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**Efficient microwave-assisted production of furanics and hydrochar from bamboo
(*Phyllostachys nigra* "Boryana") in a biphasic reaction system: effect of inorganic salts**

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Abstract

In this study, a microwave-assisted process was developed for the production of 5-hydroxymethylfurfural (HMF), furfural and hydrochar from bamboo (*Phyllostachys nigra* “Boryana”) in a biphasic reaction system. The system consisted of an acidified aqueous phase and methyl isobutyl ketone (MIBK) as the organic phase, and enabled the instantaneous extraction of HMF and furfural in the organic phase. In this way, unwanted side and rehydration reactions are avoided. The aim of the study was to maximize HMF and furfural yields from bamboo in short reaction times. Building on previous studies, an HCl concentration of 0.13 M was used to ensure the simultaneous conversion of cellulose and xylan to HMF and furfural, respectively. To shorten the reaction time considerably, higher reaction temperatures were applied in this study (200 - 240 °C). The use of microwave irradiation allowed very short reaction rates for maximum HMF and furfural production. Yields of 21 wt% HMF, 13 wt% furfural and 39.5 wt% hydrochar were achieved using bamboo culm particles and by applying 0.13 M HCl (10 wt% NaCl) and 220 °C with a reaction time of 2 min. The results show that the required reaction time to reach a maximum HMF and furfural yield was not significantly influenced by the particle size (< 200µm - 2 mm). The effect of NaCl in the production of HMF and furfural was assessed. It was clear that the addition of NaCl increased the maximum HMF yield but also enhanced the unwanted rehydration reaction to levulinic acid. Results indicated that NaCl could be absorbed on the surface of the hydrochar.

Keywords

microwave, furfural, 5-hydroxymethylfurfural, levulinic acid, hydrochar, bamboo

1. Introduction

The transition towards a bio-based economy is gaining worldwide attention because of the environmental issues associated with the exploitation of non-renewable fossil resources. The production of bio-based platform chemicals as an alternative to their fossil-based equivalents – some of them even outperform their fossil-based equivalents – is one of the driving forces behind the so-called biorefinery concept. Because of their different elemental composition and more specifically their higher oxygen content (biomass is over-functionalized with hydroxyl groups), novel insights are required on how to

convert these oxygenated molecules into high-quality and high-value chemicals. These oxygenated molecules can be provided by lignocellulose biomass, which is the most abundant biomass resource on Earth [1]. In this study, bamboo (*Phyllostachys nigra* “Boryana”) is used as the lignocellulosic feedstock because of its high biomass yield per acre and its ability to grow on polluted, infertile and even non-arable land [2]. The *Phyllostachys* genera is chosen because it showed the highest biomass potential compared to other genera (*Sasa* and *Fargesia*). Field tests in Ireland reported an annual biomass yield (dry weight) between 5 and 18 ton ha⁻¹ indicating a higher return on investment after 30 years compared to other common energy crops (e.g., *Miscanthus*, willow and poplar) [3,4].

The thermochemical conversion of lignocellulosic biomass to platform chemicals has been reported extensively in the literature, with dilute acid hydrolysis as the most widely applied technique [5,6]. Dilute acid hydrolysis requires (i) an acidified aqueous phase that is able to hydrolyze the biomass and (ii) a high temperature to convert the obtained carbohydrate hydrolyzates into platform chemicals. The required acid groups can be provided through heterogeneous or homogeneous catalysts. Homogeneous catalysts (HCl, H₂SO₄) are studied most frequently as they are highly efficient and of relatively low cost [7]. However, major drawbacks of these catalysts include waste generation, equipment corrosion and separation problems [7]. Heterogeneous catalysts do not have these drawbacks and offer an environmental benefit due to their reusability and the reduced corrosion of equipment, provided that the catalyst can be easily separated and recycled [8,9]. However, if lignocellulosic biomass is used in the reaction process, the recycling of the heterogeneous catalyst becomes highly challenging, since it is mixed with the remaining solid unreacted part of the biomass particles (i.e., lignin) [10]. For this reason, HCl was chosen as the homogeneous acidic catalyst in this study. The increased temperatures that are necessary for the conversion of carbohydrates can be supplied by microwave (MW) irradiation or conventional heating. An overview of different heating methods is presented in Figure 1. Microwave irradiation results in an energy-efficient internal heating by direct application of microwave energy (2.45 GHz) on the molecules of the reaction mixture, causing a rapid temperature increase realized by dipole rotation and ionic conduction [11]. Conventional heating, on the other hand, uses a combination of conductive and convective heat transfer steps which results in (i) a lower heating rate (compared to MW)

and (ii) the non-uniform heating through the surface of the reactor wall, potentially leading to local overheating and decomposition of unstable molecules [11,12]. In the literature, various positive effects are described by the application of MW irradiation in the conversion of carbohydrates such as (i) accelerated reaction rates [13,14] , (ii) higher product yields [13,15,16] and (iii) increased product selectivity [16,17].

