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Biosolid Management Options in Cassava Starch Industries of Thailand: Present Practice and Future Possibilities

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Abstract

Greenhouse gas (GHG) emissions from the existing biosolid management practices in cassava starch industries of Thailand have been evaluated and compared with other biosoild management options with a view to reduce GHG emissions and possible energy recovery. The study involved development and application of a spread-sheet based evaluation tool to estimate GHG emissions, benefits such as GHG offsets and possible energy recovery from four different cassava pulp waste management options viz.: (i biodrying followed by production of refuse derived fuel (RDF), (ii) composting, (iii) anaerobic digestion with energy recovery and (iv) landfilling with energy recovery. Parameters such as GHG emissions, benefits in terms of GHG mitigating potential and energy recovery ton^{-1} of cassava pulp waste were determined for each biosolid management option. Total baseline emissions from the existing cassava biosolid management practices were estimated as 4.2 kg CO_2 eq. ton^{-1} of cassava pulp waste. Among the four waste treatment alternatives, biodrying followed by RDF production scenario showed the highest GHG mitigating potential of 85.2 kg CO_2 eq. ton^{-1} cassava pulp. On the other hand, landfill option with biogas flaring resulted in highest net GHG emissions of 28.7 (kg CO_2 eq. ton^{-1} cassava pulp). Biodrying followed by RDF has the highest net heat energy gain (NEG) of 1 536 MJ · ton^{-1} of cassava pulp treated. However, for conversion of waste-to-energy, anaerobic digestion has the highest net energy ratio (NER) for heat as well as electricity recovery with high GHG mitigation potential.

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Keywords: Anaerobic digestion; biodrying; biosolid management; cassava pulp; composting; GHG emission; land filling; RDF.

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Nomenclature

BEAM	biosolids emissions assessment model	**NEG**	net energy gain
GHG	greenhouse gases	**NER**	net energy ratio
RDF	refuse derived fuel	**CO_2 eq**	carbon dioxide equivalent
MBT	mechanical biological treatment	**MSW**	municipal solid waste
WTE	waste to energy	**LFG**	landfill gas
IPCC	Intergovernmental Panel on Climate Change		

1. Introduction

Organic or bio-wastes management has become increasingly important as it can emit large amounts of methane under anaerobic conditions which is a major green-house gas. Bio-waste includes organic household waste (food waste, garden trimmings, etc), biosolids from wastewater treatment process, and organic industrial waste such as waste from food and agro-industries. The agro-industries produces large amount of waste with higher organic content during various stages of its manufacturing processes. In many tropical countries like Thailand, the agro-industries such as cassava starch industries, food industries such as fruit-canning, and vegetable oil industries such as palm oil generate a large amount of solid waste which are often referred as biosolids[1].

Waste sector accounts only about 4 % of the total GHG emissions in Thailand[2]. However, several biosolids management strategies can offer opportunities for reduction in GHG emissions with possibility of energy and nutrient recovery. Furthermore, the energy derived from biosolids is considered to be carbon neutral (CO_2) and is relatively clean[3]. These alternatives include processes like anaerobic digestion for biogas generation; RDF from MBT plants and composting for nutrient recycling. Thus, there is need to explore and compare these different waste management options in details so that task of selection of appropriate biosolid management option is simplified.

Cassava is the third largest source of carbohydrates for human consumption in the world with an estimated annual world production of about 210 million metric ton. Thailand has about 100 tapioca processing plants with total production capacity of over seven million ton of native starch per year[4]. The production process of starch from cassava is energy as well as water intensive. It also generates wastewater and solid waste with high organic load which leads to significant water as well as air pollution. Traditionally, starch wastewater is treated in anaerobic ponds which require large land area with limited or no possibility of methane recovery which escapes into the atmosphere leading to significant GHG emissions and contributes to climate change.

