http://doi.org/10.1002/bbb.1433

McHenry, M.P., Doepel, D. and de Boer, K. (2013) Rural African renewable fuels and fridges: cassava waste for bioethanol, with stillage mixed with manure for biogas digestion for application with dual-fuel absorption refrigeration. Biofuels, Bioproducts and Biorefining, 8 (1). pp. 103-113.

http://researchrepository.murdoch.edu.a/16187/

Full Title: Rural African renewable fuels and fridges: cassava waste for bioethanol, with stillage mixed with manure for biogas digestion for application with dual-fuel absorption refrigeration.

Short Title: Rural African cassava waste for bioethanol and biogas for refrigeration.

Authors: M P McHenry, D Doepel, K de Boer.

Biofuels, Bioproducts, & Biorefining

The growth and processing of cassava (*Manihot esculenta*) in Africa produces a range of waste streams which are proving problematic due to their current mismanagement. Although a range of technical solutions exist to convert these waste streams into valuable products there has been very little progress made in applying these solutions. This review provides a broad picture of the cassava waste issue in the context of African agriculture and bio-processing. As an outcome of the review process the authors propose a simple and scalable two-step process that biologically converts the waste streams into valuable products. The first step in the process is fermentation and distillation of the cassava waste to produce ethanol. The second step is the anaerobic digestion of the fermentation byproducts with other waste streams including animal manure and human excrement to produce biogas and biological fertilisers. Despite the scalability of this system, the focus of this paper is the development of a conceptual system for rural smallholders to achieve multiple beneficial outcomes including: treatment of multiple troublesome waste streams, production of a liquid biofuel, the provision of refrigeration through biogas powered absorption chillers and the co-production of organic fertilisers.

Keywords: Cassava; bioethanol; biogas; waste; sub-Saharan Africa.

Introduction

Rural agricultural production is a livelihood that directly engages most of the population in sub-Saharan Africa,[1] and new technology and institutional capacity will likely underpin transformation in the sector.[2] In parallel, around 70% of African nations are dependent on energy imports, predominantly liquid fuels, making domestically produced biofuels an attractive option, particularly to stimulate employment and wider economic benefits.[3,4] Alternative energy sources are necessary for various reasons, including strategic energy security and also fiscal stability.[4] Unfortunately, sub-Saharan Africa suffers from a combined effect of declining value of their export (primarily agricultural products), and the loss of market share to competitors.[3] Thus, a major challenge is adding value to existing domestic production, and cost-effectively securing domestic energy supplies while stimulating small-scale agricultural system productivity.[1] Parallel sustainable energy development and agricultural productivity gains are fundamental to rural development goals, and great attention is needed to successfully link existing crop production requirements with processes and technologies that best fit local social, economic, and ecological needs.[1, 3]

Current biofuel support policies remain a concern in relation to sub-Saharan implementation.[3,5] Bioenergy and food security have been presented as mutually incompatible, and in direct competition for land and other inputs rather than a rural development opportunity.[5,6] There is the logical fear that growth in first generation biofuels will increase the price of food in sub-Saharan Africa,[1,6-8] and it will be prudent that biofuel feedstocks do not contribute to land or food insecurity.[8] In general, however, sub-Saharan African food insecurity persists due to poverty, inadequate agricultural infrastructure and services, degraded lands, armed conflict, and poor records of attracting international investment.[5] It is possible that suitable biofuel programs can boost agricultural productivity through new investment. This may also reduce fuel imports, and as a result improve food and energy security, and financial stability from improved balance of payments in relation to mineral oil imports.[3,8] However, there is commonly a loss of comprehension regarding the average local capacity within the rural landscape in sub-Saharan Africa. Over 80% (~642 million) of Africans live in sub-Saharan Africa,[3] and more than half of all sub-Saharan Africans live in rural areas.[9] Large, advanced, and capital-intensive agricultural machinery for planting, maintaining, harvesting, and processing crops does not exist within the vast majority of sub-Saharan African operations at present.[7] Furthermore, it is no longer possible to meet the needs of a growing African population by simply expanding the total area under cultivation, and improved resource efficiency and new crop varieties are required.[10] There is also an increasing trend for urbanisation,[11] and the growth in economic importance of non-farm incomes in rural areas.[12] Therefore, enabling innovative bio-based solutions that are technically feasible, profitable, ecologically sound, and appropriately scaled for each unique local area, remains a considerable challenge and opportunity.[1] With targeted technological and knowledge inputs, local landholders have the potential to increase their incomes through new markets for products that are often unutilised, or with a currently low value, i.e. wastes.[7] Nonetheless, the impact of bioenergy on food insecurity, poverty, and underutilised lands is dependent on local characteristics including crop species, lands used and available, technologies employed, and the influence of the bioenergy supply chain on existing agricultural systems.[5,13-16]

This research considers new applications for cassava (*Manihot esculenta*), a high calorific food that is the staple for 500 million people in the humid tropics, and the third largest carbohydrate source consumed by humans globally.[6] Fresh cassava tubers have around 20-30% starch, and 1% ash content, the remaining being mostly water, upon drying (typically down to 14% moisture) the starch content can increases to approximately 70-85%.[6,17] The high proportion and excellent quality of this starch is the reason why cassava is a staple food in Africa and commonly a source of industrial starch in Asia. The production of food grade and industrial starch results in the production of waste streams that include cassava peels, processing pulp (containing in un-hydrolysed starch), starch residues, and effluent water.[18] There is a growing need to reduce the level of cassava waste and effluent dumped in drains, rivers, and soils, causing odour and environmental contamination.[19]

