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Electronic Supporting Information

Enhancing lignin depolymerization via a dithionite-assisted organosolv fractionation of birch sawdust

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Contents

Chemicals and materials

All commercial chemicals were used without further purification. 2-Isopropyl phenol (98%), 2-methoxy-4-methylphenol (≥98%), 4-methyl-2,6-dimethoxyphenol (≥97%), 2-methoxy-4-propylphenol (≥99%), p-cresol (99%), 4-propylphenol (99%), 3-phenyl-1-propanol (98%), ethylbenzene (99.8%), cinnamyl alcohol (98%), 4-hydroxy-3-methoxyphenylacetone (96%), 4'-hydroxy-3'-methoxyacetophenone (98%), styrene (≥99%), 2-phenoxy-1-phenylethanol, phenol (≥99%), glutaric acid (99%), levulinic acid (98%), malonic acid (99%), methylmalonic acid (99%), Succinic acid (≥99.5%), 1,2-propanediol (≥99.5%), 1,3-propanediol (98%), ethylene glycol (≥99%), furfural (99%), maltose (≥99%), acetic acid (≥99%), DL-lactic acid (85%), crotonic acid (98%), D-gluconic acid (99%), citric acid monohydrate (≥99%), sodium citrate dihydrate (≥99%), sodium dithionite (≥85%) and cellulase enzyme blend were purchased from Sigma Aldrich. Ethanol absolute (100%), tetrahydrofuran (100%), 1,4-dioxan (99.9%), dichloromethane (100%), diethyl ether (100%), 1,2-dichloroethane (≥99.5%), methanol (100%), 2-propanol (99.9%), nitric acid (69%), hydrogen peroxide (30%) and sulfur standard solution (1000 mg/L) were purchased from VWR. (D-)-Mannitol (≥99%), (D+)-glucose monohydrate (≥99%), saccharose (≥99.5%) formic acid (≥98%) and sodium azide (99%) were purchased from Merck Millipore. D-(+)-Xylose (>99%), D-(+)-galactose (99+%), D-(+)-mannose (99+%), DL-malic acid (99%) and oxalic acid (99%) were purchased from Janssen. 4-Ethylphenol (97%), 2-methoxyphenol (98+%), 2,6-dimethoxyphenol (99%), 4-ethyl-2-methoxyphenol (98%), 4-hydroxy-3,5-dimethoxybenzyl alcohol (97%), isoeugenol, cis + trans (98+%), eugenol (99%), 4'-hydroxy-3',5'-dimethoxyacetophenone (97%), 4-allyl-2,6-dimethoxyphenol (98%), 3,4,5-trimethoxytoluene (98%), syringaldehyde (98+%), 5-hydroxymethyl-2-furaldehyde (97%), xylitol (99%), D-(-)-arabinose (99%), 1-butanol (99%) and butyric acid (99+%) were purchased from Alfa Aesar. 4-(3-Hydroxypropyl)-2-methoxyphenol (≥98%) was purchased from TCI. Silver birch (*Betula pendula*) wood was collected in Belgium in 2018.

Biomass preparation

The wood was chopped, milled and sieved to obtain chips with a maximum size of 2 mm, suitable for the fractionation process, which were left to dry in air, then were stored in plastic buckets at ambient conditions.

The milled, air-dried biomass was then analyzed following standard protocols for the characterization of lignocellulosic material, including determination of dry matter and ash content, determination of extractives (water- and ethanol-soluble fractions), structural carbohydrates and acid insoluble lignin.

Analysis of dry matter and ash

Dry matter (DM) and ash of the raw biomass were determined according to National Renewable Energy Laboratory (NREL) protocols (NREL/TP-510-42621 and NREL/TP-510-42622).[1,2] Therefore, a sample of lignocellulosic material (0.5 – 2 g) was weighed in a ceramic crucible and dried at 105 °C to a constant weight to measure the dry matter content. The total ash content was then determined by ashing the dried biomass in a furnace at 575 °C.

Analysis of extractives

Determination of extractives was carried out according to established NREL procedures (NREL/TP-510-42619).[3] Therefore, biomass was milled to obtain a powder (particle size ≤ 0.5 mm). A sample (~5 g) was introduced into an alundum thimble and subjected to two consecutive extractions, first with pure water, then with pure ethanol, using a Soxhlet extractor. Each extraction was carried out for 10 hours, with 4-5 siphon cycles per hour for water and 5-6 siphon cycles per hour for ethanol (siphon cycle = total reflux of the solvent). After the extraction, the water and ethanol extracts were collected separately and dried to a constant weight at 60 °C, then for 1 hour at 105 °C, to determine the amount of water and ethanol extractives.

Analysis of structural carbohydrates and acid insoluble lignin

Determination of structural carbohydrates and acid insoluble lignin was carried out according to NREL protocols (NREL/TP-510-42618).[4] Therefore, dried samples of extractives-free biomass (~0.3 g) were subjected to acid hydrolysis by treating them with sulfuric acid (3 mL, 72% w/w) in a water bath at 30 °C for 2 hours. Then, the solutions were diluted to a concentration of sulfuric acid of 4% w/w and autoclaved at 121 °C for 1 hour. The hydrolysates were filtered using fritted ceramic funnels (pore size: 4-8 µm) and the acid insoluble lignin content was measured as the weight of the acid insoluble residue minus the ashes. The hydrolysates were then filtered (nylon filters, pore size: 0.2 µm) and analyzed for carbohydrates via High Performance Liquid Chromatography (Agilent 1200 series). A Hi Plex-H column (Biorad) and refractive index detector (RID) were used to determine the concentrations of glucose, xylose, and arabinose at 65 °C using 0.005M H_2SO_4 as the mobile phase (eluent) with a flow rate of 0.6 mL min^{-1}. Response factors were determined by calibration with commercial standards.

The equations below summarize the calculations made for the quantification of C5 polysaccharides (xylan and arabinan), C6 polysaccharides (glucan) and acid insoluble lignin (AIL).

$$\mathrm{C5, C6}_{extractives-free}\ (\mathrm{wt\%}) = \frac{\mathrm{C_{anhydro}\ V_{hydrolysate}\ \frac{1\ L}{1000\ mL}}}{m_{DM,extractives-free}} \quad \text{Eq. 1}$$

$$\mathrm{C5, C6}_{as\ received}\ (\mathrm{wt\%}) = \mathrm{C5, C6}_{extractives-free}(1 - \%\mathrm{Extractives}) \quad \text{Eq. 2}$$

$$\mathrm{AIL}_{extractives-free}\ (\mathrm{wt\%}) = \frac{m_{AIL}}{m_{DM,extractives-free}} \quad \text{Eq. 3}$$

$$\mathrm{AIL}_{as\ received}\ (\mathrm{wt\%}) = \mathrm{AIL}_{extractives-free}(1 - \%\mathrm{Extractives}) \quad \text{Eq. 4}$$

Wherein
Subscript "Extractives-free" indicates the content of a component in the extractives-free biomass.
Subscript "As-received" indicates the content of a component in the raw biomass.
$C_{anhydro}$ indicates the concentration of the carbohydrates converted into their polymeric form (glucose in form of glucan, etc.) using an anhydro correction (0.88 for pentoses and 0.90 for hexoses) also corrected for any degradation that may have occurred during the dilute-acid step of the hydrolysis according to methodology well known in the art (e.g. by using a recovery factor calculated from replicates enriched with known concentrations of the carbohydrates analyzed) [g L^{-1}].
$V_{hydrolysate}$ indicates the volume of the hydrolysate [mL].
m_{DM} indicates the amount of dry matter [g].
%Extractives indicates content of extractives in the raw biomass [wt%].
m_{AIL} indicates the amount of acid insoluble lignin [g].

Dithionite-assisted organosolv fractionation and products separation

The dithionite-assisted organosolv fractionation (DAOF) experiments were carried out in a Parr reactor (Parr Instrument Company, Moline, IL, U.S.). The lignocellulosic biomass (3 g) was loaded in the reactor, together with sodium dithionite (1g), 60 mL of n-butanol and 60 mL of milli-Q water. The reactor was sealed, purged with N_2, then pressurized with 30 bar of N_2, introduced at ambient temperature. Subsequently, the mixture was stirred (750 rpm) and the temperature was ramped up to 200 °C, at a rate of ~10 °C min^{-1}. When the set-point temperature was reached, it was maintained constant and the mixture was left to react for a duration of 3 hours.
Afterwards, the reactor was cooled down to room temperature and depressurized. The reactor content was collected and centrifuged (8000 rpm, 10 min) to separate the solid pulp from the liquid fraction. The pulp underwent two consecutive washing cycles, first with n-butanol (40 mL) then with water (40 mL), centrifuging each time to separate the solid and liquid fractions. The washing liquids were added to the liquid fraction from the reaction and filtered under vacuum (glass fiber filter, pore size: 1.6 µm) to eliminate residual solid particles. Subsequently, the liquid was introduced into a separating funnel and let to rest overnight. Thereafter, an aqueous liquid fraction and an organic liquid fraction were collected and stored at -20 °C for further analysis.
The recovered solid fraction was dried at 60 °C to a constant weight, to remove residual solvent, then it was stored at ambient temperature in view of further analysis.