About 0.33 ton of cassava pulp waste is generated from 1 ton of cassava root processed[5]. Thus, on average 5.15 million ton of cassava pulp waste is generated annually from the Cassava Starch Industries in Thailand. Currently cassava waste has been dumped in lowland which, under anaerobic conditions, generates methane; thus contributing to global warming. It also poses considerable risk to the environment since its organic content can contaminate the soil and groundwater. Thus, there is an increasing interest to develop appropriate management options to derive value added products from cassava pulp waste. The pulp waste can be treated and converted to biofuels using different bio-chemical conversion processes such as: i) biodrying followed by RDF production, ii) composting, iii) anaerobic digestion and iv) landfilling. These four waste management options have different GHG emissions and potentials for GHG mitigation or benefits as their material and energy recovery potential are different.

Biodrying is a drying technique relying on biological activity of microorganism viz. bacteria and fungi, to reduce the moisture content of wet organic waste. The drying effect can be achieved through microbial activity coupled with enhanced aeration[6]. As the microbes feed themselves on carbon, nitrogen and other nutrients available in the waste, heat energy is produced due to their metabolic activity. This heat, assisted by induced air supply, can be utilized to evaporate the excessive moisture from organic waste. A generalized reaction for aerobic degradation is shown below (Eqn. 1).

$$\text{COHN} + O_2 + \text{Aerobic microorganism} \rightarrow CO_2 + NH_3 + \text{other end products} + \text{Energy} \quad (1)$$

Biodrying is an attractive option producing RDF as its main output because it removes excessive moisture from the input waste, facilitates mechanical processing and improves its potential for energy recovery[7]. It also improves the waste handling and lessens the transportation cost due to reduction in weight from moisture loss. Biodrying can be adopted as an option to pre-treat the cassava pulp waste for moisture removal. A biodried waste can then be converted into RDF by densification techniques such as pelletization or briquetting which could be utilized as a solid fuel.

Composting is one of the safest approaches for biosolid treatment and disposal since the final product is well stabilized which is free from pathogens and ready for use as organic manure in agriculture[8]. The process offers appropriate alternative for recycle of stabilized biosolids by supplementing essential nutrients to the farmland which are beneficial for plant growth. During composting large fraction of degradable organic carbon (DOC) in the waste is converted to CO_2 as a result of microbial activities[9]. Though CO_2 emitted from degradation is of biogenic origin, there might be anaerobic pockets that emit CH_4. In addition[9], reported to account the possible N_2O emission during the composting. Also, the GHG emissions can occur as a result of operation of composting facilities such as from the use of electricity and fossil fuels.

Anaerobic digestion is a biological treatment process which treats waste in the absence of oxygen (i.e. anaerobic process) to produce a valuable biogas and stabilized digestate as an end product. The generated biogas can be utilized as a fuel for heating or can be converted into electricity, thus can avoid GHG emissions from displacing conventional energy sources. However, there might be fugitive emissions and indirect emission can be from the consumption of purchase electricity.

Landfills have been the most popular method for disposal of solid waste. Landfills are the physical facilities used for the disposed of residual solid waste in the surface soil of earth. Here, waste is disposed in controlled manner through the procedure entails alternating layers of composted MSW with cover material like soil. Organic waste subjected to landfilling undergoes the anaerobic degradation process thus emitting landfill gas (LFG) that generally comprises methane and carbon dioxide as major constituents. Also there are associated emissions from the transportation of solid waste to the landfill site, spreading and the compaction of waste in landfills. On the other hand, conversion of LFG to energy and or flaring i.e. oxidizing the methane to carbon dioxide by burning can mitigate GHG.

The basic objective of the study is to develop a GHG and energy accounting tool and evaluate the GHG impact of waste management options for cassava pulp waste management in the rapidly developing countries such as Thailand. The study was directed to achieve the following specific objectives:

- Estimation of baseline GHG emissions from cassava pulp waste management in cassava starch industries in Thailand
- Modeling of GHG emissions and benefits from cassava pulp waste management options
- Evaluating energy recovery from the waste management options

2. Material and method

2.1. Methodology for baseline data collection

The primary data for baseline scenario of cassava pulp waste management is obtained from Sanguan Wongse Industries Co., Ltd (SWI), Nakhon Ratchasima, Thailand. Secondary data has been collected from the published literature such as peer reviewed papers and project design documents for the Cassava Starch Industries.

