EXPLORING TECHNOLOGICAL STRATEGIES FOR VALORIZATION OF SOLID SISAL WASTE: A RESEARCH REVIEW

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ABSTRACT

The sisal industry in Tanzania generates large amounts of waste which is an un-tapped bioresource. Research was undertaken to establish appropriate technologies for its valorisation to mushrooms, biogas and biogas manure (BGM).Physical and biological pre-treatments achieved methane yield increments of 23-30% whereas co-digestion with fish waste achieved methane yield increments of 59-94%. Sisal fibre waste was demonstrated to be a novel biofilm-carrier for treating sisal pulp leachate. With a loading rate of 9.0 kgVS/m^3/day, the packed-bed bioreactor was operated without process stress. Sisal decortication waste (SLDW) and sisal boles (SBW) were found to be suitable for oyster mushroom cultivation. With water-pretreated SBW and saline-SLDW, biological efficiencies of 26-86% were obtained. SBW was utilized for commercial-scale mushroom cultivation and yielded 250kg/ton of wet substrate. Residues of mushroom cultivation (SMS) were anaerobically co-digested with cow dung manure and yielded 230-300L CH_4/kg VS_{added} which indicated the potential of SMS for AD.Co-digestion of SLDW with cow dung manure in a 10m^3 continuous stirred tank reactor gave about 400 litres CH_4/ m^3/day, and 260 L/day of BGM which was superior to NPK fertilizer. In conclusion, sisal waste has potential for valorisation, and integrating mushroom and biogas production for better economics is feasible.

Key words: sisal waste, anaerobic digestion, mushrooms, valorisation

INTRODUCTION

Valorization of waste refers to the conversion of waste biomass via chemical, thermal, biological or electrochemical treatments to food, feed, bio-energy as well as valuable chemicals. It is emerging as a strong trend for sustainable development in terms of safely reusing biomass in the era of a biobased economy (bio-economy) (Tuck et al. 2012). Sisal waste has been recognized as one of the waste streams with potential for valorization.

Sisal is a semiarid and marginal land crop of the tropics whose leaves are used for extraction into natural hard fibres by either wet or dry decortications. The sisal sub-sector is the oldest commercially organized agricultural undertaking and one of the longest surviving industries in Tanzania. Sisal (*Agave sisalana*) was introduced in 1893 from Mexico via Hamburg and grew to become the extensive commercial agriculture and primary processing industry in East and Central Africa, spreading to Kenya, Mozambique, Madagascar and Angola (FAO 2013). In 2011, Tanzania was the third world major producer after Brazil and China at about 35,000 tonnes of sisal fibre (FAO 2012) earning the country foreign exchange through exports. Production is increasing and in 2016, the country was reported to earn USD 20.6 M from import of sisal fibre and products (www.tanzaniainvest.com/agriculture/tanzania). Nevertheless, sisal fibre production is a high waste process currently using only 2% of the plant and the remaining 98% biomass being various fractions of wastes. Sisal processing wastes include: sisal leaf decortications wastes (SLDW) which is a combination of pulp and residual fibre, short fibres (flume tow), wastewater and sisal dust. The industry also produces post harvest waste (SPHW) that comprises of sisal stems (comprising of boles and leaf remnant stubs) and poles (Muthangya et al. 2009a, Mshandete et al. 2013).

Although a menace to the environment, previous studies have indicated the viability of transforming sisal waste into high value commodities and thus should be regarded as a bioresource not a waste. Potential high value commodities from sisal waste include but not limited to biofuels, foam liquid (cement foaming substance which enlarge sand and cement mixture), organic acids, composite, low calorie dietary fibres, functional foods, sweeteners, thickeners in ice creams, sandwich spreads, chocolate products, breads pastries, fine and green chemicals (Kimaro et al. 1994, TSA 1995, Bisanda and Enock, 2003, Elisante and Msemwa 2010). Despite this big potential, sisal waste in Tanzania and the region at large, remains grossly underutilized and disposed off untreated or by burning leading to environmental pollution, and it is a wastage of a valuable bioresource. This situation is mainly due to scarcity of innovative technologies and their adoption for production of valuable products. On realizing this problem back in 1993, the Department of Molecular Biology and Biotechnology (former Applied Microbiology Unit) at the University of Dar es Salaam embarked on research to explore technical feasibility for production of biogas and mushrooms from sisal waste.

