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Synthesis of a sustainable integrated rice mill complex

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ABSTRACT

A rice mill produces many by-products that can be further utilised into value-added products. For instance, rice bran can be further processed to produce rice bran oil. On the other hand, rice husk can be utilised as biomass in the cyclonic husk furnace or cogeneration system to supply thermal energy for paddy drying. Alternatively, rice husk can be the raw material to produce bio-char, bio-oil and biofuel. This paper presents a framework to synthesise the sustainable pathways for an Integrated, Resource-Efficient (IRE) rice mill aimed at maximising its profitability while minimising the environmental impact of its by-product utilisation. The key factors considered include the availability of resources, the cost-effectiveness of the available technology options and the trade-off between profitability and environmental impact such as global warming, photochemical ozone production and eutrophication. The developed model was applied on a case study where five different scenarios representing different economic and environmental objective functions were analysed. The proposed model allows rice millers to target for the maximum profit and synthesise the sustainable process pathways prior to the detailed design of the IRE rice mill complex.

1. Introduction

Rice has been the main staple food for more than half of the world population (Slayton and Timmer, 2008). In addition, rice also accounts for more than 20% of calorie intake by human (Smith, 1998). This makes the rice industry vital for the global food supply security. According to FAOSTAT (2010), in year 2010, the global rice industry produces 672×10^6 t of paddy (unmilled rice) and 134×10^6 t of rice husk, the main rice residue (Table 1). Considering the higher heating value of rice husk at 15.09 MJ/kg, the potential energy that can be derived from the global output of rice husk is a significant 2129×10^9 MJ (Jenkins et al., 1998). Despite the growing global importance and the modernisation of rice industry, many rice mills still operate at a small profit. This is mainly due to the inefficient utilisation of rice mill by-products and the high utility cost (Lim et al., 2013b). A rice mill typically produces mixed full head rice and broken rice as the main products. During the rice milling process, rice mill produces other by-products including rice bran and rice husk. The unused broken rice and rice bran are often sold to the downstream industries at small profits. Rice husk, on the other hand, is often randomly disposed as a waste, thereby causing environmental problems (Mansaray and Ghaly, 1998). In addition, rice mills typically consume extensive amount of thermal energy from fossil fuel to dry paddy during the harvesting period. The utility cost needed for paddy drying typically contributes to 55% of rice mill operating cost. The poor utilisation of by-products and high energy cost in rice mills have motivated the transformation of a conventional rice mill into an integrated, resource-efficient (IRE) rice mill complex (Lim et al., 2013b).

By efficiently utilising its by-products, an integrated, resource-efficient (IRE) rice mill complex integrates various processes into an existing rice mill to produce power, fuel and value-added products. With proper planning, the by-products can be furthered processed into value-added products such as vermicelli and rice bran oil. The unused broken rice can be milled into rice flour. Rice bran which is rich in nutrients, can be processed in an extraction plant to produce rice bran oil. Rice husk can be utilised as a source of energy either in the cyclonic husk furnace (CHF) or the cogeneration system. In the CHF, the generated hot air is directly sent to the dryers. In the cogeneration system, the turbine exhaust steam flows into the air radiators to generate hot air that is utilised for paddy drying. The electricity generated from the cogeneration system can be used to supplement the electricity from the grid. Apart from being used as a source of fuel, the rice husk can be utilised in the pyrolysis process to produce bio oil. However, one major drawback of rice husk is its low density. Also, the high alkali content (Na and K) and the presence of phosphorous in the rice husk will result in a low melting temperature of rice husk ash. This

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Table 1
Global outlook of rice biomass.

Regions	Harvested paddy ($\times 10^6$ t)	Rice husk ($\times 10^6$ t)	Potential energy from rice husk ($\times 10^9$ MJ)
Africa	22.86	4.57	72.42
Americas	37.17	7.43	117.75
Asia	607.33	121.47	1924.02
China	197.21	39.44	624.76
India	120.62	24.12	382.12
Indonesia	66.41	13.28	210.39
Bangladesh	49.36	9.87	156.37
Vietnam	39.99	8.00	126.69
Myanmar	33.2	6.64	105.18
Thailand	31.6	6.32	100.11
Malaysia	2.55	0.51	8.08
Europe	4.44	0.89	14.07
Oceania	0.22	0.04	0.70
World	672.01	134.40	2128.93

may lead to fouling and corrosion of the heat transfer surfaces and the possibility of agglomeration in fluidised bed combustors (Armesto et al., 2002).

The integration of value-added processes can improve the profitability of a rice mill while offering some cleaner production options. However, due to the vast options of process technology and product portfolio available in the rice value chain, it becomes a challenge for a rice enterprise to select the most profitable and sustainable rice processing route. In addition, the emissions resulting from the different processes can adversely impact the environment through global warming, photochemical ozone production and eutrophication.

