



Composition, Utilization and Economic Assessment of Torrefaction Condensates

Leena Fagernäs,* Eeva Kuoppala, and Vesa Arpiainen

VTT Technical Research Centre of Finland Ltd., P.O. Box 1000, 02044 VTT, Espoo, Finland

ABSTRACT: The aim of this study was to determine the yields and chemical compositions of condensates formed at torrefaction conditions with different kinds of feedstocks and to assess their utilization from an economic perspective. Test runs for spruce and bamboo were carried out with a slow pyrolysis test rig, and the liquids collected at 20–105, 105–240, and 240–300 °C temperature ranges were analyzed for chemical characteristics and compositions. The results were compared with those obtained earlier for a birch condensate. The mass yields and compositions of condensates differed between the feedstocks and the temperature ranges. The amount of organic compounds in the total condensates was 12–19 wt %. The main compounds were acetic acid, 1-hydroxy-2-propanone, methanol, furfural, and 2-hydroxyacetaldehyde. Total condensates formed at ≤ 280 °C are promising to be utilized for different purposes, for example as a biopesticide. Higher temperatures are critical, because at 290 °C, strong exothermic reactions occur, which decreases considerably the yield of torrefied material and produces tar containing condensates. It is possible to produce, in addition to biocoal, valuable liquids. Economic assessments were performed for three torrefaction cases without and with the recovery of condensates. The production costs of torrefied pellets can be lowered significantly, for example on the order of 5–10 € MWh⁻¹ in medium scale pellet production, by recovering and selling the condensates to new applications.

■ INTRODUCTION

Torrefaction is a thermal process where a biomass feedstock is heated at 200 to 300 °C in the absence of oxygen. It has also been called a mild pyrolysis process.¹ The main objective is to use the torrefied biomass (“biocoal”) as a fuel, especially as a pellet for cofiring at pulverized coal power plants.² Torrefied pellets have a number of characteristics that offer clear advantages compared with conventional wood-based fuels, such as low moisture content, low uptake of moisture, high energy content, resistance against biological degradation, and good grindability in coal mills.^{3–6} Torrefaction gases and vapors are normally burned in a combustion unit with an additional solid or gaseous fuel (biomass, natural gas), to produce the heat energy needed in drying and torrefaction units.^{7,8} The volatiles can also be condensed and potentially utilized for other purposes in a similar fashion as the distillates from the slow pyrolysis process of charcoal production, which are also known as wood vinegars or pyroligneous acid.

Composition and thermal behavior of wood varies between different wood materials, which affects the quality of condensates.^{9,10} Hardwoods contain more hemicelluloses and cellulose than softwoods.¹¹ Softwood lignin is composed of guaiacyl-type lignin, whereas hardwood lignin contains syringyl and guaiacyl units. Bamboo resembles more woods than nonwoody grasses.¹² The composition of bamboo is, however, dependent on its age and species.¹³ Hemicelluloses are the most reactive constituent of wood^{9,14} decomposing in the temperature range of 200–260 °C. The reactive glucuronoxylan (xylan) comprises about 25 wt % of birch and also of bamboo.^{11,12} Cellulose decomposes at 240–350 °C and lignin at about 250–500 °C.^{14,15} According to Prins et al.⁹ the kinetics of torrefaction reactions at 230–300 °C can accurately be described by a two-step mechanism. The first step represents the decomposition of hemicelluloses and the second step

cellulose decomposition. Hardwood was shown to be much more reactive than softwood, and produced more volatiles than softwood.

So far, torrefaction studies have not been focused on the utilization potential of condensable substances. Instead, the chemical changes in wood caused by torrefaction have been investigated.^{1,16,17} Recently, for example Shoulaifar et al.¹⁶ studied with several methods the effect of torrefaction temperature on the chemistry of birch wood. The proportions of hemicelluloses, cellulose, lignin, and extractives degraded in torrefaction were determined in detail. Decrease in the components was presented to be attributed not only to volatile production but also char formation.

Wood vinegars from charcoal production are used in agriculture as a fertilizer and growth-promoting agent in Asia.¹⁸ In the studies of Mu et al.,^{19–21} treatments with bamboo vinegar showed an increase in vegetable growth, and germination and radicle growth for several seeds. The collection temperature was found an important factor for controlling the quality of distillates.²¹ Bamboo vinegars collected at temperatures of up to 250 °C promoted radicle and hypocotyl growth, but the vinegar collected from 250 to 400 °C had a strong inhibition on germination and radicle growth.

Wood vinegars have also been reported to be effective fungicides.²² Bamboo distillates were suggested to be used as coagulating and antifungal agents in natural rubber production to replace mainly formic acid and acetic acid.²³ The distillates showed higher antifungal efficiency than these acids. The efficiency was presented to be affected by phenolic compounds.