Following the emphasis given in the Energy Policy of Tanzania (1992) on the development of biogas technology and use of biogas as a renewable energy source, first priority was put on biogas research. During a pre-investment study for UNDP (1993) to appraise projects which can utilize agro-industrial residues for production of biogas and electricity in Tanzania, methane yields from pure sisal pulp (without free fibre) and sisal processing wastewater were determined. The wastewater and solid waste were each estimated to yield 400 ml CH_4/g of volatile solids (VS) (Kivaisi and Rubindamayugi 1996). During the early 1990s, Tanzania was estimated to generated 100,000 tons of organic matter (VS) of sisal pulp and 100,000 tons COD from wastewater annually (Jungersen et al. 1998). Based on these results, the estimated total annual potential electricity production from these residues was 120 million kWh for each waste fraction. From the same residues, total oil substitution was estimated at 33,680 million tons crude diesel oil per annum. These findings motivated further research on utilization of the various sisal waste fractions for production of valuable products.

This paper presents a summary of research initiatives in attempt to establish appropriate technological strategies suitable for utilization of sisal processing and post-harvest wastes for production of biogas and edible mushrooms.

RESEARCH INITIATIVES AND FINDINGS

Anaerobic digestion of solid sisal waste to biogas

Anaerobic digestion is a multistep process whereby organic matter is degraded and converted mainly to carbon dioxide and methane by a consortium of microorganisms in the absence of oxygen. Although solid sisal waste fractions are rich in organic matter in the form of volatile solids (Table 1), their biodegradability under anaerobic conditions is limited due to their lignocellulosic nature. Besides, their C:N ratio is in the range of 27-48 which is well above the proposed optimum of 20-30 (Monnet 2003, Yadvika et al. 2004, Chen et al. 2008). In attempt to enhance its conversion into biogas, a number of technological strategies were investigated.

Pre-treatment: As mentioned above, the extent of conversion of materials of lignocellulosic nature into biogas is limited under anaerobic conditions. Therefore, in order to improve their biodegradability and increase calorific value of the gas, pre-treatment is applied. Pre-treatment breaks down the complex structure of organic compounds into simpler molecules and makes them more susceptible to microbial enzyme attack for degradation (Fang et al. 2011, Montgomery and Bochmann 2014). Pre-treatment may be done by various techniques such as mechanical, thermal, chemical, and biological (using whole microorganisms or enzymes).

Using a particle size reduction technique, the degradation and biogas production from sisal fibre waste was investigated (Mshandete et al. 2006) in batch bioreactors with fibre sizes ranging from 2 to 100 mm at an ambient temperature of 33°C. An increment of 39% in total fibre degradation and 23% in methane yield were achieved for the 2 mm fibres compared to the un-treated ones. These results demonstrated the possibility of significantly increasing the degradation and biogas production potential of sisal fibre waste by a mere reduction of particle size of the substrate.

Although size reduction was found to significantly improve on AD of sisal fibre waste, biological pre-treatment which does not require additional energy for mechanical processing of the material was investigated using sisal pulp. Pre-treatment of the substrate was done by using activated sludge mixed culture under micro-aerobic conditions in batch bioreactors at 37 °C for different periods (Mshandete et al. 2005). The progression of the microaerobic pre-treatment of the substrate in relation to activities of some extracellular hydrolytic enzymes namely, filter paper cellulose, xylanases, and carboxymethyl cellulase in the slurry was studied. A correlation was observed between high enzyme activity and high methane yield (0. 243 m^3 $kgVS^{-1}$ added) at 9 hours pretreatment suggesting that such a short pre-treatment period could be an alternative option for increasing solubilisation of sisal pulp and methane yield during anaerobic digestion. The methane yield obtained represented an increment of 27% over that obtained without pre-treatment. Longer periods of pre-treatment however, resulted in lower bio gas yields. A loss of methane yield of between 27% and 40 % were recorded for 48 and 72 hours of pre-treatment, respectively. This clearly showed that prolonged treatment periods led to significant loss of easily degradable compounds, which contributed to the decrease in biogas production potential from the substrate.

