.1. Effects of thinning treatment on structural composition

The two-way ANOVA indicated that in stemwood, both hemicelluloses and lignin contents were affected by the number of stems per stump (hemicelluloses: $P = 0.021$, lignin: $P = 0.048$). The hemicelluloses content was higher in single stem treatment than multi-stem. Whereas,

**Table 5**
Effects of thinning treatments on elemental composition (on dry basis).

| Sample | Treatment | N (dry basis %) | N (dry ash free basis %) | Std Deviation % | C (dry basis %) | C (dry ash free basis %) | Std Deviation % | H (dry basis %) | H (dry ash free basis %) | Std Deviation % |
|---|---|---|---|---|---|---|---|---|---|---|
| Stemwood | 1100-MS | 0.26 | 0.26 | 0.03 | 51.47 | 51.81 | 0.19 | 6.37 | 6.41 | 0.16 |
| | 550-MS | 0.29 | 0.29 | 0.01 | 50.14 | 50.52 | 0.36 | 5.96 | 6.01 | 0.22 |
| | 1100-SS | 0.29 | 0.29 | 0.03 | 50.04 | 50.31 | 0.48 | 6.19 | 6.22 | 0.25 |
| | 550-SS | 0.33 | 0.33 | 0.04 | 50.78 | 51.11 | 0.49 | 6.05 | 6.09 | 0.3 |
| Bark | 1100-MS | 0.76 | 0.81 | 0.05 | 48.75 | 52.25 | 0.49 | 5.79 | 6.21 | 0.05 |
| | 500-MS | 0.76 | 0.82 | 0.02 | 49.12 | 52.88 | 0.27 | 5.78 | 6.22 | 0.07 |
| | 1100-SS | 0.75 | 0.80 | 0.05 | 48.97 | 52.10 | 0.34 | 5.89 | 6.27 | 0.04 |
| | 550-SS | 0.74 | 0.79 | 0.05 | 48.85 | 52.22 | 0.41 | 5.85 | 6.25 | 0.04 |

**Table 6**
Effects of stem diameters on elemental composition in unthinned stand (on dry basis).

| Sample | Diameter (cm) | N (dry basis %) | N (dry ash free basis %) | Std Deviation (%) | C (dry basis %) | (C dry ash free basis %9 | Std Deviation % | H (dr basis %) | H (dry ash free basis %) | Std Deviation % |
|---|---|---|---|---|---|---|---|---|---|---|
| Stemwood | 8–10 | 0.33 | 0.33 | 0.03 | 49.75 | 50.21 | 0.34 | 6.18 | 6.24 | 0.25 |
| | 15–17 | 0.34 | 0.34 | 0.02 | 49.87 | 50.24 | 0.39 | 6.29 | 6.34 | 0.08 |
| | 19–24 | 0.26 | 0.26 | 0.03 | 51.47 | 51.80 | 0.19 | 6.37 | 6.41 | 0.16 |
| Bark | 8–10 | 0.75 | 0.81 | 0.01 | 49.74 | 53.57 | 0.50 | 5.84 | 6.29 | 0.23 |
| | 15–17 | 0.75 | 0.81 | 0.02 | 48.68 | 52.46 | 0.49 | 5.77 | 6.22 | 0.03 |
| | 19–24 | 0.76 | 0.81 | 0.05 | 48.75 | 52.25 | 0.49 | 5.79 | 6.21 | 0.05 |