2.2. Modeling of GHG emissions and benefits

The GHG emission and energy recovery model accounts both the GHG emissions from the waste treatment processes and GHG benefits from the recovery of energy or utilization of end products from the treatment processes.

The accuracy or predictive capacity of the accounting model depends upon the data availability and the selection of default values and assumptions during calculation.

2.2.1. Biodrying and RDF sub-model

The sub-model assumes that biodrying and RDF production take place at the factory site and the RDF is combusted for heat and electricity generation in the factory. And the energy derived from the use of RDF avoids GHG emission from the use of diesel and or electricity from Thai Grid.

2.2.2. Composting sub-model

The composting process in this study is also considered to be carried within industrial site. Two types of composting process are selected for this study namely in-vessel composting and windrow composting. The qualities of compost from the both type of composting processes are assumed to be of same quality. The degradation process and emissions from both type of composting is assumed to be same. However, the two processes are different in degradation speed and energy consumption as the in-vessel system demands slightly more energy than the windrow systems[10]. Aerobic in-vessel composting model uses an in-vessel system for composting cassava pulp waste which gives higher process control than windrow system. These systems are good for composting large amount of organic waste such as yard waste with food waste and takes less space than windrow systems[11]. The model considers the input of materials and energy and emission from the in-vessel composting process. However, model does not consider the leachate treatment in analysis. Open windrow composting systems are less energy intensive than the in-vessel systems. Energy consumption is due to the use of heavy machinery like front loader or windrow turner used to turn the compost piles.

2.2.3. Anaerobic digestion sub-model

The anaerobic digestion sub-model is based on laboratory scale experiment[12]. The result of co-digestion of cassava pulp with pig manure with highest biogas yield was taken for as default biogas yield factor for this model. The default values for the electricity and fuel requirements of the literature are taken and the total emission determined by considering the total daily activity. The model keeps the accounting of GHG emission and benefits of the bio-methanation of cassava pulp. The reduction potential of GHG from anaerobic digestion is evaluated with use of biogas for heat or electricity generation.

GHG benefits from the anaerobic digestion of waste are depended upon the final use of biogas. The environmental benefits is dependent upon the use of biogas; for example, use of biogas as compressed fuel in vehicles replacing fossil fuels might give higher environmental benefits than using it for electricity generation. The process parameters such as energy consumed in the process, additional waste amendment required in the process is calculated based on literature value. The products of the anaerobic digestion are biogas (assume 60 % methane and 40 % carbon dioxide) and digestate. The biogas is used for energy recovery while the byproduct, digestate is disposed in landfill site.

2.2.4. Landfill sub-model

In this study landfill option is considered as a waste treatment process rather than as a final disposal option. The landfill sub-model is modeled as a managed-anaerobic landfill site with landfill gas (LFG) recovery facilities. The major GHG emission is LFG from the degradation of organic matter contained in cassava pulp waste. Landfilling activities such as energy utilized for the transportation of waste to landfill site is included in the accounting model. The life cycle GHG inventory of this waste treatment options is based on the input and output of energy and materials.

The model does not include the activities involved in the management of the landfill site such as waste spreading, leachate treatment, putting soil cover, etc. This sub-model evaluates the reduction potential of GHG emissions from MSW landfill by considering three scenarios i) with LFG used for electricity production, ii) with LFG used for heat energy production and iii) with flaring of the collected LFG.

This study evaluates and compares the environmental implications of LFG use for electricity and heat energy production and flaring using a life cycle perspective. The model calculates the average daily emissions for a period of three years after the deposition of waste. The landfill sub-model uses first order decay method[9] and CDM Methodological tool[13] to estimate methane from LFG generation. The GHG emission from the generation of methane from the landfill site is estimated by the first order decay method[9]. Flaring of methane in LFG: Flaring has been used as a traditional method to control GHG emissions from the landfills or to destroy the excess biogas produce in the bio-methanation plant. This option helps to mitigate the methane emissions from the landfill and bio-methanation plants by flaring or oxidizing the methane gas into carbon dioxide which is considered as biogenic in origin and doesn't contribute to global warming. About 75 % of the total generated LFG is assumed to be flared in an open flaring. This model assumed the flaring efficiency of 50 %[14].