The effect of biological pre-treatment of SLDW was also investigated using solid state fermentation with a local ligninolytic fungal strain (CCHT-1) at an inoculation rate of 10 % and incubation period of 4 days. A methane yield of 0.203±0.019 m^3 CH_4/kg VS_{added} which was an increment of 30% over that obtained for the untreated samples was reported by Muthangya et al. (2009). These results once more demonstrated the potential of biological pre-treatment method using fungi for enhancement of biomethanation of sisal waste and there is room for further improvement. Many previous and recent studies have also demonstrated the capability of lignocellulosic microorganisms, especially fungi for large scale industrial applications due to their ability to produce large amounts of extracellular enzymes (Dashtban et al. 2009, Isroi et al. 2011, Wang et al. 2014, Temu, 2015).

Table 1: Composition of some sisal waste fractions (Mean ± SD)

Waste fraction	TS	VS	AC	TC	TN	TSU	CFB	Cellulose	Reference
Fresh sisal bole1	31±1.0	98.2±0.5	1.8±0.5	54.4±0.6	1.13±0.1	15.3±3.9	51.4±1.1	ND	Mshandete et al. 2013
Fresh sisal bole2	30±0.6	87.8±0.6	12.3±0.6	50.0±1.0	1.14±0.8	ND	11.0±3.0	ND	Raymond et al. 2013
SLDW	35±0.8	74±0.8	26.2±0.1	46.6±0.6	1.7±1.0	ND	14.2±0.7	14±0.7	Raymond et al.
Saline[a] SLDW	12±0.1	67.3±3.0	ND	49.4±0.4	ND	ND	ND	76.7±5.6	Muthngya et al 2013

[a]: Chlorides (mg/l) = 23.510; Sodium (mg/l)= 15,251; SLDW = Sisal leaf decortications waste. TS= Total solids (% fresh wt); VS= Volatile solids % TS); AC= Ash content (% TS); TC= Total carbon (% TS); TN= Total Nitrogen (% TS); TSU= Total sugars (% TS); CFB= Crude fibre (% TS).

Co-digestion: Co-digestion is digesting a mixture of at least two substrates with complementary characteristics. Co-digestion can offer several benefits most important of which are: a better nutrient balance, improved co-substrate handling, increased loading of readily biodegradable substrates, dilution of toxic substances, improved fluid dynamics and process stability, and improved overall process economics whereby an increase of bio-methane potential is achieved when the substrates mixture is prepared with proper percentages of the different substrates to be digested (Alvarez et al. 2010, Borowski et al. 2014). To improve on the AD of sisal pulp,fish waste was co-digested with sisal pulp in batch bioreactors. A mixture of 33% fish waste and 67% sisal pulp gave a methane yield of 0.62 m^3CH_4/kg VS added and this was an increase of 59 - 94 % in the methane yield compared to the yields obtained for the digestion of pure sisal pulp and fish wastes at 5 % of TS (Mshandete et al. 2004). Although the C:N ratio achieved in this investigation was 16, which was slightly below the optimal range, the results further demonstrated the potential of enhancing the anaerobic digestion process through combining materials with complimentary nutrient compositions.

Microbial biomass immobilization: Apart from hydrolysis as a rate limiting step in AD of particulate matter, methanogenesis is also rate limiting in the digestion of soluble organic matter. This problem has been attributed to slow growth of methanogenic bacteria (Yang et al. 2004). To maintain high microbial cell densities in anaerobic bioreactors, immobilization of microbial cells on various support materials is employed and the technology has proved effective. However, the materials so far used in packaged bed bioreactors are costly and hence a hindrance to adoption of the technology in poor developing countries. For the production of biogas from solid sisal waste therefore, Mshandete et al. (2008) dwelt also on identifying alternative, cheaper and locally available materials for use as carriers for immobilization of microbial cells for anaerobic digestion. Sisal fibre waste, pumice which is a porous volcanic stone, and porous beads were evaluated as carrier materials in the methanogenesis of sisal leaf leachate. Each process was evaluated by analyzing the volume and content of the gas, concentration of VFAs, COD, Partial Alkalinity (PA), Total Alkalinity (TA) and the pH of the outflows. OLRs in the range of 2.4-25 g COD L^{-1} d^{-1} were investigated, and each OLR was maintained for at least three retention times in order to attain a steady state. With the highest chemical oxygen demand (COD) removal efficiencies of 80-93% at OLRs in the range of 2.4-25 g COD L per day, sisal fibre waste was shown to be superior and a novel promising biofilm carrier and would work very well in methanogenic biofilm bioreactors treating sisal leaf tissue waste leachate.

