Densified Mango Residues as Biofuel from Low-Resource Agricultural Processing

Christopher R. Rumple, Siri Maley, and Khanjan Mehta
Humanitarian Engineering and Social Entrepreneurship (HESE) Program
School of Engineering Design, Technology & Professional Programs
The Pennsylvania State University
University Park, USA

Abstract—**Producing biofuels, bio-power, or other bio-products depends on supply systems that can ensure high-volume, reliable, environmentally sustainable, and on-spec availability of source feedstocks. Implementing these recycling and repurposing systems can lead to more ecologically and financially sustainable supply chains and business, but this endeavor is particularly complicated for small businesses in underdeveloped areas. This article examines the role of biomass and biofuel in the potential scalability of small businesses in underserved regions. It includes a discussion of potential benefits and applications, with emphasis on densified biowaste and Organic Rankine Cycle turbo-generators. The article's case study occurs in Sierra Leone, which has an abundance of potential biomass resources—specifically mango—but where local facilities that do not widely utilize biowaste. This case study assessed the waste stream of a local Sierra Leonean fruit processing facility as a potential densified biofuel feedstock source. Using only low-resource and low-capital materials, freshly processed refuse was sampled and densified for industry-standard fuel properties. The results of this study indicate that the low-resource formulation of mixed feedstocks from niche high-production crops can still meet industry standards as an Organic Rankine Cycle biomass heat source for electrical energy production.**

Keywords — biofuel, biomass, food value chain, Sierra Leone

I. Introduction

Global fruit and vegetable production reached 1.34 billion metric tonnes in 2003, up from 396 million in 1961 [1]. Most of the related processing facilities are located in developing countries, and many lack sufficient waste management infrastructure to effectively repurpose biomass refuse. In fact, fruit processing plants must often dispose of their own waste directly, and yet there is no modern industry standard for the sustainable management of leftover fruit residues. Many of these businesses end up simply setting refuse alight and then burying the remaining ash, a combustion process that does nothing to harvest additional energy. Failure to harness this combustion (which naturally occurs during decomposition) means additional greenhouse gas emissions that contribute to worldwide atmospheric perturbations [2].

Notwithstanding current shortfalls in the industry, some national and international efforts have pursued sustainable biomass recycling. Starting most notably at the 1992 United Nations Conference on Environment and Development, 178 world governments agreed upon the need for sustainable municipal solid waste management, including maximizing environmentally sound reuse and recycling [3]. To that end, some countries have built infrastructure to champion carbon-neutral energy production with biomass waste. Thailand is among the industry leaders, yet even in such a major agricultural exporter—where biomass generates over 1700 MW versus barely 100 MW for solar, wind, and hydroelectric combined [4]—biomass only represented 3.5% of Thailand's total power production in 2011 [5]. In contrast, estimates predict that biomass *could* provide up to 25% of the country's primary energy demand [4]. The situation in China is similar, where 850 million tonnes of agricultural residue is available annually, of which 500 million tonnes could readily be used as an energy source. Yet less than half that available amount is used effectively, currently just 240 million tonnes [6].

The biofuel industry faces a number of obstacles to growth, many involving lack of infrastructure, but also lack of clear economic potential and feasibility. Closing this knowledge deficit and developing viable biofuel ventures requires better characterization of real densified biowaste in low-resource contexts [7]. This information can then be used to model energy conversion processes, establish return-on-investment calculations, and expand business models. The authors begin this process for mango residue by examining a particular fruit processing plant, Africa Felix Juice in Sierra Leone. Sections II and III of this article discuss the production and use of biowaste in Africa Felix Juice's plant and similar low-resource contexts. Section IV presents a literature review specifically for densified biofuels. The rest of the paper then recounts the authors' new study to characterize locally sourced mango biomass that is densified using only low-infrastructure technologies.