2.3. Method of accounting GHG emissions, benefits and energy recovery modeling of GHG emissions and benefits

Three major GHG viz. carbon dioxide, methane and nitrous oxide are considered for accounting GHG emission and benefits of the four waste treatment sub-models. The different activities within the waste treatment sub-models are described in the above sections. The total emissions from an activity were determined based on the emission factors of the activity. Thus, the activity data which were collected and the GHG emissions is calculated as:

$$\text{Emissions} = \text{Activity data (AD)} \times \text{Emissions factor (EF)} \qquad (2)$$

where AD are defined by the sub-models and EF are taken from the literature.

The emissions from different activities in a waste treatment models are summarized in an accounting format in Microsoft Excel 2010®. The accounting framework of BEAM version 1.3[15] is followed while developing the model. The assumptions and the method of calculations used are presented in following sections.

2.3.1. Assumptions and conventions for GHG accounting

Assumptions and conventions from the IPCC protocols[9], Clean Development Mechanism (CDM) guidelines[13,14,16], results of the peer reviewed papers were followed for accounting GHG emissions and benefits from the four waste treatment sub-models with various operation and use scenarios of end products. The modeling of GHG emission and benefits depends upon assumptions and pre-conditions made for the waste-treatment sub-models. The major assumptions made in order to model the estimation of GHG emissions and benefits are:

- The direct carbon dioxide emissions from the treatment processes and disposal of organic waste are considered as biogenic and doesn't include in the GHG accounting[9]
- The purchased electricity production is considered from the Thai Electricity grid and the corresponding values of emission factor i.e. 0.5113 is used[17]
- Crediting the waste management options when the use of end products or byproducts of treatment results in displacement of fossil fuels and displacement of the use of sources that adds GHG to the atmosphere such as electricity generation, production of chemical fertilizers
- Debiting CO_2 emission from fossils fuel consumption during the waste treatment processes applied for cassava pulp waste treatment is debits
- Debiting the direct emission of methane and nitrous oxide from the solid waste management options such as fugitive emissions from the anaerobic digestion or the emission from anaerobic pockets in compost pile

2.3.2. Calculation of GHG emissions

CDM Executive Board approved baseline and monitoring methodology[16] was followed to calculate GHG emissions from a waste treatment sub-models. The emission from a waste treatment sub-models can be calculated by dividing the activities into sub-categories. GHG emissions are calculated from the direct emissions from process, use of fossil fuels and electricity in the waste treatment sub-models.

GHG emissions from onsite fossil fuel consumption

$$\text{Fuel oil Emissions (ton CO}_2\cdot\text{ton}^{-1}\text{ of cassava pulp treated)} = \text{Fossil fuel (diesel) used on-site (liter}\cdot\text{ton}^{-1}\text{ of waste treated)} \times \text{Carbon emissions factor of diesel (ton CO}_2\cdot\text{liter}^{-1}\text{)} \qquad \text{Eqn. 2.1}$$

GHG emission from the use of purchased electricity

$$\text{Offsite Electricity Emissions (kg CO}_2\text{ eq. ton}^{-1}\text{ cassava pulp)} = \text{Electricity consumption (kWh}\cdot\text{ton}^{-1}\text{ of waste to composting facility)} \times \text{Carbon emissions factor of grid electricity (kg CO}_2\text{ eq. kWh}^{-1}\text{)} \qquad \text{Eqn. 2.2}$$

Direct emissions from the process (leakage, fugitive emissions)
Methane emissions from a waste treatment options can be determined as follows:

$$\text{CH}_4\text{ emissions from treatment process (ton CO}_2\text{ eq. day}^{-1}\text{)} = \text{Waste treated (ton}\cdot\text{day}^{-1}\text{)} \times \text{Emission factor for CH}_4\text{ (ton CH}_4\cdot\text{ton}^{-1}\text{ of waste treated)} \times \text{Global Warming Potential of CH}_4\text{ (GWPCH}_4\text{)} \qquad \text{Eqn. 2.3}$$