Analysis of the solid fraction

The dried solid fraction obtained after the organosolv process was analyzed for dry matter and ash, as well as for carbohydrates and acid insoluble lignin, according to the procedures reported above for biomass characterization. Recovery and removal of polysaccharides and lignin in the pulp were calculated with respect to the amount of polysaccharides and lignin in the initial biomass, and with respect to the DM initially introduced, according to the following equations.

$$Recovery_{C5/C6/lignin}\big|_{C5/C6/AIL}\ (\mathrm{wt\%}) = \frac{m_{C5/C6/AIL,pulp}}{m_{C5/C6/AIL,in}} \quad \text{Eq. 5}$$

$$Recovery_{C5/C6/lignin}\big|_{DM}\ (\mathrm{wt\%}) = \frac{m_{C5/C6/lignin,pulp}}{m_{DM,in}} \quad \text{Eq. 6}$$

Wherein
Subscript "pulp" indicates the content of a component in the pulp.

Subscript "in" indicates the content of a component in the raw biomass.
$m_{C5/C6/AIL}$ indicates the amount of C5 or C6 polysaccharides or acid insoluble lignin [g].
m_{DM} indicates the amount of dry matter [g].

Cellulose crystallinity in the solid fraction was determined by subjecting pulp samples to X-ray powder diffraction. Therefore, samples of pulp were milled to obtain a fine powder (particle size ≤ 0.1 mm) and analyzed with a D8 advanced diffractometer, equipped with XE-T detector (Bruker) using a Bragg Brentano geometry. Diffractograms were recorded in a 5 – 80° 2θ range, with an increment of 0.015° (2θ) and an integration time of 0.15 s. The cellulose crystallinity index (CI) was determined for each sample according to Segal's method.[5] The equation adopted for the calculation of CIs is reported below.

$$CI\ (\%) = \frac{I_{002} - I_{AM}}{I_{002}} \qquad \text{Eq. 7}$$

Wherein
I_{002} indicates the maximum intensity of the diffraction at 2θ ~ 22.5°, assigned to the crystalline portion of cellulose and corresponding to the (002) lattice planes.
I_{AM} indicates the intensity of the diffraction at 2θ ~ 18°, assigned to the amorphous portion and corresponding to the minimum intensity between the peaks for the (002) and (101) lattice planes.

Microstructural analysis of the solid fraction was carried out via field emission gun scanning electron microscopy (FEG-SEM). Therefore, solid samples were milled to obtain a fine powder (particle size ≤ 0.1 mm). Specimens were mounted on stubs and coated with a 10 nm gold layer (Cressington sputter 208HR) to create a thin conductive layer, minimizing degradation and drift due to thermal expansion. FEG-SEM analyses were performed in a Jeol FEG-SEM 7600F, operating at 15 keV, with a working distance between 9.5 and 12 mm.

Enzymatic convertibility of the solid fraction was determined by subjecting pulp samples to enzymatic hydrolysis, according to NREL protocol (NREL/TP-510-42629)[6]. Therefore, pulp samples (0.1 g) were introduced in glass tubes and mixed with a citrate buffer (4.72 mL, pH 4.8) and sodium azide (50 µL). The hydrolysis was performed with an enzyme loading of 15 FPU (Cellic CTec2), at a temperature of 50 °C and samples were shaken at 150 rpm for a duration of 72 hours. Subsequently, the samples were centrifuged to separate residual solids, filtered (nylon filters, pore size: 0.2 µm) and monosaccharides in the liquid were analyzed via High Performance Liquid Chromatography (HPLC), applying the same conditions illustrated above for the analysis of structural carbohydrates in biomass. Conversion yields were calculated with respect to the amount of polysaccharides in the pulp determined via acid hydrolysis, according to the following equation.

$$Conversion_{C5,C6}\ (\text{wt\%}) = \frac{C_{Monosaccharide}}{C_{DM,pulp}\ (C5, C6_{as\ received}/AF)} \qquad \text{Eq. 8}$$

Wherein
$C_{Monosaccharide}$ indicates the concentration of monosaccharide determined by HPLC, after enzymatic hydrolysis [g L^{-1}].
$C_{DM,pulp}$ indicates the concentration of dry matter from the pulp [g L^{-1}].
$C5,C6_{as\ received}$ indicates the concentration of polysaccharide in the pulp, determined via acid hydrolysis [wt% DM].
AF indicates the anhydro factor for the conversion of carbohydrates into their polymeric form (glucose in form of glucan, etc.), equal to 0.88 for pentoses and 0.90 for hexoses.

The degree of polymerization (DP) of cellulose in the solid fraction was measured by viscosimetry according to the NF G 06-037 norm. Therefore, samples of pulp (~0.075 g) were dissolved in 15 mL of a 0.5 M cupriethylenediamine solution. The solution was stirred for 2 hours at room temperature. Viscosity data were determined in a UBBELOHDE thermostated capillary tube viscosimeter at 298 K. The DP was determined according to the NF G 06-037 norm.

Analysis of the organic fraction

The organic liquid fraction obtained after the organosolv process was analyzed for dry matter and ash according to the protocols reported above for biomass characterization, then lignin oil was extracted and analyzed following a procedure developed by Van Den Bosch et al.[7] and widely adopted in the literature.[8–13] Therefore, a sample of the organic phase (~5 mL) was dried under nitrogen flow to remove the solvent, then underwent a three-fold liquid-liquid extraction with dichloromethane (6 mL) and water (6 mL), recycling the water phase. The three dichloromethane extracts were mixed, and the solvent was removed by drying under

vacuum to determine the weight of lignin oil. A correction was applied to account for the presence of extractives in lignin oil, and the yield of oil was calculated with respect to acid insoluble lignin and with respect to the DM introduced, according to the following equations.

$$Yield_{Lignin\ oil}\big|_{AIL}\ (\text{wt\%}) = \frac{m_{Lignin\ oil} - m_{EtOH\ extractives}}{m_{AIL,in}} \quad \text{Eq. 9}$$

$$Yield_{Lignin\ oil}\big|_{DM}\ (\text{wt\%}) = \frac{m_{Lignin\ oil} - m_{EtOH\ extractives}}{w_{DM,in}} \quad \text{Eq. 10}$$

Wherein
$m_{Lignin\ oil}$ indicates the total amount of lignin oil obtained from the process [g].
$m_{EtOH\ extractives}$ indicates the amount of ethanol extractives present in the biomass initially introduced in the reactor [g].
$m_{AIL,in}$ indicates the amount of acid insoluble lignin present in the biomass initially introduced in the reactor [g].
$m_{DM,in}$ indicates the amount of dry matter present in the biomass initially introduced in the reactor [g].

The molecular weight distribution of the lignin oil was then investigated via gel permeation chromatography (GPC). Therefore, lignin oil was dissolved in tetrahydrofuran to achieve a concentration of about 5 mg mL^{-1} and the solution was filtered (PTFE filter, pore size: 0.2 µm). GPC analysis was performed at 40 °C, using tetrahydrofuran as a solvent (flowrate: 1 ml min^{-1}) on a Waters E2695 equipped with an Agilent PL Gel column (Mixed E, 3 µm) and a Waters 2998 Photodiode array detector (UV detection at 280 nm). Commercial standards for phenolic monomers and polystyrene standards were employed to create calibration curves.
In order to determine the phenolic monomers composition in the lignin oil, the dichloromethane extract, obtained following a procedure analogous to that reported above, was added with a known amount of 2-isopropyl phenol (internal standard) and analyzed via gas chromatography (GC).
Identification of phenolic monomers was performed using a Thermo Fisher Scientific Trace 1310 equipped with a Rxi-5Sil MS column and an ISQ QD Mass Spectroscopy (MS) detector. The following operating conditions were used: injection temperature of 280 °C, column temperature program: 40 °C (1 min), 10 °C/min to 300 °C (5 min), detection temperature of 310 °C.
Quantification of phenolic monomers was carried out using a Thermo Fisher Scientific Trace GC Ultra equipped with a Rxi-5Sil MS column and a flame ionization detector (FID). The following operating conditions were adopted: injection temperature 280 °C, column temperature program: 40 °C (1 min), 2 °C/min to 150 °C, 5 °C/min to 240 °C, 30 °C/min to 300 °C (15 min), detection temperature of 305 °C. Response factors for the different products were determined by calibration with commercial standards or via calculations based on Effective Carbon Number theory.
The yield of phenolic monomers was calculated with respect to the amount of acid insoluble lignin and with respect to the DM introduced, according to the equations below.

$$Yield_i|_{AIL}\ (\text{wt\%}) = \frac{m_i}{m_{AIL,in}} \quad \text{Eq. 11}$$

$$Yield_i|_{DM}\ (\text{wt\%}) = \frac{m_i}{m_{DM,in}} \quad \text{Eq. 12}$$

Wherein
m_i indicates the amount of component *i* obtained from the process, determined via GC-FID analysis [g].
$m_{AIL,in}$ indicates the amount of acid insoluble lignin present in the biomass initially introduced in the reactor [g].
$m_{DM,in}$ indicates the amount of dry matter present in the biomass initially introduced in the reactor [g].

