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Characterization and comparison of cellulose fiber extraction from rice straw by chemical treatment and thermal steam explosion

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A B S T R A C T

Rice straw is one of the major agricultural wastes in Thailand. It can potentially be processed to extract natural fibers from which environmentally sustainable products, e.g. papers, can be subsequently made. This research studied the characteristics of cellulose fibers extracted from rice straw by two different treatments: (i) chemical treatment and (ii) thermal steam explosion. For the chemical treatment, sodium-hydroxide (NaOH) solutions with varying concentration were applied to treat fibers. Life Cycle Assessment (LCA) was used to evaluate and compare the potential environmental impacts of the natural-fiber thermal insulation pads produced by different rice-straw cellulose extraction processes. The morphological results show that an increase of NaOH concentration decreases the fibers' average diameter and length and fiber yielding; however, the aspect ratio of length-to-width increases with increasing NaOH concentration. For the thermal steam explosion, the cellulose fibers were extremely broken down resulting in significant reduction in the fiber diameter and length. The results of Fourier transform infrared spectrometer (FTIR) spectrum analyses reveal that both treatments only lightly dissolved lignin and hemicellulose from the cellulose fibers. Thermal insulation pads were produced from the extracted cellulose fibers using natural rubber as a binder. The thermal conductivity coefficient of the natural-fiber thermal insulations was in the range of 0.11–0.14 W/m-K. The LCA results showed that the thermal steam explosion process potentially reduced the environmental impacts as compared to the chemical extraction treatment due to a significant reduction in an eco-toxicity impact and a higher fiber yielding. However, the energy consumption of the thermal explosion process is a main issue that needs to be improved for the further development of eco fiber insulation pads produced from extracted rice-straw cellulose.

1. Introduction

Thailand is an agricultural country with 41% of the total area used for agriculture resulting in a large amount of agricultural waste. Rice straw is one of the major agricultural wastes in Thailand. To help reduce waste problem, the agricultural waste can potentially be processed to extract natural fibers from which environmentally sustainable products can be subsequently made, e.g. papers (Mazhari Mousavi et al., 2013), eco-composites (González-Sánchez et al., 2014), thermal insulation (Panyakaew and Fotios, 2011; Klinklow et al., 2013). The present study focuses on the production of a thermal insulation from agricultural waste as it can potentially be one of value-added products in building or

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packaging industries. Different agricultural wastes, e.g. corn cob (Pinto et al., 2012), narrow-leaved Cattail fibers (Luamkanchanaphan et al., 2012), flax and hemp (Kymäläinen and Sjöberg, 2008), Sunflower stalk (Binici et al., 2014), kenaf–fiber (Ardente et al., 2008), and coconut husk and bagasse (Panyakaew and Fotios, 2011), were reportedly processed to form natural-fiber insulations.

To produce a thermal insulation from straw cellulose fibers, the fibers must first be extracted from rice straws. Rice straws are natural fiber composites that consist of cellulose as main fibers, hemicellulose as inter-connected branch, and lignin as a binder (Sain and Panthapulakkal, 2006). Normally, the fiber-extractive treatment on rice straws leached out most of hemicellulose and lignin to retrieve dominantly-cellulose fibers. The treatment of rice straws to extract natural fibers may be done by physical or chemical methods (Chen et al., 2013a). Physical treatments include the techniques of ionized gas (plasma or corona), laser or thermal-steam explosion.

The steam exploded treatment, which is the method of interest in this study, can be accomplished by an application of high pressure steaming, involving heating of the materials at high temperature and pressure followed by mechanical disruption of the pretreated material by violent discharge (explosion) into a collection tank (Iroba et al., 2014). The steam treatment is an effective pre–treatment process for wheat straw fibers to destroy lignin proportion and extract the bundle of rice straw fibers (Zhang et al., 2008). Higher steam temperature and longer retention time resulted in more homogeneous fiber with the fiber surface wettability was improved. The ash and extractives (e.g. silicon) were reduced and the tensile strength of the treated fiber was enhanced by the steam explosion treatment (Han et al., 2009, Han et al., 2010).

