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Supercritical Water Biomass Gasification Process As a Successful Solution to Valorize Wine Distillery Wastewaters

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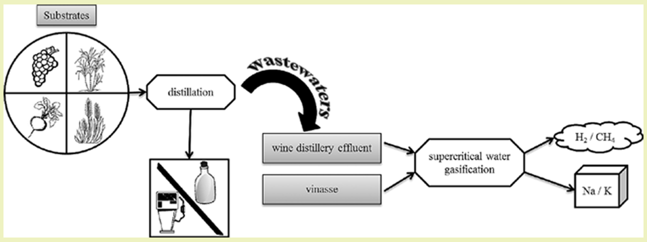

ABSTRACT: The biomass is the whole organic matter of vegetable or animal origin. This material can be valorized in various ways: it can be used by manufacturers (lumber, paper, and biochemistry); it can be used as energy (heat, electricity, and fuel); and it can be used as food or in cosmetics. Various processes are nowadays used to valorize biomass. This work deals with the potentialities of the biomass gasification in supercritical water. The objective is to demonstrate the potentiality of this process to treat some aqueous waste from distillery to obtain a syngas with a high hydrogen yield. The bioresources of this study come from some agricultural alcohol (beet, sugar cane, and cereal) and wine-producing distilleries. Experiments have been carried out at different conversion severities, using a 100 mL batch reactor, during 0−60 min, at a pressure of 25 MPa and at temperatures between 400 and 500 °C. Complete product analyses will be presented. Particularly detailed gas analyses have been performed. The sodium and potassium behaviors during the process have been accurately studied as a function of the substrate. Correlations between the experimental operating conditions and these analyses will be discussed in order to determine optimal experimental conditions to gasify this specific biomass.

KEYWORDS: *Supercritical water, Gasification, Biomass, Bioresource, Vinasse, Potassium, Sodium*

INTRODUCTION

The conversion of organic waste material to energy can proceed along three main pathways—thermochemical, biochemical, and physicochemical. Thermochemical conversion includes incineration, pyrolysis, and gasification. Thermochemical conversion, characterized by high temperature and conversion rates, is best suited for lower moisture feedstock and is generally less selective for products. Biochemical conversion processes, which include anaerobic digestion and fermentation, are preferred for wastes having a high percentage of biodegradable organic matter and high moisture content. The physicochemical technology involves various processes to improve physical and chemical properties of solid waste. The combustible fraction of the waste is converted into high-energy fuel pellets that may be used in steam generation. Fuel pellets have several distinct advantages over coal and wood because they are cleaner, free from incombustibles, have lower ash and moisture contents, are of uniform size, are cost-effective, and are eco-friendly.

Gasification is the conversion of biomass to a gaseous fuel. There are many gasification technologies that could potentially be part of the future energy industry. The gasification process converts the intrinsic chemical energy of the carbon and hydrogen in the biomass into a combustible gas.[1] A supercritical biomass gasification process (SCBG) is a suitable gasification process for wet biomass.[2−4]

The novelty of this paper is to study the supercritical water gasification of a real biomass coming from the winery industry. The studied bioresources are two problematic wastewaters of this type of industry. Various methods to treat (destruction or valorization) this type of bioresource exist. Chemical and physical methods are based on membrane processes, chemical oxidations, and surface sorption/ion-exchange processes. Each of these technologies has its own main drawbacks: membrane fouling and failure, incomplete conversion, and expensive technologies, respectively, for membrane processes, chemical oxidations, and ion-exchange processes.[5−7] In biological methods, anaerobic processes are more economical than aerobic processes and are more developed in recent years.[8,9] However, only one study has been focused on the supercritical water treatment of organic industrial wastes; among them some vinasses have been treated, with the addition of catalysts and oxygen.[10] This study is focused also on supercritical water gasification but without any oxidant. No other works on the thermochemical treatments and valorization of these bioresources have been carried out to our knowledge. Obviously supercritical water gasification process is potentially more efficient than conventional thermal processes, which require energy for drying the biomass. Biochemical processes proceed slowly and lead to unconverted matter. Moreover in the SCBG process water acts as a solvent and as a reactant. Another novelty of this study is the focus on the behavior of minerals.