Governments are aware of the need to curtail cassava processing waste, yet are sensitive to the economic costs involved in waste reduction (as cassava processors state that the capital cost of cassava waste treatment is around 20-50% of the total cost of the entire processing factory).[18] To overcome this barrier it is necessary to convert cassava processing waste streams into valuable byproducts that generate new industrial-scale and small-scale opportunities for entrepreneurial locals. Options for cassava processing waste streams include livestock feed both fresh and dried, silage, bioethanol production, biogas production, or even a source of bioplastics.[1,18,20] The focus in this review is on the use of cassava processing wastes for the production of bioethanol and biogas as these two methodologies are well proven technically and commercially at a wide range of production scales. The objectives of this research are to propose a simple and scalable two-step process for conversion of various waste streams into valuable products by assessing small-scale fermentation and distillation to produce ethanol, and anaerobic digestion of fermentation byproducts with other waste streams to produce biogas and biological fertiliser.

Smallholder cassava production, and new bioenergy technology and development

Sub-Saharan Africa is a major producer of cassava, and Nigeria alone produces 18% of total global production.[6] Cassava is currently grown in the region with low inputs (both fertiliser and labour) relative to other crops such as maize,[7,19] and the region has the agro-ecological capacity to produce more food (and bioenergy) than it currently requires to satisfy demand.[5] Cassava does not need to be harvested at a particular point in the plants maturity and can remain in the soil to reduce spoilage.[6,18,19,21] In general, root crops like cassava can be left in situ until needed and give producers some flexibility in reducing losses by small-scale continuous harvests, although in practice producers often need to harvest to plant another crop as cassava occupies the field for a very long period relative to other crop growing seasons.[18,21] Cassava is also a rain-fed crop and does not require expensive irrigation infrastructure.[22] The abiotic advantages of cassava cultivation in the region contrast against growing biotic concerns such as weeds, African cassava mosaic virus, and poor planting/varietal availability, alongside socio-economic and management related deficiencies.[21] Yet, at present in many regions the dominant cassava production constraints (neither abiotic or biotic), with the lack of finance availability, lack of policy support for the crop, and the lack of a stable market are major barriers to expansion and commercial production.[18,21]

There is a growing concern that where cassava is a staple food and a major crop, industrial-scale bioethanol produced from food-grade cassava may compromise subsistence livelihoods and regional food security.[7] Around half of the total cassava produced globally is used for human food, with around one quarter for animal feed and seed, and the remainder used for various industrial processes.[6] Larger cassava processors (including food-grade processors) generate large quantities of pulp waste from cassava starch processing. This pulp waste contains around 20% of the original root mass on a dry basis.[18] Other cassava processing wastes include peelings from initial processing, fibrous pulpy byproducts from crushing and sieving, starch residues after settling, and the associated decaying wastes are commonly dumped in drains, rivers, and land, causing odour, health concerns, and environmental contamination.[18,19] As cassava and cassava waste exhibits poor post-harvest storage capacity and deteriorates within days to a week, technologies that add value to these wastes are necessary to reduce the economic losses, in addition to minimise aesthetic, health, and environmental concerns.[6,18]

Creative value-adding of cassava waste byproducts is preferable in reducing cassava-related pollution.[19] As smallholder and industrially produced cassava and cassava waste is produced and available year-round in many regions,[6] sub-Saharan African smallholders are likely to play a crucial role in both cost-effective processing and transporting sufficient cassava and cassava waste feedstock at scales sufficient to supply the growing number of cassava bioethanol plants.[7] In addition to industrial-scale bioethanol, there is an opportunity for using cassava wastes in smallholder bioethanol production for liquid fuels, and the subsequent use of the stillage in small biodigesters to produce biogas, both of which have numerous domestic applications including as inputs for heat absorption refrigeration. At the industrial scale, industrial waste-to-energy options include cassava processors using their wastes to provide input energy for processing operations and also cooled storage of cassava marketable product. As in theory the value chain and technology are scalable from industrial down to the smallholder, there are several flexible options where rural areas may adopt cassava waste-to-energy technologies as an input into agricultural systems, and increase local energy service provision. To understand the application of the two step process it is necessary to first review the current status of ethanol and biogas in sub-Saharan Africa.

Sub-Saharan bioethanol production and cassava bioethanol

Bioethanol (ethyl alcohol) is produced by the biological fermentation of organic feedstocks that contain high levels of sugars, or that can be converted into sugars.[8,23-28] Bioethanol production methods are numerous, and use a diverse range of feedstocks, providing some operational flexibility.[8, 25-27, 29, 30] In general, bioethanol production is a three step process: the first step is a pre-treatment that either releases sugars or converts the feedstock into fermentable sugars; the second step is fermentation of these sugars into ethanol, and; the final step is purification via distillation.[8] There are also three major bioethanol feedstock classifications: lignocellulosic-based feedstocks (wood, straw, grass); sucrose-based (sugar beet, sweet sorghum, sugarcane), and; starchy materials (wheat, corn, barley, cassava).[23,25-27,30,31] (See Table 1 for a comparison of approximate yield, conversion rates, and potential bioethanol production from major global feedstocks). Cassava is a low-cost starchy bioethanol feedstock, and the Empresa Brasileira de Pesquisa Agropecuária/Brazilian Enterprise for Agricultural Research (EMBRAPA) have bred cultivars with higher sugar contents specifically for improved bioethanol production yields.[1] While large-scale bioenergy production systems are not yet widespread in sub-Saharan Africa,[32] they are not a new concept and have proved quite promising in some sub-Saharan countries. For example, thirty years ago in 1982, Malawi started producing bioethanol using sugar wastes.[7] A major factor in developing the Malawian bioethanol industry was the reduction of the wastewater volumes from Malawian sugar processing.[4,7] At the time the bioethanol was used domestically to blend with petrol at a ratio of 1:9.[7,8] Malawi's 18 ML year^{-1} capacity Dwanga Estate Plant, and the 12 ML year^{-1} Nchalo bioethanol plants were constructed in 1982 and 2004, respectively.[4] Presently, the two Malawian private companies who own Dwanga and Nchalo (Ethanol Company of Malawi, and Press Cane, respectively) still produce 30 ML year^{-1} for blending with petrol imports (totalling ~90 ML year^{-1}).[7] Yet, Malawi was not the first, as in 1980, bioethanol production commenced in Zimbabwe using sugarcane and sugarcane molasses.[4] Zimbabwe's Triangle Ethanol Plant was built with 60% local content, including workers trained for the particular construction, leading to one of the lowest Capex per unit of facility output at the time (US$6.4 million in 1980 dollars, 120 kL day^{-1}).[3] The Triangle Ethanol Plant production has varied initially between 37.5 ML year^{-1}, and has reduced down to around 23 ML in 2004, and currently exports the total annual production of 30 ML to European markets.[4] For comparison, the estimated current Capex of a large modern (45 kL day^{-1} or ~12 ML year^{-1}) bioethanol plant in sub-Saharan Africa using a molasses feedstock, and constructed adjacent to a sugar factory will likely cost only US$3 million.[33]