Analysis of organic acids and dehydration products from carbohydrates was carried out by subjecting the organic liquid phase to High Performance Liquid Chromatography. Therefore, a sample of the organic phase was filtered (PTFE filter, pore size: 0.2 µm) and analyzed via High Performance Liquid Chromatography (HPLC), applying the same conditions illustrated above for the analysis of structural carbohydrates in biomass. Peaks identification was based on the comparison of retention times with those of pure standards. Response factors were determined by calibration with commercial standards. The yield of carbohydrate derivatives was calculated with respect to the total amount of polysaccharides in the initial biomass and with respect to the DM introduced, according to the following equations.

$$Yield_i|_{C5+C6}\ (\text{wt\%}) = \frac{m_i}{m_{C5+C6,in}} \quad \text{Eq. 13}$$

$$Yield_i|_{DM}\ (\text{wt\%}) = \frac{m_i}{m_{DM,in}} \quad \text{Eq. 14}$$

Wherein
m_i indicates the amount of component *i* obtained from the process, determined via HPLC analysis [g].
$m_{C5+C6,in}$ indicates the total amount of polysaccharides present in the biomass initially introduced in the reactor [g].
$m_{DM,in}$ indicates the amount of dry matter present in the biomass initially introduced in the reactor [g].

Analysis of the aqueous fraction

The analytical procedures applied to characterize the aqueous liquid fraction are analogous to those described for the organic liquid fraction.

Overall mass balance

An overall mass balance for the main biomass components (C5, C6 carbohydrates and lignin) was carried out considering three product streams: a solid fraction, an organic liquid fraction, an aqueous liquid fraction. In addition, a residual "not found" fraction was introduced to account for losses (mainly due to the generation of volatiles). Ash was not taken into consideration in the mass balance, since it only accounts for a marginal fraction of DM in biomass, while most of the ash content in the reaction products derives from the reducing agent. In addition, a correction was applied to account for the presence of non-ash DM originating from the reducing agent, determined via *blank* reactions carried out in absence of biomass. Therefore, the following system of equations (Eq. 15–22) describes the mass balance:

$$C5_S + C5_O + C5_A + C5_{NF} = C5_{in} \quad \text{Eq. 15}$$

$$C6_S + C6_O + C6_A + C6_{NF} = C6_{in} \quad \text{Eq. 16}$$

$$L_S + L_O + L_A + L_{NF} = L_{in} \quad \text{Eq. 17}$$

$$Extr_S + Extr_O + Extr_A + Extr_{NF} = Extr_{in} \quad \text{Eq. 18}$$

$$C5_S + C6_S + L_S + Extr_S + Other_S = Solid_{tot} \quad \text{Eq. 19}$$

$$C5_O + C6_O + L_O + Extr_O + Other_O = Organic_{tot} \quad \text{Eq. 20}$$

$$C5_A + C6_A + L_A + Extr_A + Other_A = Aqueous_{tot} \quad \text{Eq. 21}$$

$$C5_{NF} + C6_{NF} + L_{NF} + Extr_{NF} + Other_{NF} = Residual_{tot} \quad \text{Eq. 22}$$

Wherein
Subscript "S" indicates the amount of a component in the pulp.
Subscript "O" indicates the amount of a component in the organic liquid fraction.
Subscript "A" indicates the amount of a component in the aqueous liquid fraction.

Subscript “NF” indicates the amount of a component in the “not found” fraction.
Subscript “in” indicates the amount of a component in the biomass initially introduced in the reactor.
C5 indicates the amount of xylan and arabinan [g].
C6 indicates the amount of glucan [g].
L indicates the amount of acid-insoluble lignin [g].
Extr indicates the amount of extractives [g].
Other indicates the amount of biomass components that do not originate from C5, C6, lignin or extractives [g].
$Solid_{tot}$ indicates the total amount of biomass components in the solid fraction [g].
$Organic_{tot}$ indicates the total amount of biomass components in the organic liquid fraction [g].
$Aqueous_{tot}$ indicates the total amount of biomass components in the aqueous liquid fraction [g].
$Residual_{tot}$ indicates the total amount of biomass components that are not recovered in the solid or liquid product streams [g].

Variables that can be measured include: $C5_S$, $C5_{in}$, $C6_S$, $C6_{in}$, L_S, L_{in}, $Extr_{in}$, $Solid_{tot}$, $Organic_{tot}$, $Aqueous_{tot}$, $Residual_{tot}$.
Unknown variables include: $C5_O$, $C5_A$, $C5_{NF}$, $C6_O$, $C6_A$, $C6_{NF}$, L_O, L_A, L_{NF}, $Extr_S$, $Extr_O$, $Extr_A$, $Extr_{NF}$, $Other_S$, $Other_O$, $Other_A$, $Other_{NF}$.
Thus, the system is unsaturated. In order to solve the mass balance, the following assumptions were introduced:

- Water- and ethanol-soluble extractives are entirely recovered in the aqueous phase and in the organic phase, respectively.
- Lignin contributes marginally to the formation of volatile compounds (L_{NF} is negligible).
- The components deriving from C5 and C6 in the organic and aqueous fractions consist either of condensed derivatives (humins) incorporated in lignin oil, or non-condensed derivatives (saccharides, polyols and organic acids).
- The amount of condensed derivatives from C5 (and C6) in lignin oil is inversely proportional to the amount of C5 (and C6) in the solid fraction.
- The amount of non-condensed derivatives from C5 (and C6) in the organic or aqueous fraction is inversely proportional to the amount of C5 (and C6) in the solid fraction.
- Solubilized lignin and humins migrate to the organic or the aqueous phase proportionally to the amount of lignin oil contained in that phase.

Leading to the additional equations (Eq. 23 – 38).

$$Extr_A = Extr_{in,H_2O}$$ Eq. 23

$$Extr_O = Extr_{in,EtOH}$$ Eq. 24

$$Extr_S = 0$$ Eq. 25

$$L_{NF} = 0$$ Eq. 26

$$C5_O = C5_{OL} + C5_{OC}$$ Eq. 27

$$C6_O = C6_{OL} + C6_{OC}$$ Eq. 28

$$C6_{OL} = \frac{C6_{in} - C6_S}{(C6_{in} - C6_S) + (C5_{in} - C5_S)} (C5_{OL} + C6_{OL})$$ Eq. 29

$$C5_{OC} + C6_{OC} = CarbDer_O$$ Eq. 30

$$C6_{OC} = \frac{C6_{in} - C6_S}{(C6_{in} - C6_S) + (C5_{in} - C5_S)} (C5_{OC} + C6_{OC}) \quad \text{Eq. 31}$$

$$C5_A = C5_{AL} + C5_{AC} \quad \text{Eq. 32}$$

$$C6_A = C6_{AL} + C6_{AC} \quad \text{Eq. 33}$$

$$C6_{AL} = \frac{C6_{in} - C6_S}{(C6_{in} - C6_S) + (C5_{in} - C5_S)} (C5_{AL} + C6_{AL}) \quad \text{Eq. 34}$$

$$C5_{AL} + C6_{AL} = \frac{LigninOil_A}{LigninOil_O} (C5_{OL} + C6_{OL}) \quad \text{Eq. 35}$$

$$L_A = \frac{LigninOil_A}{LigninOil_O} (L_O) \quad \text{Eq. 36}$$

$$C5_{AC} + C6_{AC} = CarbDer_A \quad \text{Eq. 37}$$

$$C6_{AC} = \frac{C6_{in} - C6_S}{(C6_{in} - C6_S) + (C5_{in} - C5_S)} (C5_{AC} + C6_{AC}) \quad \text{Eq. 38}$$

Wherein
Subscript “OL” indicates the amount of a component in the organic liquid fraction, contributing to lignin oil.
Subscript “OC” indicates the amount of a component in the organic liquid fraction, contributing to non-condensed carbohydrate derivatives.
Subscript “AL” indicates the amount of a component in the aqueous liquid fraction, contributing to lignin oil.
Subscript “AC” indicates the amount of a component in the aqueous liquid fraction, contributing to non-condensed carbohydrate derivatives.
$Extr_{in,H_2O}$ indicates the amount of water-soluble extractives in biomass [g].
$Extr_{in,EtOH}$ indicates the amount of ethanol-soluble extractives in biomass [g].
CarbDer indicates the amount of non-condensed C5, C6 derivatives [g].
LigninOil indicates the amount of lignin oil [g].

Variables that can be measured include: $CarbDer_O$, $CarbDer_A$, $LigninOil_O$, $LigninOil_A$.
Unknown variables include: $C5_{OL}$, $C5_{OC}$, $C6_{OL}$, $C6_{OC}$, $C5_{AL}$, $C5_{AC}$, $C6_{OL}$, $C6_{AC}$.
Overall, considering Eq. 15–38, the system of equations has one degree of freedom. Instead of making further assumptions to saturate the system, the two following inequalities were considered, thanks to which it was possible to determine upper and lower limits for all the unknown variables.

$$Other_O \geq 0 \quad \text{Eq. 39}$$

$$Other_{NF} \geq 0 \quad \text{Eq. 40}$$

Assessment of butanol recovery

The assessment of the recovery of the butanol co-solvent in the liquid fractions was performed by measuring the butanol content of each fraction via High Performance Liquid Chromatography, following a procedure analogous to that described above for the analysis of organic acids and dehydration products from carbohydrates. The recovery of butanol in each liquid fraction was

calculated with respect to the total amount of butanol utilized during the process (for the reaction and for washing the isolated pulp), according to the following equation.

$$Recovery_{Butanol}|_{O/A}\ (\text{wt\%}) = \frac{C_{Butanol,O/A}\ V_{O/A}\ \frac{1\ \text{L}}{1000\ \text{mL}}}{m_{Butanol,in} + m_{Butanol,wash}} \quad \text{Eq. 41}$$

Wherein
$C_{Butanol,O/A}$ indicates the concentration of butanol measured in the organic or aqueous fraction [g L^{-1}].
$V_{O/A}$ indicates the volume of organic or aqueous fraction [mL].
$m_{Butanol,in}$ indicates the amount of butanol employed for the fractionation [g].
$m_{Butanol,wash}$ indicates the amount of butanol employed for washing the isolated pulp [g].

