Industrial Crops & Products 107 (2017) 184–197

Contents lists available at ScienceDirect

Industrial Crops & Products

journal homepage: www.elsevier.com/locate/indcrop

Comparison between two different pretreatment technologies of rice straw fibers prior to fiberboard manufacturing: Twin-screw extrusion and digestion plus defibration

Dyna Theng[a,c], Gerard Arbat[b], Marc Delgado-Aguilar[a], Bunthan Ngo[c], Laurent Labonne[d], Philippe Evon[d,*], Pere Mutjé[a]

[a] LEPAMAP Research Group, University of Girona, C/Maria Aurèlia Capmany, 61, 17003 Girona, Spain
[b] Department of Chemical and Agricultural Engineering and Food Technology, University of Girona, C/Maria Aurèlia Capmany, 61, 17003 Girona, Spain
[c] Royal University of Agriculture, Dangkor District, 2696 Phnom Penh, Cambodia
[d] Laboratoire de Chimie Agro-industrielle (LCA), Université de Toulouse, INRA, INPT, 4 Allée Emile Monso, BP 44362, 31030 Toulouse Cedex 4, France

ARTICLE INFO

Keywords:
Rice straw
Twin-screw extrusion
Digestion
Defibration
Energy consumption

ABSTRACT

The present work compares two different pretreatment technologies, i.e. twin-screw extrusion, and steaming digestion plus defibration, for producing a thermo-mechanical pulp from rice straw for fiberboard manufacturing. Five liquid/solid ratios from 0.43 to 1.02 were tested for twin-screw extrusion pretreatment, while liquid/solid ratios from 4 to 6 were used for digestion pretreatment. Energy consumption, and characteristics of the extrudates (twin-screw extrusion) and pulps (digestion) (including fiber morphology, chemical composition, thermal properties, apparent and tapped densities, as well as color) were the analyzed parameters for the resulting lignocellulosic fibers. The results showed that liquid/solid ratio had influence on energy consumption of the equipment for both defibrating methods For the twin-screw extrusion method, a lower liquid/solid ratio required more energy while for the digestion plus defibration the effect was the opposite. The corresponding total specific energy consumption ranged from 0.668 kW h/kg to 0.946 kW h/kg dry matter for twin-screw extrusion, and from 6.176 kW h/kg to 8.52 kW h/kg dry matter for digestion plus defibration. Thus, the pulping method consumed about nine times more energy than that of the twin-screw extrusion. In addition, for twin-screw extrusion, the liquid/solid ratio did not have a substantial effect on fiber characteristics with similar chemical compositions and thermal properties. For twin-screw extrusion, the energy consumption was 37% reduced when the liquid/solid ratio was increased from 0.43 to 1.02. Instead, for digestion plus defibration, the energy increase was 38% when the liquid/solid ratio increased from 4 to 6.

1. Introduction

Rice (*Oriza Sativa* L.) is cultivated to feed more people and animals over a longer period than any other crop. As far back as 2500 B.C., rice has been documented in the history books as a source of food and for tradition as well (Thomas, 1997). Rice straw is a by-product of rice crop with a straw to grain ratio of 1.4 (Kim and Dale, 2004). In terms of total production, rice is the second most important grain crop in the world after maize. The world annual rice production in 2014 was about 741 million tons (FAOSTAT, 2016). It gives an estimation of about 1139 million tons of rice straw per year worldwide (FAOSTAT, 2016), and a large part of this is used for cattle feed, for bioethanol production, or incorporated into the soil as an organic amendment. Possible uses for rice straw are limited by its low bulk density, a slow degradation in the soil, the harboring of rice stem diseases (the possible transmission of diseases to the future crop), and a high ash content which can be a problem for subsequent ethanol or energy production (Binod et al., 2010). Currently, field burning is still the major practice for removing rice straw, particularly in less developed countries, causing air pollution, thus affecting public health (Mussatto and Roberto, 2004) and contributing to the global warming (Kanokkanjana and Garivait, 2013; Sarnklong et al., 2010). According to Kanokkanjana and Garivait (2013), about 56% of the total rice straw production was burned in Thailand in 2010. As climate change is extensively recognized as a threat to development, there is a growing interest to find alternative uses for rice straw.