Nitrous oxide emissions from a waste treatment options can be determined as follows:

$$\text{N}_2\text{O emissions from treatment process (ton CO}_2\text{ eq. day}^{-1}\text{)} = \text{Waste treated (ton}\cdot\text{day}^{-1}\text{)} \times \text{Emission factor for N}_2\text{O (ton CH}_4\cdot\text{ton}^{-1}\text{ of waste treated)} \times \text{Global Warming Potential of N}_2\text{O (GWPN}_2\text{O)} \qquad \text{Eqn. 2.4}$$

GHG emission from transportation of waste and amendments
For a heavy load diesel truck emissions from the distance travelled can be calculated as

$$\text{Emissions from distance travelled (kg CO}_2\cdot\text{day}^{-1}\text{)} = \text{Distance travelled (km)} \times \text{Emission factor (kg CO}_2\cdot\text{km}^{-1}\text{)} \times \text{Number of vehicle}\cdot\text{day}^{-1} \qquad \text{Eqn. 2.5}$$

The total GHG emission is determined by adding the emissions from the different activities.

2.3.3. Calculation of GHG benefits

Conversion of waste to biofuels from waste-to-energy (WTE) conversion processes is one of a possible solution to mitigate GHG emissions. This WTE processes gives the benefit of emission avoidance by displacement of heat and electricity that will be generated from fossil fuels. The amount of fossil fuel or the unit of electrical energy displaced by the heat and electricity generated from the biofuels or the end products of waste treatment process can be calculated in terms of CO_2 eq.

The estimation of GHG offset is same as that of the emission from the fuel and electricity use but with negative values that signifies the amount of CO_2 eq. avoided from the use of biofuels. Thus, GHG benefits are calculated from the emission avoided from the use of biofuels and compost from the waste treatment sub-models. The GHG benefits or offsets from waste treatment can be calculated using the Eqn. 2.6 to Eqn.2.9.

GHG benefits (offsets) from onsite heat production

$$\text{On Site Heat Emissions (-ton CO}_2\text{ eq. day}^{-1}\text{)} = \text{Fossil fuel (diesel) displaced (-liters}\cdot\text{day}^{-1}\text{)} \times \text{Carbon emissions factor of diesel (ton CO}_2\text{ eq. liter}^{-1}\text{)} \qquad \text{Eqn 2.6}$$

GHG benefits from electricity production

$$\text{Offsite Electricity Emissions (-ton CO}_2\text{ eq. day}^{-1}\text{)} = \text{Electricity production displaced by biofuels (either used on system or exported to grid) (-kWh}\cdot\text{day}^{-1}\text{)} \times \text{Carbon emissions factor of electricity (ton CO}_2\text{ eq. kWh}^{-1}\text{)} \qquad \text{Eqn 2.7}$$

GHG benefits from the use of compost
If compost use replaces commercial nitrogen (N) fertilizer, then

$$\begin{array}{c}\text{Emissions}\\ \text{avoided}\\ (-\text{ton CO}_2\text{ eq. day}^{-1})\end{array} = \begin{array}{c}\text{Dry waste mass}\\ (\text{ton}\cdot\text{day}^{-1})\end{array} \times \begin{array}{c}\text{Total N in}\\ \text{waste}\\ (\%)\end{array} \times \begin{array}{c}\text{N fertilizer credit}\\ (-\text{ton CO}_2\text{ eq. ton}^{-1}\text{ N})\end{array} \quad \text{Eqn. 2.8}$$

If compost use replaces commercial phosphorus (P) fertilizer, then

$$\begin{array}{c}\text{Emissions}\\ \text{avoided}\\ (-\text{ton CO}_2\text{ eq. day}^{-1})\end{array} = \begin{array}{c}\text{Dry waste mass}\\ (\text{ton}\cdot\text{day}^{-1})\end{array} \times \begin{array}{c}\text{Total P in waste}\\ (\%)\end{array} \times \begin{array}{c}\text{P fertilizer credit}\\ (-\text{ton CO}_2\text{ eq./ton P})\end{array} \quad \text{Eqn. 2.9}$$

3. Results and discussions

3.1. Baseline GHG emission from waste management

The baseline GHG emission from cassava pulp waste management was estimated taking a case of Sanguan Wongse Industries Co., Ltd. (SWI) located in Nakhon Ratchasima province, Thailand.