Until recently, the vast majority of African bioethanol was primarily blended with petrol for domestic consumption.[8] Due to the increasing demand of mineral oil, bioethanol can now only replace a fraction of total of transport liquid fossil fuel demand.[4] Kenya, Sudan, and Uganda also established similar bioethanol blending programs, some of which survives today, and/or is being revived under various guises.[4,7,32,34] However, only Malawi and Zimbabwe have maintained the ability to support and operate industrial scale bioethanol facilities.[4,7,8,32] Nonetheless, bioethanol production programs in Malawi, Zimbabwe, and also Kenya were on the whole successful and sustained over some time, generating important local economic and environmental benefits.[32] In contrast, the processing of sugarcane molasses for bioethanol in Mozambique, Tanzania, Zambia, Angola, Egypt, and Ethiopia, endured numerous issues and required consistent government support.[4] While bioethanol production is usually supported by governments due to a combination of agricultural sector, energy security, and environmental benefits,[3] in practice biofuel subsidies and plant investments are often complicated financially due to variable subsidies and the common existence of concurrent subsidies of imported mineral oils, in addition to the associated price volatility of imports/exports.[32] Furthermore, the development of a biofuel industry in sub-Saharan Africa based primarily on exporting production to industrialised nations with strong biofuel demand risk becoming involved in complex, politically charged, highly regulated, protected, and subsidised international markets.[7] It is also difficult to project over time both the Capex and Opex of industrial-scale bioethanol production facilities in the region,[4] despite the installation and site work costs being generally minor cost components in sub-Saharan Africa.[33]

In general, global biofuel market fundamentals relate to bioethanol production efficiency, cost competitiveness with mineral oil prices, commercial viability of the production system, availability of biofuel distribution infrastructure, and the demand derived from ratios of ethanol blending.[34] Conventional sub-Saharan industrial-scale bioethanol production remains relatively stagnant in terms of new large facilities in operation.[8] However, the small country of Benin constructed a 3.8 ML $year^{-1}$ capacity bioethanol plant in 2002 that uses food-grade cassava (albeit from a large domestic production surplus) as the primary input feedstock.[4, 7] The system is able to produce 0.3 kg (~0.379 L) of ethanol per kg of fresh cassava. Bioethanol produced from fermenting and distilling cassava waste is suitable for blending with gasoline and conforms to the American Standard of Testing and Material (ASTM) quality controls.[19] The industry has major potential in cassava growing areas as cassava-based ethanol can be competitive in European biofuel markets, depending on import tariff barriers.[6] Nigeria is also known to have produced cassava ethanol at the smaller-scale, and numerous other countries in sub-Saharan Africa have likely some autonomously developed bioethanol systems using cassava, as it is common for cassava foods to be fermented. Research by Amigun et al (2008)[3] investigated optimum bioethanol plant sizing in Delta and Lagos, Nigeria. They found that the agricultural productivity of cassava had an influence in the optimal size of the plant, where lower productivity increased the total costs of using cassava to feed the plant.[3] While very small facilities are somewhat insulated from feedstock issues, large cassava bioethanol facilities in the region run the risk of being unable to procure sufficient feedstock throughout the year in areas where agricultural productivity and yields are low, leading to increased bioethanol production costs from longer transportation distances.[6] Therefore, it is in the best interest for a large biofuel producer to facilitate local cassava processors and producers to increase their productivity and reduce waste to minimise their cassava bioethanol operating costs. If well managed biofuel production facilities and feedstock production systems can operate profitably, they are likely to stimulate further development in the wider rural economy, and may allay fears of local food security, particularly if cassava wastes are used.[7]