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Bamboo distillates have also been found to inhibit fungi that destroy wood material.^{24,25} They were effective against sap staining fungi and had potential to be used as natural preservatives in wood industries.

Distillates of hardwood are used to repel insects from plants and households. Wood tars produced from alder, larch, and birch were found effective repellents for control of vole in Japan.²⁶ The distillate produced from birch in barbecue charcoal production in Finland was found a promising source for many kinds of biodegradable pesticides.^{27,28} The birch distillate was considered an effective, noncostly, and environmentally friendly method against molluscs. It showed an herbicidal effect on many species of weeds and was an effective repellent to control the land snail and the Iberian slug.

In our previous studies, birch distillates were studied for chemical composition and utilization potential in plant protection.^{29–31} The tar-free distillate produced at ≤ 280 °C was found to be a promising and marketable product for various purposes. It acted as a repellent against snails and field vole in tests and in practice. The repellence effect was partially due to acetic acid and furfural. The effects of these compounds and also other fractions of birch distillate, on snails, were, however, considerably lower than the effect of the distillate.³² Tar, which comprised mainly of pyrolytic lignin, was not formed in the distillate until at >280 °C.³¹ In wood protection, the tar substances were essential.

The main objectives of the present paper were to determine the yields and chemical compositions of condensates formed at torrefaction conditions (<300 °C) from spruce and bamboo, and to assess their utilization potential. One aim was to compare the results with those of the birch distillate studied earlier by us and used herein as a reference. Spruce was selected to represent softwood, bamboo herbaceous grasses, and birch hardwood. The liquids were collected at different temperature ranges in the test runs carried out with the bench-scale slow pyrolysis equipment. Economic assessments were performed for three torrefaction cases including the recovery of condensates. The work was carried out within the EC 7th FP project “Production of solid sustainable energy carriers from biomass by means of torrefaction” (SECTOR).

MATERIALS AND METHODS

Feedstock Properties. The spruce and bamboo feedstocks were reference samples of the SECTOR project and were provided by Energy research Centre of the Netherlands (ECN) to VTT. The chip size of the materials used in the experiments was $30\text{--}40 \times 10\text{--}20 \times 5\text{--}10$ mm. For the feedstocks, physicochemical characteristics were analyzed with following standard methods: moisture content (SFS-EN 14774), ash content (SFS-EN 14775), volatile matter (SFS-EN 15148), fixed carbon (ASTM D 3172), elemental composition (C, H, N; SFS-EN 15104), and sulfur content (SFS-EN 15289).

Torrefaction Test Runs. The raw materials were torrefied in a bench-scale batch testing facility. The equipment was a controlled slow pyrolysis steel reactor heated indirectly in an electric oven (Figure 1). The capacity of the reactor was about 6 kg for feedstock. The torrefied material, condensable liquids, and noncondensable gases produced were recovered. Volatiles and gases were carried with nitrogen gas into a water-cooled vertical condenser. After separation of the liquids, noncondensable gases were introduced into filtering, volume measurement, and gas analysis.

In the test runs, the spruce and bamboo feedstocks (3.5–4 kg) were placed on wire levels of the sample holder in the reactor. A stepwise temperature program was used and the condensates were collected at the temperature ranges of 20–105 °C, 105–240 °C, and 240–300 °C. The temperature was raised at 6 °C min^{-1} and the nitrogen flow rate



Figure 1. Slow pyrolysis testing facility. 1: Electric oven. 2: Reactor. 3: Cooling section.

was 5 L min^{-1} (NTP, 0 °C, 0.1 MPa). Due to the low heat transfer inside the reactor, the temperature set point was maintained at 105 and 240 °C until the desired temperature was attained inside the reactor. After the heat-up sequence, the reactor was maintained at the final temperature of 300 °C for 1 h. The temperature inside the reactor increased almost linearly. With the heating rate used, the low heat transfer in the reactor did not have a practical significance on condensables when comparing with torrefaction processes.

The birch distillate that was used as a reference in the study, was obtained with the same slow pyrolysis equipment in a test run, where the temperature was raised directly to 300 °C and held for 3 h. In terms of chemicals recovery and environmental load, the aim was to maximize the organic content of the condensate.

The physicochemical characteristics of the torrefied materials were analyzed with the same standard methods presented above for the feedstocks.

Analysis of Condensables. The condensates recovered in the test runs were analyzed for chemical characteristics. The pH was determined with a pH meter, water content by Karl Fischer titration (ASTM E 203), total organic carbon (TOC) with a Shimadzu analyzer, chemical oxygen demand (COD) with a Hach Company spectrophotometer (SFS 5504), and total acid number (TAN) with a 785 DMP Titrino analyzer (ASTM D 664). The organic matter content was calculated by difference ($100\% - \text{water content}$).