**Table 7**
Effects of thinning treatment on structural components (received basis).

| | Sample | Cellulose (%) | Hemicelluloses (%) | Lignin (%) | Extractives (%) | Ash (%) | Total (%) |
|---|---|---|---|---|---|---|---|
| Stemwood | 550-SS | 40.85 ± 0.70 | 32.81 ± 0.07 | 24.97 ± 0.62 | 2.33 ± 0.29 | 0.64 ± 0.02 | 101.60 ± 0.98 |
| | 1100-SS | 41.55 ± 0.00 | 32.47 ± 0.22 | 25.40 ± 0.44 | 2.26 ± 0.11 | 0.54 ± 0.05 | 102.21 ± 0.50 |
| | 550-MS | 41.22 ± 0.62 | 30.94 ± 0.63 | 26.28 ± 1.30 | 2.13 ± 0.04 | 0.76 ± 0.02 | 101.33 ± 1.57 |
| | 1100-MS | 41.24 ± 0.10 | 30.99 ± 0.58 | 26.76 ± 0.44 | 2.18 ± 0.15 | 0.65 ± 0.01 | 101.82 ± 0.75 |
| Bark | 550-SS | 26.74 ± 0.21 | 31.98 ± 0.35 | 25.69 ± 0.09 | 12.28 ± 0.17 | 6.46 ± 0.02 | 103.15 ± 0.46 |
| | 1100-SS | 27.07 ± 0.06 | 31.83 ± 0.22 | 28.14 ± 0.14 | 9.36 ± 0.22 | 6.00 ± 0.03 | 102.41 ± 0.35 |
| | 550-MS | 27.73 ± 0.24 | 30.14 ± 0.15 | 27.80 ± 0.20 | 9.99 ± 0.39 | 7.11 ± 0.02 | 102.77 ± 0.52 |
| | 1100-MS | 28.12 ± 0.58 | 30.79 ± 0.53 | 28.55 ± 0.41 | 8.92 ± 0.02 | 6.69 ± 0.12 | 103.07 ± 0.89 |

**Table 8**
Effects of thinning treatments on structural components (extractive free basis).

| | sample | cellulose (%) | hemicelluloses (%) | lignin (%) |
|---|---|---|---|---|
| Stemwood | 550-SS | 41.82 ± 0.72 | 33.59 ± 0.07 | 25.57 ± 0.63 |
| | 1100-SS | 42.51 ± 0.00 | 33.52 ± 0.22 | 25.99 ± 0.44 |
| | 550-MS | 42.11 ± 0.63 | 31.61 ± 0.64 | 26.86 ± 1.32 |
| | 1100-MS | 42.16 ± 0.10 | 31.68 ± 0.59 | 27.36 ± 0.45 |
| Bark | 550-SS | 30.48 ± 0.24 | 36.46 ± 0.40 | 29.29 ± 0.11 |
| | 1100-SS | 29.86 ± 0.07 | 35.12 ± 0.25 | 31.05 ± 0.15 |
| | 550-MS | 30.81 ± 0.26 | 33.48 ± 0.16 | 30.89 ± 0.23 |
| | 1100-MS | 30.87 ± 0.64 | 33.8 ± 0.58 | 31.35 ± 0.45 |

lignin content was higher in multi-stem than single stem. Cellulose content, however, showed no significant variation with either factor. In bark, hemicelluloses and lignin contents were significantly influenced by stems per stump (hemicellulose: $P = 0.015$ and lignin: $P = 0.003$), while cellulose content again remained unaffected. Additionally, bark lignin content showed a significant effect of stump density ($P = 0.0021$) and a significant interaction between stump density and stem type ($P = 0.014$). In bark, hemicellulose content was higher in single stem trees than multi stem. The highest bark lignin content was found in trees grown under high stump density with multi-stems; (1100-MS), followed by 1100-SS, 550-MS, and lowest in 550-SS.

