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Effect of torrefaction on physiochemical characteristics and grindability of stem wood, stump and bark

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HIGHLIGHTS

- Changes in chemical composition and grindability of torrefied samples.
- Principal component analyses reveal statistical correlations between grindability and chemical compositions.
- SEM analyses show torrefied sample particles having lower length-to-diameter ratios.

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ABSTRACT

In this work, Norway spruce stem wood, stump and bark were torrefied in a bench scale tubular reactor at 225, 275 and 300 °C with two residence times (30 and 60 min). Effect of torrefaction on general properties, chemical composition, grindability and microstructure and morphology of biomass samples were studied. An increase in heating value and fixed carbon content of the torrefied biomass was observed for increasing torrefaction temperature and residence time. Chemical compositions of torrefied biomass samples considerably changed with increase of torrefaction severity. For the stem wood and stump, the relative hemicellulose content significantly decreased from respectively 42.3% and 29.8% to less than 1% after torrefaction at 300 °C for 60 min. The hemicellulose content of untreated bark decreased from 27.5% to 0.14% after torrefaction at the same conditions. Additionally, the cellulose content of the torrefied bark drastically decreased already to half the initial value at a torrefaction temperature of 275 °C, with only trace amounts left in the 300 °C torrefied products. The grindability of stem wood and stump were substantially improved after torrefaction treatment. The energy required for grinding stem wood and stump torrefied at 225 °C decreased to respectively 87 and 70 kWh/ton, which are less than 50% of the energy needed for grinding the untreated samples. For raw bark, much less grinding energy is required compared to those for raw stem wood and stump, and torrefaction has minor effects on the grindability of bark. The ground torrefied biomass samples have much smaller particles than those of the untreated ones. SEM analysis results show that particles from ground torrefied samples lose their fibrous structure with decrease of length-to-diameter ratios, compared to untreated biomass samples. It explains the shift in particle size distribution curves towards smaller particles as obtained from the sieving tests.

1. Introduction

Adoption and utilization of renewable energy sources are important for the modern society, considering the ever increasing energy demands and severe global warming due to use of fossil fuels. In future energy scenarios, biomass will play an important role in the energy supply [1]. A wide range of energy products can be produced from biomass via thermochemical conversion and biological conversion routes, which can be in the form of solid (bio-solid), liquid (bio-oil) or gas (bio-gas or syngas) [2]. Therefore, biomass is a flexible energy source that can be converted into various energy products to meet different demands. Norway has abundant forest resources and more than 40% of the land is covered by forest [3]. Biomass materials from the forest has a great potential to provide suitable feedstocks for bioenergy.

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However, further development of bioenergy and utilization of biomass in a large scale have been hindered by limitations of the biomass as solid fuel. These limitations are mainly related to physical and chemical properties of the biomass [4,5]. Compared to coal, biomass materials normally have low bulk density, poor grindability, low calorific value, high moisture content and hydroscopicity [6]. These limitations greatly affect the conversion efficiency of biomass materials into energy. In addition, the whole biomass-to-energy value chain is considerably impacted by these limitations due to costly storage, handling and transportation of biomass [7,8]. Among many pretreatment technologies, torrefaction of biomass has gained continuous interests in the past decade [1,5,6,9,10]. Torrefaction is usually conducted in inert atmosphere at a temperature range from 200 to 300 °C, driving out the moisture, and parts of the volatile organic compounds in the biomass [1,11]. Torrefied biomass retains most of the chemical energy in the raw biomass materials. Upon torrefaction, biomass can be ground easily into small particles with higher shape uniformity and sphericity [12–14]. This is mainly due to reduction of moisture content and change of chemical compositions of the raw biomass during torrefaction [10,15,16]. Torrefied biomass with unique properties are more suitable for logistics and further conversion to energy. Key torrefaction process parameters include temperature, residence time, pressure, gas atmosphere and heating rate [1]. These parameters have critical effects on torrefaction behaviour, distribution and properties of torrefaction products and the overall energy and mass conversion efficiency [17]. On the other hand, the characteristics of biomass materials will also play an important role in the torrefaction process.