Akin to many agricultural and rural sectors, industrial cassava bioethanol production and processing byproducts have the potential to stimulate the establishment of numerous small-scale commercial opportunities for entrepreneurial locals. For example, the wastewater and residues from cassava fermentation and distillation is known to be suitable for biodigestion, reducing the associated wastes of both cassava processing for food, and bioethanol production.[6] Cassava fermentation is a cheap detoxification process (decreasing levels of naturally occurring toxins) and also increases the final product protein content, improving suitability as a livestock feed.[18] However, further distillation for pure bioethanol is an energy-intensive process, and low-value combustible waste biomass or available waste-heat resources are commonly used.[35] Even in areas with a good solar resource in cassava producing regions (typically an average daily insolation of 6 kWh m^{-2}) most flat plate solar collectors are unable to attain sufficient temperatures for distillation of ethanol form ethanol-water solutions, particularly in low insolation seasons.[35] In contrast, solar evacuated tube collectors can be effective at generating the higher temperatures required for small-scale ethanol distillation, and commercial systems of ~1 m^3 are able distil between 10-20 L day^{-1} under optimal conditions.[36] As is standard practice, each renewable energy resource and enabling technology requires on-site assessment for suitability, and the scalability of each is of primary importance in cost minimisation. If the net cost of producing bioethanol is less than US$1 L^{-1}, there is much opportunity to displace existing liquid fuels in rural regions, particularly for major domestic needs such as cooking, lighting, and refrigeration using heat absorption in rural regions without affordable electricity availability.

[Insert Table 1 approximately here]

Biogas technology in rural areas

Anaerobic digestion of biological wastes to produce biogas is a method for ‘closing the loop’ in many food and bioenergy related bioindustries. The production of biogas through anaerobic digestion provides a low cost means of dealing with multiple high-nutrient liquid waste streams, while at the same time producing a valuable energy carrier and facilitating the cycling of nutrients from products back into agricultural cultivation. Increasing fuel costs is enhancing the appeal of anaerobic digestion technology for biogas production in both industrialised and non-industrialised nations, and at several scales of system operation.[39] Biogas is a flammable mixture of 50-80% CH_4, 15-45% CO_2, and other gases (1-2% H_2, 1-2% N_2, 0.3% H_20, and traces of H_2S), and is usually produced by organic digestion of biodegradable matter under anaerobic conditions with mixed microorganism populations.[39-41] Biogas is an odourless and colourless gas, which when ignited burns with a clear blue flame at around 650-750°C [42]. Biogas energy density is generally around 22,000-28,000 kJ m^{-3}, depending on the ratios of combustible gas in the total gas volume, which can be highly variable between seasons and technologies.[17] Simple anaerobic digesters are a traditional technology used to process wastes on a continual basis, and generally process a waste product in around 10-25 days.[18] Alongside biogas production, biodigesters accelerate the cycling of wastes and nutrients,[18,39] and the range of agricultural and domestic wastes suitable for biodigestion include, manure, vegetable waste, biodegradable municipal solid wastes, crop wastes, high-nutrient wastewater, twigs, leaves, (etc.) with most requiring minimal or no pre-processing.[41-45] In terms of application, biogas displaces cooking and industrial fuels, and in developing countries is commonly used to reduce the local demand for imported liquid fuels and local wood, reducing deforestation pressures.[3,45] At the non-industrial scale, biodigesters are a common option in rural and remote areas with little infrastructure,[39,45] and most of the several million small biodigesters in operation worldwide are household-scale systems.[45]

There are many indirect practical and economic benefits of biogas technologies in rural agricultural regions in developing countries.[45] Besides displacing wood demand and avoiding the associated need to collect wood, biogas emissions are lower relative to traditional fuels, reducing emission-related lung and eye disease, and also eliminating the need to clean solid fuel-derived particulates off cooking/lighting/appliances.[45] Increasingly expensive fertiliser costs have also increased the utility of digestion technology.[18,43] Biodigester output liquid and solid components contain plant growth regulators that can stimulate plant development, plant rooting, foliage development, flowering, and seed germination.[18] Biodigesters are also a safe and affordable means to treat human and animal faeces, reducing disease burdens, improving water quality, and as a consequence provides safer organic fertilisers to millions of people worldwide in addition to energy.[42] The digestion process does not kill 100% of pathogens, yet it does heavily reduce the faecal-water contamination disease burden from worms (hook, round, etc.), bacterial disease (typhoid, paratyphoid, dysentery, cholera), and viral infections (gastro-enteritis, hepatitis, etc.).[18,44,45] The majority do not have access to a quality operating toilets in many sub-Saharan African countries, and toilet facilities are able to be built into a biodigester design.[43] At present most biogas systems in sub-Saharan Africa are established as a human waste abatement need, with the ancillary benefits being largely incidental.[3] Several small-scale biogas programmes are in existence in Kenya, Rwanda, Burundi, Lesotho, and Benin, although sub-Saharan Africa does lag behind most developing countries in terms of biodigester technology implementation.[43,45]

Where cassava and biogas intersect

Biogas production converts 40-60% of dissolved organic matter into a combustible gas,[18,39] and thus can recover energy remaining in cassava waste post-bioethanol processing.[18] With a high C/N ratio of around 50:1, cassava does not easily produce biogas when unmixed in a biodigester (~0.6 L kg^{-1}, total solids, wet),[17,46] (Table 2), and it is common to add urea to increase N ratios.[17] Cassava peels and waste can either be mixed with manure for digestion directly, or can be fed to animals, and then used in the biodigester to effectively reduce cassava wastes and produce energy and fertiliser.[18] Research by Anunputtikul (2004)[17] found that 1 kg of dried and shredded cassava tubers (2.11 kg when fresh) could produce 235-497 L of biogas with 67.5 % CH_4 biogas under intensively monitored laboratory conditions (with a 5-20 L batch biodigester). However, simpler 'low-tech' single stage continuous biodigestion of cassava tubers can also yield biogas methane contents of 60-70%,[17,40] although at lower volumetric yields. Simple single-phase biodigesters using cassava yield low gas volumes due to low pH conditions caused by acid-forming bacteria, and pH must remain around neutral levels for higher volumes.[40] In these conditions sodium bicarbonate is commonly used to maintain the neutral pH in biodigesters to maximise gas production.[17,40] Alternatively, two-phase biodigester systems can be used separate out the acidification phase with the methanogenesis phase, also providing good pH buffering ability, which enables effective cassava biogas generation.[40]