For a traditional chemical treatment, a solution of hydroxyl group (NaOH, KOH) was used to remove lignin from natural fibers for producing hybrid composites (K. Majeed et al., 2013; Liu et al., 2015). Hemicelluloses was broken and eliminated by the chemical treatment. From TG-FTIR analysis, the absorbance intensities of C=O was decreased through acid treatment, while increased through NaOH treatment (Sheng et al., 2014), which might indicate that the stretching vibration of free carbonyl groups was broken and separated by NaOH solution more than by the acid treatment. To minimize the environmental impact due to chemical waste and maximize the extraction efficiency, the application of combined steam explosion and alkaline treatment have been used to extract cellulose fibers from bark of cotton stalks with high cellulose-yielding percentage and high aspect ratio (Hou et al., 2014). Also, a hybrid of chemical and mechanical method was reportedly co-ordinated in a pre-treatment of rice straw, e.g. the acid–catalyzed steam exploded process which was used for saccharification (Chen et al., 2013b). Currently, the chemical treatment of fibers by NaOH solution is one of the most common extraction process, which results in toxic side-effect regarding hydroxides of alkaline or alkaline earth and requires large amount of water to clean fibers after extraction process treatment (Klinklow, 2012; Klinklow et al., 2013). Therefore, it is imperative that an alternative, environmental-friendly method for fiber extractions, e.g. the steam explosion treatment, should be considered in place of the chemical treatment.

Environmental-friendly methods have been developed and discussed in several reports. Panyakaew and Fotois (Panyakaew and Fotios, 2011) produced a thermal insulation board from Coconut husk and bagasse without chemical binding additive, aiming to develop a thermal insulation process with lower environmental footprint than conventional materials. A life cycle assessment was used to analyze an environmental impact of a kenaf-fiber insulation board focusing on main environmental impact, pointing out critical issues and suggesting the highest improvement potentials for the insulation boards (Ardente et al., 2008). Life cycle assessment has been increasingly applied for analyzing waste-recycled products, such as building materials, which is a broad international acceptance as means to improve environmental processes and prevent adverse environmental impacts (Ortiz et al., 2009). It has been reported that a steam explosion process can be favorable over the chemical process in pre-treatment of natural fibers, according to the environmental sustainability study on comparing wheat straw production pathways in bioethanol production using the LCA approach (Wang et al., 2013). However, the LCA comparison, between the thermal insulation pads made of fibers extracted by the steam explosion and the chemical treatment of the rice straws, has not been reported.

In this work, the steam explosion and the NaOH solution treatment of rice straws are investigated and compared on the aspects of both physical properties and environmental impact. The extracted fibers from both treatments were characterized and subsequently used to form a thermal insulation pad by spray lay-up method with a natural rubber as a binder. The thermal conductivities and LCA-based environmental impacts of the insulation pads from different fiber-extraction processes are reported and discussed herein.

2. Materials and methods

2.1. Preparation of the rice straw fibers

The rice straws, obtained from a local field in Loppburi province, Thailand, were cut to 1 and 3 cm in length. The straws were cleaned, dried at 80 °C for 8 h and then treated by either the sodium hydroxide (NaOH) chemical treatment or the steam explosion treatment. The chemical treatment conditions, e.g. NaOH concentration and extraction time, were obtained from the previous reports (Klinklow, 2012; Klinklow et al., 2013). The fiber-extraction treatments can be summarized as following:

2.1.1. Laboratory-scale chemical treatment

The 10-g of 1-cm straws were treated with 1, 5, 10 and 15 wt% NaOH solution for 30 min using a fiber to solution ratio of 1:20 by weight. The optimal length of a pre-treated straw is approximately 1 cm for a NaOH solution treatment; as a result, only 1-cm straws were used for the chemical treatment in this study. The chemical solution was continuously agitated using a magnetic stirrer. The extracted fibers were rinsed with water, then air-dried.

2.1.2. Pilot-scale chemical treatment

The 500-g of 1-cm straws were treated with 15 wt% NaOH solution in a 40-L batch blending machine for 30 min using a fiber to solution ratio of 1:20 by weight. The extracted fibers were rinsed, and then dried in an oven at 100 °C for 8 h.

2.1.3. Thermal steam explosion

The thermal steam exploded process was conducted with assistance from Kasetsart Agricultural and Agro-Industrial Product Improvement Institute (KAPI), Kasetsart University. The 1-cm and 3-cm straws were steamed at 17 bar (205 °C) for 5 min in a 2-L batch reactor. After the first-batch characterization, 3-cm pre-treated straws yielded better results of extracted fibers. As a result, the second batches of 3-cm straws were mechanically steamed under varying pressure: 13 bar (192 °C), 15 bar (200 °C) and 17 bar (205 °C). At the end of the 5-min steaming, the valve was opened for the “explosive depressurization” to occur (Ibrahim et al., 2011). The steam-exploded fibers were shot through a connecting