Analysis of dithionite derivatives

In order to inspect the presence of derivatives from dithionite in the isolated fractions, the sulfur content in each fraction was determined via mineralization followed by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES). Therefore, a sample of the solid fraction (~20 mg) was mixed with 2 mL of HNO_3 (69%) and 1 mL of H_2O_2 (30%) and the mixture was left to react for 10 minutes. Then, the mixture was dried at 100 °C. The obtained residue was redispersed in 2 mL of HNO_3 before being diluted with 25 mL water for the analysis. An analogous procedure was followed for the mineralization of the organic fraction (a sample of 0.5 mL was used in this case). Sample preparation for the aqueous fraction consisted simply in the dilution of a sample in HNO_3 (8%). ICP-AES analyses were performed using a Thermo iCAP 6500 Duo spectrometer. The system was calibrated using pure sulfur standard solutions. The recovery of sulfur in each fraction was calculated with respect to the total amount of sulfur introduced in the process, according to the following equation.

$$Recovery_{Sulfur}|_{S/O/A}\ (\%) = \frac{C_{Sulfur,S/O/A}\ \frac{1\ \text{g}}{1000\ \text{mg}}\ m_{S/O/A}\ \frac{1\ \text{kg}}{1000\ \text{g}}}{\frac{N_{Sulfur}\ M_{Sulfur}}{M_{Na_2S_2O_4}}\ m_{Na_2S_2O_4,in}} \quad \text{Eq. 42}$$

Wherein
$C_{Sulfur,S/O/A}$ indicates the concentration of sulfur measured in the solid, organic or aqueous fraction [mg kg^{-1}].
$m_{Sulfur,S/O/A}$ indicates the amount of solid, organic or aqueous fraction obtained from the process [g].
N_{Sulfur} indicates the number of sulfur atoms in sodium dithionite.
M_{Sulfur} indicates the atomic mass of sulfur [g mol^{-1}].
$M_{Na_2S_2O_4}$ indicates the molecular weight of sodium dithionite [g mol^{-1}].
$m_{Na_2S_2O_4,in}$ indicates the amount of sodium dithionite introduced in the process [g].

Milled wood lignin: preparation and organosolv treatment

Isolation of milled wood lignin (MWL) was performed following a procedure that is well-established in the literature.[14] Therefore, water- and ethanol-soluble extractives were removed from biomass according to the methods reported above, then the extracted biomass was milled at 800 rpm for 12 hours (with pauses of 5 minutes every 5 minutes of milling to avoid overheating) using a Retsch Emax ball mill. Subsequently, the milled wood was dispersed in an aqueous solution of dioxane (96% v/v) at a concentration of 40 g/L and stirred at ambient temperature for 24 hours. Thereafter, the suspension was centrifuged (8000 rpm, 10 min) and the solid residue was redispersed in fresh aqueous dioxane under stirring for an additional 24 hours. The extracts were combined and dried under vacuum to yield crude MWL. This intermediate product was dissolved in an aqueous solution of acetic acid (90%) at a concentration of 50 g/L. Afterwards, lignin was precipitated by dropwise addition of the acetic acid solution to water (220 mL of water per gram of crude MWL), centrifuged (8000 rpm, 10 min) and air dried to a constant weight. The isolated lignin was refined further by dissolving it in a solution of 1,2-dichloroethane and ethanol (2:1 v/v) at a concentration of 50 g/L, which was then centrifuged to remove residual solids. Lignin was precipitated once again by dropwise addition of the 1,2-dichloroethane – ethanol solution to anhydrous ethyl ether (230 mL of ether per gram of lignin). After centrifugation (8000 rpm, 10 min), the isolated MWL was washed three times with fresh ether, centrifuging after every washing step, and, finally, air dried to a constant weight to yield purified MWL.

MWL was subjected to organosolv treatment performed as described above. Therefore, 0.63 g of MWL were introduced in the reactor, together with 1 g of sodium dithionite, 60 mL of n-butanol and 60 mL of milli-Q water. The reaction was carried out at a temperature of 200 °C, following the procedure illustrated above. The subsequent product separation and analysis was conducted

as previously described. For the reaction with MWL and formic acid, 0.63 g of MWL and 0.11 g of formic acid were subjected to an identical process.

Reactions with model compounds

The reactions with model compounds were carried out using the same equipment and an analogous procedure as that presented for organosolv fractionation experiments. Therefore, a weighed amount of the model compound (0.02 g for 2-phenoxy-1-phenylethanol and 0.05 g for 4-propenyl guaiacol and 3-phenyl-1-propenol) was introduced in the reactor, together with 60 mL of n-butanol, 60 mL of milli-Q water and the selected amount of sodium dithionite (between 0 and 12 molar equivalents). The reaction was performed following the procedure described above. For the treatment of 2-phenoxy-1-phenylethanol, a higher reaction temperature of 250 °C was adopted, to promote the cleavage of the dimer.[15] Subsequently, the reactor content was collected, transferred into a separating funnel and let to rest overnight. Thereafter, the aqueous liquid fraction and the organic liquid fraction were collected and stored at -20 °C for further analysis.
The reaction products were then analyzed via GPC and GC-MS/FID following the procedures reported above.
The C-based yields of phenolic monomers were calculated according to the equation below.

$$Yield_i\ (\mathrm{C\%}) = \frac{m_i\ \frac{C_i\ M_C}{MW_i}}{m_{Model}\ \frac{C_{Model}\ M_C}{MW_{Model}}} \qquad \text{Eq. 43}$$

Wherein
m_i indicates the amount of component *i* obtained from the process, determined via GC analysis [g].
C_i indicates the number of carbon atoms in the molecule of component *i*.
M_c indicates the atomic mass of carbon [g mol^{-1}].
MW_i indicates the molecular weight of component *i* [g mol^{-1}].
m_{Model} indicates the amount of model compound introduced in the reactor [g].
C_{Model} indicates the number of carbon atoms in the molecule of the model compound.
MW_{Model} indicates the molecular weight of the model compound [g mol^{-1}].

Simplified economic assessment of monophenolics production via dithionite-assisted organosolv fractionation

Dithionite-assisted organosolv fractionation was shown to enhance depolymerization of lignin from lignocellulosic biomass compared to classical organosolv treatment. With the process configuration examined in this work, about 8.5 grams of sodium dithionite are consumed per gram of phenolic monomers produced. Assuming the process is scalable and considering a market price for sodium dithionite of about 600 €/ton (estimated from industrial suppliers online), the cost of dithionite per ton of phenolic monomers produced would be of about 5100 €. Even though this represents a quite large operative cost, the market values reported in the literature for phenolic monomers range between ~2000 €/ton and ~12000 €/ton,[7,16] suggesting that dithionite-assisted organosolv fractionation can potentially represent an economically viable alternative to conventional pulping processes.

Figures

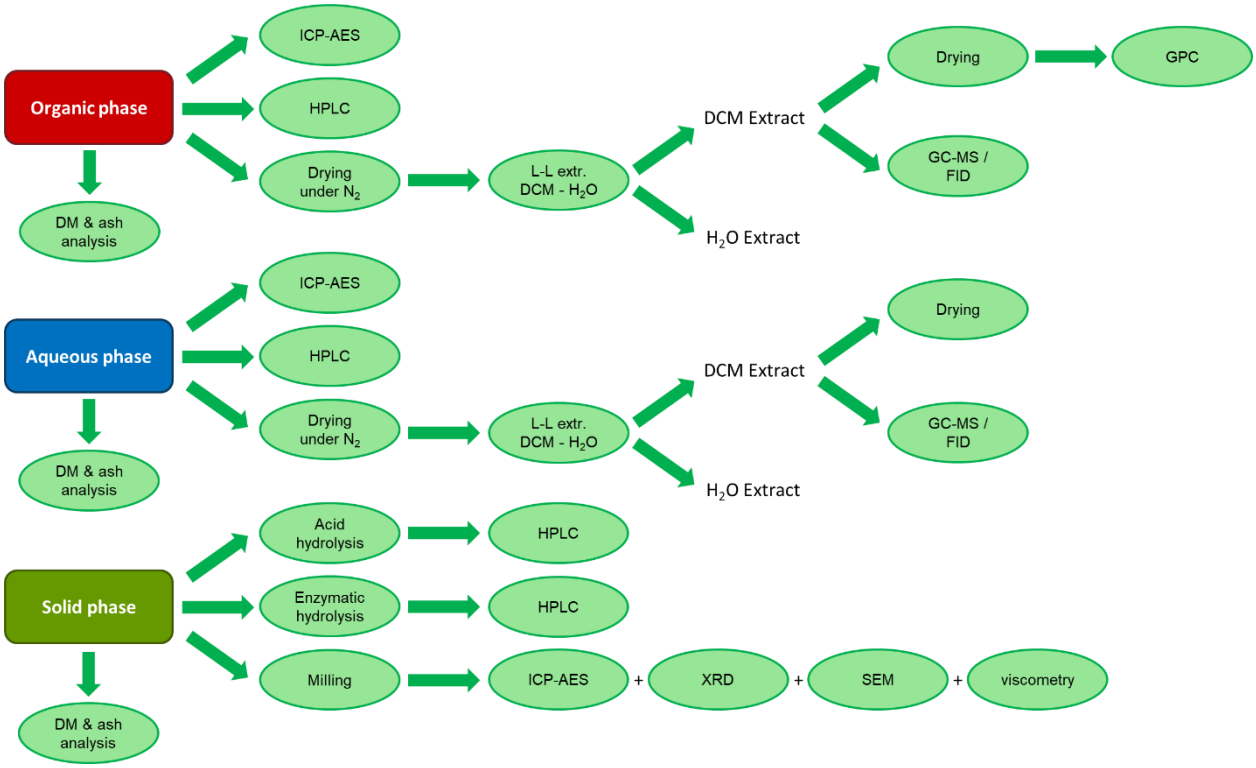


Figure S1 Schematic representation of the analytical procedures adopted for the characterization of the output streams obtained from biomass fractionation.