II. Biomass in Sustainable Supply Chains

Across the world, producers and consumers waste or lose 650 million tonnes of fruit, vegetable, and root crops per year. Though losses occur for many different reasons, in developing countries, causes are concentrated in the farming and storage phases of the food value chain [8]. This is because many agricultural efforts in underserved areas lack the financial and technical infrastructure to put harvested crops to use. The mango is a prime example of this problem, as it is world's principal tropical fruit and is not labor-intensive [9]. In many tropical areas, mangos grow freely and require no farmer intervention to produce regular yields. In 2013, Sierra Leone produced 23.4 thousand tonnes of the crop, a supply that far exceeded immediate local demand [10]. For that reason, many mangos are left to rot under their trees even as import demand in Europe and the United States rises at a ten-year forecast of 9.7% as of 2010 [9].

Africa Felix Juice (AFJ) is among a few enterprising businesses in Sierra Leone working to reduce food waste from locally abundant tropical fruits [11]. The company collects and juices mangos that would otherwise rot. The juice is then exported overseas, primarily to Europe. Fig. 1 provides a diagram of these interconnected food and energy value chains. AFJ's current chain is shown in green along the top, with a normal progression through farming, harvesting, collection, juicing and then transportation to export markets. Currently, the resulting biowaste is dumped or burned. Alternatively, this fruit waste might be densified (turned to pellets with higher energy density) and either combusted for heat in cooking, etc, or for electrical power production. Electrical power can be produced via an Organic Rankine Cycle turbo-generator as illustrated in Fig. 2 and can subsequently be used to power the factory's juicing operations. At large scales or from combined facilities, excess power might be available for resale.

As a company, AFJ is aware of its potential benefits and wants to recycle biowaste for both environmental and economic reasons. Despite their interest though, there is little guidance or precedent for sustainable recycling within local infrastructure and capital constraints. Thus, like many facilities, AFJ currently burns and buries biomass residues without attempting to harness any energy. Fig. 3 shows how much biomass is wasted in just one load from AFJ. This constant waste has also become a major barrier to AFJ's scalability, as its loan proposal to the World Bank was denied on these environmental grounds.

The World Bank, the International Finance Corporation (IFC), and all of the four of the world's main regional multilateral development banks have requirements that align with the United Nations seventh Millennium Development Goal: ensuring environmental sustainability [12, 13, 14, 15, 16, 17]. All organizations including small and medium-sized enterprises (SMEs) must undergo a variety of environmental assessment procedures in order to receive loans. Though results are evaluated on a case-by-case basis, waste management and recycling is a core concern.

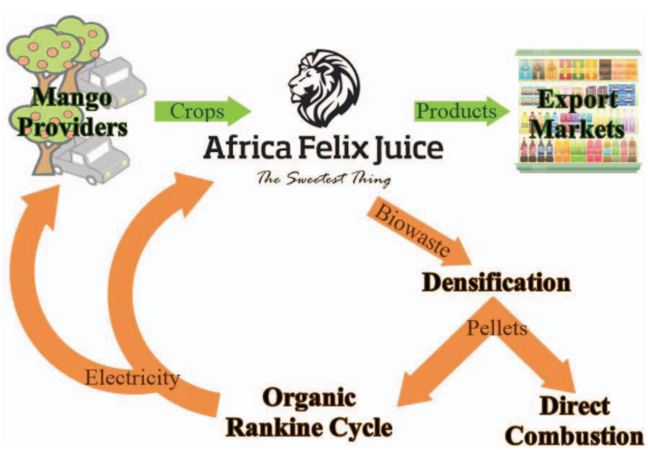

Fig. 1. Agricultural processing facilities like AFJ produce biowaste in addition to food value. Introducting biowaste densification can recycle this waste back into the factory and/or community as direct heating or electrical energy.

Fortunately, a number of competing markets have developed in the field of agricultural refuse recycling. Cereal, fruit, and vegetable byproducts can be and are used as livestock feed. Mango products have several advantages in this regard, but other aspects of their chemistry limit maximum concentrations. Mango peels are have little protein and must be post-processed and/or mixed with other feeds for most animals. Mango seeds are high in tannin, which depresses feed intake and growth in popular livestock species [18]. Both residues also require considerable time to decompose for soil compost. In higher-resource settings, post-processed peels may provide dietary fiber and other health benefits to humans [18, 19]. Chemically modified waste can also be useful in the paper and textile industries [20], but low-infrastructure settings preclude such uses. Among the most popular application in both high- and low-technology infrastructure, however, is the production of biofuels.