The main water-soluble organic compounds were analyzed quantitatively by gas chromatography (GC) with a flame ionization detector, using an HP Innnowax column (polyethylene glycol, 60 m \times 0.25 mm, film thickness 0.25 μm). The oven temperature was programmed at 6 °C min^{-1} heating rate from 60 °C (hold 1 min) to 230 °C (hold 30 min). Most compounds identified were calibrated by model substances at 500–1000 ppm concentrations, whereas for the main compounds higher concentrations were used. The compounds were of analytical grade. In the analyses, *n*-butanol was used as an internal standard.

Polycyclic aromatic hydrocarbons (PAHs) were analyzed with GC/mass spectrometry (GC/MS) and the selected ion monitoring (SIM) technique after extraction of the samples with ethanol and hexane and subsequent purification of the extracts by dimethyl sulfoxide extraction, at Nablabs laboratories, Finland.³⁰

Economic Assessment. An economic assessment was carried out for three different torrefaction cases including the recovery of condensables. The cases were a stand-alone torrefaction plant (base case), a new sawmill integrated with a new torrefaction plant (sawmill integrate case), and a large overseas stand-alone torrefaction plant (overseas case). The total condensates were recovered. In the base case and the sawmill integrate case, forest fuels were used as raw materials, and in the overseas case, local feedstocks, mainly stem wood,

Table 1. Key Factors of the Estimate of Production Costs

cost factor	value
feedstock costs, € MWh ⁻¹	
forest residues, up to 150 MW _{th}	18
bark	16
sawdust	16
wood chips (sawmill)	18
plantation stem wood	15
electricity (with transfer costs), € MWh ⁻¹	60
labor cost (including payroll overheads), € manhour ⁻¹	55
annual capital charges factor	0.1175 (10% interest, 20 a)
costs for plant startup, interest during construction	21% of plant investment
scale-up exponent	0.7
maintenance, insurance, taxes	4% of total investment
operating time, h a ⁻¹	8 000
condensate price, € t ⁻¹	100, 250 or 400
evaluation time, 2012	CEPI-index 584.6

Table 2. Physicochemical Characteristics of Feedstocks and Torrefied Materials in Test Runs

analysis	feedstock spruce	feedstock bamboo	torrefied spruce	torrefied bamboo
moisture content, wt %	11.5	12.9	1.0	1.1
ash content, wt % of dry wood	0.5	6.5	0.5	9.8
volatile matter, wt % of dry wood	82.6	73.9	61.4	45.6
fixed carbon, ^a wt % of dry matter	16.9	19.6	38.1	44.6
carbon (C), wt % of dry wood	50.6	46.9	63.4	62.0
hydrogen (H), wt % of dry wood	5.8	5.4	5.4	4.9
nitrogen (N), wt % of dry wood	0.1	0.3	0.1	0.5
sulfur (S), wt % of dry wood	0.01	0.07	0.01	0.21
oxygen (O), ^b wt % of dry wood	43	42	31	23

^aDetermined by difference: 100% – (volatile matter + ash). ^bDetermined by difference: 100% – (CHNS + ash).

Table 3. Mass Yields of Products in Torrefaction Test Runs with Different Feedstocks

product	spruce	bamboo	birch (reference)
torrefied material, wt % (on wet input basis)	61	51	46
torrefied material, wt % (on dry input basis)	69	59	50
total condensate, wt % (on wet input basis)	29	32	39
noncondensable gases, wt % (on wet input basis) ^a	10	17	15

^aCalculated by difference: 100% – (torrefied material + total condensate).

were used. The base case was foreseen as a typical European commercial plant and was chosen as a bench mark.

In the condensate recovery concept, the torrefaction gas was cooled from 280 °C to room temperature (20 °C). The condensation equipment was placed in the torrefaction gas line prior to the combustor. The reduction in the energy content of the torrefaction gas due to the condensation of liquids was compensated with biomass feedstock. The water content of the condensed liquid was about 70 wt %. The water-insoluble substances were decanted out of the product and used as a boiler fuel. The torrefaction gas was cooled directly with the aqueous liquid.

The main mass and energy flows for the cases with or without condensate recovery were calculated. The product of all processes was torrefied pellets. The net calorific value of wood used as a raw material in the torrefaction process and as a boiler fuel was 8.4 MJ kg⁻¹ at 50 wt % moisture content. The net calorific value of torrefied pellets was 22.0 MJ kg⁻¹. Energy need in the drying of wood was for all cases 4.0 MJ kg⁻¹ evaporated H₂O using a belt dryer.³³ Torrefied wood was cooled down with steam (directly) and water (indirectly) before the pelletization unit. Power need for grinding was 18 kWh_e t⁻¹ and for pelletization 64 kWh_e t⁻¹ torrefied pellets.

The economic assessment was mainly based on in-house information on VTT and Pöyry Management Consulting Ltd.³⁴ Assessment of investment costs was based on a number of feasibility

studies and budget offers of commercially available equipment and components. Key input data and base for calculation of production costs are presented in Table 1. These figures reflect mainly costs applied in a Nordic European context. The price of plantation stem wood was based on the worldwide data on pulp wood prices of Pöyry Management Consulting, Ltd.³⁴ No subsidies were included in the calculations.