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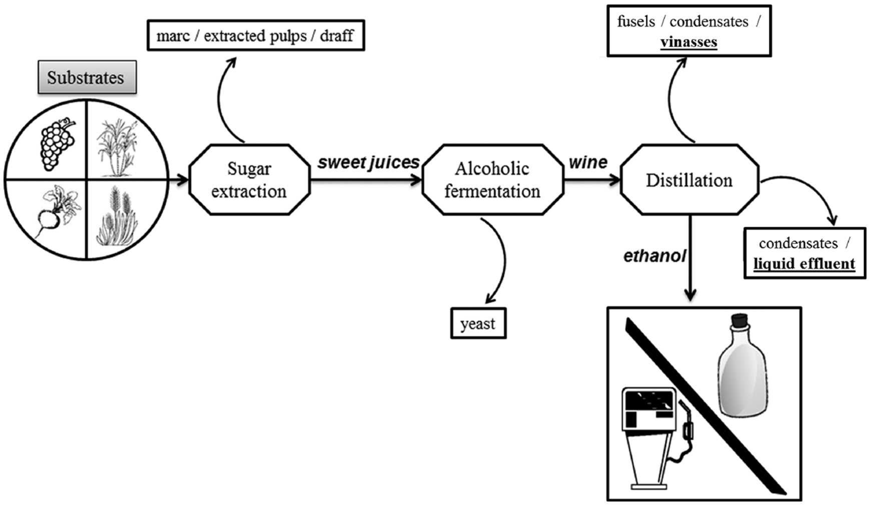

Figure 1. General scheme of a distillery (the underlined wastes are the bioresources studied in this paper).

Indeed inorganics behave in a particular way in supercritical water including catalytic effects, for instance, or different solubility properties as a function of the element and/or of the operating conditions (temperature and pressure). Sodium and potassium have been carefully focused because they are the major elements in these biomasses.

In this study wine distillery wastewaters were treated in supercritical water at various temperatures. We have also turned our attention to physicochemical analyses before and after the reaction in order to better understand the SCBG process. Detailed analyses of the gas phase have been carried out.

■ MATERIALS AND METHODS

Materials. The bioresources in this paper are three aqueous wastes of a wine distillery. In our experiments they were from a distillery located in Coutras near Bordeaux (France), called UCVA (Union des Coopératives Vinicoles d'Aquitaine). Figure 1 is a general scheme of a distillery. We have focused our study on the liquid output of the process: the effluent (obtained at the end of the process), which contains <5% of particles in suspension in water, and the vinasse. This original vinasse recovered at the end of the distillation (called "clarified vinasse") is concentrated mainly to reduce its volume in the distillery. This new sample was therefore called the "concentrated vinasse", whose concentrations are different. Finally three bioresources have been studied in this paper. These slurries present a very viscous aspect, similar to caramel. Figure 2 is a picture of the "clarified vinasse" and of the effluent. The reasons for this choice are that the water contained in the biomass is used as a reactant in the supercritical processes, and the supercritical biomass gasification process (SCBG) has the natural capacity to convert efficiently wet biomass.

Figure 2. Picture of the clarified vinasse (on the left) and of the effluent (on the right).

Experimental Setup. Experiments of biomass gasification in supercritical conditions are carried out in a batch reactor build with Inconel 625. The setup allows one to carry out experiments at temperatures up to 500 °C and a maximal pressure of 35 MPa. The experimental setup has been described elsewhere.[11]

The experimental setup is composed of security parts and control equipment such as a digital manometer connected to a pressure captor, a manometer, a valve for the gas collection, thermocouples (in the batch reactor and in the furnace), a rupture disc (40 ± 1 MPa), a temperature regulator (Eurotherm), and a mobile furnace (with a pneumatic jack), allowing the interruption of an abrupt temperature increase. The reactor was heated to the desired temperature with a 12 °C min^{-1} heating rate. At the end, the reactor was cooled to room temperature under atmospheric conditions. Initially the reactor has been purged with nitrogen in order to remove oxygen. The experiments in this paper have been carried out at different temperatures, 400, 450, and 500 °C, at a pressure of 25 MPa.

ICP-OES Analyses. Inorganic element concentrations of the samples were determined by inductively coupled plasma−optical emission spectrometry (ICP-OES) analysis (Varian 720-ES instrument) after wet-digestion in HNO_3/H_2O_2 (for the solid samples). Concentrated (30%) nitric acid (10 mL) was added to a weighed solid sample (0.5 g dry weight) during 1 h, and then hydrogen peroxide (2 mL) and milli Q water (1 mL) were added. The solutions were heated in a microwave until 180 °C (CEM Marsexpress). Solutions were filtered through ashless filter (Whatman filter papers 40) into 100 mL volumetric flasks and volumed with distilled water. This method is very efficient in terms of detection and yields. The inorganic elements of interest quantified in this paper are as follows: Al, As, Ba, Ca, Cr, Fe, K, Mg, Na, P, Si, and Zn.

Heating Values. The heating value (or combustion heat) of a combustible material corresponds to the reaction enthalpy of the combustion reaction per mass unit. It is the energy released as heat by the combustion reaction with oxygen. There are two types of heating value:

(1) The higher heating value (HHV, also known as the gross heating value) is defined as the amount of heat released by a specified quantity of a fuel (initially at 25 °C) once it is burnt and the products are cooled down to room temperature. The higher value takes into account the latent heat of water vaporization in the combustion products. In other words, the HHV assumes that all the water is liquid at the end of the combustion (product combustion).