[Insert Table 2 approximately here]

A two-stage bioethanol and biogas system

The excellent match between Africa's current situation and the benefits of both bioethanol and biogas production from cassava wastes lead the authors to the concept of a two stage process that firstly utilises the starch rich processing waste to produce bioethanol, and secondly uses bioethanol byproducts and other organic matter to produce biogas and recycle nutrients (Figure 1).[18,20,46] Bioethanol can be used in vehicles, cooking appliances and can also be traded both domestically and internationally. Biogas can be used for cooking, heating and also absorption based refrigeration. To improve the effectiveness of the anaerobic digestion (biogas producing process) the 'stillage' from the bioethanol production is required to be mixed with other agricultural wastes (manures, other biological wastes) to yield relatively high biogas volumes.[6] Thus, livestock availability is a key consideration for a successful biogas programme,[43] and several synergies exist. For example, the dairy sector in sub-Saharan Africa countries is generally a major (~10%) contributor to national GDP, underpinning rural economies and numerous livelihoods. Dairies that are off-grid still require a means to cool milk, which is currently expensive and commonly requires imported diesel fuel in internal combustion generators.[36] There is an enormous global demand for low-cost heat absorption refrigeration systems that can operate on a range of resources, including waste heat, solar, biogas, biomass, or even geothermal inputs.[47,48] Existing heat absorption fridges commonly operate on kerosene or LPG (frequently imported fuels derived from mineral oils), although can be adapted to run on biofuel/biogas.[42] Within the sub-Saharan context, bioenergy/biofuel production requires both a rural development focus and a commercial imperative.[7] Therefore, there is a great need for generating workable examples of technological and economic biofuel production and utilisation for smallholder sub-Saharan African conditions, enabling entrepreneurial and creative entities to adapt existing technologies for this unique socio-agricultural circumstance.[3,49]

[Insert Figure 1 approximately here]

Absorptive refrigeration and biofuels

There is a basic need for refrigeration for industrial, agricultural, and domestic applications, including for food and medicine.[36,45,47,48] Vapour-absorption refrigeration is generally used either when there is an excess of process heat at industrial scales, or where electricity is unreliable, or unavailable. These systems, often known as heat absorption fridges, commonly operate on liquid or gaseous fuels, and can be easily modified to run with biofuel and biogas.[39,42] Heat absorption refrigeration can produce chilled water from heat, and was displaced by electric-powered mechanical compression technology in industrialised nations only when electricity utilities began providing cheap and reliable electricity supplies.[39] The flexibility of heat absorption refrigeration systems operating on waste heat, solar, biogas, biomass, or even geothermal inputs remains an attractive technical option in off-grid areas.[39,47,48] Heat absorption refrigeration can use a range of heat carrier mediums, including hot water, steam, and combustion exhaust gas, and can also be air or water-cooled, and utilise several internal working fluids that undergo vapour-absorption including the common ammonia/water technology, and the water/lithium bromide, the latter being generally cheaper and operating at lower temperatures (75-120^{o}C).[39,48] While absorption refrigerators are generally more expensive than compression refrigeration, they are available in a range of technology types and scales between large commercial installations, and small portable products, and range in complexity from single to multiple-effect systems.[39,47] Solar thermal evacuated tube collectors, and also biodigesters have been analysed as a generation technology to couple with absorption refrigeration suitable for off-grid milk cooling in Uganda, with the solar collector the most cost-effective, and more cost-effective than a conventional diesel-powered system.[36] The volume and the characteristics of biogas for a particular custom heat absorption refrigeration systems requires detailed assessment for each system type.[39] Biogas consumption for heat absorption refrigeration generally requires between 0.6-1.2 m^3 per hour per m^3 of fridge capacity.[45,50] For example, a 300 L fridge will consume between 4.3-8.6 m^3 of average biogas per day. It is clear that the applications for heat absorption refrigeration in the agricultural value chain are enormous. In rural and remote off-grid regions, the need to store produce in cooler conditions is fundamental to reducing waste, and also enabling increased productivity above self-consumption levels through being able to safely store a marketable surplus.

Conceptual design of small scale two stage system

Assuming a conversion rate of 0.38 L (0.3 kg) of bioethanol per kg of fresh cassava, approximately 70% of the initial cassava biomass is available for digestion. Simple calculations using the conservative research findings from Adelekan (2012)[46] the resultant cassava waste of 0.7 kg when mixed at a 1:1 ratio with cattle manure in a biodigester would produce a biogas volume of 29.8 L per kg of fresh cassava when mixed with an appropriate volume of water (~1 L kg^{-1} of manure and cassava peel). Assuming an average biogas demand for a heat absorption fridge of between 0.6-1.2 m^3 per hour per m^3 of fridge capacity, based on research by Consolidated Management Services Nepal (1997) and United Nations (1984),[45,50] an average of between 48-96 kg of original fresh cassava is theoretically required for both use as bioethanol feedstock, with an equal volume of manure to produce sufficient biogas to operate a 100 L fridge (requiring between 1.4-2.9 m^3 of biogas per day). It is also common for biodigesters to produce around 1-4 times the biogas per unit of input than the conservative Adelekan (2012)[46] research. This simple calculation suggests that 18-36 L of bioethanol would theoretically be produced from the fresh cassava waste equivalent to the cassava stillage required to meet the theoretical daily heat absorption refrigeration demand when mixed with manure.