GHG emission from present cassava pulp waste management practice is due to methane emission from the anaerobic degradation of cassava pulp during its storage in the industrial yards. The details of the cassava waste generation in SWI for baseline conditions (7 months) as a result of processing of cassava 3 500 ton of cassava root are as follows[18]:

Amount of cassava pulp waste generated (ton per day-wet basis) (Calculated from 0.3 ton of pulp per ton of roots processed)	=	1 050
Total time duration for storage of pulp (7 months from April to October) (days)	=	210
Total amount of cassava pulp waste (ton per year-wet basis)	=	220 500

Emission from decay of cassava pulp during its storage site was estimated using first order decay method[9]. The amount of waste decayed under anaerobic conditions was calculated from the first order decay method and the baseline emission from CH_4 emission was estimated using "Tool to determine methane emissions from the solid waste disposal sites"[13]. The summary of the GHG emissions from baseline conditions of cassava pulp waste management is as follows:

Total baseline GHG emission from CH_4 generation (ton CO_2 eq.) = 934.65
Total baseline GHG emission from CH_4 generation (ton CO_2 eq. per ton of cassava pulp) = 0.00 424
Total baseline GHG emission from CH_4 generation (kg CO_2 eq. per ton of cassava pulp) = 4.2

Therefore, the total baseline emission from the current cassava management practice at SWI is 4.2 kg CO_2 eq. ton^{-1} of cassava pulp waste.

3.2. GHG emission and benefits from waste treatment sub-models

GHG emission from the four waste treatment sub-models with different scenarios of waste treatment option and type of energy recovered was estimated using the GHG and energy accounting tool. The default, experimental and calculated values were used in the modeling of GHG emissions, benefits and energy recovery.

The accounting tool calculates the total annual GHG emission, and benefits from the waste treatment options. However, the results of summary of GHG and energy accounting are expressed as CO_2 eq. ton^{-1}

of waste treated. The comparison of GHG emission, benefits and net GHG impact of ten scenarios are done. The results of the GHG and energy modeling tool applied to a case study of Sanguan Wongse Industries Co., Ltd is presented in the Table 1. The potential of waste treatment option to mitigate GHG emissions are represented by negative values while the positive values represent the emissions of GHG.

Table 1. Net GHG emission and benefits from various waste management scenarios

Management options	GHG emission (kg CO_2 eq. ton^{-1} cassava pulp)	GHG Benefits (kg CO_2 eq. ton $^{-1}$ cassava pulp)	Net GHG impact (kg CO_2 eq. ton^{-1} cassava pulp)
Baseline emissions (Storage)	4.2	0.0	4.2
Biodrying and RDF (E)	79.0	-136.5	-57.5
Biodrying and RDF (H)	79.0	-164.1	-85.2
Composting (W)	23.9	-70.2	-46.2
Composting (I)	60.0	-70.2	-10.1
Anaerobic digestion (E)	32.9	-116.0	-83.1
Anaerobic digestion (H)	32.9	-68.3	-35.4
Landfilling (E)	28.7	-12.8	15.9
Landfilling (H)	28.7	-8.2	20.5
Landfilling (F)	71.7	-43.0	28.7

Note: the letter in parenthesis denotes the following scenarios in four waste treatment models
(E) - Scenario with energy recovery in the form of electricity
(H) - Scenario with energy recovery in the form of heat
(F) - Scenario with flaring of LFG
(W) - Scenario with open air windrow composting
(I) - Scenario with in-vessel composting

Table 1 presents the GHG emission associated with various treatment scenarios for one ton of cassava pulp waste. GHG benefits is determined by calculating the GHG emissions avoided from the use of end products of waste treatment process such as use of biofuels i.e. RDF in biodrying and RDF scenario, biogas in anaerobic digestion and LFG in landfill option. Similarly in composting option, benefits are calculated from emissions avoided from use of chemical fertilizers by using the compost generated.