(2) The lower heating value (LHV, also known as net heating value) is defined as the amount of heat released by burning a specified

quantity of a fuel (initially at 25 °C) and the combustion products are cooled down to room temperature. The LHV assumes that all the water is vapor at the end of the combustion (product combustion). The LHV assumes that the latent heat of water vaporization in the fuel and the reaction products is not recovered.

Experimentally the HHV is determined in a bomb calorimeter after introduction of oxygen (under pressure); then the exothermic reaction is initiated by an ignition device to start the combustion reaction. The apparatus is a Parr 1266 calorimeter. The LHV is calculated by deducting from the HHV the heat of condensation of the water formed during the combustion or optionally of the water in the sample.

Elementary Analysis. The elementary analysis was investigated with a CHNS-O Analyzer model 2400 from PerkinElmer.

Gas Analysis. Two gas chromatography apparatuses were used. The first instrument is a “micro-chromatograph” Varian CP-4900. It is a mobile analysis instrument conceived for online analysis on an installation. The instrument has two columns for the separation of different gases. Each column is bound to a catharometer. It is used for the detection of H_2, O_2, N_2, CH_4, and CO.

The second instrument is a gas chromatography Varian (GC-3600) for the analysis of CO_2. Two detectors are present: thermal conductivity detector (TCD) and flame ionization detector (FID). The detector sensibility is of a few ppm. A capillary column is connected to a FID detector (Carbowax for polar compounds and particularly flighty hydrocarbons). Two columns are connected and are online to a TCD detector (a column Porapaq for the separation of CO_2 to the others gases and a molecular sieve separating the others gas). A system of valves separates CO_2 from the molecular sieve.

■ RESULTS AND DISCUSSION

Analytical Strategy. During the process, the three aqueous wastes from the wine distillery have been treated at supercritical operating conditions. The result is that, at the end of the reaction, four different phases have been collected: a gas phase, an organic solid phase, an organic liquid phase, and an aqueous phase. According to the operating conditions, the yields of the different phases, as well as their physicochemical properties, will be different. This is the reason why several analyses have been carried out in order to follow the behavior of the biomass during the process. These analyses will also allow us to understand the key parameters to optimize the gasification process. The following scheme (Figure 3) shows the different analyses that are performed.

Initial Bioresources Composition. Table 1 shows the water content for each initial bioresource (in wt %), the elementary composition in C, H, O, N, and S (in wt %), the amount of mineral elements (in wt %), and the HHV and LHV (in MJ/kg). Concentrated vinasse and clarified vinasse have, respectively, a water content of 48 and 53 wt %, also with a mass content of C equal to, respectively, 23 and 16 wt %. For the effluent, the analyses show a water content of about 95 wt %. This substrate is mainly water; therefore, little organic content is introduced into the reactor. It must be pointed out that the effluent contains a lot of matter in suspension, which makes difficult the elementary analysis (absence of data in Table 1).

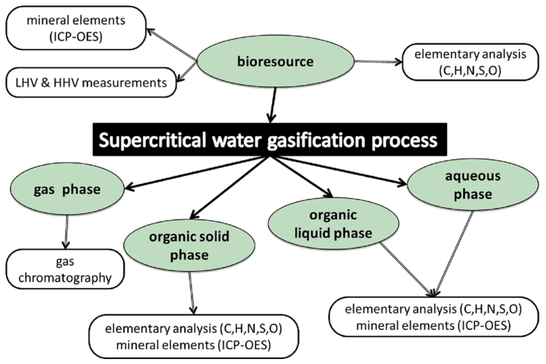

Figure 3. Analytical procedure.

The HHV and LHV have to be compared to those of wood and cereals. A wood has a mean HHV at ∼20 MJ/kg, herbaceous crops at ∼18.5 MJ/kg, and corn stover at ∼18 MJ/kg.[12] Our substrates have HHV near 16 MJ/kg for the vinasses and almost 9 MJ/kg for the effluent. But these values are on a dry basis. Both vinasses and the effluent are wet biomass. That means that they are interesting biomass for the supercritical water process because in this case water acts as a reactant and as a solvent. Moreover they contain enough carbon and hydrogen for the production of gas. Inversely they will not be chosen directly for the “standard” thermochemical gasification processes.

The initial content of mineral elements in both vinasses is ∼9 wt %. Figure 4 shows the percentages of the different elements. The results show that the major element contained in the effluent, in the concentrated vinasse, and in the clarified vinasse is potassium. The amount of potassium is between 67 wt % and 72 wt % of the total inorganic elements of the samples. For the concentrated vinasse and the clarified vinasse, the analyses show a relatively important amount of sodium. It is between 22 and 25 wt % of the total mineral elements of the samples. The effluent is a biomass that contains more phosphorus than the “concentrated vinasse” and the clarified one: 12 wt % of the total inorganic elements of the sample versus <4 wt % for the others.