RESULTS AND DISCUSSION

Properties of Feedstocks and Torrefied Materials.

Physicochemical characteristics of the feedstocks and torrefied materials are presented in Table 2. The main differences between the feedstocks were higher ash, nitrogen and sulfur contents in the bamboo material. Ash forming components in bamboo are mostly alkali metals dominated by potassium, silica, and phosphorus.³⁵ The ash content varies considerably between different bamboo species and ages.¹² During torrefaction, carbon contents increased and volatile matter contents decreased in the materials. Especially, the ash content of bamboo increased considerably, reducing the energy content of the torrefied product while simultaneously increasing the

transportation and handling costs. The sulfur content of torrefied bamboo was higher than that of torrefied spruce.

Mass Yields of the Products. The mass yields of the products in the torrefaction test runs for spruce and bamboo and also for the reference birch are presented in Table 3. The mass yield of torrefied material was considerably higher for spruce than for bamboo and birch, while higher condensate and gas yields were consequently observed for bamboo and birch. This was likely affected by the higher hemicellulose and xylan contents of bamboo and birch in comparison to spruce. For birch, the longer residence time at the final temperature also had a considerable effect on the extent of decomposition, which was clearly reflected in the amount of liquids and gases produced. The mass yields of torrefied materials were lower than what has been generally presented in the literature^{1,3,17} for wood materials, which was likely due to the high final temperature of 300 °C and the long residence times used.

Formation of Condensables. In the spruce and bamboo torrefaction test runs, the collected condensates included fractions formed at 20–105, 105–240, and at 240–300 °C. The formation rate of the condensate was measured at 30 min intervals as a function of time and temperature. It was quite similar for both spruce and bamboo, and the results for the bamboo test run are presented in Figure 2. At 20–105 °C, the

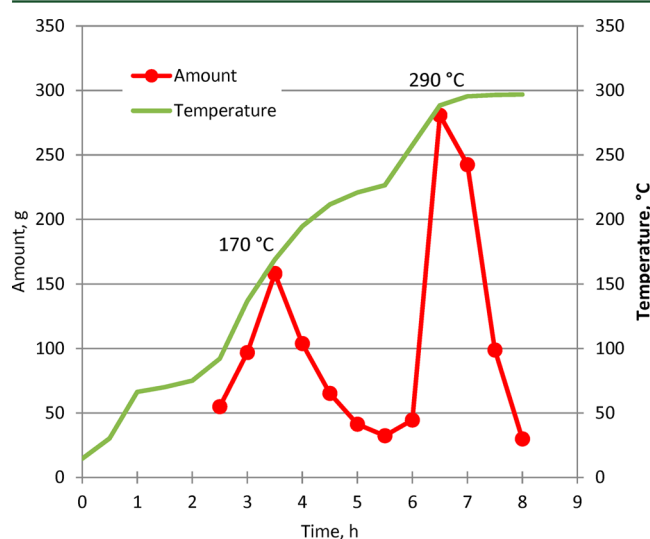


Figure 2. Formation of the condensate amount, measured at 30 min intervals, as a function of time and temperature inside the reactor in the bamboo test run.

amount of condensates was very small (about 1 wt %, on wet input basis). At 105–240 °C, the condensates contained a major part of the feedstock moisture and their amounts increased. The maximum amounts were obtained at about 170

°C, when the color of condensates also changed from light yellow into brown. By 240 °C, 12–14 wt % of the original feedstocks had been cumulatively collected as condensates (Table 4).

The main part of total condensates was formed at 240–300 °C. The maximum amount was obtained at 280–300 °C (Figure 2), when visible tar began to form and strong exothermic reactions occurred, which was also corroborated by the gas analyses (Figure 3). The maximum concentrations of carbon dioxide (CO₂) and carbon monoxide (CO) were 23 vol % (in nitrogen flow) and 19 vol %, respectively.

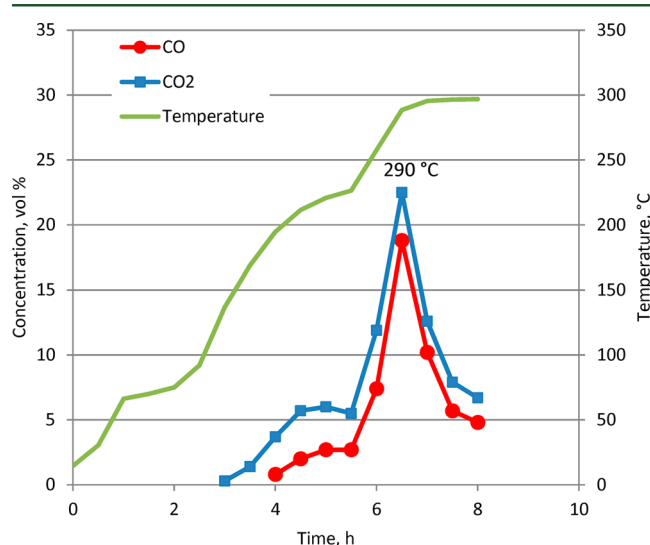


Figure 3. CO₂ and CO concentrations (% in nitrogen flow) as a function of time and temperature in the torrefaction test run for bamboo.