All plants including rice straw have the form of a heterogeneous complex of carbohydrate polymers. Cellulose and hemicelluloses are

* Corresponding author.
E-mail address: Philippe.Evon@ensiacet.fr (P. Evon).

http://dx.doi.org/10.1016/j.indcrop.2017.05.049
Received 30 January 2017; Received in revised form 5 May 2017; Accepted 27 May 2017

densely packed by layers of lignin, which protect them against enzymatic hydrolysis. Thus, a pretreatment step is necessary to break lignin seal, until exposing cellulose and hemicelluloses for a subsequent enzymatic action or contributing to the biomass defibration (Vandenbossche et al., 2016, 2015, 2014).

Several researchers have investigated the use of rice straw and other agricultural wastes as fiber source in the composite industry (El-Kassas and Mourad, 2013; Evon et al., 2012; Halvarsson et al., 2008; Li et al., 2010; Pan et al., 2010; Theng et al., 2015a; Wu et al., 2011; Zhang and Hu, 2014; Zhao et al., 2011), in particular to produce fiberboards by thermopressing, the latter being usable for furniture or in the building industry. Different methods for fiber pretreatment were tested, i.e. chemical, mechanical, and thermo-mechanical pretreatment to obtain resources for their purposes. Recently, Vandenbossche et al. (2016, 2015, 2014) used the twin-screw extrusion technology for conducting the thermo-mechanical and thermo-chemo-mechanical pretreatment of different lignocellulosic biomass sources, in the case not for the subsequent manufacture of composite materials but for the production of second-generation bioethanol using a biocatalytic action. Evon et al. (2015, 2014, 2012, 2010a, 2010b) also produced self-bonded fiberboards from the cake generated during the biorefinery of sunflower whole plant using a twin-screw extruder. In addition, Theng et al. (2015a) prepared a thermo-mechanical pulp from corn biomass by digestion plus defibration to produce binder-free fiberboards. Migneault et al. (2010) produced medium-density fiberboards using thermo-mechanical pulps from different pulping processes. Lastly, Mancera et al. (2012, 2011) developed fiberboards using thermo-mechanical pulps from different agricultural wastes, all produced using steam-explosion. However, there is no scientific literature dealing with the energy consumption of equipment for fiber preparation using different defibrating technologies prior to board manufacturing.

The present paper aimed to explore the appropriate and beneficial technology for fiber preparation as a raw material for fiberboard manufacturing using the same batch of rice straw, comparing two different techniques: twin-screw extrusion and digestion plus defibration, without any chemical agent addition. A Clextral (France) Evolum HT 53 twin-screw extruder model and a digester reactor (designed by LEPAMAP, University of Girona, Spain) with Sprout-Waldron defibrator (model 105-A) were used in this study. The overall energy consumption of the equipment and the properties of the pretreated rice straw fibers (i.e. fiber morphology, apparent and tapped densities, chemical composition and thermal stability) from both technologies were compared to provide more options to industrial sectors.

2. Experimental

2.1. Material

Thermo-mechanical fractionation was conducted using a single batch of rice straw (*Oriza Sativa* L.), i.e. the whole plant except the panicle and the grain. The rice straw was of French origin and it was supplied by the JCL AGRI company (Bouge-Chambalud, France). It was harvested in October when the plant maturity was reached. The rice straw was previously crushed using a hammer mill (Elecra BC P, France) fitted with a 6 mm screen. The moisture content of the rice straw was 7.4 ± 0.2% (French standard NF V 03-903).