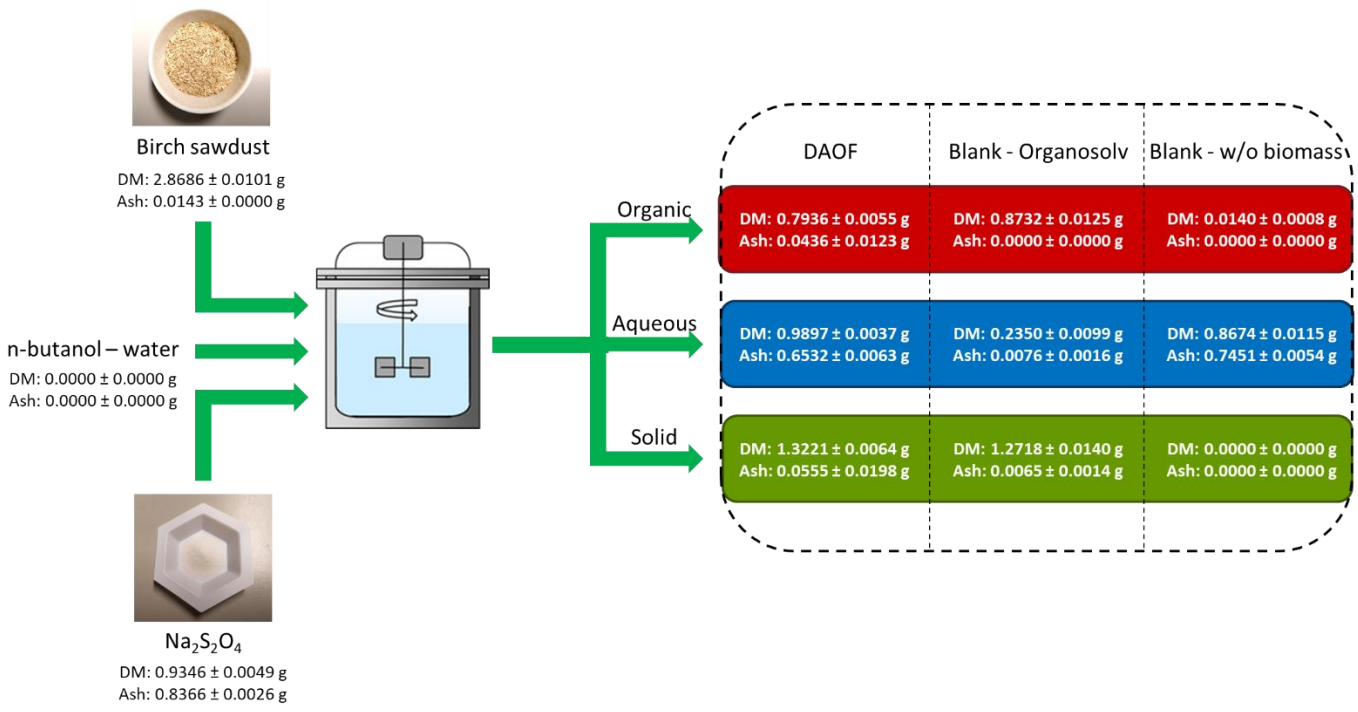


Figure S2 DM and Ash contents measured in each process stream for the dithionite-assisted organosolv fractionation (DAOF) of birch sawdust, for the organosolv treatment of birch sawdust (Blank - Organosolv), and for a reaction performed without biomass (Blank - w/o biomass). The reactions were carried out treating biomass (3 g, particle size < 2 mm) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature), for a duration of 3 hours.

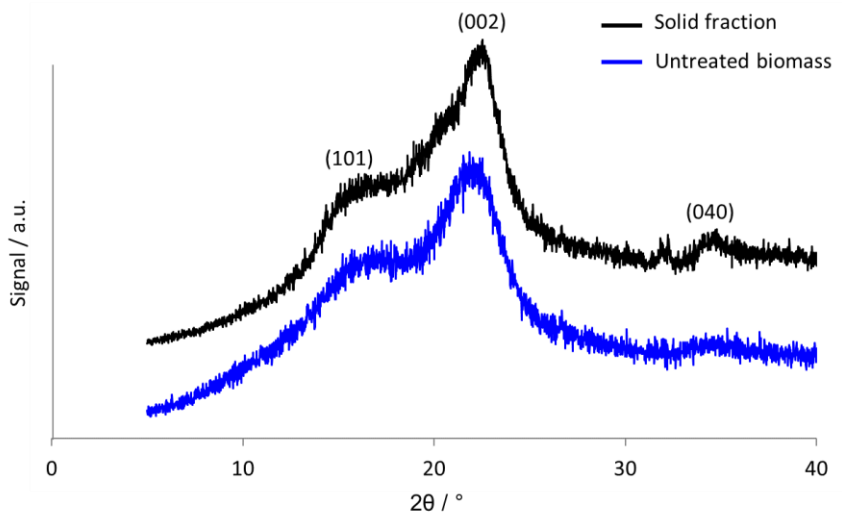


Figure S3 XRD profiles obtained for untreated birch sawdust and for the solid fraction isolated after treating birch sawdust (3 g, particle size < 2 mm) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature), in the presence of $Na_2S_2O_4$ (1 g), for a duration of 3 hours.

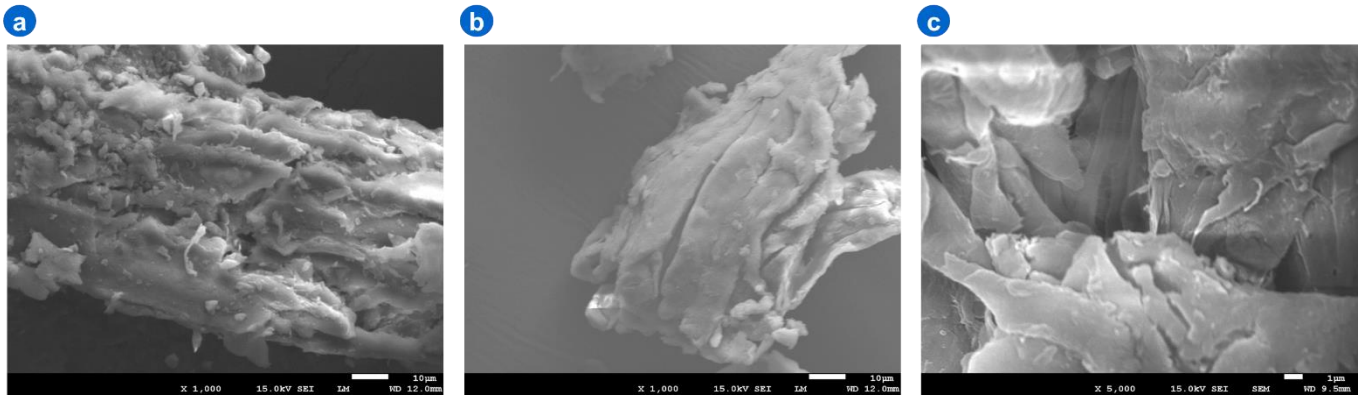


Figure S4 SEM images obtained for untreated birch sawdust (a) and for the solid fraction isolated after treating birch sawdust (3 g, particle size < 2 mm) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature), in the presence of $Na_2S_2O_4$ (1 g), for a duration of 3 hours (b and c). (b) Fiber cells bundles. (c) Detail of fiber cells.