Fig. 1 Microwave heating versus conventional heating

One of the most promising bio-based chemicals that can be produced via dilute acid hydrolysis are the so-called furanics. Furanics are produced from carbohydrates via dehydration and rehydration reactions (see Figure 2) and are key precursors in the production of a wide variety of fine chemicals, bio-fuels and bio-plastics. For example, HMF is a furanic derived from C6 sugars (e.g., cellulose) and is the precursor of 2,5-furandicarboxylic acid, a substitute for the petroleum-based terephthalic acid [18]. Therefore, HMF has a huge potential in the bio-plastic market and has, therefore, often been referred to as the “sleeping giant” in the field of bio-based platform chemicals [19]. HMF is ranked in the top 10 green chemicals with the potential of driving a disruptive new bio-based industry in Europe [20]. Another example is furfural, a furanic derived from C5 sugars (e.g., hemicellulose/xylan), which is mainly used

in the production of resins and lubricants, and is mentioned as one of the top 30 biomass-derived platform chemicals according to the U.S. Department of Energy [21].

Fig. 2 Conversion pathway of bamboo biomass to furanics and hydrochar

In previous research we established the simultaneous conversion of cellulose and hemicellulose to HMF and furfural, respectively, under the same process conditions (temperature, acid concentration and reaction time) [22,23]. In this research, a maximum HMF and furfural yield of 37 mol% and 35 mol%, respectively, were obtained from bamboo culm, by applying 0.13 M HCl and 177 °C under microwave (MW) heating [22]. A biphasic reaction system consisting of methyl isobutyl ketone (MIBK) and acidified water was applied to (i) avoid the formation of unwanted solid particles (i.e., humins), (ii) avoid unwanted side reactions due to the continuous extraction of HMF and furfural in the organic phase and (iii) an easy recovery of HMF and furfural from the reaction mixture. However, this research was fundamental research oriented by assessing the occurrence of microwave effects and the influence of the particle size on the conversion pathway, rather than creating an efficient MW process. As a result, the applied reaction times to reach maximum HMF and furfural yields were quite long (> 1 h), which are not favored in MW reactions.

Therefore, the goal of this research is to (i) develop an efficient microwave-assisted process for the simultaneous production of HMF and furfural with emphasis on short reaction times, (ii) to characterize the resulting hydrochar enabling the full valorization of the lignocellulosic feedstock and (iii) assess the influence of inorganic salts on the dilute acid hydrolysis of bamboo to furanics and hydrochar.

2. Materials and methods

2.1 Feedstock & Chemicals

All experiments were conducted using bamboo (*Phyllostachys nigra* (Lodd. ex Lindl.) Munro "Boryana") feedstock that were obtained from the Arboretum at Bokrijk, Belgium. Directly after harvesting, the culm was separated from the leaves and oven dried at 105 °C for 48 h. The composition of the bamboo culm was determined in a previous study and is presented in Table 1 [24]. The oven-dried samples were subjected to a rough grinding step with a disk mill (Fritsch Pulverisette 13), resulting in particle sizes between 2 mm and 150 μ m. Subsequently, the obtained particles were ground in a centrifugal mill (Retsch ZM 100) and sieved to retain particles < 250 μ m (< 60 mesh). Thereafter, the culm particles were fractionated with a Retsch vibratory sieve shaker into particle size intervals of: < 200 μ m, 800 μ m - 1 mm, and 1.5 - 2 mm. The hydrolysis experiments were performed in an aqueous medium (demineralized water) acidified with HCl (Fisher Scientific, 5M) as the homogeneous acid catalyst and an organic phase consisting of MIBK (Acros Organics, 99.5%). Various amounts of NaCl (0 - 10 wt%, Acros Organics) were added to the reaction mixture to assess its influence on the reaction pathway.

