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Techno-economic feasibility of using recycled polymer plastic in torrefied and pelletized herbaceous biomass

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Abstract

Using torrefied herbaceous biomass such as wheat and barley straw as a biofuel has shown promising results for overcoming a shortage of raw materials in the wood pellet industry. Using a proper type and amount of additives and binders with torrefied herbaceous biomass (e.g. wheat and barley straws) can increase its combustion efficiency. Technical feasibility in terms of production technique of adding recycled linear low density polyethylene (LLDPE) as binder to torrefied and pelletized herbaceous biomass was investigated. Non-ground wheat and barley straws were torrefied at 250ºC for 15 min. The torrefied biomass was mixed with LLDPE as an additive at four levels (1, 3, 6 and 10%). One minute preheating of biomass using the heating chamber was found to be the best process condition that resulted in the production of pellets with the best quality characteristics. Adding LLDPE showed an increase in density and higher heating value (HHV) of the studied pellets while the ash content decreased. The economic feasibility of using LLDPE as a binder for torrefied and pelletized herbaceous biomass by calculation of its capital and operating cost was investigated.

Keywords: Torrefaction, Densification, Binder, Pellets, LLDPE, Biomass, Bioenergy

1 Introduction

The demand for biomass-based energy and fuel as a renewable energy to replace fossil fuels has been on the upswing. Limitations of fossil fuel sources, oil price fluctuations, and the production of large amounts of greenhouse gases, key contributors to global warming, are major drivers towards this replacement (Shahrukh et al., 2016). In this regard, lignocellulosic agricultural biomass such as straw is considered as an abundant renewable energy feedstock (Li et al., 2012). However, in an unprocessed form, raw cellulosic biomass possesses a low bulk density (Mani et al. 2004, 2006), making it too bulky for efficient transportation, storage, and handling without expensive material transformation systems to pre-process the biomass and increase its bulk density (Adapa et al., 2009; Mupondwa et al., 2012). Pelletization is one of the pre-processing biomass methods that is increasingly in demand in order to increase specific biomass density by transforming the original biomass into a densified homogeneous intermediate with higher energy and mass density, thereby rendering the biomass as an efficient and cost-effective feedstock (Sokhansanj and Turhollow, 2004; Mani et al., 2006; Sokhansanj et al., 2010). However, pelletization is also constrained by challenges associated with attributes of most raw material. For instance, studies suggest that agricultural straw do not bind efficiently during pelleting, thereby resulting in poorly formed straw pellets which are often dusty, difficult to handle, and costly to produce. While lignin, protein, starch, and water soluble carbohydrates provide natural binders in lignocellulosic biomass materials (Kaliyan, 2008; Kaliyan and Morey, 2009), agricultural straws generally lack sufficient quantities of these constituents that provide natural binding components, thus requiring various physico-chemical and biological pretreatments and addition of additives to enhance the pellet durability and strength (Kashaninejad and Tabil, 2011).

Hence, the use of other sources of raw materials such as agricultural residues as the main material and recycled polymer plastics as a binder has been suggested (Emadi et al., 2017). Pelletization of torrefied agricultural residues was introduced to the pellet industry several years ago. Although torrefaction is an energy intensive process, using some techniques will make it profitable. For instance, Tiffany (2013) reported that the cost of torrefaction is about $42 per finished tonne (t) while selling the produced steam from combustion of volatile organic compounds (VOC) off gases can reduce the price of torrefaction to $17 per finished tonne. Torrefied agricultural residues need higher quality and quantity of binders due to their low adhesive nature. Adding polymer plastics like linear low density polyethylene (LLDPE) from 3% to 10% to wheat and barley straws before densification showed promising results (Emadi et al., 2017). It was demonstrated that adding LLDPE from 1% up to 10% resulted in increasing higher heating values (HHV) and a decreasing ash content for both torrefied wheat and barley straw pellets. The higher heating value of the pellets at all levels of added LLDPE except 10% meet the current standard specifications of DIN 51731 for commercial pellets (Pellet Atlas, 2009). The ash content of the torrefied barley pellets at all levels of LLDPE addition except at 1% were in agreement with requirements of the Pellet Fuels Institute Standard Specification for Residential/Commercial Densified Fuel (66.0%).