2.2. Twin-screw extruder

The thermo-mechanical fractionation of the grinded rice straw was conducted using a pilot-scale Clextral Evolum HT 53 (France) co-penetrating and co-rotating twin-screw extruder. The twin-screw extruder had eight modular barrels, each 4D in length (with D corresponding to the screw diameter, i.e. 53 mm), except module 1 having an 8D length, and different twin-screws which had segmental screw elements. Module 1 was cooled by water circulation. Modules 2–8 were heated by electric resistance and cooled by water circulation. The material temperature was measured at the end of modules 2, 5 and 7, and at the beginning of module 8. The material pressure was measured at the end of modules 2, 5 and 7. The screw rotation speed (Ss), the inlet flow rates of grinded rice straw and water (Qs and Q_L, respectively), and the barrel temperature (θc) were monitored from a control panel.

2.3. Thermo-mechanical fractionation of grinded rice straw in the twin-screw extruder

Grinded rice straw was fed into the extruder inlet port using a constant weight feeder (Coperion K-Tron SWB-300-N, Switzerland) in the first module, at a 15 kg/h wet matter inlet flow rate. Water was injected using a piston pump (Clextral DKM Super K Camp 112/12, France) at the end of module 3. After water injection, two series of BL22-90° bilobe paddle-screws (2D in total length) were located in modules 5 to disperse intimately water inside the grinded rice straw. The CF1C reversed simple-thread screws with grooves (1.5D in total length) were positioned at the beginning of module 8 to give an intense shearing/mixing action to the liquid/solid mixture. The screw speed (S_S) was fixed at 150 rpm and the set values for the barrel temperature were 25, 80, 110, 110, 110, 110, 110 and 100 °C at the level of modules 1–8, respectively. The experimental variable of this part of the study was the liquid/solid (L/S) ratio (i.e. Q_L/Q_S), the latter varying in five levels from 1.02 (E_1 extrudate) to 0.43 (E_5 extrudate), as it can be seen in Table 1. This operation condition is in agreement with previous work (Uitterhaegen et al., under review) in order to obtain a good thermo-mechanical extrudate for fiberboard production.

Twin-screw extrusion was performed for 10 min before any sampling to ensure the stabilization of the operating conditions. The operating conditions, including in particular the feed rates of grinded rice straw and water, the temperature along the screw profile and the current feeding the motor, were recorded during sampling and then used for the production cost calculation. Upon achieving steady operation, the extrudate was immediately collected over a period of 10 min to avoid any variability of the outlet flow rate. Sample collection time was determined with a stopwatch. For each liquid/solid ratio tested, sample collection was carried out once and the extrudate was then weighed. Its moisture content was also measured immediately after its collection according to the NF V 03-903 French standard.

The total specific energy (TSE) consumption (in W h/kg dry matter) of the extrusion process is defined as the sum of three specific terms, i.e. (i) the specific mechanical energy (SME), (ii) the specific cooling energy (SCE) and (iii) the specific thermal energy (STE). All these three specific energies are calculated from the recorded data of the operating conditions using Eqs. (1), (2), and (3), respectively.

$$SME = (454 \times I \times \cos\varphi \times S_s/S_{max})/Q_s \quad (1)$$

Where: I is the current feeding the motor (A), $\cos\varphi$ the theoretical yield of the twin-screw extruder motor ($\cos\varphi = 0.95$), S_s the screw rotation speed (rpm), S_{max} the maximal screw rotation speed ($S_{max} = 800$ rpm), and Q_s is the inlet flow rate of dried grinded rice straw (kg dry matter/h).

$$SCE = m \times C_p \times |\Delta T|/Q_s \times 3600 \quad (2)$$

Where: m is the inlet flow rate of cooling water (kg/h), C_p the calorific capacity of water ($C_p = 4180$ J/kg K), and $|\Delta T|$ is the difference in temperature between the inlet and the outlet of the cooling water circuit (K).

$$STE = P \times 1000/Q_s \quad (3)$$

Where: P is the heating power. The heating power used in this calculation was the sum of the heating powers of all the heated modular zones along the twin-screw extruder barrel (i.e. modules 2–8). The control panel of the extruder was set to record the heating power as a