Moreover Table 2 lists the results obtained for the main mineral elements contained in our three substrates. It is well-known that metals catalyze the SCBG process, as alkali metals and alkaline earth metals do.[13] Therefore we have focused our attention on sodium and potassium particularly because they are known to act as catalysts in the supercritical water processes.[3,14,15]

Supercritical Water Gasification Results: Gas Production. The results obtained during the gasification process are presented in Table 3. The yields of the different phases at the end of the supercritical gasification process have been listed. The yield of the organic solid phase is obtained after efficient drying. The yield of the resulted aqueous phase is the sum of the recovered water and the water collected from the drying of the organic solid phase.

The last column is the total yield of the supercritical water gasification for the three winery wastewaters. It allows us to know the efficiency of the process in term of mass balance. The process has a suitable total yield. No striking trend has appeared regarding the yields of the different phases. No organic liquid phase has been obtained for the effluent whereas about one-third of the resulted mass is an organic liquid phase for the winegrape slurries. It is easily explained by the initial amount of organic matter in the effluent (only 5 wt % of organic matter). The amount of the organic solid phase has been always low, regardless of what is the treated biomass.

The amount of the gas produced during the reaction increases when the temperature increases from 400 up to 500 °C. This result has been observed for the effluent and for the vinasse also. However, the evolution is not so clear regarding the yields. Table 4 shows, therefore, the volumes really

Table 1. Initial Biomass Features

bioresource	water content (wt %)[a]	mineral elements in the sample (wt %)[b] (w.b.)[c]	elemental analysis (wt %) (w.b.)[c] C	H	N	O[d]	HHV[e] (MJ/kg) (d.b.)[f]	LHV[e] (MJ/kg) (d.b.)[f]
concentrated vinasse	48.3	9.0	23.3	8.1	3.8	55.8	15.7	14.6
clarified virasse	53.0	8.1	15.7	5.7	2.9	67.6	16.1	15.5
effluent	95.3	2.6	–	–	–	–	8.7	8.6

[a] Water content = 100% − dry matter content. [b] Determined by ICP-OES. [c] On a wet basis. [d] By difference (O% = 100% − mineral elements % − C% − H% − N%). [e] Higher heating value (HHV) and lower heating value (LHV). [f] On a dry basis.

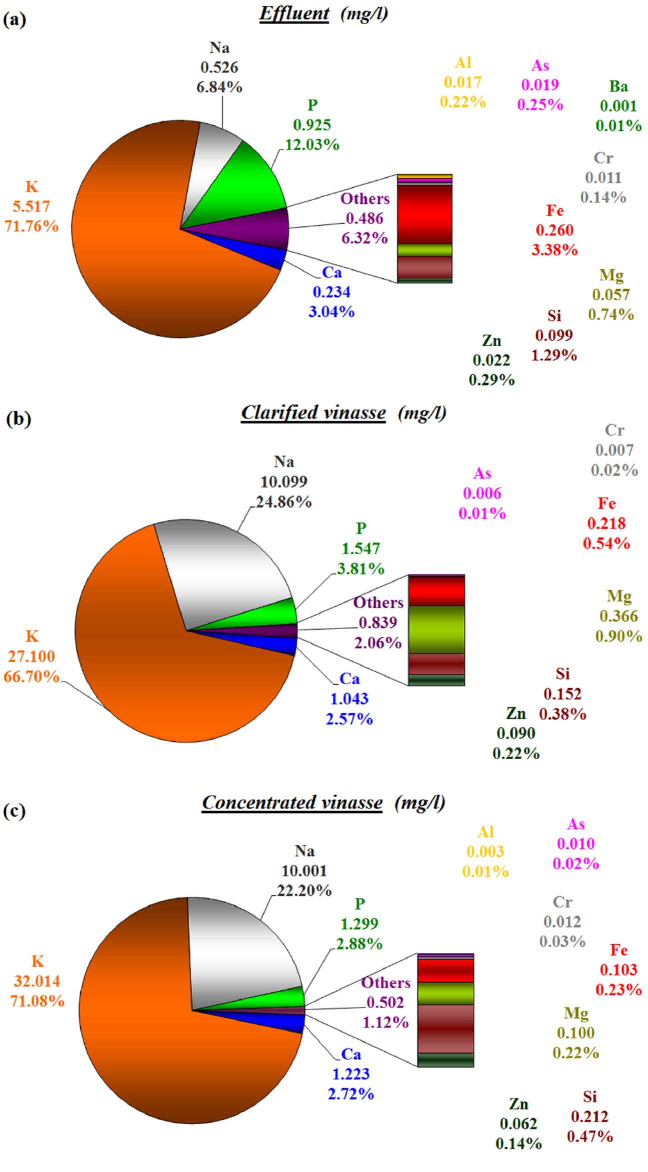

Figure 4. Initial mineral elements composition (mg/L) in the effluent (a), in the clarified vinasse (b), and in the concentrated vinasse (c).