As the cost of cassava and manure waste is generally the cost of transport and collection, there is a high likelihood that using waste cassava for bioethanol is cost effective by itself when displacing liquid fuel demand such as kerosene or wood. When waste cassava from the ethanol production is combined with manure in a biodigester for a small-scale heat absorption refrigeration application, the resultant system has several potential agricultural productivity and domestic applications. This basic calculation suggests that a 6 m^3 biodigester will be able to produce the required biogas volume to operate a refrigeration unit of 100 L (as commonly biodigesters can produce around half of their rated volume per day in gas output, i.e. 6 m^3 can produce around 3 m^3 of biogas per day). The volume of the NPK equivalent fertiliser displacement was outside the scope of this work. Yet the value of the fertiliser and the reduced disease and pathogen burden in both humans and livestock is likely to be the most important commercial byproducts from the energy production system in rural areas, and requires additional research to quantify any benefit to agricultural productivity. A full net present value calculation of the entire Capex and Opex of the bioethanol brew and still, the biodigester, heat absorption refrigeration, and the resultant value of bioethanol, biogas, fertiliser, and ancillary cashflows will require site-specific primary data particular to each local rural economy and application.

Conclusion

There is growing pressure for African governments to improve food and land security, and biofuel policies are no exception.[8] At the industrial scale, the highly variable economic, political, and social environmental conditions at the international level are fundamental considerations in the selection of appropriate biofuel/bioenergy technology.[3] As landlocked countries have little opportunity to export volumetric agricultural products, they may fous on suitable biofuel feedstocks to increase national biofuel production.[33] Conversion of cassava waste to bioethanol coupled with digestion of excess fermentation and distillation wastes mixed with other local organic biomass resources may become a new area of interest with promising benefits.[51] In relation to the exceptional challenges faced in the sub-Saharan region, while the African agro-ecological complexity and mix of cropping systems are much overplayed, the challenges in relation to institutions, infrastructure, and markets are probably not.[52] In any case, locally derived and customised information will be essential to the development of feasibility studies in determining a realistic cost of developing rural bioenergy industries.[3] When the uncertainty of a bioenergy project capital costs are high, cautious investors are unlikely to fund them, and the reduction of uncertainty can enable a project to proceed.[33]

Despite the known challenges, the opportunity to both reduce post-harvest losses and the burden of cassava waste using small-scale conversion technologies to produce bioethanol and biogas may result in regionally-specific production benefits, even down to the level of the smallholder. The concomitant reduction in waste-related pathogen and pollution burdens, alongside increasing availability of cleaner cooking fuels and off-grid refrigeration can significantly improve food and energy security in rural sub-Saharan regions. If the numerous, yet disparate economic and industry development activities in progress within the region where cassava is commonly grown are able to collaborate to demonstrate the production stream in detail at the small-scale, artisanal biofuel production may eventually and incrementally improve agricultural productivity and food security as a consequence. This review suggests the potential role of bioethanol and biogas technologies as a simple, scalable, and profitable means of processing cassava waste. The authors have outlined the following requirements to further pursue this analysis: identification of the most suitable scale options for bioethanol/biogas systems for a selection of locations; identification and management of key technology adoption barriers; development of small-scale trial sites to generate real world technical and economic data, and; assessment of socio-economic appropriateness within the context of off-grid smallholder and householder needs and ability to operate/fund/maintain.

References

1. Langeveld JWA, Dixon J and Jaworski JF, Development perspectives of the biobased economy: a review. *Crop Sciences* **50**:S-142-S-151 (2010).
2. International Food Policy Research Institute, The future of small farms. Proceedings of a research workshop; 2005 26-29 June; Wye, UK.
3. Amigun B, Sigamoney R and von Blottnitz H, Commercialisation of biofuel industry in Africa: A review. *Renewable and Sustainable Energy Reviews* **12**:690-711 (2008).
4. Amigun B and Von Blottnitz H, Operating cost analysis of an annexed ethanol distillery in a rural, landlocked African Country. *Environmental Progress & Sustainable Energy* **30**(3):DIO:10.1002/ep (2011).
5. Lynd LR and Woods J, A new hope for Africa: Bioenergy could help bring food security to the world's poorest continent. *Nature* **474**:S20-S21 (2011).
6. Kuiper L, Ekmekci B, Hamelinck C, Hettinga W, Meyer S and Koop K, Bioethanol from cassava. Ecofys Netherlands BV, Utrecht, Netherlands (2007).
7. Jumbe CBL, Msiska FBM and Madjera M, Biofuels development in Sub-Saharan Africa: Are the policies conducive? *Energy Policy* **37**:4980-4986 (2009).
8. Deenanath ED, Iyuke S and Rumbold K, The bioethanol industry in sub-Saharan Africa: history, challenges, and prospects. *Journal of Biomedicine and Biotechnology* (doi:10.1155/2012/416491)(2012).
9. Rosegrant M, Ringler C and de Jong I, Irrigation: tapping potential. The Africa Infrastructure Country Diagnostic (AICD)/African Development Bank, (2009).