Table 1: Lignocellulosic [24] and elemental composition of bamboo culm

	BAMBOO CULM	
	w%	std
Cellulose	40.87	1.00
Hemicellulose	14.81	0.52
Extractives	15.77	0.86
Lignin	26.73	0.79
Ash	1.81	0.10
C	43.58	0.24
H	5.74	0.02
N	0.49	0.09
S	0	0

2.2. Experimental set-up

The experiments were performed in a dedicated microwave reactor system (Monowave 300, Anton Paar, 2.45 GHz). The temperature was monitored by means of a ruby temperature sensor (optic fiber) placed inside the reaction vessel. The volume of the reaction vessel was 10 mL. For each experiment, the

reaction vessel was filled with 25 - 400 mg bamboo culm particles, 500 μ L - 5 mL acidified water (0.13 M HCl, 0 - 10 wt% NaCl) and 0 - 4.5 mL MIBK to reach a total volume of 6 mL. The stirring rate was set at 800 rpm for all experiments. The maximum power output of the microwave device was set at 800 W. It was shown in a previous paper that a simultaneous conversion of cellulose and xylan to HMF and furfural is achieved under these conditions [23]. As soon as the reaction time was complete, the reaction vessel was cooled rapidly by placing it in an ice bath to stop the reaction. After cooling, the reaction mixture was filtered (Macherey Nagel, 0.6 μ m retention capacity), before analysis. The resulting particulate matter is referred to as “hydrochar”. Product concentrations (HMF, furfural and levulinic acid) were measured in the organic and aqueous phase (after filtering).

2.3. Analytical techniques

Samples (1 μ L) of the organic and aqueous phase were analyzed using a gas chromatograph (Agilent 7890A-series) equipped with a flame ionization detector (FID) to determine HMF, levulinic acid and furfural concentrations. The GC was equipped with a HP-FFAP column (Agilent, J&W HP-FFAP length 30 m, internal diameter 0.25 mm, film thickness 0.25 μ m); oven temperature program: 1 min, 45 $^{\circ}$ C, and 5 min, 200 $^{\circ}$ C at 10 $^{\circ}$ C/min; injection temperature: 200 $^{\circ}$ C; injection mode: split (30 : 1); flow: 3.0 mL/min) equipped with FID detector (240 $^{\circ}$ C). Helium was used as a carrier gas. Concentrations of HMF, levulinic acid and furfural were calculated after calibrations of all 3 compounds using external standards. Linear regressions for each compound (determined by retention time) were obtained between peak areas for three injections of samples containing known concentrations of each compound at ten levels of concentrations (50 - 3000 ppm). The mass of the residual particulate matter was determined by filtering the reaction medium through a glass fiber filter (Macherey Nagel, 0.6 μ m retention capacity), washing it with 20 mL of demineralized water and drying it for 24 h at 105 $^{\circ}$ C.

The product yield is defined according to Equation (1).

$$Y_{prod} = \left(\frac{c_{prod,org} \cdot V_{org} + c_{prod,Aque} \cdot V_{aque}}{m_{bamboo}} \right) \cdot 100 \quad (1)$$

With Y_{prod} the product yield (HMF, furfural, levulinic acid) (wt%), $c_{prod,org}$ concentration of product in organic MIBK phase (ppm), V_{org} volume of the organic phase, $c_{prod,aque}$ concentration of product in the aqueous phase (ppm), V_{aque} volume of the aqueous phase, m_{bamboo} mass of bamboo feedstock (mg). The

content of carbon, hydrogen, nitrogen and sulfur in the prepared hydrochars were determined using an organic elemental analyser (Thermo Finnigan, Flash 2000, ThermoScientific). The solid samples were weighted into tin capsules and then introduced sequentially into the equipment for the analysis.