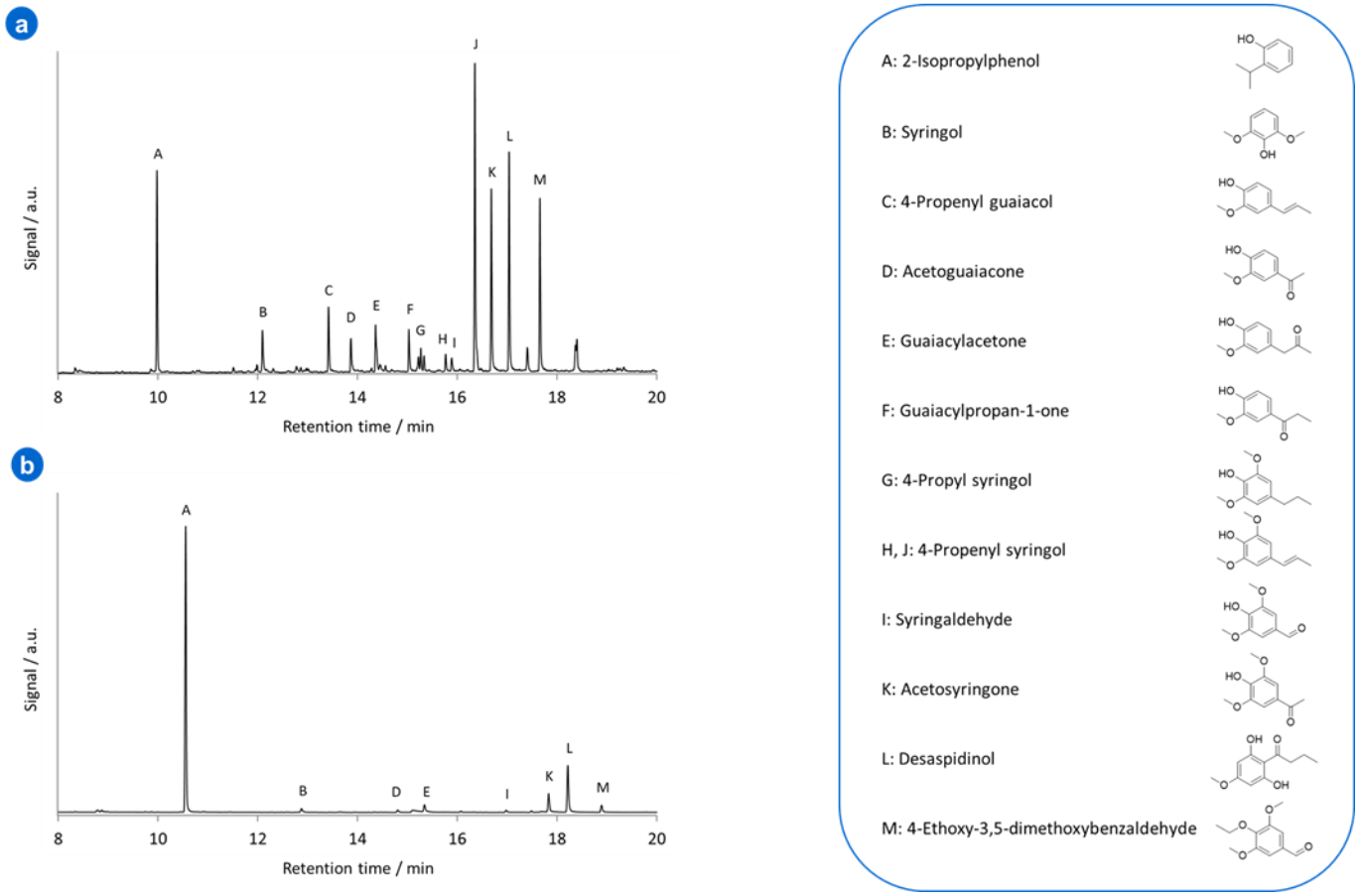


Figure S5 Gas -chromatograms of the lignin oil isolated from the organic fraction (a) and aqueous fraction (b), obtained after treating birch sawdust (3 g, particle size < 2 mm) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature), in the presence of $Na_2S_2O_4$ (1 g), for a duration of 3 hours.

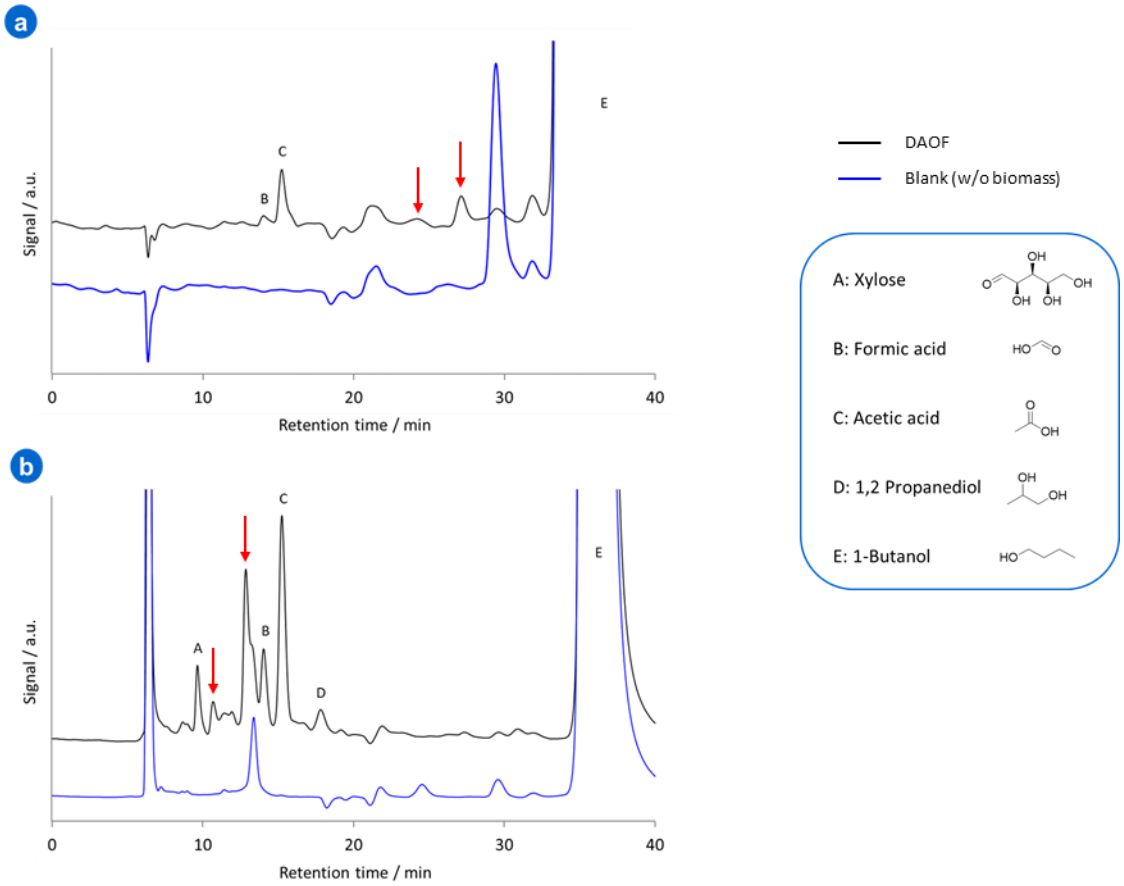


Figure S6 HPLC chromatograms of the organic fraction (a) and aqueous fraction (b), obtained after treating birch sawdust (3 g, particle size < 2 mm) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature), in the presence of 1 g of $Na_2S_2O_4$ (1 g), for a duration of 3 hours. Chromatograms obtained for blank reactions (without biomass), at identical conditions were added for comparison. Red arrows in the chromatograms point toward peaks corresponding to components that originate from biomass, but could not be identified.

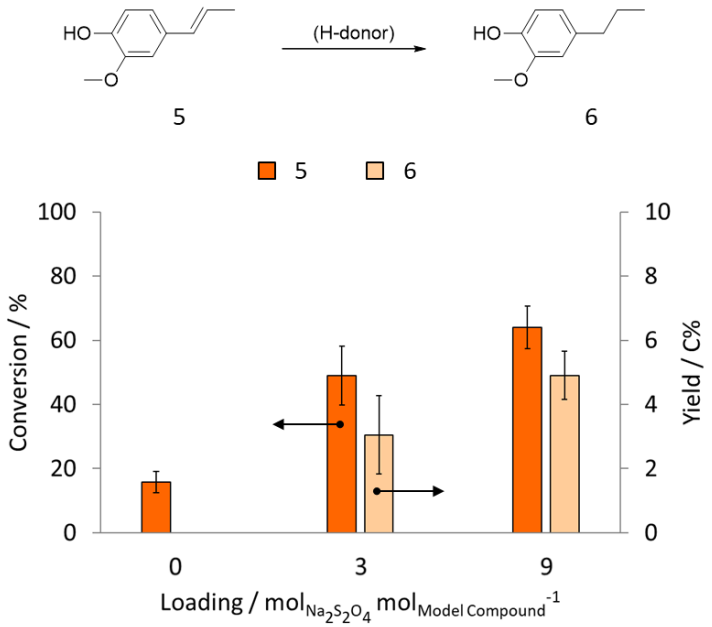


Figure S7 Effect of $Na_2S_2O_4$ on the conversion of 4-propenyl guaiacol and on the yields of monomeric products obtained from the reaction of 4-propenyl guaiacol (0.05 g) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature), for a duration of 3 hours. The reactions were performed in duplicates. The arrows in the figure indicate the reference axis.

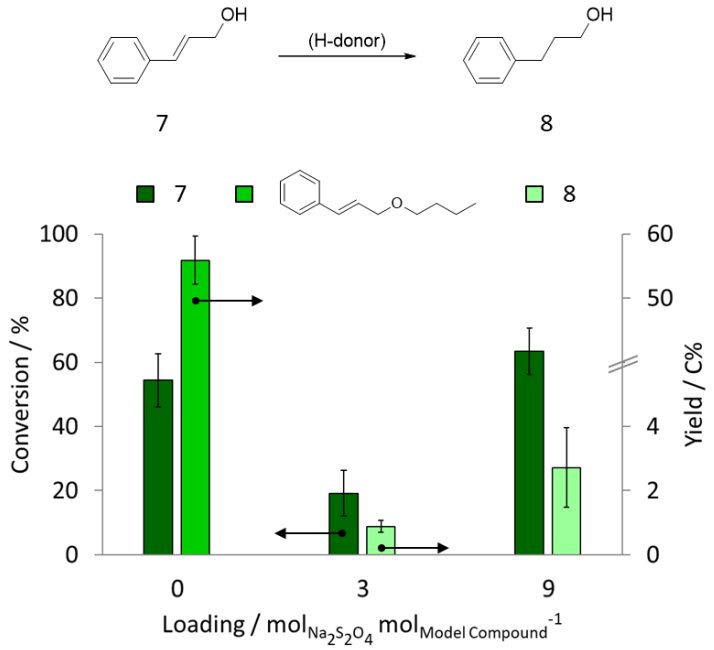


Figure S8 Effect of $Na_2S_2O_4$ on the conversion of the 3-phenyl-1-propenol and on the yields of monomeric products obtained from the reaction of 3-phenyl-1-propenol (0.05 g) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature), for a duration of 3 hours. The reactions were performed in duplicates. The arrows in the figure indicate the reference axis.