Despite the breadth of research on various aspects of the pellet industry and available literature, more information is needed as the industry expands especially when new technologies are introduced. The necessary information on new technologies include production and financial characteristics, logistic barriers including market pricing practices, transportation, storage and operating cost, in addition to delivered cost, equipment, energy consumption, and labor costs (Pirraglia et al., 2010). The objective of this study is to develop a techno-economic model to estimate production costs of pellets made of torrefied agricultural residues which incorporate plastic polymers as a binder.

2 Methodology

2.1 Model development and assumptions

A techno-economic model for pellet production (Fig.1) based on individual processes of torrefied agricultural residues added with polymer plastic was developed using available literature (Pirraglia et al. 2010; Shahrukh et al., 2016; Mani et al., 2006). Other than the torrefaction and conditioning processes, all other processes are considered to be the same as conventional pellet production methods. In the conditioning process of new technology, polymer plastic was considered for use as a binder for the torrefied biomass instead of common binders used in a non-torrefied conventional method.

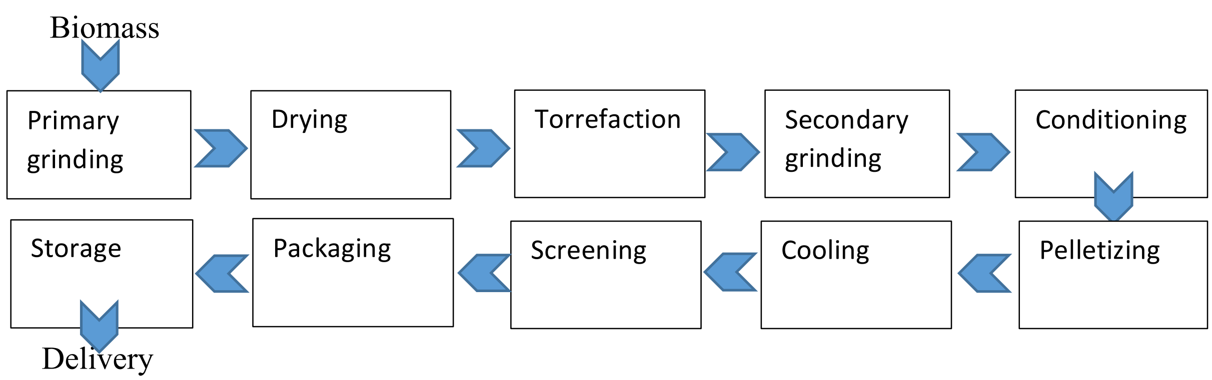

Fig. 1. Process flowchart for typical manufacturing of torrefied bio-pellets added polymer plastic as binder

The approach for this study was “err on the high side” which means the model and its estimated cost meet or exceeds requirements (Campbell, 2007). The developed model assumes the cost of biomass at plant gate, and does not involve biomass collection and its transportation to the plant. In addition, the cost of pellet transportation to the delivery point was not considered either. Cost parameters were developed based on a detailed literature review, in consultation with experts, and available market price data. The considered life of the plant in this study was 30 years (Sultana et al., 2010; Shahrukh et al., 2016). The price of recycled polymer plastic was considered as the cost of added binder for the torrefied pellets. The cost parameters generated for this study focus on the effects of energy requirements in the method but do not consider cost differences arising from changes in the quality of the final pellet product. All currency figures are in $US. Western Canada was selected as the region of this study. Equipment prices quoted in different years are adjusted to 2017 U.S. dollar values using an inflation calculator by the Federal Reserve Bank of Minneapolis (FRBM, 2017).

The production cost of an added polymer plastic torrefied pellet was studied and analyzed. A production capacity of 6 tonnes of pellets per hour (t/h) was selected as the base case for this model. The plant operates for 24 hours 310 days per year at an 85% annual utilization period, for total annual production of 45,000 t (Mani et al., 2006) for the base case.

2.2 Pellet production cost

Various effective costs of pellet production have been studied in previous techno-economic assessment models (Pirraglia et al. 2010, Shahrukh et al., 2016, Mani et al., 2006). The costs were classified into capital and operating cost. Related costs include labour, energy, and consumables (Sultana et al., 2010). All calculations were conducted using suggested formulas and equations by Mani et al. (2006).

2.2.1 Capital cost

Capital cost includes the cost of pellet processing equipment and their installation, for process as outlined in Fig. 1. One electrical driven stationary tub grinder (hammer mill) was considered for the model as a primary grinder. A primary grinder is needed to chop either long straws or densely baled biomass to smaller pieces of less than two inches in all dimensions (Campbell, 2007). The total installed cost of a hammer mill or dryer is about 50% more than the equipment price (Campbell, 2007). A rotary drum dryer driven by natural gas was assumed for use in the model to reduce moisture content of delivered feedstock from 14% to 10%.