Stratified bed approach: Two in-one stages bioreactor

For continuous production of biogas, a number of bioreactor designs have been developed and are being employed for improved biogas production from wastewater and particulate biomass. Recent advances include two stage anaerobic digestion (separation of acidification phase from the methanogenic phase) and high rate bioreactor systems with short retention times and high loading rates. In the latter systems, washout of active microbial biomass is reduced with a possibility of reduced bioreactor volume and investment costs. To achieve reduced reactor volumes, a stratified bed approach is applied. Strategies engaged here include a single plug-flow reactor with phase separation along flow path by manipulation of feed rates and concentration; a solid phase stratified bed digester with decomposing biomass bed at the bottom and fresh biomass at the top; and a fixed solid bed with acidification zone at the top and a methanogenic zone at the bottom. The performance of a two-in-one sisal fibre fixed bed anaerobic digester (Fig. 1) for biogas production from sisal pulp was evaluated. With the highest OLR of 9.0 kgVS/m^3/day, methane yield of 0.48m^3/kg VS was achieved without process stress (Mshandete et al. 2005). This simple technology using sisal fibre fixed bed is yet to be investigated at pilot scale. It is imperative that such pilot scaling-up be conducted since the technology is credited as an emerging, attractive, cost-effective simple technology for high solid anaerobic digestion.

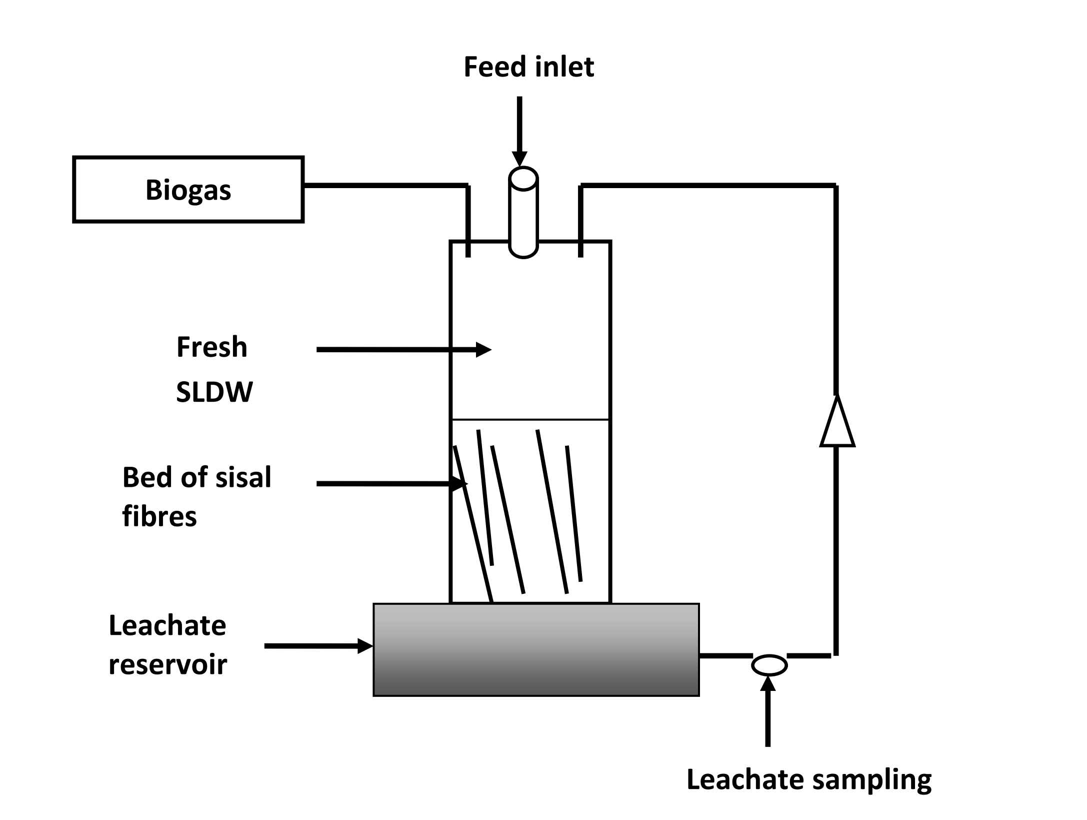

Figure 1: Schema of a sisal fibre fixed bed anaerobic digester. SLDW = Sisal leaf decortications waste