The biofuel industry benefits from many diverse research initiatives on scales ranging from high-technology industries to low-capital domestic use. The ultimate goal of this article's research vein is to develop one or more generalizable and scalable biofuel production systems that directly complement the needs and resources of SME tropical fruit-processing plants in developing countries. Such production platforms could then be packaged into efforts to establish or upgrade processing plants, making their businesses more environmentally and economically sustainable. These combined processing and biofuel plants would be able to apply for multilateral development bank loans and use or sell their own energy in addition to recycling their waste. Tropical Food Machinery (TFM), a multinational company that specializes in building fruit-processing plants in developing countries, also reports that successful processing plants bring tertiary benefits to local economies. Benefits have included increased farming, higher direct and indirect employment, and better access to capital for the community [11]. Husk Power Systems, which uses rice husks to electrify remote villages, found similar results with their electrified villages. Farmers irrigated more land, students studied after dark, and residents experienced decreases in crime and snakebites [21].

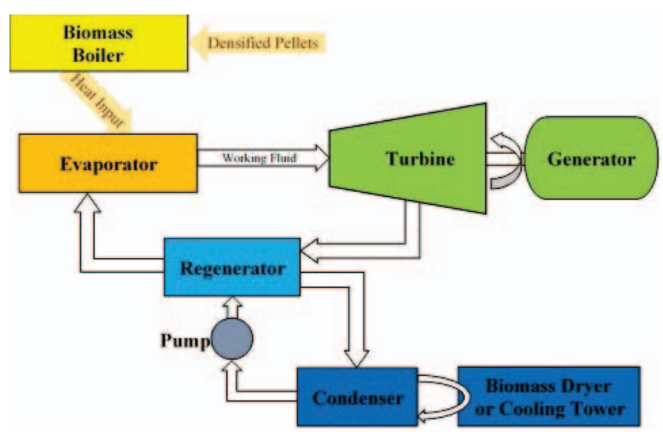

Fig. 2. The Organic Rakine Cycle uses an organic working fluid with a lower steam point than water, allowing the use of a lower-temperature heat source while trading off lower electrical efficiency. This fluid is vaporized and the expanding gas fed into a turbine whose mechanical motion turns an electrical generator.

III. BIOFUEL FOR RECYCLING IN LOW-RESOURCE PROCESSING CONTEXTS

There are a number of different mechanisms for producing liquid, gas, and solid biofuels from solid agricultural residues [22]. Fig. 4 provides a basic typology of biofuels along the spectra of complexity and energy density. A variety of other factors including daily yield and physical and chemical properties also dictate potential uses.

As a brief overview, liquid biofuels include bioalcohols and biodesiel, which are produced by fermentation and transesterification of agricultural waste, respectively. Popular gas biofuels include syngas produced by partial combustion and biogas by anaerobic digestion of agro-waste. In low-resource contexts, biogas is by far the most popular of these four types. Biogas digesters are already desirable status symbol among Indian farmers [23]. In these cases, biogas is largely confined to small digesters used for domestic cooking and lighting, though some larger biogas plants use the fuel for their own engines and equipment [23]. In addition, researchers have characterized both bioethanol from mango peel [24, 25] and biodiesel from mango seed oil [26].

In contrast to the liquid and gas counterparts, solid biofuels are primarily gradated by their volatile matter content. At the low end are the raw feedstocks followed by densified briquettes and pellets. Mild pyrolysis removes some volatiles during torrefaction, and removal increases through full carbonization (e.g. charcoal). Though solid fuels are made from a variety of biomass sources, some characterization has been conducted based on agro-waste sources [27, 28]. This article will conduct a similar characterization of densified mango residue, except with the densification conducted using low-resource materials that can be sourced and scaled by the processing plant.