Torrefaction is an additional operation for making torrefied pellets compared to pellets made via conventional (non-torrefied) methods. Although this pre-treatment operation consumes more energy and cost than non-torrefied methods, its benefits have encouraged biomass pellet industries around the world to use it. The temperature of the feedstock must be increased up to 250-280ºC directly or indirectly. Most of the current technologies including rotary drum, toroidal reactor, and moving bed can produce about 5.5 t/h torrefied biomass (Canadian Biomass, 2017). An electrical torrefaction reactor (62 kWh) was considered in this model (Tiffany, 2013).

One more electrical driven hammer mill was considered for the model as a secondary grinder. The hammer mill grinds feedstock to appropriate particle size for pelleting. This size should not be bigger than the diameter of a pellet which is roughly a 6.35 mm (0.25 in) (Campbell, 2007). The resulting brittleness of biomass due to torrefaction makes this step much easier with lower consumed power than conventional pelleting method.

The aim of using a conditioner in pellet processes is to prepare the mixture of the pellet with high temperature as well as to mix necessary additives and binders to the raw/torrefied feedstock. Agricultural residues have low binding capacity because of a lackof free lignin; it is worst when they are in a torrefied condition. Companies use glycerine, paraffine, molasses, lignin, bioplastics or condensable fraction of torrefaction gas as binder if torrefaction treatment was involved in the pellet fabrication process (Koppejan et al., 2012). The price of glycerine, for instance, is considered to be $600/t (Alibaba, 2017). It is much higher than the price of recycled and shredded LDPE which is $437/t. Although rising pressure inside the pellet mill will raise temperature, to ensure good bending of the mixture when polymer plastic is being used as a binder, the temperature of the mixture must be increased up to 150ºC especially for torrefied biomass. Emadi et al. (2017) reported that the preheating of a mixture including torrefied biomass residues and polymer plastic before pelletization is necessary. They revealed that adding a plastic polymer will improve the binding capability of torrefied biomass particles. Recycled LDPE which is almost the same as LLDPE is considered for addition to the torrefied pellets as a binder in this model.

A boiler driven by natural gas was considered in this model to provide the necessary heat for the torrefaction unit. The exhaust of the torrefaction unit can be used for preheating of the mixture before pelletization.

Hot pellets (over 93ºC) are transferred to the cooler in the next step. The temperature of the pellets is reduced to make them ready for shaking/screening. Although hot exhaust from the cooler can be used as a heat source in the drying step, it was not considered in this model to make it realistic.

2.2.2 Operating cost

Labour cost

Labour cost is a major cost section of the operating cost (Shahrukh et al., 2016). Workers are hired either permanently or hourly in the production, administration, and marketing sections. The number of workers in a pellet plant depends largely to the main labour demanding operations including loading, unloading, handling and storing of raw materials and pellets. The economically optimum size of the plant is largely affected by the number of employees as it is not linearly correlated to production capacity (Sultana et al., 2010, Shahrukh et al., 2016). Seven hourly employees and four permanent employees are required for a base case production of 45,000 t/yr (Sultana et al., 2010, Shahrukh et al., 2016). Two more hourly employees are considered for pre-treatment of polymer plastic in pellet production.

Energy cost

The cost of two sources of consumed energy including electricity and natural gas were considered for the studied model. Electricity cost is the main source of energy cost for pellet production (Sultana et al., 2010). Although the main source of electricity consumption is the pellet mill, its cost in pellet production is affected by the type, size and moisture content of the feedstock, and pellet size. For instance, straw needs less power for pelleting compared to softwood, but needs more energy for chopping than wood (Sultana et al., 2010). Natural gas was considered as the second energy source for pellet production. It provides support for the dryer and boiler. Average electricity rate in Canada is $0.12 per kWh.