**Table 10**
Effects of stem diameter on structural components (extractive free basis).

| | diameter (cm) | cellulose (%) | hemicelluloses (%) | lignin (%) |
|---|---|---|---|---|
| stemwood | 19–24 | 42.16 ± 0.10 | 31.68 ± 0.59 | 27.36 ± 0.45 |
| | 15–17 | 42.33 ± 0.15 | 31.79 ± 0.36 | 27.07 ± 0.63 |
| | 8–10 | 42.41 ± 0.59 | 32.92 ± 0.17 | 27.92 ± 0.50 |
| Bark | 19–24 | 30.87 ± 0.64 | 33.8 ± 0.58 | 31.35 ± 0.45 |
| | 15–17 | 29.82 ± 0.38 | 34.44 ± 0.69 | 32.13 ± 0.12 |
| | 8–10 | 28.32 ± 0.02 | 35.01 ± 1.33 | 32.65 ± 0.15 |

**Table 9**
Effects of stem diameter on structural components (received basis).

| | Diameter (cm) | Cellulose (%) | Hemicelluloses (%) | Lignin (%) | Extractives (%) | Ash (%) | Total (%) |
|---|---|---|---|---|---|---|---|
| stemwood | 19–24 | 41.24 ± 0.10 | 30.99 ± 0.58 | 26.76 ± 0.44 | 2.18 ± 0.15 | 0.65 ± 0.01 | 101.82 ± 0.75 |
| | 15–17 | 41.51 ± 0.15 | 31.18 ± 0.36 | 26.55 ± 0.61 | 1.94 ± 0.05 | 0.74 ± 0.03 | 101.92 ± 0.73 |
| | 8–10 | 41.76 ± 0.58 | 32.42 ± 0.17 | 27.50 ± 0.49 | 1.53 ± 0.08 | 0.91 ± 0.10 | 104.11 ± 0.79 |
| Bark | 19–24 | 28.12 ± 0.58 | 30.79 ± 0.53 | 28.55 ± 0.41 | 8.92 ± 0.02 | 6.69 ± 0.12 | 103.07 ± 0.89 |
| | 15–17 | 26.94 ± 0.35 | 31.11 ± 0.63 | 29.02 ± 0.11 | 9.67 ± 0.40 | 7.21 ± 0.03 | 103.95 ± 0.83 |
| | 8–10 | 25.32 ± 0.02 | 31.30 ± 1.19 | 29.19 ± 0.14 | 10.59 ± 0.02 | 7.15 ± 0.03 | 103.56 ± 1.20 |

These results (Table 8) suggest that thinning the number of stems per stump had a more pronounced effect on hemicelluloses and lignin. In single-stem trees, resources are less divided, possibly allowing for more complete cell wall development, including matrix polysaccharides like hemicelluloses. Lignin accumulation increases with both high stump density and multi-stem growth, suggesting it responds to mechanical stress and competition. Since lignin serves a protective function, it tends to lignify more under crowded or complex growth conditions [52,53].

Some studies indicate that only substantial increases in growth rate result in significant changes in wood chemistry following thinning [41]. Whereas, research on Norway spruce (a softwood) reported increased lignin content due to thinning [60], likely resulting from earlywood development, as earlywood cell walls contain a lignin-rich middle lamella [61]. However, poplar, a fast-growing hardwood, does not exhibit distinct earlywood and latewood characteristics as softwood, which may also explain why thinning did not increase lignin content in this study [18,19].

Regarding extractive content (Table 7), no significant variation was detected in stemwood. Thinning generally increases the heartwood development, which increases the extractive content [35,62]. However, the distinct separation of heartwood and sapwood is more prominent in softwood than hardwood [16,17], which can be the reason for not having a significant change in the extractive content in stemwood. However, ANOVA results indicated significant differences in bark extractive content due to stump density ($P = 0.0002$), number of stems per stump ($P = 0.001$), and their interaction effect ($P = 0.005$). Specifically, 550-SS exhibited the highest extractive content, followed by 550-MS, 1100-SS, and 1100-MS. The increased extractive content in single-stem trees with low stump density is likely due to increased bark thickness resulting from reduced competition and wider spacing. These trees also showed lower lignin content suggesting a negative correlation between extractives and lignin. The increased extractive content may also explain the higher volatile matter content observed in thinned trees, as several studies have demonstrated a positive correlation between extractive content and volatile matter [54–56].