Suitable technological approach for AD of sisal waste

On comparing the methane yields reported previously for agricultural and crop residues used as feedstock for biogas production with the yields obtained for the various strategies reported above for sisal waste (Table 2), it is obvious that sisal waste is one of the suitable feedstocks for AD to biogas. However, it is quite difficult to conclude which one is the best technological approach to use. This is because the studies used different sisal waste fractions, which had different characteristics. Overall, co-digestion appeared to be superior followed by AD using microbial biomass immobilization in a two-in-one bioreactor. However, it should be observed that, the effect of a co-digestion on methane yield depends on the composition of the co-substrates, and that of biological pre-treatment depends on the type of organism used, hence the choice of the organism is crucial (Temu 2015). Besides, combining various strategies with co-digestion may significantly improve on biogas yield and the overall economics of the AD process. The effect of combining pre-treatment with co-digestion is evidenced by a number of previous reports. Neves et al. (2006) found out that when the waste was subjected to alkaline hydrolysis pre-treatment before co-digestion with activated sludge, methane production increased by 67%, while, when co-digested with kitchen waste, methane production increased by 61%. Similarly, Aboderheeba (2013) achieved a significant increase on methane production by a beating treatment of maize silage and fresh grass followed by anaerobic co-digestion with digested sludge.

Table 2: Biogas yield from sisal waste fractions (**in bold)** and common agricultural residues

Residue/waste	Methane yield (m^3 per kg of VS)	Reference
Sisal pulp + fish waste	0.62	Mshandete *et al.* (2004)
Sisal fibre waste	0.243	Mshandete *et al.* (2005
Sisal pulp	0.48	Mshandete *et al.* (2005)
SLDW[a]	0.203	Muthangya *et al.* (2009)
Maize (whole crop silage)	0.39	Amon *et al. (*2007)
Maize silage	0.320-417	Aboderheeba (2013)
Fresh grass	0.355-480	Aboderheeba (2013)
Potato waste	0.340-551	Aboderheeba (2013)
Maize straw	0.34	Gunaseelan *et al. (*1997)
Corn cob mix	0.35-0.36	Appels et al. (2011)
Sugar beet leaves	0.21	Amon *et al.(*2007)
Sunflower oil cake	0.227	Raposo *et al.* (2008)
Barley stalks	0.23	Raposo *et al.* (2011)

[a]: = Sisal leaf decortications waste

Utilization of sisal waste for mushroom cultivation

The first attempt to grow mushrooms on sisal waste started with three wild indigenous edible mushrooms, namely *Coprinus cinereus*, *Pleurotus flabellatus* and *Volvariella volvaceae*. (Mshandete 1998). There was no information then in the literature on the use of sisal waste as substrate for mushroom cultivation and so the study investigated the suitability of composted and non-composted sisal decortications residues for growing these mushrooms. Duration of spawn running, pinhead and fruit formation, number of flushes and biological efficiency (BE) were studied (Mshandete 1998). The entire crop cycles of all the 3 mushrooms on both substrates ranged between 21-28 days and *C. cinereus* had the shortest time. All the mushrooms also gave at least 3 flushes of which the first flush gave the highest yield. About 93-99% of the total fresh weight for all the mushrooms was obtained in the first 3 flushes. This was an indication that economic flushes could be limited to 3 flushes hence shortening the cropping cycles. Biological efficiencies (BE) for the composted substrate were 68, 64 and 28% for *C. cinereus*, *P. flabellatus and V. volvaceae*, respectively (Mshandete 1998). Interestingly, the BE of 74% obtained for *P. flabellatus* grown on non-composted sisal decortications residues was significantly higher than that obtained for the composted substrate. This finding compared very well with previous results for *P. flabellatus* on non-composted water hyacinth (Kivaisi et al. 2003). Overall, the results of this study demonstrated for the first time, the suitability of sisal decortications residues for domestication of wild saprophytic edible mushrooms.

Further research on utilization of sisal waste for mushroom cultivation focused on mixed fractions and N-supplementation. Composted sisal bole fractions (SBW) and SLDW supplemented with cow dung manure at various rates used singly and/or in combination were investigated for cultivation of a commercial strain of oyster mushroom (*Pleurotus* HK-37). A substrate combination of SBW+SLDW (1:1) supplemented with 30% cow dung manure was reported to give the best mushroom yield of 184.6g/kg of moist substrate with a BE of 63% (Raymond et al. 2013). Although not significant, N-supplementation seemed to improve on the yield.