Previous works related to the rice mill are mainly focused on the process improvement of the individual processes in rice mill. For paddy drying, Atthajariyakul and Leephakpreeda (2006) developed a systematic approach using the adaptive fuzzy logic control to determine the optimal conditions for fluidised bed to be energy-efficient while producing good quality products. In another study on paddy drying, Rao et al. (2007) formulated an optimisation model with multiple objectives to achieve the maximum head yield, the minimum specific energy consumption and the minimum drying time by optimising key process parameters such as the bed depth, the air velocity and the air drying temperature. Zare and Chen (2009) developed a model to simulate the profiles of the grain moisture content, grain temperature and air humidity during the drying process. The model is optimised with the objective function of minimising the specific energy consumption of the paddy drying process.

Wong (2004) used the space-time network configuration on the production planning of a rice mill to model the post-harvest rice supply chain in Malaysia. The approach is later applied to rice mills in Thailand (Wilasinee et al., 2010). These studies do not consider the by-product utilisation, and are limited to the resource coordination of the rice supply chain. To address this research gap, Lim et al. (2013c) proposed the utilisation of by-products within an existing rice mill. They formulated a mixed integer linear programming (MILP) model and performed the multi-period resource allocation and process synthesis for an IRE rice mill complex. As an extension of this work, Lim et al. (2013a) included the supply chain planning element such as the selection of location to construct the IRE rice mill complex and determine the inventory levels of the key resources. However, none of the aforementioned research considered the environmental factors in the process synthesis stage.

On the utility system of a rice mill, Sookkumnerd et al. (2005) performed an economic analysis to investigate the feasibility of installing the rice husk-based steam engine in the rice mills of Thailand. The study also determined the maximum purchasing cost of rice husk for various rice mills processing capacity. In another study, Lim et al. (2011) formulated an MILP model that considered the optimal logistic network for rice husk, to determine the economic scale of the rice mill utility system that consists of cyclonic husk furnaces and rice husk-based cogeneration system. Bergqvist et al. (2008) evaluated the economic feasibility of utilising the rice husk to fulfil the rice mill electricity requirement and to export electricity to the grid in Vietnam. In India, Mujeebu et al. (2011) studied the feasibility of incorporating the steam turbine-based cogeneration into a rice mill and the potential of supplying electricity to the grid. Ng et al. (2013a,b) proposed an improved stoichiometric equilibrium model for a biomass fluidised bed gasifier that includes a correction factor for the equilibrium constants as a function of temperature. The operating conditions of the biomass fluidised bed gasifier are optimised to determine the corresponding syngas composition, where rice husk was one of the biomass studied. The above research shows that it is economically feasible to utilise the rice husk as a fuel, which is a cleaner alternative as compared to the fossil fuel-based utility system in a rice mill. None of the aforementioned research have considered the environmental impacts of utilising the by-products.

There has been some works focusing on evaluating the environmental impact of rice mill processes. Burritt et al. (2009) used the environmental management accounting as a tool to evaluate the rice husk utilisation via carbonisation and cogeneration without considering the implication of these technologies on the existing rice mills resource planning. Chungsangunsit et al. (2005) used the life cycle assessment methodology to evaluate whether the energy production from biomass achieve lower emissions than the conventional fuel production. Chungsangunsit et al. (2009) evaluated the environmental performance of a 10 MW rice husk-based power generation system. Kami Delivand et al. (2012) later evaluated the socio-economic feasibility of rice straw conversion to power and ethanol in Thailand. None of the studies mentioned have addressed the trade-off between the economic and environmental impacts of a rice mill that is integrated with its value-added processes.

An approach to solve such multi-objective optimisation problem is to use the fuzzy mathematical programming as proposed by Zimmermann (1978). Given a set of alternatives, governed by constraints, the fuzzy optimisation determines the preferable alternatives that result in a more desired objective function values (maximum/minimum). Using the fuzzy programming method, it can eliminate the biases of human decision makers by assigning different weight factors to each objective function, as required in the weighted averaging objective method. The fuzzy multi-objective optimisation has since been adapted and applied in different fields, for instance, production planning (Peidro et al., 2010), energy planning (Pohekar and Ramachandran, 2004), water network synthesis (Tan and Cruz, 2004), life cycle analysis (Tan, 2005) and process parameter determination for grinding process (Winter et al., 2014).

A few recent studies have used the fuzzy mathematical programming method to solve process systems engineering problems. For water network synthesis, Aviso et al. (2010) developed the bi-level optimisation model to evaluate the effect of charging fees for fresh water purchase and wastewater treatment on the water exchange network in an eco-industrial park. Tan (2010) proposed a fuzzy mathematical programming model for the synthesis of water networks with model parameters that exhibit fuzzy uncertainties. Boix et al. (2012) developed an MILP model to determine the minimum fresh water, regenerated water flow rates as well as the number of network connections (integer variables) in an eco-