Figure S9 Parr batch reactor used for the experimentation.

Figure S10 Organic and aqueous liquid fractions (left), lignin oil (middle) and solid fraction (right) obtained for the dithionite-assisted organosolv fractionation of birch wood.

```
Solve[C5s + C5o + C5a + C5nf == C5in &&
  C6s + C6o + C6a + C6nf == C6in &&
  Ls + Lo + La + Lnf == Lin &&
  Extrs + Extro + Extra + Extrnf == Extrin &&

  C5s + C6s + Ls + Extrs + Others == Solidtot &&
  C5o + C6o + Lo + Extro + Othero == Organictot &&
  C5a + C6a + La + Extra + Othera == Aqueoustot &&
  C5nf + C6nf + Lnf + Extrnf + Othernf == Residualtot &&

  C5o == C5ol + C5oc &&
  C6o == C6ol + C6oc &&

  C6ol == ((C6in - C6s) / ((C6in - C6s) + (C5in - C5s))) * (C5ol + C6ol) &&

  C5oc + C6oc == CarbDero &&
  C6oc == ((C6in - C6s) / ((C6in - C6s) + (C5in - C5s))) * (C6oc + C5oc) &&

  C5a == C5al + C5ac &&
  C6a == C6al + C6ac &&

  C6al == ((C6in - C6s) / ((C6in - C6s) + (C5in - C5s))) * (C6al + C5al) &&
  (C5al + C6al) == LigninOila / LigninOilo * (C5ol + C6ol) &&
  La == LigninOila / LigninOilo * (Lo) &&

  C5ac + C6ac == CarbDera &&
  C6ac == ((C6in - C6s) / ((C6in - C6s) + (C5in - C5s))) * (C6ac + C5ac),
 {C5o, C5a, C5nf, C6o, C6a, C6nf, Lo, La, Extrnf, Others, Othero, Othera, Othernf, C5ol, C5oc, C6ol, C6oc, C5al, C5ac, C6al, C6ac}]
```

Measured variables

```
C5in = 21.8
C6in = 36.6
Lin = 22.0
Extrin = 8.2

Solidtot = 44.1
Organictot = 26.6
Aqueoustot = 17.6
Residualtot = 11.2

C5s = 4.0
C6s = 33.5
Ls = 6.2
Extrs = 0.0
Extro = 2.3
Extra = 5.9

LigninOilo = 20.5
LigninOila = 0.7
CarbDero = 0.1
CarbDera = 4.4

Lnf = 0.0
```

```
{{C5a → 3.74446 + 0.0341463 C5o, C5nf → 14.0555 - 1.03415 C5o, C6o → 0. + 0.174157 C5o, C6a → 0.652125 + 0.00594683 C5o, C6nf → 2.44787 - 0.180104 C5o, Lo → 15.2783, La → 0.521698,
  Extrnf → 0., Others → 0.4, Othero → 9.0217 - 1.17416 C5o, Othera → 6.78172 - 0.0400932 C5o, Othernf → -5.30341 + 1.21425 C5o, C5ol → -0.0851675 + 1. C5o, C5oc → 0.0851675,
  C6ol → -0.0148325 + 0.174157 C5o, C6oc → 0.0148325, C5al → -0.00290816 + 0.0341463 C5o, C5ac → 3.74737, C6al → -0.000506477 + 0.00594683 C5o, C6ac → 0.652632}}
```

```
Reduce[9.021698113207547 - 1.1741573033707866 * C5o ≥ 0 &&
  -5.303414634146343 + 1.2142504795834475 * C5o ≥ 0,
 {C5o}]
```

```
4.36764 ≤ C5o ≤ 7.68355
```

```
C5oset = (7.683551503114562 + 4.3676446691342425) / 2
```

```
6.0256
```

```
Solve[C5a == 3.744460263741394 + 0.03414634146341463 * C5oset &&
  C5nf == 14.055539736258606 - 1.0341463414634147 * C5oset &&
  C6o == 0.17415730337078653 * C5oset &&
  C6a == 0.6521251021122652 + 0.005946834749246371 * C5oset &&
  C6nf == 2.4478748978877363 - 0.18010413812003329 * C5oset &&
  Othero == 9.021698113207547 - 1.1741573033707866 * C5oset &&
  Othera == 6.781716520938795 - 0.040093176212661 * C5oset &&
  Othernf == -5.303414634146343 + 1.2142504795834475 * C5oset &&
  C5ol == -0.08516746411483254 + C5oset &&
  C6ol == -0.014832535885167461 + 0.17415730337078653 * C5oset &&
  C5al == -0.0029081573112381843 + 0.03414634146341463 * C5oset &&
  C6al == -0.000506476835103279 + 0.005946834749246366 * C5oset,
 {C5a, C5nf, C6o, C6a, C6nf, Othero, Othera, Othernf, C5ol, C6ol, C5al, C6al}]
```

```
{{C5a → 3.95021, C5nf → 7.82419, C6o → 1.0494, C6a → 0.687958, C6nf → 1.36264,
  Othero → 1.9467, Othera → 6.54013, Othernf → 2.01317, C5ol → 5.94043, C6ol → 1.03457, C5al → 0.202844, C6al → 0.0353268}}
```

Figure S11 Solution of the equations describing the overall mass balance for the treatment of birch sawdust (3 g, particle size < 2 mm) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature), in the presence of $Na_2S_2O_4$ (1 g), for a duration of 3 hours. Equations and inequalities were solved using Wolfram Mathematica 11.2.

Tables

Table S1 Compositional characterization of birch sawdust.

Component	Content (wt%)[a]
Lignin	
Acid insoluble lignin	22.0 ± 0.2
C5	
Xylan	21.4 ± 1.0
Arabinan	0.4 ± 0.1
C6	
Glucan	36.6 ± 0.3
Extractives	
Ethanol-soluble	2.3 ± 0.1
Water-soluble	5.9 ± 0.1
Ash	0.5 ± 0.0
Other	10.9 ± 1.6

[a] The contents of the different components are expressed as percentages of dry matter. Four replicates were performed for each analysis.

Table S2 Characterization of the solid and liquid fractions obtained from the treatment of birch sawdust (3 g, particle size < 2 mm) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N2 (introduced at ambient temperature), for a duration of 3 hours. No $Na_2S_2O_4$ was added to the mixture. The reaction was carried out in triplicates.

Solid fraction	Recovery (wt%)	C5	15.5 ± 1.1
		C6	92.5 ± 3.0
		Lignin[a]	30.7 ± 8.5
	Conversion (%)	Glucan	87.5 ± 3.9
		Xylan	99.0 ± 4.0
	CI (%)		52.5 ± 1.4
Organic fraction	Yield (wt%)	Lignin oil[b]	95.2 ± 1.9
		Monophenolics[b]	3.4 ± 0.6
		C5, C6 derivatives[c]	0.0 ± 0.0
Aqueous fraction	Yield (wt%)	Lignin oil[b]	4.1 ± 0.4
		Monophenolics[b]	0.1 ± 0.0
		C5, C6 derivatives[c]	3.4 ± 0.5

[a] Acid-insoluble lignin

[b] Expressed with respect to the weight of acid-insoluble lignin contained in the initial biomass.

[c] Non-condensed carbohydrate derivatives, expressed with respect to the total weight of polysaccharides contained in the initial biomass.

Table S3 Values of cellulose degree of polymerization (DP), determined by viscosimetry for the solid fractions obtained from the treatment of birch sawdust (3 g, particle size < 2 mm) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature),) for a duration of 3 hours, in the presence of 1 g of $Na_2S_2O_4$ (DAOF), or in the absence of $Na_2S_2O_4$ (Blank). The DP of Avicel cellulose was measured as a reference standard. Pulp samples were analyzed in duplicates.

Experiment	Cellulose DP (AGU)
DAOF[a]	780.0 ± 23.0
Blank	227.0 ± 2.7
Avicel cellulose	150.0 ± 0.1

[a]A small amount of solid residue was observed which did not dissolve in cupriethylenediamine, likely related to structural modification of the pulp triggered by dithionite (e.g. incorporation of sulfur). This phenomenon likely explains the larger error in the measurement.

Table S4 Phenolic monomer composition of the lignin oil isolated from the organic and the aqueous fractions obtained after treating birch sawdust (3 g, particle size < 2 mm) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature), in the presence of $Na_2S_2O_4$ (1 g), for a duration of 3 hours. The reaction was carried out in triplicates.