10. Asfaw S, Kassie M, Simtowe F and Lipper L, Poverty reduction effects from agricultural technology: a micro-evidence from Tanzania. Centre for the Study of African Economies; 2011; Oxford University, UK.
11. Opara UL, Editorial: the urgent need to transform small-scale subsistence farming in Africa towards sustainable agribusiness value-chains. *International Journal of Postharvest Technology and Innovation* **2**(2):115-119 (2011).
12. Start D, The rise and fall of the rural non-farm economy: poverty impacts and policy options. *Development and Policy Review* **19**(4):491-505 (2001).
13. McHenry MP, Agricultural bio-char production, renewable energy generation and farm carbon sequestration in WA: Certainty, uncertainty & risk. *Agriculture, Ecosystems and Environment* **129**:1–7 (2009).
14. McHenry MP, Australian carbon biosequestration and bioenergy policy co-evolution: mechanisms, mitigation, and convergence. *Australian Forestry Journal* **75**(2):901-913 (2012).
15. McHenry MP, How farming and forestry converge: enhancing the interface between agricultural production, and tree biomass/bioenergy systems to improve farm-scale productivity in Western Australia. In: Allard MC, editor. Bioenergy systems, biological sources and environmental impact. Hauppauge, New York, USA: Nova Science Publishers (2013).
16. McHenry MP, Practicalities of establishing forestry carbon sequestration projects in the agricultural sector: a technical and economic analysis with implications. In: Ryan BJ and Anderson DE, editors. Carbon sequestration: technology, measurement technologies and environmental effects. Hauppauge, New York, USA: Nova Science Publishers (2012).

17. Anunputtikul W and Rodtong S, Laboratory scale experiments for biogas production from cassava tubers. The Joint International Conference on Sustainable Energy and Environment (SEE); 1-3 December; Hua Hin, Thailand (2004).
18. Ubalua AO, Cassava wastes: treatment options and value addition alternatives. *African Journal of Biotechnology* **6**(18):2065-2073 (2007).
19. Aisien FA, Aguye MD and Aisien ET, Blending of ethanol produced from cassava waste water with gasoline as source of automobile fuel. *Electronic Journal of Environmental, Agricultural and Food Chemistry* **9**(5):946-950 (2010).
20. Kamukondiwa W, Alternative food crops to adapt to potential climatic change in southern Africa. *Climate Research* **6**:153-155 (1996).
21. Waddington SR, Li W, Dixon J, Hyman G and Carmen de Vicente M, Getting the focus right: production constraints for six major food crops in Asian and African farming systems. *Food Security* **2**:27-48 (2010).
22. Hoogeveen J, Faures J-M and van de Giessen N, Increased biofuel production in the coming decade: to what extent will it affect global freshwater resources? *Irrigation and Drainage* **58**:S148-S160 (2009).
23. Demirbas A, Progress and recent trends in biofuels. *Progress in Energy and Combustion Science* **33**:1-18 (2007).
24. Hankamer B, Lehr F, Rupprecht J, Mussgnug JH, Posten C and Kruse O, Photosynthetic biomass and H_2 production by green algae: from bioengineering to bioreactor scale-up. *Physiologia Plantarum* **131**:10-21 (2007).
25. Borines MG, McHenry MP and de Leon RL, Integrated macroalgae production for sustainable bioethanol, aquaculture and agriculture in Pacific island nations. *Biofuels, Bioproducts, and Biorefining* **5**(6):599-608 (2011).

26. Moheimani NR, McHenry MP, Mehrani P and Microalgae biodiesel and macroalgae bioethanol: the solar conversion challenge for industrial renewable fuels. In: Razeghifard R, editor. Natural and artificial photosynthesis: solar power as an energy source. Hoboken, New Jersey, USA: John Wiley & Sons Inc. (2013).
27. Borines MG, De Leon RL and McHenry MP, Bioethanol production from farming non-food macroalgae in Pacific island nations - Chemical constituents, bioethanol yields, and prospective species in the Philippines. *Renewable and Sustainable Energy Reviews* **15**(9):4432-4435 (2011).
28. Olugbenga AO and O II, Bioethanol production from brewer's spent grain, bread wastes and corn fiber. *African Journal of Food Science* **5**(3):148-155 (2011).
29. Yoosin S and Sorapipatana C, A Study of ethanol production cost for gasoline substitution in Thailand and its competitiveness. *Thammasat International Journal of Science and Technology* **12**:69-80 (2007).
30. Balat M, Balat H and Oz C, Progress in bioethanol processing. *Progress in Energy and Combustion Science* **34**:551-573 (2008).
31. Mussatto SI, Dragone G, Guimaraes PMR, Silva JPA, Carneiro LM, Roberto IC and Technological trends, global market, and challenges of bio-ethanol production. *Biotechnology Advances* **28**(6):817-830 (2010).
32. Karekezi S, Renewables in Africa - meeting the energy needs of the poor. African Energy Policy Research Network, Nairobi, Kenya (2001).
33. Amigun B and von Blottnitz H, Cost analyses and predictions for a fuel ethanol plant in a rural and landlocked African country: Lang factor approach. *International Journal of Production Economics* **119**:207-216 (2009).

34. Martinot E, Chaurey A, Lew D, Roberto Moreira J and Wamukonya N, Renewable energy markets in developing countries. *Annual Review of Energy and the Environment* **27**:309-348 (2002).

35. Jorapur RM and Rajvanshi A, Alcohol distillation by solar energy. *ISES Solar World Congress* **1**(2):772-777 (1991).

36. Kisaalita WS, Tippie A, Faircloth W, Franklin J and Boyer B, Comparative feasibility analyses of alternative renewable energy sources for small milk cooling plants of southwestern Uganda. *Agricultural Mechanization in Asia, Africa and Latin America* **37**(4):69-75 (2006).

37. Adams J, Gallagher J and Donnison I, Fermentation study on *Saccharina latissima* for bioethanol production considering variable pre-treatments. *Journal of Applied Phycology* **21**:569-574 (2009).

38. Mojovic M, Pejin D, Grujic O, Markov S, Pejin J, Vukasinovic, Nikolic S and Savic D, Progress in the production of bioethanol on starch-based feedstocks. *Chemical Industry & Chemical Engineering Quarterly* **15**(4):211-226 (2009).