Table 2. Initial Main Mineral Elements in the Biomass

bioresource	mineral elements in the sample (mg/L) K	Na	P	Ca	others[a]
concentrated vinasse	32.014	10.001	1.299	1.223	0.502
clarified vinasse	27.100	10.099	1.547	1.043	0.839
effluent	5.517	0.526	0.925	0.234	0.486

[a] M, As, Ba, Cr, Fe, Me, Si, and Zn.

produced during the gasification process. According to the quantity of organic matter initially in the biomass, the volumes are very different. The effluent is very poor in organic matter (10 times less concentrated); then the volume of the produced gas is relatively small. On the contrary both vinasses are richer in organic matter, and then the volumes of gas are larger. However, the most interesting figure is the ratio of the gas produced over the amount of initial organic matter. We obtained for the effluent, the clarified vinasse, and the concentrated vinasse at 400 °C, respectively, 38, 56, and 70 mL/g of organic matter during the 1 h gasification. At 500 °C, the productions are, respectively, 54, 68, and 78 mL/g of organic matter.

The effect of the increase of the temperature is the same for the three samples: an increase of the temperature increases the gas volumes. The higher the concentration of organic matter, the larger the production of gas.

Supercritical Water Gasification Results: Carbon Conversion. This section presents the results for the concentrated vinasse and for the clarified vinasse. No elemental analysis (C, H, O, N, and S) has been performed for the effluent because of the very low concentration of the elements.

Initially, concentrated vinasse and clarified vinasse have a mass content of C equal to, respectively, 23.3 and 15.7 wt %. Figure 5 is the diagram illustrating the carbon conversion of the process, which means the carbon percentage in the different phases from the concentrated vinasse and the clarified one. More than 78 wt % of the carbon has been recovered at the end of the process. The amount of carbon in the gas phase is not determined very precisely; this explains the result. The main part of the carbon is recovered in the organic solid phase and in the liquid one. The amount of the solid at the end of the supercritical reaction in a batch reactor is larger at high temperature. It confirms other results.[16] Figure 5b shows an amount of carbon in the organic solid phase between ∼32 and 50 wt % for the concentrated vinasse. For the clarified vinasse (Figure 5a) this amount is between ∼50 and 56 wt % (when the temperature increases from 400 to 500 °C).

The same trend has been observed for the carbon conversion when the temperature increased for both substrates. The effect of the increase of the temperature causes for both samples an increase of mass percent of carbon content in the organic solid phase and in the gas phase. The carbon content in the gas phase was larger at 500 °C and 25 MPa. The gasification is then more efficient at higher temperature. So a compromise has to be found in order to produce more gas without producing too many solid.

Supercritical Water Gasification Results: Gas Composition. Figure 6 shows the evolution of the gas composition resulting for the supercritical water gasification of the three bioresources.

Table 3. Yields (wt %) of the Different Phases Collected at the End of the Supercritical Water Gasification at 25 MPa for the Effluent (400 and 500 °C), for the Concentrated Vinasse (400, 450, and 500 °C), and for the Clarified Vinasse (400, 450, and 500 °C)

effluent					
T (°C)	yield$_{\text{aqueous phase}}$ (%)	yield$_{\text{organic solid phase}}$ (%)	yield$_{\text{organic liquid phase}}$ (%)	yield$_{\text{gas phase}}$ (%)	mass balance (%)
500	97.21	0.27	–	0.58	98.06
400	98.03	0.34	–	0.30	98.67
concentrated vinasse					
T (°C)	yield$_{\text{aqueous phase}}$ (%)	yield$_{\text{organic solid phase}}$ (%)	yield$_{\text{organic liquid phase}}$ (%)	yield$_{\text{gas phase}}$ (%)	mass balance (%)
500	54.67	2.90	33.47	4.65	95.69
450	56.16	2.40	30.27	4.28	93.11
400	49.89	3.50	39.39	3.63	96.41
clarified vinasse					
T (°C)	yield$_{\text{aqueous phase}}$ (%)	yield$_{\text{organic solid phase}}$ (%)	yield$_{\text{organic liquid phase}}$ (%)	yield$_{\text{gas phase}}$ (%)	mass balance (%)
500	52.71	2.67	33.13	3.82	92.33
450	60.88	2.82	23.24	2.91	89.85
400	62.79	2.55	26.91	2.32	94.57

Table 4. Volumes of Gas (mL) for the Three Substrates at 25 MPa during a 1 h Supercritical Water Gasification (400 °C < T < 500°C)

T (°C)	400	450	500
effluent	190		270
clarified vinasse	2 650	3 095	3 210
concentrated vinasse	3 630	4 015	4 060