While densified biowaste is most readily used for heat (e.g. cooking), Organic Rankine Cycles (ORCs), as shown in Fig. 2, greatly expand their value to include reliable electrical energy production. The scalability of these ORC systems means that businesses can realize electrical energy savings with relatively low capital investments and reinvest cost savings into their businesses. As these ventures increase capacity, they can also scale their ORC's biomass throughput. Sufficiently large ventures can approach self-sufficient energy production or even over-production for resale. Alternatively, the fruit processor could sell the densified waste to a third-party ORC facility; this is valuable because on-site densification is far more efficient for transport. Regardless, all potential ORC production depends both on the biomass throughput a venture can source and on the characteristics of its processed biowaste, as examined hereafter.

Fig. 3. Mango biomass waste left over from Africa Felix Juice's production in Sierra Leone (10 tonnes daily). The residue is burned and buried for disposal.

IV. PREVIOUS STUDIES OF DENSIFIED BIOFUELS

While biomass is a readily available waste product in many agricultural areas, solid biofuel sources have their own challenges. The high moisture content, irregular shapes and sizes, and low bulk density of most biowaste makes it very difficult to transport, store, and utilize in raw form. Densifying these feedstocks into pellets or briquettes is thus useful for both fuel and logistical reasons [29]. The quality of the resulting pellets depends upon several parameters: ground particle size, moisture content, binding mechanisms, and temperature and forming pressure during densification. On the output side, the most notable metric for a densified pellet's economic significance is its net energy content after densification.

When considering pellet quality, binding phenomena are critical for good densification. Small particle size is a key factor here, as smaller particles have greater contact surface area [30]. Additionally, high forming pressures are crucial for binding as they force natural binding compounds such as starch, protein, lignin, and pectin out of the individual feedstock particles [29]. Forming pressures required for this interlocking reportedly start at 100-200 MPa and continue upward [31, 32, 33, 34, 35]. This also means that a high ratio of these natural binders in the feedstock will improve pellet quality [29, 31, 36]. Finally, pre-densification moisture content is also critical to binding. High-quality densification binding relies on a moisture content of 5-12% by [37] or 8-12 % by [29] w.b. (wet basis) relative to weight.

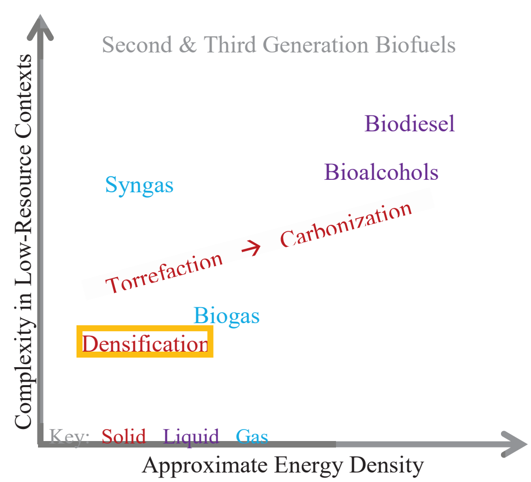

Fig. 4. Basic chart of select biofuel types comparing general production complexity to output energy density. Other factors including overall yield and output form also dictate usage. [27, 39, 40, 41, 42].

Assessing the literature on mango residues against densification standards yields promising insights. Mango seeds in particular have a high starch content at 18% w.b. [38]. In addition, the caloric content of mango waste (rind and stone) demonstrates an energy content – a high heating value (HHV) of 5.2 kWh/kg reported by [43] – comparable with other industry feedstocks like olive husk, walnut, hazelnut, sunflower, and almond shells. These sources all range between 4.58 kWh/kg and 5.83 kWh/kg HHW [44] .

V. METHODOLOGY

This study aims to assess the feasibility of using low-resource densified mango waste from fruit processing plants as a transportable combustion source for energy production elsewhere either off- or on-site. In particular, it assesses if mango refuse can bind effectively into briquettes and whether tested caloric values compare with standard feedstocks, all while using minimal capital and infrastructure.

A. *Feedstock Sources*

In Sierra Leone, mango biomass was collected locally and seed, endocarp, and exocarp were extracted. Endocarp was manually de-seeded with shears.