#### 3.3.2. Effects of stem diameters on structural composition

Table 10 shows the effect of stem diameters on cellulose, hemicelluloses and lignin content in unthinned stand. One-way ANOVA indicated no significant differences in cellulose, hemicelluloses, or lignin content in stemwood across stem diameter groups. However, a significant variation in cellulose and lignin content in bark was observed ($P = 0.021$, $P = 0.023$ *respectively*).

Cellulose content in bark increased with stem diameter, while lignin content decreased, indicating growth related shifts in bark composition within the unthinned stand. The higher lignin concentration observed in the bark of smaller trees likely reflects greater investment in defenses under resource-limited conditions [53]. However, this increased lignin content may reduce the proportion of carbon available for cellulose synthesis, resulting in a lower cellulose-to-lignin ratio in the bark of smaller trees.

Extractive content (Table 9) in both stemwood ($P = 0.016$) and bark ($P = 0.012$) varied significantly by tree diameter with contrasting trends in stem wood and bark. In stem wood, extractive content increased with increasing stem diameter, likely due to the higher proportion of stem wood in bigger trees. Although extractives are primarily associated with defense, their accumulation in stem wood may be influenced by overall biomass allocation and metabolic activity associated with rapid growth. In contrast, extractive content in bark decreased with an increase in stem diameter coinciding with reduced lignin and increased cellulose content, indicating a shift from chemical defence toward cell wall development and growth. Since bark serves as the primary protective tissue, it naturally contains higher levels of extractives than stem wood. In smaller trees, slower growth rates invest more in defense mechanisms, which may explain the higher extractive content observed in their bark [52,53].

These patterns suggest that bark and stemwood follow distinct strategies during growth, with bark adapting to mechanical and spatial demands through compositional flexibility, while stemwood shows limited structural investment under a crowded environment.

### 3.4. Expected yields of structural components

The estimated yields of structural components (cellulose, hemicelluloses, lignin and, extractives) from the living biomass varied among thinning treatments (Table 11). Separate yields for stemwood and bark are in supplementary material (Tables A.6 and A.7). The highest total biomass and structural component yield were observed in 1100-SS, with 163.10 Mg DM ha$^{-1}$ of wood (stemwood with bark) biomass yielding 65.94 Mg DM ha$^{-1}$ of cellulose, 52.88 Mg DM ha$^{-1}$ of hemicelluloses, 41.78 Mg DM ha$^{-1}$ of lignin and 4.58 Mg DM ha$^{-1}$ of extractives. This was closely followed by 1100-MS, which produced 161.82 Mg DM ha$^{-1}$ of biomass with 65.24 Mg DM ha$^{-1}$ of cellulose, 50.12 Mg DM ha$^{-1}$ of hemicelluloses, 43.51 Mg DM ha$^{-1}$ of lignin and, 4.3 Mg DM ha$^{-1}$ of extractives. 550-MS produced 148.54 Mg DM ha$^{-1}$ of biomass with 59.68 Mg DM ha$^{-1}$ of cellulose, 45.87 Mg DM ha$^{-1}$ of hemicelluloses, 39.21 Mg DM ha$^{-1}$ of lignin and, 4.07 Mg DM ha$^{-1}$ of extractives. In contrast, 550-SS resulted in significantly lower biomass and structural yields, with 113.10 Mg DM ha$^{-1}$ biomass, 45.05 Mg DM ha$^{-1}$ cellulose, 37.04 Mg DM ha$^{-1}$ hemicelluloses, 28.3 Mg DM ha$^{-1}$ lignin and 3.45 Mg DM ha$^{-1}$ of extractives.

These results suggest that moderate thinning(1100-SS), particularly with single-stem spacing, supports higher accumulation of structural components in the remaining stand over the long term. While heavier thinning (550-SS) may initially reduce competition, it appears to lead to reduced total structural yield due to lower biomass production.