Component	Organic fraction Yield (wt%)[a]	Aqueous fraction Yield (wt%)[a]
Syringol	0.6 ± 0.0	0.0 ± 0.0
4-Propenyl guaiacol	0.8 ± 0.1	-
Acetoguaiacone	0.5 ± 0.0	0.0 ± 0.0
Guaiacylacetone	0.5 ± 0.0	0.0 ± 0.0
Guaiacylpropan-1-one	0.5 ± 0.0	-
4-Propyl syringol	0.3 ± 0.0	-
Syringaldehyde	0.5 ± 0.0	0.0 ± 0.0
4-Propenyl syringol	4.3 ± 0.9	-
Acetosyringone	2.7 ± 0.2	0.1 ± 0.0
Desaspidinol	3.2 ± 0.5	0.2 ± 0.0
4-Ethoxy-3,5-dimethoxybenzaldehyde	4.3 ± 0.1	0.1 ± 0.0
Total	18.1 ± 1.7	0.5 ± 0.1

[a] Expressed with respect to the weight of acid-insoluble lignin contained in the initial biomass.

Table S5 Phenolic monomer composition of the lignin oil isolated from the organic and the aqueous fractions obtained after treating birch sawdust (3 g, particle size < 2 mm) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature), for a duration of 3 hours. No $Na_2S_2O_4$ was added to the mixture. The reaction was carried out in triplicates.

Component	Organic fraction Yield (wt%)[a]	Aqueous fraction Yield (wt%)[a]
Guaiacol	0.1 ± 0.0	-
Syringol	0.0 ± 0.0	
Methyl syringol	0.3 ± 0.0	-
Syringaldehyde	1.0 ± 0.3	0.0 ± 0.0
4-Propenyl syringol	0.9 ± 0.0	-
Acetosyringone	0.4 ± 0.0	-
Desaspidinol	0.2 ± 0.1	0.0 ± 0.0
4-Ethoxy-3,5-dimethoxybenzaldehyde	0.1 ± 0.0	-
Sinapyl aldehyde	0.2 ± 0.0	-
Sinapyl alcohol	0.4 ± 0.1	-
Total	3.6 ± 0.6	0.1 ± 0.0

[a] Expressed with respect to the weight of acid-insoluble lignin contained in the initial biomass.

Table S6 Characterization of biomass derivatives in the output streams obtained from the treatment of birch sawdust (3 g, particle size < 2 mm) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature),) for a duration of 3 hours, in the presence of 1 g of $Na_2S_2O_4$ (DAOF), or in the absence of $Na_2S_2O_4$ (Blank). The reactions were carried out in triplicates. The ash fraction was not taken into consideration, since it only accounts for a marginal fraction of DM in biomass (0.5%), while most of the ash content in the reaction products derives from $Na_2S_2O_4$.

Solid fraction (wt% DM_{in})		**DAOF**	**Blank**
Non-volatile[a]	Non-ash DM[b]	44.1 ± 0.9	44.1 ± 0.6
	C6	33.5 ± 0.4	33.8 ± 1.0
	C5	4.0 ± 0.7	3.3 ± 0.2
	Lignin[c]	6.2 ± 0.6	6.8 ± 1.9
	Non-ash other	0.4 ± 0.1	0.2 ± 0.4
Total		44.1 ± 0.9	44.1 ± 0.6
Organic fraction (wt% DM_{in})		**DAOF**	**Blank**
Non-volatile[a]	Non-ash DM[b]	25.6 ± 0.6	30.4 ± 0.4
	Lignin monomers	4.0 ± 0.1	0.8 ± 0.1
	Lignin oligomers[d]	16.5 ± 1.6	20.6 ± 0.4
	Extractives	2.3 ± 0.1	2.3 ± 0.1
	Non-ash other	2.9 ± 1.3	7.2 ± 0.9
Volatile[e]	Formic acid	0.1 ± 0.0	0.0 ± 0.0
	Acetic acid	0.9 ± 0.0	0.4 ± 0.0
Total		26.6 ± 0.7	30.9 ± 0.5
Aqueous fraction (wt% DM_{in})		**DAOF**	**Blank**
Non-volatile[a]	Non-ash DM[b]	7.5 ± 0.9	7.9 ± 0.4
	Lignin monomers	0.1 ± 0.0	0.0 ± 0.0
	Lignin oligomers[d]	0.6 ± 0.1	0.9 ± 0.1
	Xylose	0.1 ± 0.0	1.2 ± 0.1
	1,2 Propanediol	0.7 ± 0.1	0.4 ± 0.0
	Extractives	5.9 ± 0.1	5.9 ± 0.1
	Non-ash other	0.1 ± 0.6	-0.4 ± 0.7
Volatile[e]	Formic acid	3.7 ± 0.2	0.5 ± 0.2
	Acetic acid	6.5 ± 0.3	3.1 ± 0.1
Total		17.6 ± 0.7	11.4 ± 0.7
Not found (wt% DM_{in})		**DAOF**	**Blank**
Total		11.2 ± 2.9	13.1 ± 1.7

[a] Components that are present in the DM after drying.
[b] Corrected to account for the presence of non-ash DM originating from the reducing agent.
[c] Acid-insoluble lignin.
[d] Calculated assuming that lignin oil, besides phenolic monomers, only comprises oligomers.
[e] Components that are not present in the DM after drying.

Table S7 Phenolic monomer composition of the lignin oil isolated from the organic phase obtained after treating MWL (0.63 g), with and without the addition of formic acid (0.11 g), in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature), in the presence of $Na_2S_2O_4$ (1 g), for a duration of 3 hours.

Component	MWL	MWL + formic acid
	Yield (wt%)[a]	Yield (wt%)[a]
Syringol	0.2	0.2
4-Propenyl guaiacol	0.7	0.5
Acetoguaiacone	-	0.1
Guaiacylacetone	0.2	0.1
Guaiacylpropan-1-one	-	-
4-Propyl syringol	-	-
Syringaldehyde	0.4	0.5
4-Propenyl syringol	3.4	3.0
Acetosyringone	1.4	1.6
Desaspidinol	0.1	0.2
4-Ethoxy-3,5-dimethoxybenzaldehyde	0.9	0.7
Sinapyl alcohol	0.1	0.0
Total	7.6	6.8

[a] Expressed with respect to the weight of MWL introduced in the reactor.

Table S8 Recovery of sulfur in the solid, organic and aqueous fractions obtained from the treatment of birch sawdust (3 g, particle size < 2 mm) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature),) for a duration of 3 hours, in the presence of 1 g of $Na_2S_2O_4$ (DAOF). The reactions were carried out in triplicates. The analysis of the sulfur content in each fraction was performed via ICP-AES.

Fraction	Recovery (wt%)[a]
Solid	4.0 ± 0.3
Organic	50.5 ± 2.5
Aqueous	27.4 ± 0.8
Total	81.9 ± 3.6

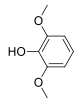
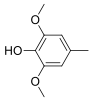
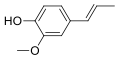
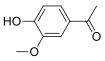
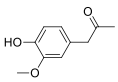
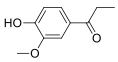
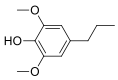
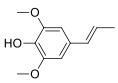
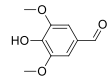
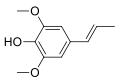
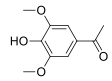
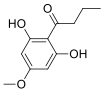
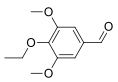
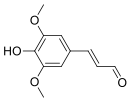
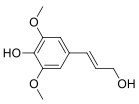
[a] Expressed with respect to the amount of sulfur contained in 1 g of $Na_2S_2O_4$

Table S9 Recovery of the butanol co-solvent in the organic and the aqueous fractions obtained from the treatment of birch sawdust (3 g, particle size < 2 mm) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature),) for a duration of 3 hours, in the presence of 1 g of $Na_2S_2O_4$ (DAOF), or in the absence of $Na_2S_2O_4$ (Blank). The reactions were carried out in triplicates.

Fraction	DAOF	Blank
	Recovery (wt%)[a]	Recovery (wt%)[a]
Organic	90.6 ± 0.2	88.9 ± 0.7
Aqueous	6.7 ± 0.0	7.2 ± 0.3
Total	97.3 ± 0.3	96.1 ± 1.0

[a] Expressed with respect to the weight of butanol introduced (for the reaction and subsequent washing).

Table S10 GC-MS identification of the peaks for phenolic monomers detected in the lignin oil isolated from the organic and the aqueous fractions obtained for the dithionite-assisted organosolv fractionation (DAOF) and for the organosolv treatment of birch sawdust (3 g, particle size < 2 mm) in a mixture of n-butanol and water (120 mL, 50% v/v), at 200 °C, under 30 bar of N_2 (introduced at ambient temperature), for a duration of 3 hours. Unless otherwise reported, peak identification was based on mass spectral database searches using the NIST MS Search 2.2 software.

Component	Structure	Weighed match (%)	Reverse match (%)
Guaiacol[a]		91	91
Syringol[a]		90	90
Methyl syringol[a]		86	89
4-Propenyl guaiacol[a]		93	93
Acetoguaiacone[a]		90	90
Guaiacylacetone[a]		88	89
Guaiacylpropan-1-one		87	88
4-Propyl syringol[b]		-	-
4-Propenyl syringol (I)		90	90
Syringaldehyde[a]		83	83
4-Propenyl syringol (II)		94	94
Acetosyringone[a]		93	93
Desaspidinol		82	83
4-Ethoxy-3,5-dimethoxybenzaldehyde		80	81
Sinapyl aldehyde		91	91
Sinapyl alcohol		92	93

[a] Peak identification was further confirmed by comparison with pure standards.
[b] Peak identification was based on spectra reported elsewhere.[17]

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