3. Results and discussion

3.1 Effect of biomass particle size and NaCl on product yield

Figure 3 depicts the conversion of bamboo culm particles of different particle sizes to HMF and furfural in a biphasic (MIBK:water) reaction system. Figure 3A shows the conversion of bamboo particles at a 10 wt% NaCl concentration and Figure 3B without NaCl addition. In both cases, the maximum HMF and furfural yield was reached at a reaction time of 2 min. Additionally, the maximum HMF yield was higher (21 wt% vs. 16 wt%) at a 10 wt% NaCl concentration. For furfural, the addition of NaCl did not cause significantly higher yields under the studied reaction conditions. The maximum yields were 21 wt% for HMF and 14 wt% for furfural. Based on the chemical composition of the biomass (Table 1), this corresponds to 53 mol% HMF, which is higher than in a previous study where a maximum HMF yield of 35 mol% was achieved when using *Phyllostachys nigra* "Boryana" as the biomass feedstock [22], and which did not include an optimization of yield or energy consumption. Based on the results of this study, it is clear that short reaction times are not only beneficial to limit energy usage but also significantly increase the maximal HMF yield by limiting (unwanted) side reactions. The effect of particle size is also negligible under the studied reaction conditions since particles up to 2 mm did not cause a decrease in HMF and furfural production rate compared to particles with a particle size of < 200 μm . Although higher HMF yields were obtained by the addition of NaCl to the reaction system, HMF degradation at longer reactions times also increased: the HMF yield decreased from 21 wt% to 11 wt% for a 20 min reaction time. Without the addition of NaCl, the HMF yield only decreased with 4% over a time span 20 min (i.e., from 15 wt% to 11 wt%). Also, levulinic acid formation is enhanced in the presence of NaCl. A maximum levulinic acid yield of 7.5 wt% (with 10 wt% NaCl) and 5 wt% (without NaCl) was obtained after 20 min of reaction.

Fig. 3 Effect of bamboo particle size on HMF and furfural yield with (A) and without (B) 10 wt% NaCl. Conditions: $T = 220\text{ }^{\circ}\text{C}$, $c_{\text{HCl}} = 0.13\text{ M}$, stirring rate = 800 RPM, 25 mg bamboo culm particles, 10:1 MIBK:water ratio.

3.2 Effect of volumetric phase ratio (MIBK/ H_2O) and NaCl on product yield

Figure 4 compares the production of HMF and furfural in a biphasic (4A and 4B) and monophasic (4C) system. In the absence of an organic phase (Figure 4C), a maximum HMF yield of 4 wt% was reached after 1 min reaction time. After 2 min of reaction, HMF was no longer measured because of the fast rehydration of HMF to levulinic acid and formic acid. Solely applying an aqueous phase also results in the formation of unwanted solid polymerization products, i.e., humins, which were visually observed as fine dispersed particles that are clearly distinguishable from the coarser residual biomass particulate matter. In the biphasic system (Figure 4A and 4B), these fine solid particle dispersions were not observed and the rehydration of HMF is suppressed by the continuous extraction of furanics in the organic MIBK phase. It is clear that the volumetric MIBK:water ratio considerably affects the levulinic acid formation. An MIBK:water ratio of 10:1 only yields 7 wt% levulinic acid for a reaction time of 20 min, whereas a MIBK:water ratio of 5:1 yields 16 wt% levulinic acid for the same reaction time. For a MIBK:water ratio of 5:1 no HMF was observed, whereas for the 10:1 ratio, still 13 wt% HMF was detected. In the case of furfural, decomposition products can be formed under extreme reaction conditions (high reaction temperature, high acid concentration, ...) [25]. It is clear from Figure 4A that furfural degradation is very limited. By decreasing the MIBK:water ratio to 5:1 (Figure 4B) the degradation becomes more pronounced with 4 wt% furfural loss over a reaction time of 20 min. In the absence of an organic phase, furfural degradation was high with a maximum furfural yield of only 10 wt% after 1 min reaction time

to 0 wt% after 20 min reaction time. The addition of NaCl to the reaction mixture resulted in a higher HMF yield (21 wt% vs. 16 wt%), especially at higher MIBK:water ratios (10:1) (Figure 4A). It is also clear that levulinic acid formation is enhanced by the addition of NaCl, because in all three cases (4A, 4B & 4C) the levulinic acid yield is higher when NaCl is added to the reaction mixture. We presume that degradation reactions involving levulinic acid are inhibited in the presence of NaCl. In the monophasic system, this effect was most pronounced after a reaction time of 20 min with a levulinic acid yield of 18 wt% in the presence of NaCl versus 14 wt% in the absence of NaCl.

Fig. 4 Effect of MIBK:water ratio (**A**; 10:1, **B**; 5:1, **C**; monophasic water) on HMF and furfural yield with and without 10 wt% NaCl. Conditions: $T = 220\text{ }^{\circ}\text{C}$, $C_{\text{HCl}} = 0.13\text{ M}$, stirring rate = 800 RPM, 25 mg bamboo culm particles (800 μm - 1mm).