During harvesting and thinning of forest, stem wood is a main product with residues such as tops and branches as well as the stumps left behind in the forest. It has been reported that stump constitute 22–24% of the stem volume of a mature conifer tree, representing a very significant bioenergy potential [18,19]. A vast amount of bark is generated as the stem wood is debarked before further utilization for pulp and paper and timber products production [20]. Both stump wood and bark are still underutilized resources and have a great potential for energy production. Compared to stem wood, the stump and bark have additional drawbacks as solid fuel, related to their physical properties and appearance, as well as to higher ash/inorganic contents [21,22]. Torrefaction is a promising technology to upgrade bark and stump into high quality solid fuels with more uniform properties. Until now, the biomasses subjected to torrefaction studies have mainly been stem wood from different wood species, agricultural wastes, short rotation coppice and algae [1,13,14,16,23–29]. In comparison to previous work, very little is known about torrefaction behaviours of bark and stump from trees and the properties of their torrefied solid counterparts [22,27]. In addition, previous studies have focused on the effect of process conditions on the mass yield and energy yield of biomass upon torrefaction treatment and general properties of torrefied biomass [10,14,17,28,30]. In the literature, there are detailed studies on chemical composition analyses of untreated wood materials. However, presently, discussion of the effect of torrefaction on chemical compositions of bark and stump wood are rarely found in public available literatures.

The main objective of the present work is to study effects of torrefaction on the physiochemical properties, grinding energy consumption and chemical composition of woody biomasses including stem wood, stump and bark from Norway spruce. The results from this work will contribute to further utilization of torrefied spruce stem and stump wood as upgraded feedstocks suitable for cofiring in power plant or gasification for energy production purpose.

2. Materials and methods

2.1. Biomass materials

In the present work stem wood, stump and bark from Norway spruce (*Picea abies*) were investigated. The Norway spruce trees harvested in South Norway were divided into three parts including trunk (with bark), stump and tops and branches. The trunk wood was debarked to get stem wood and bark. The stem wood was cut into strips and further into cubes with sides of 1 cm. The stump was shredded into chips and those with size of 3–5 cm were subjected to further experiments. The bark was chipped into pieces and the pieces with size of 5–7 cm were used. The stem wood cubes, bark and stump chips were dried at 105 °C for 24 h for further analysis and torrefaction experiments.

As can be seen from Table 1, the stump has similar properties as those of the stem wood. The fixed carbon content of the stump is 1.3% higher than that of the stem wood. On the other hand, the bark contains as much as 23.0% fixed carbon, but also 2.1% ash. Compared to stem wood and stump, contents of inorganic elements in bark are significantly higher as shown in Table 1, the stump has similar properties as those of the stem wood.

2.2. Torrefaction experiments

The torrefaction experiments were conducted in a bench-scale tubular reactor. It includes a tubular vessel, an electrical gas preheater with a temperature controller, a condensate receiver and a gas supply system. For one torrefaction experiment, around 80 g of untreated biomass sample was first loaded into the vessel. After sample loading, the tubular vessel was closed tightly and connected with the gas supply system and the condenser. The tubular vessel was then placed inside an electrically heated furnace and the temperature in the furnace is monitored by three thermocouples located on the top, middle and bottom of the furnace. The tubular vessel is continuously purged with 1 L min^{-1} nitrogen to eliminate presence of oxygen, thereby avoiding possible oxidization and ignition of the sample inside. The sample was heated up at a heating rate of 15 °C/min to three final temperatures (225, 275 and 300 °C). The residence time for one sample at each final temperature was 30 and 60 min, respectively. After each torrefaction experiment, the reactor was cooled down to room temperature with continuous purge of the nitrogen. The cooled torrefied biomass materials were discharged and weighted to determine the solid yield. The mass yield of one torrefaction experiment was calculated as the percentage of initially loaded pre-dried biomass sample, as follows:

$$Mass\ yield = \left(\frac{m_{torrefied}}{m_{untreated}}\right) \times 100 \quad (1)$$

Then the torrefied biomasses were loaded in airtight plastic bags and stored in a desiccator for further studies [10].

Table 1
Properties of the untreated woody biomass (dry basis).

Sample	Stem wood	Stump	Bark
Volatile matter content (wt%, db)	88.12	86.69	74.85
Ash content (wt%, db)	0.31	0.41	2.11
Fixed carbon content (wt%, db)	11.57	12.90	23.04
K (mg/kg, db)	272	245	2011
Ca (mg/kg, db)	1030	1235	7803
Na (mg/kg, db)	22	36	47
Si (mg/kg, db)	82	253	3602

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