In another attempt, SPHW fractions composed of SBW and leaf stubs (RLS) were also evaluated for mushroom growing. Following a pre-treatment step with water, single fractions and a combined fraction of RLS+ SBW (70:30) were used for cultivation of *Pleurotus* HK37 and *Pleurotus sapidus* (969). In terms of yield, HK 37 performed better than *P. sapidus* on the mixed fraction and gave a yield of 270g/kg moist substrate with a BE of 86% (BIO-INNOVATE, 2012). Considering the large quantities of sisal bole waste generated per hectare per annum (22 and 44 tons for SBW and RLS, respectively), these results are an indication of the potential of these wastes for large-scale mushroom production.

Although oyster mushrooms have proved to be aggressive and grow on many substrates (MushWorld 2004), preliminary attempts to utilize SLDW generated from some sisal plantations along the coast for growing of *Pleurotus spp* failed. Surprisingly, these waste streams were found to have sodium and chloride salt concentrations of about 45-70 times higher than 461ppm reported to be inhibitory to mycelia vegetative growth (Zizzo 2009). This salt inhibition was successfully mitigated by cold water pre-treatment and/or mixing of the waste with grass (*Panicum coloraturm*) at 1:1 ratio. On the pre-treated fractions, HK-37 and *P. sapidus* 969 gave BEs of 39.4 and 26.3%, respectively. On the other hand, the two mushrooms performed better on the mixed fractions with BEs of 40 and 38%, respectively (Muthangya et al. 2013). These results demonstrate the possibility that with a simple pre-treatment, saline sisal waste generated by factories along the coast can be utilized for mushroom production. The mushrooms grown on this substrate were safe to eat, and were found to be rich in macro-elements, crude protein, vitamin C, β-carotene and flavanoids (Muthangya et al. 2014).

Overall, the above results indicate a big potential in the utilization of various fractions of sisal waste for production of high protein food, the oyster mushrooms. The BEs obtained under ambient conditions are comparable with those achieved for traditional substrates (Table 3), and there is still room for optimization.

Table 3: A comparison of performance of various mushroom species on sisal waste substrates (**in bold**) with that on other substrates

Mushroom specie/strain	Substrate	BE (%)	Reference
Coprinus cinereus	Composted SLDW	68	Mshandete & Cuff (2008)
Coprinus cinereus	Composted market waste	80	Chuwa et al. (1996)
Pleurotus flabellatus	Composted SLDW	65	Mshandete & Cuff (2008)
	Corn cobs	50	Mshandete (1998)
	Banana leaves	73	Mshandete (1998)
	Sugar cane bagasse	74	Mshandete (1998)
	Water hyacinth	83	Kivaisi et al. (2003)
Pleurotus flabellatus	Composted SLDW	74	Mshandete & Cuff (2008)
Pleurotus HK-37	SBW+ RLS(30:70)	86	BIO-INNOVATE(2015)
	SLDW+SBW(50:50)	63	Raymond et al.(2013)
Pleurotus HK-37	Saline SLDW	39	Muthangya et al. (2013)
P. sapidus (936)	Saline SLDW	26	Muthangya et al. (2013)
P. citrinopilleatus	Sugarcane bagasse	64	Mtowa and Magingo (1996)
P. ostreatus	Sawdust	86	Buah et al. (2010)
	Corn cobs	91	Buah et al. (2010)
	Sawdust + cobs (40:60)	68	Buah et al. (2010)
P. ostreatus	Sawdust	65	Shah et al. (2004)
	Sawdust + Wheat Straw (50:50)	44	Shah et al. (2004)
	Sawdust + leaves (50:50)	58	Shah et al. (2004)
P. ostreatus	Rice straw + wheat Bran (80:20)	51	WenJie et al. (2013)
	Cotton seed hulls + rice Straw+ wheat bran (20:60:20)	75	WenJie et al. (2013)