3.3 Effect of NaCl concentration on product yield

Figure 5 shows the effect of different NaCl concentrations on the HMF and furfural yield. It was already clear from Figure 4 that the addition of NaCl increased the maximum HMF yield (21 wt% vs. 16 wt%). Although the maximum HMF and furfural yields were not significantly impacted by changing the NaCl concentration, the partition coefficient increased with increasing NaCl concentration. The partition coefficient (K) was calculated to quantify the extraction process by describing the distribution of HMF, furfural and levulinic acid in the aqueous and organic phase (Equation 2). The partition coefficients at different NaCl concentrations for the MIBK:water ratio of 10:1 are presented in Table 2. For HMF and furfural, the partition coefficient is higher than 1. This indicates that the concentration of HMF in the organic phase is slightly higher (> 1.22 times) and for furfural much higher (> 8.96 times) than in the aqueous phase. For levulinic acid, the partition coefficient was < 1, indicating a low solubility in MIBK. It is important to mention that in absolute terms a much higher amount of HMF and furfural was present in the organic phase because the volume of the organic phase (4.5 mL MIBK) was considerably higher than the volume of the aqueous phase (0.5 mL acidified water + NaCl) in the reaction system. For instance, for the datapoint at t = 2 min and 5 wt% NaCl, the concentration of HMF in the aqueous phase was 842 ppm and in the MIBK phase 1223 ppm. This results in a K of 1.45. However, in absolute terms this equals to 0.42 mg in the aqueous phase and 5.5 mg in the MIBK phase.

$$K = \frac{C_{(Product,org)}}{C_{(Product,aque)}} \quad (2)$$

With K: the partition coefficient; $C_{Product,org}$: the product (HMF, furfural or levulinic acid) concentration in the organic phase (ppm); $C_{Product,aque}$: the product (HMF, furfural or levulinic acid) concentration in the aqueous phase (ppm).

Table 2: Partition coefficients for different NaCl concentrations for MIBK:water ratio 10:1

	Partition coefficient			
	0 wt% NaCl	2.5 wt% NaCl	5 wt% NaCl	10 wt% NaCl
HMF	1.22	1.35	1.45	1.72
Furfural	8.96	10.04	11.35	12.66
Levulinic acid	0.49	0.57	0.63	0.76

Fig. 5 Effect of c_{NaCl} on HMF and furfural yield. Conditions: $T = 220\text{ }^{\circ}\text{C}$, $c_{\text{HCl}} = 0.13\text{ M}$, stirring rate = 800 RPM, 25 mg bamboo culm particles (800 μm - 1mm), 10:1 MIBK:water ratio.

3.4 Effect of reaction temperature on product yield

The effect of reaction temperature on the production of HMF and furfural is shown in Figure 6. It is clear that a lower reaction temperature (200 $^{\circ}\text{C}$) prolongs the reaction time (5 min) to reach a maximum HMF and furfural yield. When a reaction temperature of 220 $^{\circ}\text{C}$ is applied, the maximum HMF and furfural yield is already achieved at a reaction time of 2 min. At 240 $^{\circ}\text{C}$, the maximum HMF yield is obtained after a reaction time of 1 min, but the maximum HMF yield is lower compared to the HMF yield when reaction temperatures of 200 $^{\circ}\text{C}$ and 220 $^{\circ}\text{C}$ are applied, indicating that at 240 $^{\circ}\text{C}$ degradation of HMF already occurs at reaction times < 1 min. Hence, it can be concluded that, depending on the reactor configuration, a tradeoff needs to be made: a fast formation of HMF and furfural applying higher reaction temperatures and the occurrence of degradation reactions or working at more moderate reaction temperatures accompanied by a higher maximum yield of HMF and furfural at a (slightly) longer t .

Fig. 6 Effect of T on HMF and furfural yield. Conditions: $c_{\text{HCl}} = 0.13\text{ M}$, stirring rate = 800 RPM, 25 mg bamboo culm particles (800 μm - 1mm), 10:1 MIBK:water ratio.