All the experiments show that a temperature increase leads to a decrease of the molar proportion of carbon dioxide. This decrease is between 10 mol % for the concentrated vinasse and nearly 50 mol % for the effluent. Anyway the behavior of the effluent is unique because of its initial organic matter content. The comparison of both vinasses leads to the same trends, with more influence of the temperature when the organic concentration of the substrate is lower. Therefore the SCBG process is more efficient with the clarified vinasse, which has a slightly higher initial water content. The effect of the temperature on the molar percentage of methane is also noteworthy. This is particularly true for the supercritical water gasification of the effluent where methane is practically absent at 400 °C and becomes the major component of the gas mixture when the experiments have been carried out at 500 °C. However, the supercritical water gasification of both vinasses has produced ~20 mol % of methane. The production of methane is even 5 times larger for the clarified vinasse between 400 and 500 °C. Again the trend is more pronounced for the less concentrated vinasse. We are able to point out that a smaller concentration in organics leads to a better efficiency of the supercritical water gasification process in a certain extent. A less clear tendency is also outlined for the hydrogen, but the production of hydrogen is also higher at 500 than at 400 °C. Its molar percentage increases also with the temperature, but the extent is much lower than for methane. The ratio between the initial organic matter over the amount of each gas at the end of the reaction underlines that the increase of the concentration does not imply an increase of the production of each gas. At 500 °C, the hydrogen production is 6 mL/g of organic matter in the effluent, 17 mL/g of organic matter in the clarified vinasse, and also 17 mL/g of organic matter in the concentrated vinasse for the one hour gasification. At 500 °C, the methane production is similarly 37 mL/g of organic matter in the effluent, 16 mL/g of organic matter in the clarified vinasse, and 14 mL/g of organic matter in the concentrated vinasse when supercritical water gasification is carried out during 1 h. That means that, as a function of the aim (methane production or hydrogen production), the choice of the initial bioresource properties should be crucial.

The amount of carbon monoxide is nearly stable. In any event, carbon monoxide is the minor product in the gas phase. The same trends were noted by Lee et al. on a glucose feed.[17]

It seems important to point out that an increase of pressure will lead normally to an even bigger preference for the methane with regard to the hydrogen.[18] It will be studied in the future to better optimize the hydrogen production

Behavior of the Mineral Elements during the Gasification Process. It must be pointed out that the total inorganic elements amount accounts for 9.0 wt % maximum of the total elements of the biomass. ICP-OES analyses have been carried out with the objective to study the hypothetic influence of these elements on the thermal conversion. ICP-OES analyses have been conducted in order to evaluate the quantity of the mineral elements in the different phases obtained at the end of the process. The aim will be to follow and understand their behavior during the SCBG process. It is known that the solubilities of ordinary salts are greatly diminished in supercritical water. However, many water−salt systems pertain to supercritical water conditions and appreciable salt concentrations. Type 1 and type 2 systems have been detailed, and it has been shown that the salt solubilities are different as a function of the pair cation/anion.[19] As we do not know precisely which salts are concerned in the vinasse, we have to collect information on the behavior of the salts in our substrates in order to learn more about them. These results were obtained by the ICP-OES analyses for the different phases collected after the supercritical water gasification process. We have focused our attention on the potassium and sodium behaviors for two reasons. Alkali salts have been well-known to catalyze the SCBG process, and empirical experiments have been carried out to highlight this phenomenon.[2,3,10,11] Moreover they are the major mineral elements in our substrates.

In this part, Figure 7 shows the potassium (K) and sodium (Na) conversion (in wt %) during the supercritical water gasification of the concentrated vinasse and the clarified one at a temperature of 400 °C and a pressure of 25 MPa.