Formation rate of the condensate as a function of time and temperature in the spruce and bamboo test runs was similar to that in the birch test run.

The mass yields of condensates formed at different temperature levels, torrefied materials and noncondensable gases in the test runs are presented in Figures 4–6.

Composition of Condensates. The condensates formed at 20–105 °C were very dilute and consisted mostly of water. The spruce and bamboo condensates collected at 240–300 °C had the highest COD, TOC, and TAN values (Table 5). The organic contents of total condensates calculated on the basis of the amounts and analyses of condensate fractions, were quantitatively at the same level as that of the birch condensate (Table 5). The COD/TOC ratios were quite similar (3.4–3.7) for all condensates. The amount of PAHs was only ≤ 2 mg kg⁻¹ for all condensates.

Table 4. Proportions and Mass Yields of Condensates Formed at Different Temperature Ranges in Spruce and Bamboo Torrefaction Test Runs

	20–105 °C	105–240 °C	240–300 °C	total condensate
spruce				
proportion of total condensate, wt %	5.1	34.6	60.3	100
mass yield, wt % (on wet input basis)	1.5	10.0	17.4	29
bamboo				
proportion of total condensate, wt %	4.3	38.5	57.3	100
mass yield, wt % (on wet input basis)	1.4	12.4	18.4	32

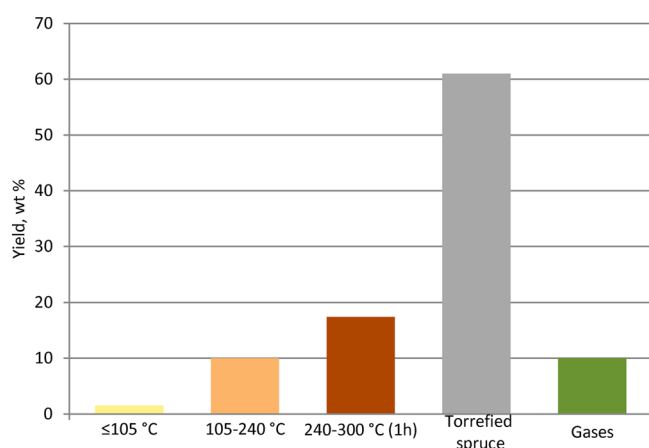


Figure 4. Mass yields of condensates formed at different temperature levels, torrefied material, and noncondensable gases in the torrefaction test run of spruce, on wet input basis.

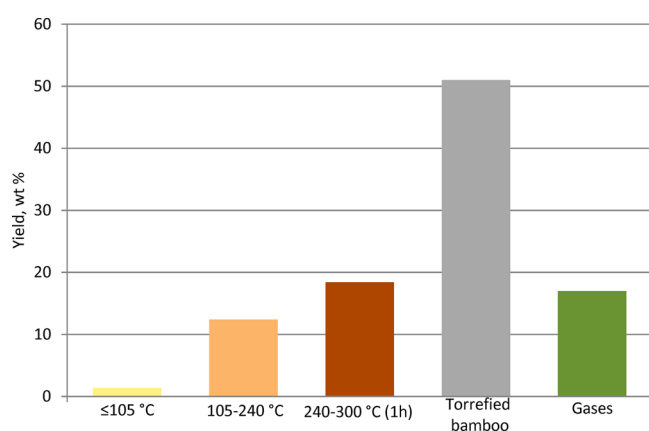


Figure 5. Mass yields of condensates formed at different temperature levels, torrefied material, and noncondensable gases in the torrefaction test run of bamboo, on wet input basis.

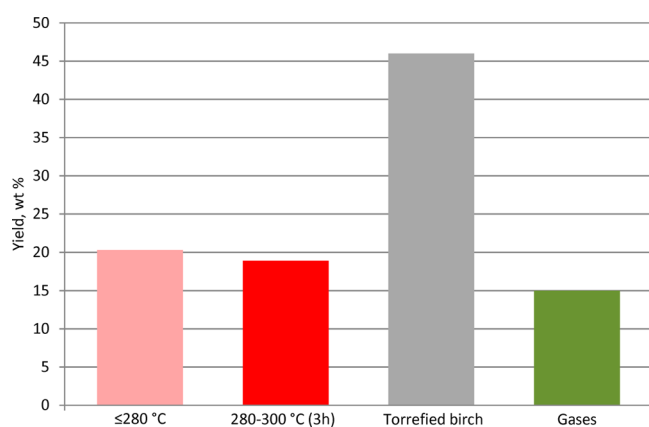


Figure 6. Mass yields of condensates formed at different temperature levels, torrefied material, and noncondensable gases in the torrefaction test run of birch, on wet input basis.