Material and Consumables cost

Wheat or barley straw cost is $70/t including transportation cost to the plant gate. The cost of plastic binder (recycled LDPE) is $23.5/t. The cost of LLDPE was assumed to be the same as that of LDPE. There are some sources of consumables cost in pellet production. Dies and rollers are reported as consumable parts especially if the raw material for pellet production is straw (Sultana et al, 2010). The consumable cost for rollers, blades and screens is $2.75/t (Campbell, 2007). Pellet bags and fuel cost of wheel loader are considered as two other sources of consumable cost. The cost of bags is $7.5/t if one tonne is loaded to 50 bags each $0.15 (Campbell, 2010). The consumable cost for wheel loader is $1.27/t if diesel cost is assumed to be $0.37/l. The wheel loader is assumed to be 82.02 kW (110 hp) with usage of 18.65 l of diesel when working at full load (Campbell, 2007).

3 Results and Discussion

3.1 Capital cost

Details of capital cost calculations are given in Table 1. The unit capital cost of pelletization plant to produce pellets of torrefied agricultural residues added with polymer plastic as binder was about $8.40 per tonne. The primary grinder had the highest cost besides conveyor tanks and other components, compared to the other equipment studied. Similar orders of magnitude were reported by other researchers previously (Sultana et al., 2010, Shahrukh et al., 2016). The estimated capital cost of $8.40 per tonne in this study can be decreased if the plant annual capacity increased to more than 45,000 tonne a year.

3.2 Operating cost

Details of operating cost are given in Table 2. The capital and operating cost of producing torrefied pellet with plastic polymer were $8.40/t and $131/t, respectively. The total cost of producing torrefied pellet ($140/t) can be reduced by increasing the annual production rate to more than 45000 t/year (base case). By comparing different process operations and cost components, it is observed that the cost of straw plus transportation accounted for the highest share (53%) of the total operating cost. It means that the total cost to produce pellets is considerably affected by the cost of raw materials. The cost of polymer plastic had the second highest (18%) total operating cost. Plastic polymer was added at the rate of 3%. The effect of binder cost for 1%, 6% and 10% polymer plastic on operating and total cost is shown in Figure 2. It is found that if binder content increased from 1% to 10%, the unit operating cost increased by 61.5%. When binder content was increased from 3% to 10%, the unit operating cost of pellets increased by $45/t, which is even higher than the cost of torrefaction ($42/t) reported by Tiffany (2013), indicating that binder content must be controlled to lower production cost. It should also be considered that using higher percentage of LLDPE as a binder will result in higher quality of pellets (Emadi et al., 2017) which affects the final price of the product. Hence, in comparison to the price of common binders like glycerine, using polymer plastic is economically feasible.

Table 1. Results of capital cost calculations for the studied model

Plant equipment	Scale factor	Base case* (1000 $)	Expected life (year)	Capital recovery factor	Annual capital cost (1000 $)	Maximum size of equipment (1000 t/y)	References
Primary grinder	0.99	737	10	0.1033	76	105	Campbell, 2007
Rotary drum dryer	0.60	488	15	0.0699	34	100	Sultana et al., 2010
Hammer mill	0.60	170	10	0.1033	17.6	108	Sultana et al., 2010
Feeder	0.57	51	10	0.1033	5.3	50	Sultana et al., 2010
Boiler	0.70	58	15	0.0699	4		Sultana et al., 2010
Torrefier reactor	0.60	149	10	0.1033	15	50	Tiffany, 2013
Pellet mill (with conditioner)	0.85	398	10	0.1033	41	50	Sultana et al., 2010
Pellet cooler	0.58	193	15	0.0699	13.5	216	Sultana et al., 2010
Screener/shaker	0.60	21	10	0.1033	2	100.8	Sultana et al., 2010
Bagging system	0.63	511	15	0.0699	36	100.8	Sultana et al., 2010
Conveyor Tanks etc.	0.75	1,283	10	0.1033	132.6	84	Sultana et al., 2010
Total cost (1000 $)					377.64		
Unit cost ($/t)					8.40		

* Including installation cost

Table 2. Results of operating cost calculations for the model

	Specific cap. cost ($/t)	Operating cost ($/t)	References
Raw material			
-Straw		70	Shahrukh et al., 2016
-Polymer plastic*		23.5	Web Ref.
Pellet process			
-Primary grinder	1.68	5.04	Campbell, 2007
-Drying operation	0.84	10.14	Campbell, 2007
-Hammer mill	0.39	0.91	Mani et al., 2006
-Torrefaction	0.33	7.50	Tiffany et al., 2013
-Pellet mill	0.91	2.43	Mani et al., 2006
-Pellet cooler	0.30	0.27	Mani et al., 2006
-Screening	0.04	0.06	Mani et al., 2006
-Packing	0.80	1.77	Mani et al., 2006
-Pellet storage	0.09	0.01	Mani et al., 2006
-Miscellaneous equipment	2.94	0.43	Mani et al., 2006
Employee cost		6.37	Shahrukh et al., 2016
Consumables cost		8.88	
Land use and building		0.06	Mani et al., 2006
Total cost	8.40	131	