Benefits represent the potential of the waste treatment scenarios to offset or sequester carbon mitigating GHG emissions thus are given negative sign. The net GHG emission is calculated after considering total GHG emission and benefits of the various treatment scenarios. The benefit from baseline scenario i.e. storage of cassava pulp waste is regarded considered as zero as the potential value of the cassava pulp waste has not been utilized.

3.2.1. GHG emissions from treatment scenarios

The comparison of results from Table 1 presents that the biodrying and RDF options have the highest GHG emissions of 79 kg CO_2 eq. ton^{-1} cassava pulp among the four treatment options. Similarly, landfilling option with flaring has second highest GHG emissions of 71.7 kg CO_2 eq. ton^{-1} cassava pulp followed by In-vessel composting with 60 kg CO_2 eq. ton $^{-1}$ cassava pulp. Among the four waste treatment options, open windrow composting has the lowest GHG emission of 23.9 kg CO_2 eq. ton^{-1} cassava pulp. High GHG emissions in biodrying and RDF option are from consumption of energy in biodrying, densification and air pollution control processes. Likewise, higher emissions in landfilling option with flaring scenario is due to fugitive emissions during the flaring of LFG and lower efficiency of flaring system (considered as 50 % efficient in this study)[14]. Similarly, emissions results from In-vessel composting are from energy consumption. In-vessel systems are more energy intensive than open windrow composting. Similarly, emissions in anaerobic digestion are mainly due to energy consumption and fugitive emissions from the process.

3.2.2. GHG benefits

The GHG benefits from the different waste management scenarios are calculated based on the recovery of energy and use of end product. GHG benefits are the potential of the treatment options to offsets GHG emission or cause carbon sequestration. The baseline scenario with cassava pulp storage shows no benefits or potential for GHG mitigation. It is revealed from the Table 1 that biodrying and RDF option with heat and electricity recovery scenario showed high potential to mitigate GHG with values of -164.1 kg CO_2 eq. ton^{-1} and -136.5 kg CO_2 eq. ton^{-1} cassava pulp respectively. Similarly, anaerobic digestion with electricity recovery scenario has good GHG mitigation potential of -116 kg CO_2 eq. ton^{-1} cassava pulp treated. Composting gives the benefits of -70.2 kg CO_2 eq. ton^{-1} cassava pulp treated. Landfilling options with LFG collection has less benefits or GHG mitigation potential.

3.2.3. Net GHG impact

The net GHG impact of waste treatment scenarios presented in Table 1 gives the net GHG emissions and benefits. The negative value is the potential to minimize GHG impact while the positive value means the treatment options is contributing in GHG emission. It is shown from Table 1 that biodrying and RDF with heat generation scenario has the highest GHG mitigating potential of -85.2 kg CO_2 eq. ton^{-1} cassava pulp treated followed by anaerobic digestion with electricity recovery of -83.1 kg CO_2 eq. ton^{-1} cassava pulp treated. Landfill sub-model with flaring options has the highest GHG impact (28.7 kg CO_2 eq. ton^{-1} cassava pulp).

3.3. Energy balance in waste treatment options

Energy balance was conducted for the three waste-to-energy (WTE) conversion sub-models namely biodrying and RDF, anaerobic digestion and landfill. These energy balances were analyzed with the help of two indicators, Net Energy Gain (NEG) and Net Energy Ratio (NER). NEG is the difference between the total energy outputs and total energy inputs and NER is the ratio of total energy outputs to total energy inputs[19]. The energy input to the system and the energy recovered from the system gives the energy recovery efficiency of WTE conversion systems. The sub-models are analyzed for the energy input in all processes from the transportation of waste and amendments, electricity requirements, fuel requirements in the unit processes and the energy recovered in the form of heat and or electricity from the end products of WTE systems.