The amounts of organic compounds quantified in total condensates were lower for spruce and bamboo (12–15 wt %) than for birch (19 wt %). This was affected primarily by the differences in the concentration of acetic acid, the main compound, between the condensates (Table 6). In contrast, the amounts of aldehydes, ketones and phenols were higher in the

spruce condensate than in the others. The main compounds including acetic acid, 1-hydroxy-2-propanone, methanol, and furfural, and in addition 2-hydroxyacetaldehyde in the spruce condensate comprised, in total, 85–97 wt % of the compounds.

In the condensate fractions of 105–240 °C, the main compounds for spruce and bamboo were acetic acid, methanol, furfural, and 1-hydroxy-2-propanone (Table 7). These compounds are mainly degradation products of hemicelluloses.^{16,17} Acetic acid and methanol comprised 80–90 wt % of the compounds in the fractions.

The organic compounds were concentrated in the condensate fractions formed at 240–300 °C (Table 7), which was due to strong exothermic reactions occurring at 270–290 °C. Cellulose degradation begins to occur already at 255 °C and becomes more significant at 270 °C, whereas lignin begins to decompose to a small extent at 240 °C.¹⁶ The guaiacols, phenols, isoeugenol, and vanillin, the concentrations of which were higher in the spruce condensate, are degradation products of lignin and especially of guaiacyl-type lignin, typical of softwood.¹¹ The bamboo condensate contained also guaiacol and phenols, but to a lesser extent.

Utilization Potential of Condensables. The condensates collected in the torrefaction test runs are promising to be utilized for different purposes. The liquid fractions recovered at 105–240 °C for spruce and bamboo were tar-free and PAH-free and contained acetic acid and furfural. They resembled the birch distillate obtained at low temperatures in slow pyrolysis, and consequently have potential to be used as a pesticide, herbicide, fungicide, insecticide, and repellent.^{29–32,36} Acetic acid and furfurals are used as pesticides in plant protection.^{37–39} Furfural is also used as a soil fumigant and a wood preservative.^{39,40} Because wood vinegars possess higher effectivity than the separate compounds,^{23,31,32} the condensate fractions of torrefaction are suggested to be used as such rather than to separate the active compounds from them. At the moment, the effectiveness of individual organic compounds in complex mixtures in use is not known and further investigations on it will be needed.

Because of the low yields and high water contents, the condensates formed at 20–105 °C are not worth a separate utilization. Instead, they can be combined with the fraction of 105–240 °C.

The condensates formed at 240–300 °C contained a high amount of organic matter (30–40 wt %) including also tar, which contains phenolic compounds. Therefore, they may not be suitable for the same purposes as the fractions collected at lower temperatures. Instead, they may have potential as wood preservatives in wood protection. Based on our studies on birch distillates,^{29–31} the spruce and bamboo condensates formed at <280 °C might, however, also be utilized similarly as the distillate obtained at ≤240 °C.

The separate compounds, such as acetic acid, furfural, methanol, hydroxyacetaldehyde, guaiacol, phenol, syringol, and catechol, found in the condensates, are among the value-added chemicals from the pyrolysis of lignocellulosic biomass presented recently by de Wild.⁴¹

Economic Evaluation. Economic evaluation was based on the main mass and energy flows calculated for the base case plant, the saw mill integrate, and the overseas plant without and with the condensate recovery (Table 8). The estimated production costs of the cases are shown in Figure 7. For the base case and the saw mill integrate, the costs were expressed as plant gate values. In the overseas case, shipping costs (3.2 €

Table 5. Characteristics of Condensate Fractions and Total Condensate in Spruce and Bamboo Torrefaction Test Runs^a

analysis	condensate fraction 105–240 °C	condensate fraction 240–300 °C	total condensate ^b
spruce			
water content, wt %	99.3	56.4	73.4
organic matter, wt %	0.7	43.6	26.6
pH	3.0	2.2	2.5
COD, g L ⁻¹	37	810	500
TOC, g L ⁻¹	10	240	150
COD/TOC	3.7	3.4	3.3
TAN, mg KOH g ⁻¹	5.5	120	77
bamboo			
water content, wt %	97.6	70.8	82.4
organic content, wt %	2.4	29.2	17.6
pH	3.2	3.1	3.2
COD, g L ⁻¹	56	470	290
TOC, g L ⁻¹	16	140	87
COD/TOC	3.5	3.4	3.3
TAN, mg KOH g ⁻¹	21	95	63

^aFor the birch condensate, pH was 2.5, water content 75 wt %, COD 300 g L⁻¹, TOC 90 g L⁻¹, and TAN 135 mg KOH g⁻¹. ^bCalculated on the basis of amounts and analyses of condensate fractions.