* http://www.recyclexchange.net/canadianplastics/

Drying and torrefaction operations had the highest share with 8% and 5%, respectively after binder cost. The thermal energy source for torrefaction in this model is the combustion of raw sources like fossil fuels and biomass. Torrefaction cost can be reduced using some smart techniques. Koppejan et al. (2012) suggested using a heat exchanger as one more step in the process design. They reported that the required thermal energy for drying and torrefaction can be supplied in three different ways including: a) redirection of flue gas for direct or indirect process heating; b) recirculation of torrefaction gas for process heating; and c) recirculation of steam for direct or indirect process heat. Involving any of three suggested ways by Koppejan et al. (2012) is strongly dependent on the moisture content of biomass and the required degree of torrefaction. They suggested use of biomass of lower moisture content as moisture entering the torrefaction reactor will make for more wet torrefaction gas which lowers the adiabatic flame temperature (Koppejan et al., 2012). Using all these types of techniques will reduce the final cost of torrefied pellets incorporating polymer plastic and make it cost competitive with pellets produced in conventional (non-torrefied) methods. However, the calculated price for the studied pellets is still acceptable and falls within the range of pellet costs estimated in previous studies quantifying the net present value and profitability of a pellet plant based in the Canadian prairies (Mupondwa et al., 2012).

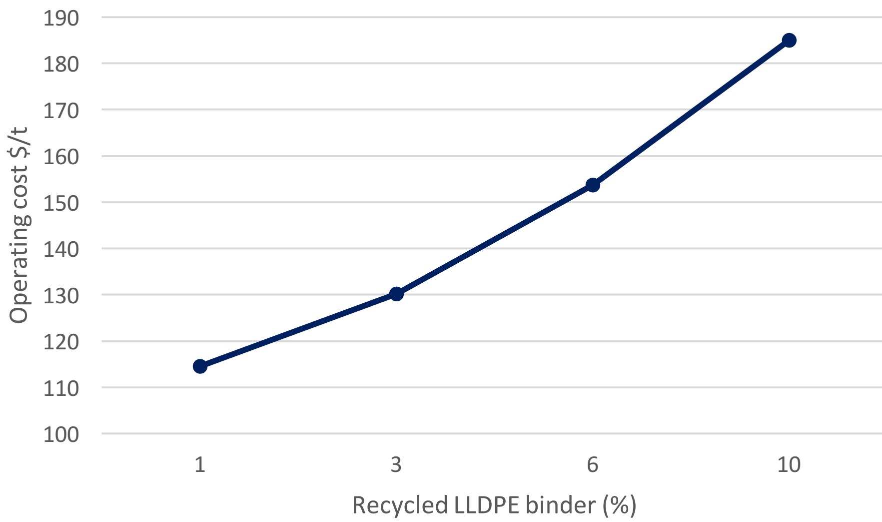

Figure 2. Effect of polymer plastic (recycled linear low density polyethylene (LLDPE)) cost on pellet operating cost of the studied model

3.3 Technical feasibility

The introduced equipment in this model is currently in use and commercially available. The blending and pelletizing process of torrefied straw using LLDPE as a binder is a new technology. The process was already investigated for wheat and barley straws (Emadi et al., 2017). It was found that the pelletizing of LLDPE with either barley or wheat straw is feasible if the mixture is preheated for one minute before pelleting. The necessary thermal energy can be provided with the exhaust of torrefaction unit.

4 Conclusions

The calculated cost of torrefied pellets included polymer plastic as binder was about $140. The price was calculated for 45000 t annual production and it can be reduced for higher annual rates. Reusing or selling the thermal energy of exhaust from torrefaction and cooling units in drying unit may reduce the final cost of the product. The calculated price considering 3% polymer plastic (LDPE) and the addition of the binder up to 10% will increase the price of pellets up to $185/t. The technical feasibility demonstrated in this study indicates that using polymer plastic in torrefied pellets is promising; producing pellets from torrefied straws incorporating recycled LLDPE as binder is economically and technically feasible.

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