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Process design and techno-economic analysis of an integrated mango processing waste biorefinery

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ABSTRACT

This study evaluated costs and profitability associated with mango processing waste biorefinery plant with the goal of generating wealth from waste. Three pathways were evaluated (i) Only Pectin recovery (PEP) (ii) Pectin and Seed Oil recovery (PSEP), and (iii) whole biorefinery with multiple products (WMB). A plant capacity of 10 tons/h was considered as a base case for analysis. Effect of biomass feed composition on product yields were also reported in this study. The PSEP was found to be the best alternative for mango waste utilization. The NPV, IRR and PEP were $41 million, 34% and 2.4 years, respectively. In case of PEP and WMB, NPVs were $14.2 and $43.2 million; IRRs were 20% and 26%, and PBP were 4.2 and 3.4 years, respectively. Sensitivity analysis showed that plant capacity, plant operating days, and raw material composition were most important factors that influenced plant economics. Selling price of main product i.e. pectin had a major influence on plant economics. The effect of raw material price fluctuation however, did not influence plant economics significantly.

1. Introduction

The search for sustainable resources in modern industrial processes has guided the production of chemicals and fuels towards a biomass-based economy. As defined by European Commission, a biobased economy is dependent on "production paradigms that rely on biological processes and, as with natural ecosystems, use natural inputs, expend minimum amounts of energy and do not produce waste as all materials discarded by one process are inputs for another process and are reused in the ecosystem" (European Commission, 2011). Biorefineries are epitomized as the prime examples of biobased economy. Industrial waste streams that are generated from food processing industries may serve as readily available and cheaper resource for a biorefinery (Banerjee et al., 2016b; Singh et al., 2015). The success of a biorefinery model depends on the availability of the raw material, therefore, the search for the resources that are generated in large quantity becomes important.

Mangoes are one of the major agricultural commodities in tropical countries (NHB India, 2015). India ranks first among the world's mango producing countries. The production of fruit in India accounts for 52.6% of the global mango production (FAOSTAT, 2015). Mangoes are popular choices for processing because of their succulent taste, richness in carotenoids, ascorbic acid and a greater availability during the summer seasons (Gouado et al., 2007). The growing popularity of fresh and processed mango products may be estimated from the fact that India exported 36,000 tons of fresh mangoes and 129,000 tons of mango pulp during the year 2015–16 (APEDA, 2016). Processors purchase mango for the production of pulp from traders as well as mango growers. Totapuri mangoes are mainly used for preparing pulp because of its high pulp-yielding rate. Processing units purchase mangoes from market yards as they are assured of large quantities to run the unit continuously till the mango season is over (Banerjee and Arora, 2014).

Processing of mangoes leads to generation of 25–40% w/w of the fruit as waste (Banerjee et al., 2016a, 2016c). Peels are the major by-product of mango processing, which contains valuable nutrients such as polyphenols, pectin, sugars and natural pigments (Masibo and He, 2009). Pectin is a bioactive hydrocolloid that has major applications in food and pharmaceutical products (Rosaria et al., 2015). Mango peel polyphenols were explored in literature for potential applications such as antioxidant and preservatives. Mango peel fibres were found to a good source for soluble fibres, which later exhibited prebiotic property (Ajila et al., 2010a,b; Jahurul et al., 2015). The other methods of utilization of the peels may include livestock feed, biochar and preparation of composts. The utility of peels as livestock feed is limited by the presence of tannins, which may act as antinutrients and interfere in growth of the animal (Wadhwa and Bakshi, 2013). Mango kernels are

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mainly reported for the recovery of lipids and starch. Mango kernel lipids (contains about 9–13% of lipids on dry basis) were classified into neutral lipids (94%), phospholipids (4%) and glycolipids (2%) (Dhingra and Kapoor, 1985). The uniqueness of lipid composition was highlighted in many recent studies especially, the application of mango-kernel oil as cocoa–butter replacement (Lipp and Adam, 1998). Food industries, in particular, are searching for the cocoa–butter alternatives due to the high price and demand (Banerjee et al., 2016b). Mango-kernel oil contains significant quantities of linoleic acid (an omega-6 fatty acid) and small quantities of α-linolenic acid, which are essential fatty acids required in the human diet (Swanson et al., 2012). The mango processing waste is available as a local raw material in western part of India and rich in potential bioactive compounds. It may therefore, be utilized in a biorefinery model for the recovery of many valuable products. The examples of biomass, which have previously been demonstrated through techno-economic analysis in biorefinery models include wheat straw, palm waste, olive waste, camelina oil and likewise (Bals and Dale, 2012; Do et al., 2015; Mupondwa et al., 2016; Qureshi et al., 2013). An experimental approach to valorize the mango peels in a biorefinery model has recently been reported in literature (Banerjee et al., 2017). To the best of author's knowledge, a techno-economic evaluation to the valorization of mango processing waste has not been reported so far.