Table 6. Amounts of Water-Soluble Compound Groups in Total Condensates^a in Spruce, Bamboo and Birch Torrefaction Test Runs, wt %

compound group	spruce	bamboo	birch
total amount	14.7	12.0	19.1
aldehydes and ketones	3.96	1.33	2.09
furans	0.06	0.08	0.01
alcohols	1.45	3.01	1.46
acids	7.62	6.80	15.4
phenols	1.65	0.78	0.18

^aFor spruce and bamboo, calculated on the basis of the amounts and analyses of condensate fractions.

MWh⁻¹) to Europe were added to the pellet production price.⁴² Fixed operating costs consisted of operating labor, maintenance labor, maintenance materials, overheads, insurances, and taxes. Variable operating costs consisted of raw materials, boiler fuels, electricity, and other utilities. Due to the dominant factor in the production price of torrefied pellets, raw material costs were separated out of other variable operating costs. The increased production costs of torrefied pellets were compensated by the extra income from the condensate utilization. The overall benefit was thus decreased production costs for torrefied pellets.

Wood pellet is the main biomass fuel in large scale pulverized coal boilers as well as at peak and back-up district heating plants. Other type of boilers, for example fluidized bed or grate boilers, use normally cheaper wood fuels, such as wood chips or forestry residues. In the overseas case, the production costs of torrefied pellets were lower than the market price 30 € MWh⁻¹ described by the PIX Index value (FOEX Indexes Ltd.) for industrial wood pellets. In all the torrefaction cases studied, condensate recovery lowered the torrefied pellet production price. Production costs were partly influenced by the production capacity. The savings in inland transport costs in Europe and in storage and use of torrefied pellets at coal power plants compared to wood pellets were not included in the cost values.

The effect of condensate price on the torrefied pellet production price is shown in Table 9. The production costs of

torrefied pellets decreased significantly, for example on the order of 5–10 € MWh⁻¹ in medium scale pellet production, when the condensates were recovered for utilization. An average revenue percentage of the whole turnover was estimated to be 15% at a condensate price of 100 € t⁻¹. Then the revenues for condensate recovery were 2.5 M€ in the base case, 8 M€ in the sawmill integrate case, and 17 M€ in the overseas case.

CONCLUSIONS

Mass yields and compositions of torrefaction condensates differed between softwood, hardwood, and herbaceous feedstocks and temperature ranges. The total condensates formed at ≤280 °C will be promising to be utilized, for example, as biodegradable pesticides to replace synthetic ones. Higher temperatures are critical, because at about 290 °C strong exothermic reactions will occur, which considerably decreases the yield of torrefied material and produces tar containing condensates. The results were in accordance with those obtained by us previously^{29,30} for birch feedstock in larger-scale slow pyrolysis retorts.

The quality and utilization potential of condensates can be affected by temperature ranges. Specific temperature ranges can be chosen, when the aim is to for example maximize the yield of some components like acetic acid. Separation of compounds from the mixture is, however, a challenging task and possibly not an economic way to utilize the condensates.

Utilization of torrefaction condensates from several wood materials for different purposes will be further studied with different tests within the Horizon 2020 EU project “Mobile and flexible industrial processing of biomass” (Mobile Flip).

On the basis of the economic assessment carried out for three different torrefaction cases including the base case plant, the saw mill integrate, and the overseas plant without and with the condensate recovery, it is possible to produce, in addition to torrefied material, valuable liquids. The production costs of torrefied pellets can be lowered significantly by recovering and selling the condensates to new applications. The biopesticide markets are, however, still undeveloped. This is due to different regulations, which are the main barriers to future applications.

Table 7. Amounts of Water-Soluble Compounds in Condensate Fractions in Spruce and Bamboo Torrefaction Test Runs, wt %