39. Carles Bruno J, Ortega-López V and Coronas A, Integration of absorption cooling systems into micro gas turbine trigeneration systems using biogas: Case study of a sewage treatment plant. *Applied Energy* **86**:837-847 (2009).

40. Sirirote P, Thanaboripat D, Klinkroon N and Tripak S, The production of biogas from cassava tubers. *KMITL Science and Technology Journal* **10**(1):30-36 (2010).

41. Bajracharya TR, Dhungana A, Thapaliya N and Hamal G, Purification and compression of biogas: a research experience. *Journal of the Institute of Engineering* **7**(1):1-9 (2009).

42. Macharia D and Musungu WN, End user biogas manual. IT Power Eastern Africa, Woodvale Groove, Westlands, Nairobi, Kenya (2008).

43. Huba E-M, Fall P, Sanogo O, Kaboré G and Bracken P, Feasibility study of a national domestic biogas programme in Burkina Faso. Deutsche Gesellschaft fur Technische Zusammenarbeit (2007).
44. Barnett A, Pyle L and Subramanian SK, Biogas technology in the third world: a multidisciplinary review. International Development Research Centre, Ottawa, Canada (1978).
45. Consolidated Management Services Nepal, Session two: relevance of biogas technology to Nepal. FAO/TCP/NEP, (1997).
46. Adelekan BA, Cassava as a potent energy crop for the production of ethanol and methane in tropical countries. *International Journal of Environmental Engineering* **4**(1):25-32 (2012).
47. Roa GS and Lakshminarayana V, Simulation and analysis of biogas operated double effect GAX absorption refrigeration system. *International Journal of Applied Research in Mechanical Engineering* **1**(1):14-19 (2011).
48. Bvumbe TJ and Inambao FL, Solar powered absorption cooling systems for Southern Africa. *Energize* **May**:66-68 (2011).
49. McHenry MP, Doepel D, Onyango BO and Opara UL, Artisanal *Rastrineobola argenta* light fishing on Lake Victoria, Kenya: traditional kerosene lamps and PV-battery modern lighting systems, markets, and improving safety and supply security. ATPS; 22 November; Addis Ababa, Ethiopia: ATPS; (2012).
50. United Nations, Updated book on biogas development. 2 ed. New York, USA: United Nations; (1984).
51. Sun F, Mao Z, Tang L, Zhang H, Zhang C, Zhai F and Zhang J, Exploration of water-recycled cassava bioethanol production integrated with anaerobic digestion treatment. *African Journal of Biotechnology* **9**(37):6182-6190 (2010).

52. Woodhouse P, Productivity constraints in African agriculture. II Confêrencia do IESE: Dinamicas da pobreza e padrões de acumulação em Moçambique; April 22-23; Maputo, Mozambique (2009).

Tables and Table captions

	Wheat (grain)	Cassava	Corn (kernel)	Sugar Beet	Sugarcane	Macro-algae	Micro-algae
Generic average yield ($t\ ha^{-1}\ yr^{-1}$)	2	20	8	70	95	54	73
Approx. spec. conversion ($L\ t^{-1}$)	360	180	410	90	70	174	157
Potential volume of bioethanol ($L\ ha^{-1}\ yr^{-1}$)*	2,100	3,600	6,600	5,600	7,300	9,400	11,500

Table 1: Comparisons of approximate yield, conversion rates, and potential bioethanol production between major bioethanol feedstocks. Sources: [25,26,37,38]. *Assumptions: carbohydrate to ethanol conversion rate is equal to 64% for wheat and corn, and 58% for sugar beet, sugarcane, macroalgae, and microalgae.

Cassava peel-to-manure ratio biogas yields ($L\ kg\text{-}TS^{-1}$)	Peel only	1:1 Peel:Manure	2:1 Peel:Manure	3:1 Peel:Manure	4:1 Peel:Manure
Pig manure	0.6	35.0	26.5	17.1	9.3
Cattle manure	0.6	21.3	19.5	15.8	11.2

Table 2: Comparisons of biogas yields per kg of total solid (wet basis) cassava peel when mixed with ratios of pig and cattle manure. Source: [46].

Figure Caption

Figure 1: Two stage process for adding value to cassava waste

Biographies

Mark P McHenry

Dr McHenry is a Postdoctoral Research Fellow at Murdoch University, a Fulbright Scholar, and physicist specialising in new technical applications. He has published widely in various subjects, including renewable energy resources and technologies, rural production systems, carbon biosequestration, electricity and power systems, bioenergy conversion technologies, soil organic carbon and biochar developments, regional biodiversity, energy security, fishery stability, energy policy, and agricultural mitigation and adaptation to climate change.

David Doepel

David has research management experience including developing multi-disciplinary groups focused on applied research projects. He is currently a Director at the Doepel Group Pty Ltd, the Chair of the

African Technology Policy Studies Network (ATPS) Chapter in Australia, and the Chair of the Africa-Australia Research Forum. David's former roles include Deputy Vice Chancellor Research & Development at Murdoch University, the Interim CEO at the Australian National Centre of Excellence in Desalination, Director of the Research Institute for Resource Technology at Murdoch University, Principal Policy Adviser at the Office of the Premier, Government of Western Australia, and the Regional Director (The Americas) for the Western Australian Trade and Investment Office.

Karne de Boer

Dr de Boer is the Managing Director of Regenerate Industries Pty Ltd, developing biodiesel and biofuel plants and integrated systems based around renewable energy. He specialises in renewable energy engineering and instrumentation and control engineering, and is currently undertaking postdoctoral research at Murdoch University's Algae R+D Centre on the conversion of algae into biofuels with a focus on energy consumption.