B. *Equiptment Description*

A simple food processor was used for grinding, an oven for drying, and a heating iron for humidification prior to densification. A 12-ton press (Central Hydraulics Model: 33497) and hand-fabricated die were used for densification. The die consisted of a 1.5 inch cylinder diameter that the press' piston fitted concentrically flush with. Bomb calorimetry was performed by BARROW-AGEE LABORATORIES, LLC in orderr to analyze caloric and moisture content.

C. *Preprocessing (Grinding, drying, and milling)*

Endocarp was physically cut into small strips no larger than 1 cm by 4 cm. Seed, rind, and endocarp were dried in a convection oven as the moisture content of the raw mango

Fig. 5. 12-ton press used to compact mango feedstock. Plastic bags tightened the tolerance between the die and piston, enabling higher pressures.

feedstock exceeds 60% w.b. [43]. The dried components were then placed together to be milled via food processor into fine particles, as seen in Fig. 6. The biomass material and the densification die were heated to 93 degrees Celsius prior to densification. Ground biomass was then pretreated with steam to appropriately replace moisture lost during preheating. This combination of heating and steaming results in optimal moisture content and temperature for high-pressure densification binding processes [29].

D. *Densification*

After heating and steam treating, the densification die and biomass were place under the piston of a 12-ton press as seen in Fig. 5. Compressive pressures were calculated in excess of 700 MPa with respect to the die cross-section.

E. *Post-Processing*

The individual density of mango briquettes was measured using oven-dried samples: samples were dried until no further measurable changes in mass were detected. Density was calculated by a crude method of dividing briquette mass by geometric volume.

VI. TEST RESULTS

E. *Processing Facility Survey*

The African Felix Juice facility in Sierra Leone was surveyed to determine its current processing and waste disposal strategies. As of 2014, the plant had a waste stream of 10 tonnes

Fig. 6. Mango waste – mango seed, endocarp, and rind – reduce to a fine particles by the high shear stresses of spinning processor blades.

Fig. 7. Cylindrical shaped briquettes produced via densification with a die and a 12-ton press. Biomass material was pre-heated to 93 degrees Celcius with steam prior to densification. Experiment indicates that mango waste to be compliant during densification, as shown.

daily with a projected increase to 30 tonnes daily in 5 years. Residues are disposed of in municipal dumps or are burned with an accelerant purely as a means of disposal before burial.

E. Densification Results

The density of the mango pellet—mango rind, endocarp, and seed—was found to be near 775 kg/m^3 after densification. A heat of combustion of 4.10 kWh/kg at a moisture content of 11.7% w.b. was determined through bomb calorimeter testing. Densification experiment was only conducted once to yield two densified specimens seen in Fig. 7.

VII. CONCLUSION

Preliminary results in the low-resource densification of mango residues demonstrate that appropriate forming pressures, moisture contents, and heats of combustion can be achieved with minimal equipment yet in line with reported standards. The 12-ton press achieved forming pressures of 700MPa, well above the minimum 100-200 MPa reported. A moisture content of 11.7% is high but still within the 5- or 8-12% suitable range. Most notably, the bomb calorimeter tests demonstrated a heat of combustion of 4.10 kWh/kg at 11.7% w.b., which is comparable both to the reported value for mango residue (HHV 5.2 kWh/kg) and to other industry feedstocks [43]. Initial calculations estimate that this average energy density from a daily throughput of 10 tonnes would yield just over 400 kW from an ORC turbo-generator sustained for an 8-hour period each day [44]. These calculations can be elaborated as further research characterizes production variances and losses. Additional studies could also examine overall energy use including the growth of various biofuel sources.

The preliminary test results of low-resource mango seed and rind densification show promising thermal caloric values for energy production (heat or electrical energy). With appropriate scaling and support, commercial ORC turbo-generators (Turboden s.r.l.) can help underserved agricultural economies approach carbon-neutral power production. Locally sourced biowaste also shortens and closes rural and small business supply chains, is another potential benefit over fossil fuels. All told, future studies would benefit from examining the potential for environmentally and economically sustainable biowaste densification and ORC electrical power production in underserved and low-capital small businesses.

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