When considering only the living biomass component, the total estimated yields of cellulose, hemicelluloses, lignin, and extractives were similar between the 1100-SS and 1100-MS. This is consistent with the comparable living stemwood biomass observed in both treatments. However, it should be noted that the 1100-SS stand had a higher total biomass yield when including thinned and dead biomass [44]. Therefore, although chemical yields appear similar when considering only living trees after thinning, the total potential recovery of structural components would be much higher in the 1100-SS stand when all biomass sources are included.

## 4. Conclusion

This study demonstrated that thinning method and stem diameter significantly influence the fuel and lignocellulosic composition of poplar from a second-rotation plantation. Thinning method significantly impacted ash content and VM/FC ratios, with single-stem trees at higher stump density (1100-SS) exhibiting the most favorable fuel quality—lower ash and higher VM/FC. These trends support the idea that reduced competition and focused growth enhance biomass quality for combustion applications. Stem diameter also influenced these properties, with smaller trees accumulating more ash and higher VM/FC ratios

**Table 11**
Expected yield of structural components in total living wood biomass (excluding thinning removals dead biomass) after thinning.

| Treatment | Total living wood biomass (Mg DM ha$^{-1}$) | cellulose (Mg DM ha$^{-1}$) | hemicelluloses (Mg DM ha$^{-1}$) | lignin (Mg DM ha$^{-1}$) | extractives (Mg DM ha$^{-1}$) |
|---|---|---|---|---|---|
| 550-SS | 113.10 | 45.05 | 37.04 | 28.3 | 3.45 |
| 1100-SS | 163.10 | 65.94 | 52.88 | 41.78 | 4.58 |
| 550-MS | 148.54 | 59.68 | 45.87 | 39.21 | 4.07 |
| 1100-MS | 161.82 | 65.24 | 50.12 | 43.51 | 4.3 |

in bark, reflecting shifts in resource allocation associated with growth rate.

Elemental analysis revealed that carbon, hydrogen, and nitrogen content was significantly not influenced by thinning treatments or stem diameter.

Compositional analysis showed single-stem trees exhibited high hemicelluloses and low lignin content in both stemwood and bark, suggesting more complete cell wall development and high growth rate. Lignin content was highest in high stump density and multi-stem growth in both stemwood and bark, likely reflecting increased mechanical stress and competition in crowded conditions. Extractive content also showed clear trends across treatments. Bark extractives were highest in single-stem trees with low stump density. Extractive content decreased with an increase in stem diameter in bark coinciding with reduced lignin and increased cellulose content. In contrast, extractive content increased with diameter in stemwood.

The overall yields of structural components were predominantly influenced by overall biomass yield, overshadowing the differences in the composition of structural components. The highest yields of structural components were found in the 1100-SS treatment, suggesting that moderate thinning with high stump density and single-stem management not only improves fuel quality but also maximizes the recovery of structural biomass components. On the other hand, the heavy thinning condition (550-SS) resulted in the lowest yield of structural components.

The findings of this study indicate potential implications for biomass utilization in second rotation poplar plantations and similar management systems. Lower ash content in high stump density, single-stem trees may be beneficial for combustion-based applications, as reduced ash may minimize slagging and fouling in boilers. Additionally, the higher VM/FC ratios in these trees could improve thermal efficiency for pyrolysis and gasification processes. The increased extractive content in bark, particularly in thinned stands, could be advantageous for bio-based chemical extraction, while the reduction in lignin content is suitable for bioethanol production. These trends highlight possible management methods for optimizing biomass properties, though further research is needed to confirm their practical significance.

## CRediT authorship contribution statement

**Sruthy Vattaparambil Sudharsan:** Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Data curation. **Henrik Böhlenius:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Marcus Öhman:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization. **Kentaro Umeki:** Writing – review & editing, Supervision, Resources, Methodology, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

We appreciate the financial support provided by Trees For Me (https://treesforme.se/en/), a center of excellence supported by the Swedish Energy Agency and almost 50 stakeholders with grant number [P2021-90272].

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2025.108856.

## Data availability

All the data is presented either in the main article or in supplimentary material.

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