Integration of mushroom cultivation with biogas production

The results of biological and co-digestion investigations indicated a potential for further improvement in the economics of the AD process utilizing various sisal waste fractions. An innovative concept to integrate mushroom cultivation as a biological pre-treatment step followed by biogas production using a mixture of the residues of mushroom cultivation (spent mushroom substrate (SMS) with cow dung manure was therefore investigated at laboratory scale. The purpose of growing mushrooms prior to AD was to change the properties of the substrates through removing lignin and exposing hemicelluloses and cellulose to microbial enzymatic attack. For SLDW, AD of SMS after cultivation of *Coprinus cinereus* was improved up to the second flush. The highest methane yield achieved was 0.285m^3/kg VS $_{added}$ with 20% cow dung manure supplementation. This was an increment of about 88% compared to the control substrate (Raymond et al. in press). A similar AD trend was observed for the SMS obtained after cultivation of *Pleurotus* HK-37 on a mixed substrate SLDW+SBW at 1:1 ratio and supplemented with 10% cow dung manure (Raymond et al. in press). After the second flush, the highest methane yield of 0.300 m^3/ kgVS$_{added}$ was achieved. This was an increment of about 38% over that obtained for the control substrate. Improvement of AD of

SPHW fractions through prior cultivation of mushrooms was later replicated by the BIO-INNOVATE project (2015) where a yield of 0.231 m^3 CH4 /kg VS was obtained for a mixture of SBW+RLS (30:70). These results confirmed that biomass left after mushroom cultivation up to the second flush still contained considerable organic matter, which was used by anaerobic microorganisms to produce bio-energy in the form of biogas. These results also indicate the prospects for integrating mushroom with biogas production.

PILOT SCALE DEMONSTRATIONS

Anaerobic co-digestion of SLDW silage with cow dung manure

To exploit the economic value of sisal waste, the Common Fund for Commodities, UNIDO and the Tanzanian sisal industry funded the first commercial plant (1700 m^3) to use sisal residues to produce biogas, electricity, and fertilizer. The plant was commissioned in 2007 at Hale in Tanga region. However, due to the fibrous nature of the residue and sub-optimal C:N ratio, the gas yield is also sub-optimal. On the other hand, various pre-treatments and co-digestion approaches at laboratory scale reported above were demonstrated to improve on AD of the waste fraction. For further improvement in AD of the waste fraction therefore, a two steps approach was recently employed for a pilot scale demonstration plant: 1) first fermentation of SLDW through silage making and 2) anaerobic co-digestion with cow dung manure in a 10 m^3 Continuous Stirred Tank-reactor. For the start-up process, the digester was fed with a mixture of sisal pulp silage (20 kg) and cow dung manure (240 litres) once a week. The plant was expected to produce 6000 litres biogas/m^3 per day, and it is currently producing 260 litres of biogas manure after every feed. The methane content of the biogas is in the range of 64-69%, and operates a biogas generator which has a capacity of 1.2Kwh with a biogas consumption of 0.65m^3/KWh. Performance of the plant under steady state conditions is yet to be evaluated.

Evaluation of fertilizer value of biogas plant effluent

During anaerobic digestion (AD), a large proportion of the energy contained in the organic waste is retained in the methane molecules (Neves et al. 2006). At the same time, the nitrogen (N) and most other nutrients are preserved in the residues (Massé et al. 2007). The AD treatment removes carbon (C) thus lowers the C/N ratio and also increases the mineral N content of the product (Morgan and Paine 2008). The resulting product has properties more similar to a mineral fertilizer (Arthursson 2009). This product is the effluent of biogas plants technically known as the digestate and commonly known as biogas manure (BGM).

Several previous studies have demonstrated the fertilizer value of BGM and its superiority over the commercial fertilizers (Svensson et al. 2004, Wang et al. 2008, Li et al. 2006, 2007, Yu et al. 2010).However, according to Matsi et al. (2007), the fertilizer value of BGM is largely dependent on its feedstock and production process implying that every BGM has its own characteristics. It was hence necessary to establish characteristics (Table 3) and value of the BGM produced by the pilot biogas plant digesting SLDW and cowdung manure for application as a bio-fertilizer. Generally, BGM exhibited a higher fertilizer value than NPK commercial fertilizer. In terms of leafy vegetable growth, BGM was demonstrated to be capable of supporting cultivation of 2-3 consecutive vegetable crops without re-application, contrary to commercial NPK fertilizer. The soil fertilized with BGM was found to be more physico-chemically improved than that in the plots that received the inorganic fertilizer. Vegetables (*Amaranthus hybrid*, *Cucurbita maxima*, *Physaulo s*sp) grown with the manure were of higher nutritive quality, and grew at a higher rate than those fertilized with

NPK commercial fertilizer (Muthangya 2016). The calculated yield for *Amaranthus hybrid* was 41.6 tons/ha while that for NPK fertilizer was 19.2 tons/ha. Anticipated quantifiable monetary gains stood at 5,324.8 USD/ha when using BGM and only 315.6 USD/ha when using NPK fertilizer.