Two scenarios are generated for the analysis of three WTE sub-models. The first scenario is the energy recovery in the form of electricity and the second scenario is the energy recovery in the form of heat. The results of the energy balances and energy efficiency of biofuels and process for electricity recovery of three WTE options is presented in the Fig 1. Net Energy Ratio (NER)electricity for biodrying and RDF, anaerobic digestion and landfilling for this scenario were 1.43, 5.20 and 2.06.

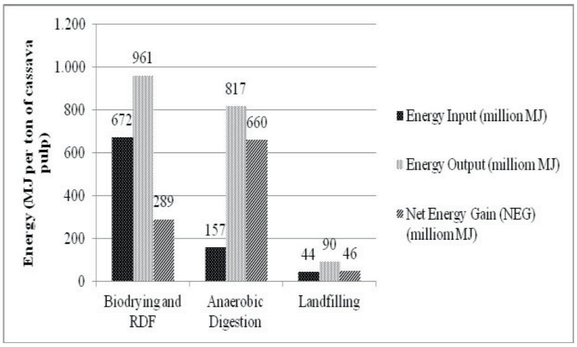

Fig. 1. Energy balance for WTE considering electricity recovery

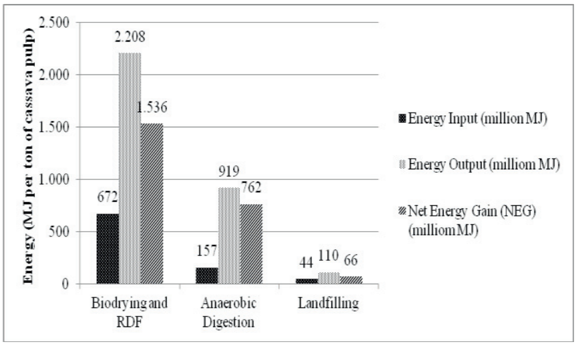

Fig. 2 Energy balance for WTE considering heat recovery

As NEG represents the energy efficiency of the biofuels, biogas generated from anaerobic digestion is shown as the most efficient biofuels with highest NEG value (659 MJ · ton^{-1} of cassava pulp waste treated) than RDF (289 MJ · ton^{-1} of cassava pulp waste treated) and LFG (46 MJ · ton^{-1} of cassava pulp waste treated). Similarly, anaerobic digestion process was more efficient than other WTE process as it has the NER for anaerobic digestion process is 5.20 in comparison with NER value of 1.43 and 2.06 respectively for biodrying and RDF and landfilling options with LFG recovery.

The analysis of WTE systems for recovery of heat energy is determined and the energy balance is presented in the Fig 2. Fig 2 indicate that RDF used for generating heat energy shows the better efficiency than other biofuels as shown by NEG value of 1 536 MJ · ton^{-1} cassava pulp treated. Biogas also demonstrated better efficiency for heat conversion as given by NEG of 762 MJ · ton^{-1} cassava pulp treated. However, the process efficiency of anaerobic digestion is higher than other WTE process as demonstrated by the NER value of 5.85 in comparison with NER value of 3.29 and 2.50 of biodrying and landfilling options.

4. Conclusions

The baseline GHG emissions from the storage of cassava waste from the industrial yard are estimated as 4.4 kg CO_2 eq. per ton cassava pulp. Biodrying followed by RDF production scenario has the highest GHG mitigating potential of -85.2 kg CO_2 eq. ton^{-1} cassava pulp treated while emissions from the landfill model with flaring options have the highest impact for GHG emissions with 28.7 kg CO_2 eq. ton^{-1} cassava pulp. The result of the analysis of waste treatment options for energy recovery shows that biodrying and RDF options have good potential for energy recovery. For heat generation, RDF shows high efficiency while biogas system has higher electrical conversion efficiency. Anaerobic digestion option is more attractive for conversion of biogas to heat and electricity. Thus, anaerobic digestion of cassava pulp waste offers duel advantage of higher GHG mitigation with energy recovery.

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