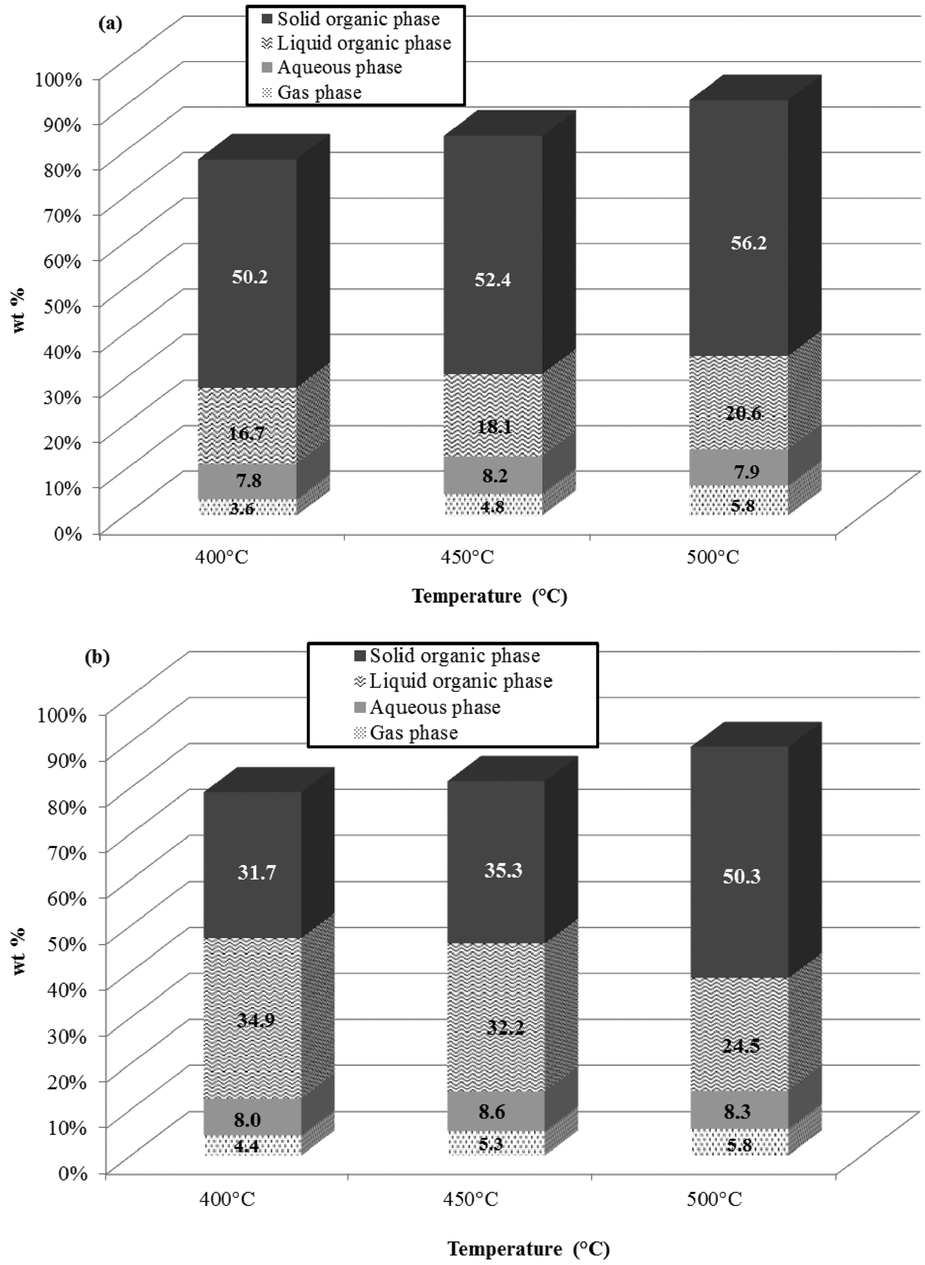

Figure 5. Carbon conversion (wtv%) of the different phases from the clarified vinasse (a) and from the concentrated vinasse (b) treatment (400 °C < T < 500 °C).

Initially, concentrated vinasse and clarified vinasse have a global mineral element composition of, respectively, 9.0% and 8.1% in weight. The amount of potassium and sodium are, respectively, about 71 and 22 wt % in the concentrated vinasse and, respectively, about 67 and 25 wt % in the clarified vinasse. The potassium and sodium behaviors for both are similar. Potassium is recovered mainly in the aqueous final phase, whereas sodium is recovered mainly in the solid organic final phase. Similar differences have already been observed in the case of other metals during supercritical water treatment. Potassium has been yet recovered in the aqueous final phase.[20] The potassium and sodium behaviors have already been studied in the literature, and these results are in agreement with our study. The explanation of Kruse et al. was that potassium acts as a catcher of sodium, which is recovered in the solid phase.[21] In summary the recovery of potassium and sodium at the end of the process could be interesting in terms of fertilizer for instance. Of course further investigations must be performed in order to determine precisely the others compounds at the end of the process, especially organic molecules, which also can be valorized.

■ CONCLUSION

This work aims at the valorization of wastewaters from wine distilleries. Nowadays it is still a challenge to reach a sustainable alcohol industry, with no waste and able to produce its own energy. The supercritical water gasification process seems to be a good solution. Then the supercritical water gasification of three selected bioresources has been carried out at a pressure of 25 MPa and temperatures of 400, 450, and 500 °C. These substrates differ essentially by their water content. A very accurate analysis procedure has been followed in order to be