Utilization of Sisal Bole Waste for commercial oyster mushroom cultivation

On the basis of bench scale results, a commercial scale pilot oyster mushroom farm utilizing SBW was set up. The farm constructed at Alavi Sisal factory owned by Mohamed Enterprise Tanzania Ltd who is the beneficiary, has capacity for production of 1 (one) tonne of fresh mushrooms/month from 4 (four) tonnes of SBW. To achieve continuous mushroom harvesting, four crops were staggered at two weeks intervals. At an ambient temperature of 27^{o}C, spawn running (vegetative growth of mushroom seed) took 2-3 weeks to completion. Fructification was achieved with basic controls of environmental conditions i.e. relative humidity of 65-75% and temperature of 25-27. Three flushes were harvested and an average yield of 250 kg per tonne of wet substrate was obtained (BIO-INNOVATE 2015).

Techno-economic feasibility of utilization of SBW for integrated production of mushrooms and biogas

A pre-techno-economic analysis based on bench scale results reported above for integrated production of mushrooms, biogas and BGM utilizing SBW was performed to predict economic feasibility of the strategy. Three scenarios were independently considered but the common factors were that the market for the mushrooms produce would be a local one, biogas would be used to power a gasoline generator and generate electricity, and a mushroom production facility on one hectare of land with capacity to produce 1 tonne fresh mushrooms per month. Scenario 1 involved production of mushrooms, biogas and electricity using 10 m^3digester, scenario 2 considered production of mushrooms, biogas and vegetables and scenario 3 involved production of mushrooms only. It was scenario 3 that was found to have the highest Internal Rate of Return (IRR=32%) attributed to low investment costs of the farm facility. The option also had a Return On Investment (ROI) of 50.4%, a net profit ratio of 56.5%, and a payback time of 2 years Scenarios 1 and 2 were also found to be economically viable with a positive financial flow (Mwaluko 2013). Economic feasibility of the demonstration facilities has yet to be determined.

INNOVATIONS AND OUTCOMES

Innovations: Among the many research findings realized, there is a number of innovations. These include 1) Discovery of suitability of sisal fibres for use as biofilm carrier in anaerobic bioreactors, 2) A technology for growing oyster mushrooms on sugar-rich sisal postharvest wastes for oyster mushroom production, 3) A method for use of saline sisal decortications waste to grow oyster mushrooms 4) A technology for growing wild indigenous edible mushrooms, namely *Coprinus cinereus*, *Pleurotus flabellatus* and *Volvariella volvaceae* on composted sisal waste, 5) Novel pre-treatment technology for sisal leaf decortication waste by micro-aerobic pre-treatment for increasing solubilization and promoting methane production, 6) A novel co-digestion approach for sisal leaf decortication wastes with fish wastes to improve biogas production and 7) A novel anaerobic high-solids single-stage fixed bed technology for biogas production from sisal decortication wastes.

Outcomes: The outcome of bench scale research findings was the setting up of a pilot scale demonstration mushroom farm and biogas plant in collaboration with an industrial partner. This was one of the few partnerships between the academia and private sector in Tanzania. Before the pilot plant, the industrial partner was not aware of the potential use of sisal post harvest waste for production of edible mushrooms. On recognition of this potential, the industrial partner is in the process of collecting data on mushroom market outlets prior to making an investment decision. Besides, dissemination of this finding to other stakeholders has prompted the interest of small and medium scale mushroom farmers and entrepreneurs to invest in mushroom production utilizing sisal postharvest waste which is more abundantly available than the commonly used substrates such as banana leaves, rice straw, and cotton seed waste.

CONCLUSION AND FUTURE RESEARCH

Solid sisal processing and postharvest waste are suitable as substrates for commercial mushroom cultivation and as feedstocks for biogas plants. Appropriate technological approaches for their valorization depend on the desired product and composition of the waste fraction. To maximize biogas production, a combination of pre-treatment and co-digestion may be employed together with microbial biomass immobilization. Future research should focus on validation of the two-in-one sisal fibre fixed bed anaerobic bioreactor and the integrated technology for mushroom cultivation, biogas and biogas manure production at pilot scale. A complete techno-economic analysis should then be carried out and disseminated to the stake-holders for possible commercialization.

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