3.5 Effect of biomass feedstock loading on product yield

The effect of biomass feedstock loading ($m_{\text{biomass}}/m_{\text{Aqueous phase}}$) on the production of HMF and furfural was assessed by increasing the mass of bamboo particles from 25 mg (1/20 biomass loading) to 400 mg (4/5 biomass loading) in the reaction mixture. Higher biomass loadings were not possible because stirring was hampered by the high number of bamboo particles, thereby causing a severe pressure increase in the reactor (above the safety limits). It is clear from Figure 7 that biomass loadings higher than 1/5 negatively affect the HMF and furfural production. Applying a biomass loading of 4/5 yields less than half of the HMF production (8 wt% and 6 wt% HMF, with and without NaCl) compared to a biomass loading of 1/20 (21 wt% and 16 wt% HMF, with and without NaCl). From Figure 7 it is also clear that the addition of NaCl only marginally affects the maximum yield of furfural for certain biomass loadings. Only at the highest biomass loading (4/5) a significant decrease in furfural yield was observed compared to the other biomass loadings.

Fig. 7 Effect of biomass feedstock loading on HMF and furfural yield with and without 10 wt% NaCl. Conditions: $T = 220\text{ }^{\circ}\text{C}$, $c_{\text{HCl}} = 0.13\text{ M}$, stirring rate = 800 RPM, 25 - 400 mg bamboo culm particles (800 μm - 1mm), reaction time of 2 min, 10:1 MIBK:water ratio.

3.6 Hydrochar characteristics and yield under optimized conditions

Table 3 listed hydrochar yields with and without salts under optimized reaction conditions. When salts are added, the yield of hydrochar increased notably (more than doubled). Previous research already showed that NaCl can be adsorbed onto the surface of hydrochar, thus, increasing hydrochar yields [26]. This is also observed in the elemental analysis (Table 3), as the content of all elements declined with the addition of NaCl compared to samples in the absence of NaCl. The presence of NaCl in hydrochar is not desired due to potential pollution issues if the hydrochar is used as a solid fuel [26]. From Table 3 it is also clear that small bamboo particle sizes ($< 200\ \mu\text{m}$) cause lower hydrochar yields (- 43%), which is interesting since particle size did not influence the furanic yield. This indicates that non-polysaccharides carbonaceous material is solubilized into water and/or MIBK at particle sizes ($< 200\ \mu\text{m}$) which could potentially cause issues in further product purification steps.

Table 3: Hydrochar yield and elemental composition under optimized reaction conditions (220 °C, $C_{\text{HCl}} = 0.13\ \text{M}$, stirring rate = 800 RPM, reaction time of 2 min, 10:1 MIBK:water ratio)

Feedstock	NaCl	Hydrochar yield (wt%)	Elemental composition			
			C	H	N	S
800 μm - 1 mm bamboo particles	/	19.2	54.8	5.1	0.8	0
800 μm - 1 mm bamboo particles	10 wt%	39.5	22.5	2.6	0.4	0
$< 200\ \mu\text{m}$ bamboo particles	/	11.2	57.1	5.0	0.8	0
$< 200\ \mu\text{m}$ bamboo particles	10 wt%	22.7	38.7	3.5	0.6	0

4. Conclusion

An efficient microwave-assisted process was developed for the production of HMF, furfural and hydrochar from bamboo with HCl as the acid catalyst in a biphasic reaction system. The bamboo feedstock generated a maximum HMF yield of 21 wt%, furfural yield of 13 wt% and 39.5 wt% hydrochar. The biphasic system allowed a maximum HMF and furfural yield, contrary to the monophasic system where the complete rehydration of HMF to levulinic acid occurred, yielding 17 wt% levulinic acid. The addition of NaCl allowed higher maximum HMF yields (21 wt% vs. 16 wt%) but also enhanced the production of levulinic acid. Although the NaCl concentration caused higher partition coefficients for the studied compounds, the overall furanic yield (organic + aqueous phase) did not change significantly with increasing NaCl concentration. A biomass loading higher than 1/5 caused a decrease in furanic production, especially for HMF (21 wt% HMF at 1/20 to 8 wt% HMF at 4/5). The

bamboo particle size (< 200 μm - 2mm) did not significantly affect the HMF and furfural production. However, particle size did influence the hydrochar yield, as small particle sizes (< 200 μm) enhanced the solubilization of carbonaceous material into the liquid phase. In general, the merits of the developed process such as low reaction time, high product yields, and being environmentally friendly in terms of both the applied energy source and the product properties (e.g., low potential of environmental contamination) can satisfy the sustainability criteria for the production of furanics and hydrochar from the biomass feedstock.

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