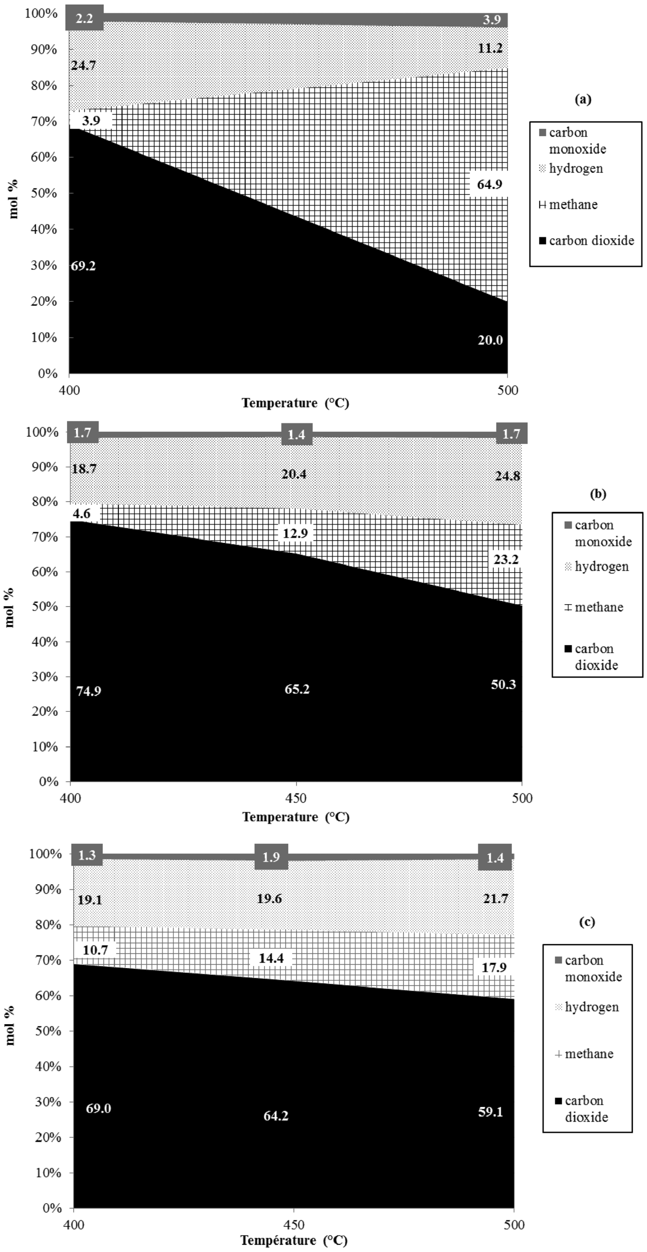

Figure 6. Composition (mol %) of the gas collected from the supercritical water gasification of the effluent (a), of the clarified vinasse (b), and of the concentrated vinasse (c) (400 °C < *T* < 500 °C).

able to study the precise behavior of these biomasses. We have pointed out the behaviors of mineral elements, particularly the potassium and sodium ones. It is a significant contribution because a lot of empirical results have shown the effect in terms of process but very few data points are available. The nature of the gases produced during the reaction was also determined.

The main conclusions of this work may be summarized as follows:

- The yield of gas is improved with the temperature.
- The amount of carbon dioxide decreases with the temperature, while the productions of hydrogen and methane increase. However, the hourly production of each gas is not a regular function of the organic content of the initial bioresource but it is dependent on it.

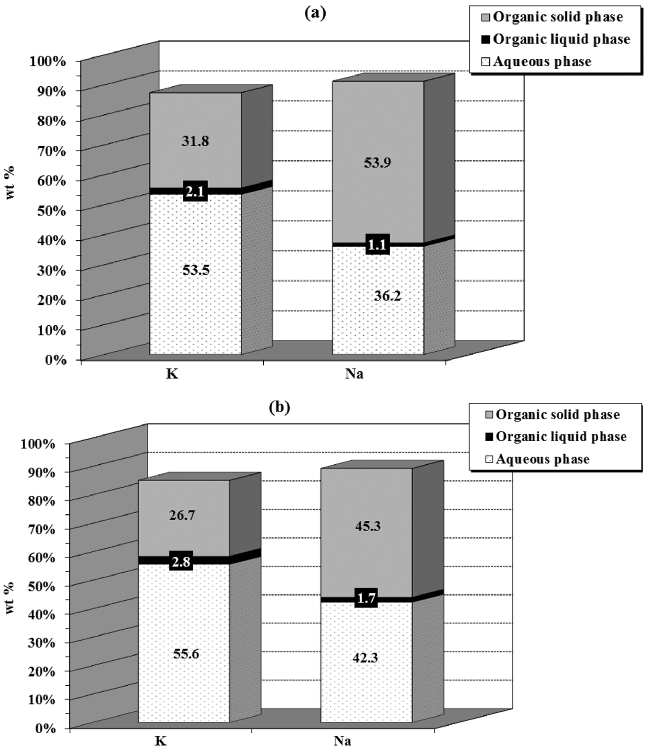

Figure 7. Potassium and sodium recovery (wt %) in the different phases from the clarified vinasse (a) and from the concentrated vinasse (b) treatment (*T* = 400 °C, *P* = 25 MPa).

- The sodium is mainly recovered in the final organic solid phase, whereas the potassium is recovered in the final aqueous phase regardless of what is the bioresource.

Future works will consist of the study of the supercritical water process at higher temperature in order to produce more gases, with higher hydrogen and methane content. Moreover, we will continue to study more thoroughly the role of the mineral elements of the initial biomass on the process. Clearly it is a key point. Particularly the behavior of sodium and potassium will be under investigation. The study of supercritical water gasification in a continuous process and with an addition of catalysts will be also performed.

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Notes

The authors declare no competing financial interest.

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