With emerging research trends in the production of bio-based products, the biorefinery concept will continue to gain momentum. In this study, a computer model simulation was developed to understand integrated process and economical implication of mango processing waste based biorefinery model. Only discrete lab studies are available in literature. Therefore, exhaustive set of experiments were conducted at lab scale for optimized product recovery (Banerjee et al., 2017). Models were developed using Superpro Designer 9.0 (Intelligent,Inc., Scotch Plains, NJ). Since there is no existing commercial plant, a lot of information has been taken from industry experts, mango processers, researchers and equipment suppliers of fruit processing companies. Sensitivity analyses was carried out to determine the variation in the Net Present Value (NPV), Internal rate of return (IRR) and pay back period (PBP) with the variables used in the economic analysis. Before the adoption of this laboratory based technology by processing plants, a techno-economic analysis is warranted to estimate the costs.

In a biorefinery, one of the most important determinants of success of a plant would be high quality and consistent supply of feedstock. It is also true, however, that biomass always carries inherent variability in chemical composition and how each component behaves in the process is fundamental to addressing the issues of variability. Many factors contribute to biomass compositional variability, and this variation can have a significant impact on the conversion of biomass to value-added products. The chemical properties of mango processing waste are primarily controlled by five key components: peel-seed ratio, pectin and cellulose content in peel, starch and oil content in seed kernel. An understanding of how pre and post harvesting operations and natural variability effect physical and chemical properties of the feedstock would help one develop strategies to sustainable extraction and production of high value products.

In India, there are more than 30 popular varieties of mangoes but when it comes to processing, there are only handful varieties that are preferred by the processing industries. More than 80% of mango processing market in India is contributed by Alphonso, Totapuri and Kesar varieties (APEDA, 2016). There are certain regions in India where a particular type of variety is processed at very large scale. For example, In Maharashtra State, processing of Alphonso variety is most popular, and Chittoor district of Andhra Pradesh, Totapuri variety is processed at very large scale. The unique selling point of the proposed biorefinery is that variation due to varietal differences could be avoided by decentralized approach of procurement of waste unlike agriculture residue biomass supply chain where feedstock is sourced from multiple locations and residues of multiple different crops. Procurement within 20 km radius of mango processing units ensures that mango processing waste would have similar traits. Even though procurement of raw material can happen from multiple suppliers, consistency of feedstock can be ensured by accepting only a single variety to minimize variations in chemical composition. The low variability in the unit value realization in case of mango pulp as against the unit value realization of mango fruits demands greater incentives for the processing sector. Standardization of raw material quality is possible with mango processing waste because top grade mangoes are procured by mango processing units and they need to pass stringent quality criteria before they can be pulped for export purpose. This was evaluated during survey of 10 processing units within 20 km radius and it was observed that 8 units were processing same variety of mango for pulping and canning. Samples were collected from processing units and chemical composition was analyzed and representative values were used in the model development. The compositions of the mango processing waste for both varieties are provided in supplementary data (Tables S1–S3). Large processing units are encouraging contract farming in India where in companies can be sure of receiving good quality raw material and farmers have the assurance of a complete buy-back from the company. In our personal communication with processing unit personnel, it was brought out that up to 10% compositional variability cannot be ruled out in a given season. Natural variability in the fruit within same variety has been considered in this work. Given the quantum and concentration of Alphonso and Totapuri varieties of mango in specific regions, we have analyzed their processing waste in this study. For this study, we have taken 30% peels, 47% kernel and 23% seed coat based on mass balance and chemical composition analysis (Tables S1–S3). Based on compositional analysis data, 26% pectin (d.b) and 0.8% polyphenols (d.b) were assumed in peels. Likewise, 55% starch (d.b) and 12% oil (d.b) were assumed to be present in seed kernel. Techno-economic implications associated with the variability of raw material attributes are discussed in the sensitivity analysis.

2. Methods

2.1. Scenario selection

The size of biorefinery should be feasible with typical mango processing waste generated in a region and within a realistic collection area. For this model we assumed collection of mango processing waste within 20 km radius of the facility.

2.2. Process design

Except composting and biogas generation, there is no commercial facility for valorization of mango processing waste into value added products. However, there are studies available for separation of individual components such as mango seed oil, pectin and total polyphenols (Ajila et al., 2010a,b; Banerjee et al., 2016c; Jahurul et al., 2013). An integrated approach has been developed in our laboratory to recover and purify valuable products from mango processing waste (Banerjee et al., 2016a, Banerjee et al., 2016c, Banerjee et al., 2017). Feedstock availability in large quantity is feasible when proposed plant is located within 20–30 km radius of pulping facilities (Mupondwa et al., 2016).

In Indian context, if we consider large mango processing units, they process between 60,000–100,000 tons of mangoes in 3–4 months which essentially means that each plant products about 25,000–40,000 tons of waste in 90–120 days of operation. Average pulping waste collected from a medium scale mango processing industry is about 50–100 tons/day (Banerjee, 2011). Some regions have more than 10 units within 20–30 km radius. Therefore, collection of even 500–1000 tons waste/day is feasible in Indian context. Our assumption therefore, is to take lower side of the processing capacity for a biorefinery plant so that supply chain remains feasible for smooth plant operations.