compound	spruce	spruce	bamboo	bamboo
temperature level	105–240 °C	240–300 °C	105–240 °C	240–300 °C
total amount	1.59	23.5	3.49	18.6
acetaldehyde	0.011	0.200	0.032	0.193
furan	0.004	0.035	0.005	0.058
2-propanone (acetone)	0.001	0.073	0.004	0.108
methanol	0.712	1.982	0.460	4.902
2-butanone	0.002	0.053	0.007	0.090
isopropyl alcohol	0.001	0.005	0.002	0.012
ethanol	0.000	0.003		0.005
2-pentanone	0.009	0.023	0.001	0.020
<i>n</i> -propanol	0.000	0.004	0.000	0.014
1-hydroxy-2-propanone	0.081	3.380	0.106	1.345
2-hydroxyacetaldehyde (glycolaldehyde)	0.018	1.295	0.001	0.127
1-hydroxy-2-butanone	0.035	0.073	0.003	0.100
acetic acid	0.521	12.188	2.740	9.840
furfural	0.174	0.885	0.051	0.172
2-acetylfuran		0.063	0.001	0.072
<i>n</i> -propanoic acid	0.001	0.002	0.001	0.044
isobutanoic acid	0.000	0.033	0.001	0.007
5-methylfurfural		0.012	0.000	0.006
butanoic acid	0.002	0.068	0.004	0.119
pentanoic acid	0.002	0.014	0.001	0.010
hexanoic acid	0.000	0.031	0.000	0.007
guaiacol	0.007	0.405	0.012	0.213
4-methylguaiacol	0.000	0.284	0.003	0.052
2-methylphenol, <i>o</i> -cresol	0.000	0.009	0.001	0.009
phenol	0.000	0.026	0.020	0.222
4-ethylguaiacol	0.001	0.115	0.003	0.045
3-methylphenol, <i>m</i> -cresol	0.001	0.701	0.004	0.241
2-propylphenol	0.000	0.013	0.000	0.006
eugenol	0.000	0.054	0.001	0.067
4-ethylphenol	0.001	0.154	0.009	0.210
<i>o</i> -vanillin		0.432	0.006	0.057
syringol, 4-propylphenol ^a	0.000	0.058	0.001	0.025
isoeugenol		0.254	0.006	0.069
4-methylsyringol	0.000	0.018	0.002	0.007
5-hydroxy-methylfurfural	0.004	0.383	0.001	0.028
catechol		0.180		0.088
4-methylcatechol	0.000	0.011	0.000	0.003
4-ethylcatechol		0.014		0.007

^aSyringol in hardwood; 4-propylphenol in softwood.

Table 8. Main Mass and Energy Flows of Stand-Alone Torrefaction Plants (Base Case, Overseas Case) and Saw Mill Integrate without and with Condensate Recovery

alternative/utility	base case	base case condensate recovery	sawmill integrate	sawmill integrate condensate recovery	overseas case	overseas case condensate recovery
fuels for pellets, MW	54	54	175	175	368	368
forest fuel, MW	54	54	136	136	368	368
wood chips, MW	0	0	39	39	0	0
torrefied pellet production, MW	56	56	177	177	382	382
torrefied pellet production, t a ⁻¹	72 800	72 800	231 600	231 000	500 000	500 000
boiler fuels, MW	8	16	25	50	55	107
forest fuel, MW	8	16	0	26	55	107
bark, MW	0	0	12	12	0	0
sawdust, MW	0	0	14	12	0	0
purchased electricity, MWe	2	2	6	6	12	12
condensate, t a ⁻¹	0	25 000	0	80 000	0	171 000

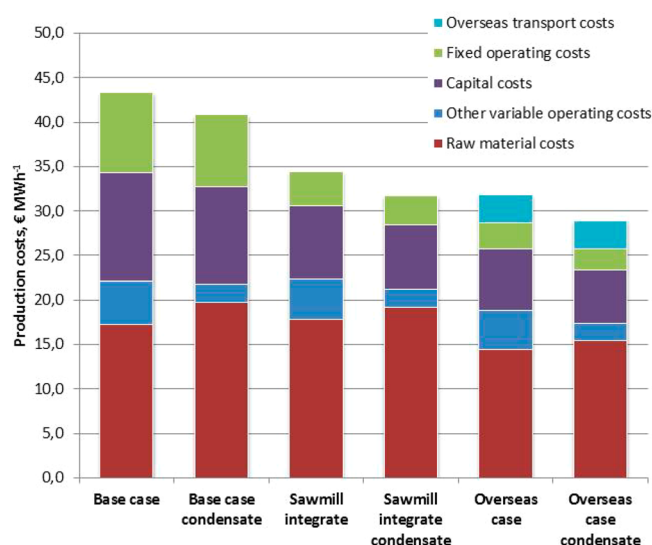


Figure 7. Breakdown of torrefied pellets production costs of different cases without and with condensate recovery: condensate price 100 € t⁻¹, condensate profit shared evenly into other costs excluding overseas transport costs.

Table 9. Torrefied Pellet Production Price at Different Condensate Price Values in Torrefaction Cases without and with Condensate Recovery

alternative	condensate price, € t ⁻¹	torrefied pellet price, € MWh ⁻¹
base case		43
base case with recovery	100	40
base case with recovery	250	32
base case with recovery	400	24
saw mill integrate		35
saw mill integrate with recovery	100	31
saw mill integrate with recovery	250	23
saw mill integrate with recovery	400	15
overseas case		29
overseas case with recovery	100	25
overseas case with recovery	250	17
overseas case with recovery	400	9

AUTHOR INFORMATION

Corresponding Author

*L. Fagernäs. Telephone: +358 20 722 5453. Fax +358 20 722 7048. E-mail: Leena.Fagernas@gmail.com; Leena.Fagernas@vtt.fi.

Notes

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